DEVELOPMENT AND VALIDATION OF A SOUTH AFRICAN ENGLISH SMARTPHONE-BASED SPEECH-IN-NOISE HEARING TEST

by

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A thesis submitted in fulfilment of the requirement for the degree

D. Phil. (Communication Pathology)

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Firstly, to the Lord my God:

Phillippians 4:13

“I can do all things through Christ which strengheneth me”. KJV

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PUBLICATIONS AND RESEARCH OUTPUTS

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ABSTRACT

Title: Development and validation of a South African English smartphone-based speech-in-noise hearing test

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Approximately 80% of the adult and elderly population ≥65 years have not been assessed or treated for a hearing loss, despite the effect a hearing loss has on communication and quality of life (World Health Organization [WHO], 2013a). In South Africa, many challenges to the health care system exist of which access to ear and hearing health care is one of the major problems. This study aimed to develop and validate a smartphone-based digits-in-noise hearing test for South African English towards improved access to hearing screening. The study also considered the effect of hearing loss and English speaking competency on the South African English digits-in-noise hearing test to evaluate its suitability for use across native (N) and non-native (NN) speakers. Lastly, the study evaluated the digits-in-noise test's applicability as part of the diagnostic audiometric test battery as a clinical test to measure speech recognition ability in noise.

During the development and validation phase of this study the sample size consisted of 40 normal-hearing subjects with thresholds ≤15 dB across the frequency spectrum

(250 – 8000 Hertz [Hz]) and 186 subjects with normal-hearing in both ears, or normal-hearing in the better ear. Single digits (0 – 9) were recorded and spoken by a N English female speaker. Level corrections were applied to create a set of homogeneous digits with steep speech recognition functions. A smartphone application (app) was created to utilize 120 digit-triplets in noise as test material. An adaptive test procedure determined the speech reception threshold (SRT). Experiments were performed to determine headphones effects on the SRT and to establish normative data. The results showed steep speech recognition functions with a slope of 20%/dB for digit-triplets presented in noise using the smartphone app. The results of five headphone types indicate that the smartphone-based hearing test is reliable and can be conducted using standard Android smartphone headphones or clinical headphones.

A prospective cross-sectional cohort study of N and NN English adults with and without sensorineural hearing loss compared pure-tone air conduction thresholds to the SRT recorded with the smartphone digits-in-noise hearing test. A rating scale was used for NN English listeners' self-reported competence in speaking English. This study consisted of 454 adult listeners (164 male, 290 female; range 16 – 90 years), of which 337 listeners had a best ear 4 frequency pure-tone average (4FPTA; 0.5, 1, 2 and 4 kHz) of ≤25 dB hearing level (HL). A linear regression model identified three predictors of the digits-in-noise SRT namely 4FPTA, age and self-reported English speaking competence. The NN group with poor self-reported English speaking competence (≤5/10) performed significantly ($p<0.01$) poorer than the N & NN (≥6/10) group on the digits-in-noise test. Screening characteristics of the test improved with separate cut-off values depending on self-reported English

speaking competence for the N & NN (≥6/10) group and NN (≤5/10) group. Logistic regression models, that include age in the analysis, showed a further improvement in sensitivity and specificity for both groups (area under the receiver operator characteristic curve [AUROC] .962 and .903 respectively).

A descriptive study evaluated 109 adult subjects (43 male, 66 female) with and without sensorineural hearing loss by comparing pure-tone air conduction thresholds, speech recognition monaural performance score intensity (SRS dB) and the digits-in-noise SRT. An additional nine adult hearing aid users (4 male, 5 female) was utilized in a subset to determine aided and unaided digits-in-noise SRTs. The digits-in-noise SRT was strongly associated with the best ear 4FPTA (r=0.81) and maximum SRS dB (r=0.72). The digits-in-noise test had high sensitivity and specificity to identify abnormal pure-tone (0.88 and 0.88 respectively) and SRS dB (0.76 and 0.88 respectively) results. There was a mean signal-to-noise ratio (SNR) improvement in the aided condition that demonstrated an overall benefit of 0.84 dB SNR. A significant individual variability between subjects in the aided condition (-3.2 to -9.4 dB SNR) and unaided condition (-2 to -9.4 dB SNR) was indicated.

This study demonstrated that a smartphone app provides the opportunity to use the English digits-in-noise hearing test as a national test for South Africans. The smartphone app can accommodate NN listeners by adjusting reference scores based on a self-reported English speaking competence. The inclusion of age when determining the screening test result increases the accuracy of the screening test in normal-hearing listeners. Providing these adjustments can ensure adequate test performance across N English and NN English listeners. Furthermore, the digits-in-

noise SRT is strongly associated with the best ear 4FPTA and maximum SRS dB and could therefore provide complementary information on speech recognition impairment in noise in a clinical audiometric setting. The digits-in-noise SRT can also demonstrate benefit for hearing aid fittings. The test is quick to administer and provides information on the SNR loss. The digits-in-noise SRT could therefore serve as a valuable tool in counselling and management of expectations for persons with hearing loss who receives amplification.

KEYWORDS

Adult hearing screening

Digits-in-noise

Hearing in noise

Hearing loss

Hearing screening

Hearing test

National hearing screening test

Native

Non-native

Signal-to-noise ration

Smartphone application

Smartphone hearing test

South Africa

Speech recognition in noise

Speech-in-noise

ABBREVIATIONS

AIC:	Akaike information criterion
ANCOVA:	Analysis of covariance
ANOVA:	Repeated measure analysis of variance
App:	Application
AUROC:	Area under the receiver operator characteristic curve
BIC:	Bayesian information criterion
dB:	Decibel
DIN:	Digits-in-noise test
4FPTA:	Four frequency pure tone average
GBD:	Global Burden of Disease
HL:	Hearing level
Hz:	Hertz
IC4D:	Information and Communication for Development
ISO:	International Standards Organization
N:	Native
NN:	Non-native
NPV:	Negative predictive variable
PPV:	Positive predictive variable
ROC:	Receiver operator characteristic curve
SPL:	Sound Pressure Level
SNR:	Signal-to-noise ratio
SRS:	Speech recognition monaural performance score
SRT:	Speech reception threshold

STATSSA: Statistics South Africa

WHO: World Health Organization

WMA: World Medical Association

CHAPTER 1

INTRODUCTION

1.1. Background

Hearing loss is estimated to affect 33% of adults over the age of 65 years across the world (WHO, 2013a). Sub-Saharan Africa, Asia Pacific and South Asia have the highest estimated prevalence of hearing loss in people over 65 years in the world (WHO, 2013a). An estimated 6.4% of adults older than 15 years of age have a disabling hearing loss in sub-Saharan Africa (WHO, 2013a). Audiology service delivery in sub-Saharan countries is very limited as audiology services have only increased by 2.5% from 2009 to 2015 (Mulwafu, Ensink, Kuper & Fagan, 2017). This means that little progress had been made to implement ear and hearing service delivery across these countries (Mulwafu et al., 2017). As a result, many people will not be able to access ear and hearing services due to inaccessibility to the health care system (Mulwafu et al., 2017).

The latest Global Burden of Disease study (GBD) indicates that 1.33 billion people suffer from hearing loss making it the 2nd most common impairment evaluated (GBD, 2016). Approximately 2.67 million people with a hearing loss reject the use of hearing aids despite the adverse effect that a hearing loss has on health (Smits, Kramer & Houtgast, 2006a; Davis, Smith, Ferguson, Stephens & Gianopoulos, 2007; Kochkin, 2007; Watson, Kidd, Miller, Smits & Humes, 2012). The impact of hearing loss can be reduced effectively by using amplification devices such as hearing aids, FM microphones, assistive listening devices, counselling and aural rehabilitation that

have demonstrated the ability to improve quality of life, cognitive functioning and delays the onset of auditory deprivation (Arlinger, 2003; Boothroyd, 2007; Davis et al., 2016; Simpson, Simpson & Dubno, 2016). Early identification of hearing loss in adults is important to ensure opportune diagnosis, counselling, prompt medical referral, assistive listening devices and aural rehabilitation (Kiessling et al., 2003; Swanepoel, Eikelboom, Hunter, Friedland & Atlas, 2013; Willot, 1991; WHO, 2013a).

1.2. Early detection of hearing loss in adults with speech-in-noise tests

Hearing loss in adults can be identified at an early stage by using various hearing screening techniques. Some of the techniques include pure-tone audiometry, otoacoustic emissions, self-reported hearing disability questionnaires and speech-in-noise hearing screening tests (Smits, Goverts & Festen, 2013; Swanepoel et al., 2013).

Speech-in-noise hearing screening tests have become popular over the last ten years as the greatest difficulty encountered by the hearing impaired is to understand speech in background noise (Jansen, Luts, Wagener, Frachet & Wouters, 2010; Smits et al., 2013; Koole et al., 2016). Conventional pure-tone audiometry is not sufficient to evaluate the everyday speech in noise on account of the poor relationship between the 4FPTA and speech in noise understanding (Smits, et al., 2013). In 2004 the first speech-in-noise hearing screening test that can be performed telephonically was reported (Smits, Kapteyn & Houtgast, 2004).

This speech-in-noise hearing screening test presents with several qualities that make it appropriate to be used as a screening test. Laypersons can conduct the test, a fully automatic test can be developed, tests can be conducted in a few minutes and the test is sensitive to a hearing loss (Jansen et al., 2010; Smits et al., 2004; Zokoll, Wagener, Brand, Buschermöhle & Kollmeier, 2012; Koole et al., 2016). The limitations to the speech-in-noise hearing screening test discussed by Smits & Houtgast (2005) include speech material that may sound distorted to a hearing impaired person. People may respond incorrectly to the test if they do not understand the instructions. Furthermore, the speech-in-noise hearing screening test does not measure pure-tone thresholds, but merely the ability to understand speech in noise (Smits et al., 2013; Koole et al., 2016).

The speech-in-noise hearing screening test is operated by varying the speech intensity level while having a fixed noise level at 65 dB sound pressure level (SPL) (Jansen et al., 2010; Smits et al., 2004). The noise starts 500 ms and end 500 ms after the triplet presentation (Jansen et al., 2010). The digits are spoken by a female speaker with natural pauses between digits, for example 2-5-1, spoken as two-five-one. The first digit-triplet speech set is presented repeatedly while raising the speech intensity (step size 4 dB) until the digits is entered correctly. The digit-triplet speech set is automatically increased (incorrect answer) or decreased (correct answer) by 2 dB, depending on the subject's response (Smits et al., 2004).

Smits, Kramer and Houtgast (2006a) named the Dutch digit-triplet test the National Hearing Test and successfully launched this speech-in-noise hearing screening test in the Netherlands, January 2003. Within the first 4 months 65 000 people dialed the

test. After two and a half years >159 000 people used the screening test (Jansen et al., 2010; Smits & Hougast, 2005; Smits et al., 2004). Smits, Merkus and Houtgast (2006b) also found that 50% of callers, who failed the screening test, obtained a diagnostic hearing test (Jansen et al., 2010; Smits, Merkus & Houtgast, 2006b). This provides evidence of the large interest and need for an easily accessible hearing screening test (Jansen et al., 2010; Smits & Hougast, 2005; Smits et al., 2004). Due to the successful performance of the National Hearing Test, the United Kingdom, Australia, Germany, Poland, Switzerland and France also developed a similar digit-based telephone screening test in different languages (Watson et al., 2012). It is therefore ideal to develop an objective speech-in-noise hearing test that could be conducted as a self-test in the comfort of a home setting (Jansen et al., 2010).

1.3. Rationale

According to the global estimates updated version of the WHO Burden of Disease: DALY Part 4, hearing loss is estimated to rank third on the list of non-fatal disabilities in the world (WHO Burden of Disease: DALY Part 4, 2004). Despite the fact that hearing loss is a major concern in developing countries, ear and hearing health care services are mostly inaccessible (Fagan & Jacobs, 2009; WHO, 2013b). A major barrier in South Africa is also related to limited access to audiologists and audiology service delivery (Malwafu et al., 2017). In 2009 there was an estimated 490 audiologists compared to 444 in 2015 per 100,000 people in South Africa of whom most audiologists reside in cities, because governmental audiology services are under-sourced, understaffed and outdated (Malwafu et al., 2017; Fagan & Jacobs, 2009; Theunissen & Swanepoel, 2008).

Geographic accessibility and proximity to health care clinics has a direct influence in the development of health care services (Arcury, Gesler, Preisser, Spencer & Perin, 2005; Buor, 2003; Gething et al., 2004; Tanser, Gijsbertsen & Herbst, 2006). Temporal and spatial coverage by public transport is sporadic, unreliable and expensive. In the rural areas in South Africa, walking is the primary mode of transportation (Tanser et al., 2006; Tanser, Hosegood, Benzler & Solarsh, 2001). People living in rural areas in South Africa will therefore find it difficult to access audiology services and hearing screening because of under-sourced, understaffed, and outdated Ear- Nose and Throat specialist and audiology services in Africa (Mulwafu et al., 2017). A speech-in-noise hearing test developed and modified to accommodate a multilingual client population, may offer a way to provide widespread access to identify and refer a person with a hearing loss to a health care clinic where diagnosis can be made at an early stage (Davis et al., 2007; Kaandorp, De Groot, Festen, Smits & Goverts, 2016). Using a smartphone app with a headphone can bring a speech-in-noise hearing test into areas that were previously inaccessible for audiology screening.

Innovation follows a “mobile first” developmental trajectory in developing countries, because mobile technology enhances human development, providing access to education and health information (Information and Communication for Development [IC4D], 2012). Mobile phones are relatively inexpensive and have low airtime recharge costs; therefore more people in developing countries possess mobile phones than having access to a bank account, electricity and clean water (IC4D, 2012). In South Africa a National Household Survey indicated that 79.5% of South Africans have access to only a mobile phone, 0.3% of South Africans have access to

only a landline telephone and 13.9% of South Africans have access to both a mobile phone and landline telephone (STATSSA, 2013). A smartphone app based speech-in-noise hearing test in South Africa may provide access to rural and urban areas of different socio-economic levels.

South Africa is a multicultural and multilingual country, therefore posing challenges to speech-based testing. The South African census of 2011 reported 11 official spoken languages in South Africa (Statistics South Africa [STATSSA]: Census, 2011; Draft Language Policy for Statistics South Africa, 2016). Multilingualism is a challenge in South Africa as language proficiency depends on a person's linguistic profile in terms of age, number of languages spoken and the age the additional language was acquired (Ramkissoon & Khan, 2003). Linguistic diversity can impose limitations to audiology service delivery due to language misunderstanding (Ramkissoon & Khan, 2003). The choice of speech material is essential in developing a speech-in-noise hearing test for South Africa, because the test should accommodate and be accessible by all South Africans. Therefore, digit-triplets might be a solution, as digits are highly familiar spoken words, it is a closed set pattern (digits 0-9), it depends on low linguistic demands and numerous South Africans from different linguistic backgrounds use English numerals (Branford & Claughton, 2002; Smits et al., 2013). A digit-triplet speech-in-noise hearing test may therefore provide a means by which South Africans can access a hearing test using a smartphone-based South African English speech-in-noise hearing test.

The aim of this study was therefore to develop and validate a smartphone-based speech-in-noise test for detection of hearing loss in South Africa.

CHAPTER 2

METHODOLOGY

2.1. Research objectives

This study developed and validated a South African English digits-in-noise hearing test. The effect of age, hearing loss, speaking competence and gender of N and NN South African English speakers were determined and the test's suitability as part of the audiometric test battery was evaluated.

Research objectives were determined to create a research article for submission to an accredited peer-reviewed journal. Table 2.1 summarises three research objectives according to titles, objectives, and peer-reviewed journals to which the research articles were submitted.

Table 2.1. A summary of the study according to the titles, objectives and journal submissions

Research study	I	II	III
Title	Development and validation of smartphone-based digits-in-noise hearing test in South African English.	The South African English smartphone digits-in-noise hearing test: Effect of age, hearing loss and speaking competence.	Evaluating a smartphone digits-in-noise test as part of the audiometric test-battery.
Objectives	To develop and validate a digits-in-noise hearing test in South African English. • Selecting and recording speech material to develop a digits-in-noise hearing screening test for South Africa. • Determine the psychometric functions of single stimuli. • Based on the psychometric functions of the stimuli, level corrections of the stimuli were conducted. • Evaluating of the digits-in-noise hearing screening test on normal-hearing N English speaking listeners. • Evaluating of the digits-in-noise hearing screening test on hearing impaired N English speaking listeners (mild – profound hearing loss). • Determine the cut-off values for "pass" and "refer" criteria and compared the digits-in-noise SRT to the 4FPTA. • Determine the effect of different headphone/earphone types on the digits-in-noise SRT.	To evaluate the South African English smartphone digits-in-noise hearing test on English N and NN language listeners. • Evaluating the South African digits-in-noise hearing test's suitability for use as a national hearing screening test. • Determine the effect of language differences and the possible interaction with hearing loss on the South African English smartphone digits-in-noise SRT. • Determine the cut-off values for "pass" and "refer" criteria for NN English listeners. • Determined the relationship between the digits-in-noise SRT and age. • Provide adjustments to the smartphone digits-in-noise app to accommodate NN English listeners to conduct the test.	To determine the South African digit-in-noise hearing test's applicability in a clinical audiometric setting. • Determine the relationship between the digits-in-noise SRT, best ear 4FPTA and best ear SRS dB HL. • Determine the digits-in-noise SRT in aided and unaided hearing aid conditions. • Provide recommendations on the clinical use of the digits-in-noise hearing test in counselling and hearing aid adjustments.
Journal	International Journal of Audiology (Accepted)	Ear and Hearing (Accepted)	South African Journal of Communication Disorders (Submitted)
Chapter in Thesis	3	4	5

2.2. Ethical considerations

The research project was approved by the Faculty of Humanities Research Proposal and Ethics Committee 24 April 2014 (Appendix A) and the Health Science Ethical Committee 27 June 2014 (Appendix B) of the University of Pretoria. The research study was conducted according to the ethical guidelines set out by the World Medical Association (WMA) Declaration of Helsinki (2013) and the WHO (2011). The ethical principles are presented and dicussed in Table 2.2.

Table 2.2. Ethical principles applied to during the preparation of the research design, participant selection, data collection and data analysis procedures (WMA Declaration of Helsinki, 2013; WHO, 2011)

Ethical Principle	Application to Study
The research proposal was submitted for consideration, comment, guidance and approval to the research ethical committee of the University of Pretoria (WMA Declaration of Helsinki, 2013).	The study only commenced after ethical clearance had been granted by the Faculty of Humanities Research Proposal and Ethics Committee of the University of Pretoria (Appendix A and C), the Health Science Ethical Committee of Steve Biko Academic Hospital and Tshwane District Hospital (Appendix B and E), the Health Science Ethical Committee of Fezi Ngubentombi Hospital (Appendix D) and a private audiologist practitioner in Pretoria (Appendix F).
The researcher was ethically obliged to be experienced, truthful and capable to conduct the various audiometric tests (WMA Declaration of Helsinki, 2013; De Vos, Strydom, Fouché & Delport, 2011).	The researcher ensured competence due to her qualification as an Audiologist. The research was supervised to ensure a seamless research process. All the professionals involved in the study were registered with the Health Professions Council of South Africa.
The researcher did not expose the subjects to any form of anxiety, discomfort, physical or psychological discomfort that could have raised from the research study, within all probable realistic limits (WMA Declaration of Helsinki, 2013; De Vos et al., 2011).	The welfare of the subjects was held paramount in this study. The research involved non-invasive audiometric testing which included an otoscopic examination, tympanometry, pure-tone air and bone conduction audiometry, speech testing, the smartphone-based digits-in-noise hearing test and a language competence questionnaire, thus no harm was inflicted.
All research participation was voluntary and informed consent was provided by the subjects. The research subjects were also informed on the aims, methodology, potential risk and benefit of the research study (WMA Declaration of Helsinki, 2013).	Permission was obtained to use subjects from the Steve Biko Academic Hospital, Tshwane District Hospital, and private audiology practices in Pretoria. • The research proposal was reviewed by the Faculty of Health Science Research Ethics Committee of the University of Pretoria in terms of the National Health Act as well as the policy (Rt 429/99) to gain ethical clearance at the Steve Biko Academic Hospital and Tshwane District Hospital. • A letter explaining the purpose of the research was provided to two audiology private practices (Appendix H). The audiologist provided written informed consent to partake in the research (Appendix F). Each patient received a letter explaining the research and requesting permission to partake in the research. The patient provided written informed consent to partake in the research. o Each participant received an English informed consent letter before the testing commenced (Appendix G). o The letter described the nature of the components of the study, and the terms and conditions for participation. The letter also stated that participation is voluntary, and that subjects could withdraw from the study at any time. Contact details of the researcher and study supervisor was provided whenever the subjects had any questions. Subjects needed to sign the letter of informed consent before the testing began.

Caution was taken to maintain confidentiality of subject information at all times (WMA Declaration of Helsinki, 2013).	Every subject had the right to privacy and the decision to what range his or her behaviour, attitudes, beliefs and test results would be exposed. It was the duty of the researcher to respect the privacy of the subjects and to act with understanding where privacy of subjects was pertinent (De Vos et al., 2011; Leedy & Ormrod, 2014). By no means was any audiological or clinical results presented in such a way that others became aware of the subject's test results, unless the subject had granted permission for disclosure (Leedy & Ormrod, 2014). Confidentiality of subject information was maintained. No names were used when describing the subjects and codes were assigned to each subject in the research report.
Accurate results of the research study were provided in each publication (WMA Declaration of Helsinki, 2013).	A research report was made available to the scientific community upon completion (Struwig & Stead, 2001). The report contained all the information necessary for the readers to understand what had been investigated and the outcomes of the investigation (De Vos et al., 2011). The subjects were informed that the research might be published as a journal article, discussed at conferences, seminar presentations, and academic gatherings which adhere to ethical considerations.
All literature references were acknowledged when cited in the research report (WMA Declaration of Helsinki, 2013; Struwig & Stead, 2001).	Plagiarism was avoided by acknowledging all professionals who contributed to an integral part of this research project and development of the smartphone-based digits-in-noise hearing test.

2.3. Research design

The developmental phase of study I followed a developmental research design and the validation phase of study I followed a quantitative cross-sectional research design (Leedy & Ormrod, 2014; De Vos et al., 2011). Study II and III followed a descriptive cross-sectional research design (Leedy & Ormrod, 2014). All research methods were quantitative in nature (Leedy & Ormrod, 2014). A summary of the research designs are provided in Table 2.3.

2.4. Research context

The research was conducted at the Steve Biko and Tshwane District hospitals in Pretoria in the Gauteng Province and the Fezi Ngubentombi hospital in Sasolburg in the Free State Province. Students from the Department of Speech-Language Pathology and Audiology at the University of Pretoria assisted with data collection at as well as two private audiology practices in the Gauteng Province.

2.5. Research participants

The research study included a total of 463 N and NN English speakers. A detailed summary of the participant selection criteria, sample size and characteristics are provided in Table 2.3.

Table 2.3. Research design and participants

Study	I	II	III
Title	Development and validation of smartphone-based digits-in-noise hearing test in South African English.	The South-African English smartphone digits-in-noise hearing test: Effect of age, hearing loss and speaking competence.	Evaluating a smartphone digits-in-noise test as part of the audiometric test-battery.
Study design	**Developmental phase:** A developmental research design was followed (Leedy & Ormrod, 2014). **Validation phase:** A quantitative cross-sectional research design with a comparative component (De Vos et al., 2011).	**Comparative and Correlational study:** A descriptive research design that examined the degree to which differences in one variable were related to differences in another variable was followed (Leedy & Ormrod, 2014).	**Correlational study:** A descriptive research design examining the degree to which differences in one variable were related to differences in another variable was followed (Leedy & Ormrod, 2014).
Participant selection criteria	Probability cluster sampling approach (de Vos et al., 2011; Monette, Sullivan & De Jong, 2005)		
Sample size and study sample characteristics	**Study sample:** 206 N English speaking normal-hearing listeners were used in this study. **Characteristics of the study sample:** • Pure-tone audiogram recorded at 250-8000 Hz. Pure-tone thresholds in the better ear did not exceed 15 dB HL at any octave frequency (International Standards Organization [ISO] 389-1, 1998). • Tympanometry indicated normal middle ear function.	**Study sample:** 454 N and NN English speaking listeners with normal or impaired hearing. **Characteristics of the study sample:** • Pure-tone audiogram recorded at 250-8000 Hz. • Normal-hearing was classified as pure-tone thresholds not exceeding 15 dB HL at any octave frequency (ISO 389-1, 1998). • Hearing losses of mild – profound degrees were included. • Tympanometry indicated normal middle ear function.	**Study sample:** 109 N or NN English speaking subjects with normal or impaired hearing. **Characteristics of the study sample:** • Pure-tone audiogram recorded at 250-8000 Hz. • Normal-hearing was classified as pure-tone thresholds not exceeding 15 dB HL at any octave frequency (ISO 389-1, 1998). • Hearing losses of mild – profound degrees were included. • Tympanometry indicated normal middle ear function.
Chapter in Thesis	3	4	5

2.6. Research equipment

A detailed summary of the equipment used during data collection for studies I, II and III are provided separately in Table 2.4.

Table 2.4. Summary of research equipment and intended use

Study	I	II	III
Title	Development and validation of smartphone-based speech-in-noise hearing screening test in South African English.	The South African English smartphone digits-in-noise hearing test: Effect of age, hearing loss and speaking competence.	Evaluating a smartphone digits-in-noise test as part of the audiometric test-battery.

Equipment and apparatus	• **Otoscope:** ReddyLite™
	• **Tympanometer:** A diagnostic tympanometer was used to determine the external ear canal volume, middle ear pressure and tympanic membrane compliance (Martin & Clark, 2003).
	• **Audiometry:** A diagnostic audiometer was used to determine hearing sensitivity at octave frequencies (250 – 8000 Hz).
	• **Disposable foam tips**
	• **Digits-in-noise hearing screening test:**
	  ○ *Developmental phase:* The test was conducted on a computer with headphones for data collection purposes.
	  ○ *Validation phase:* The digits-in-noise test was developed as a smartphone app.
	• **Smartphones:** 1 Samsung Trend, 4 Vodafone Smart Kicka.
	• **Headphones/earphones:** Three intraconchal earphones were used that accompanied the Vodafone Smart Kicka, Samsung S4 mini and Samsung S5. Headphones included a Sennheiser HD 202 II headphone and a TDH 50-P audiometric headphone.
	• **Acer laptop computer**
		• **Otoscope:** ReddyLite™
		• **Tympanometer:** A diagnostic tympanometer was used to determine the external ear canal volume, middle ear pressure and tympanic membrane compliance (Martin & Clark, 2003).
		• **Audiometry:** A diagnostic audiometer was used to determine hearing sensitivity at octave frequencies (250 – 8000 Hz).
		• **Disposable foam tips**
		• **Digits-in-noise hearing screening test:** The digits-in-noise test was conducted on a smartphone using a downloadable smartphone app.
		• **Acer laptop computer**
		• **Smartphones:** 1 Samsung Trend, 4 Vodafone Smart Kicka.
		• **Headphones:** Sennheiser HD 202 II headphone.
			• **Otoscope:** ReddyLite™
			• **Tympanometer:** A diagnostic tympanometer was used to determine the external ear canal volume, middle ear pressure and tympanic membrane compliance (Martin & Clark, 2003).
			• **Audiometry:** A diagnostic audiometer was used to determine hearing sensitivity at octave frequencies (250 – 8000 Hz) and SRS dB HL.
			• **Disposable foam tips**
			• **Digits-in-noise hearing test:** The digits-in-noise test was conducted on a smartphone using a downloadable smartphone app.
			• **Acer laptop computer**
			• **Smartphones:** 1 Samsung Trend, 4 Vodafone Smart Kicka.
			• **Headphones:** Sennheiser HD 202 II headphone.

2.7. Research procedures

The various research sites (Steve Biko Hospital, Tshwane District Hospital, Fezi Ngubentombi Hospital, private audiology practices and the Department of Speech-Language Pathology and Audiology at the University of Pretoria) were contacted and informed of the research project after ethical clearance was obtained from the Faculty of Humanities and the Faculty of Health Science at the University of Pretoria. Qualified audiologists were involved in the data collection. A site visit was conducted by the researcher to determine whether the relevant audiometric equipment was available at the data collection site and the data collection procedures were discussed with the audiologist. Each site provided written informed consent to participate in the research study. Students from the Department of Speech-Language Pathology and Audiology at the University of Pretoria received training in the specific procedures for the research project was supervised by a qualified audiologist at the Stanza Clinic.

2.7.1. Data collection material

Each research site provided the participants with a letter that explained all the test procedures in detail before testing commenced (Appendix G). The participant signed the informed consent form after he/she read through the procedure letter and understood the procedures to be conducted for the research project (Appendix G). An audiogram was used to record audiometric data (Appendix I) and a language speaking competence questionnaire was completed by each participant (Appendix J). An Excel data sheet was used to analyze the data.

2.7.2. Data collection procedures

A letter of informed consent was submitted to the various sites and institutions for data collection (Steve Biko Hospital, Tshwane District Hospital, Fezi Ngubentombi Hospital, private audiology practices and the Department of Speech-Language Pathology and Audiology at the University of Pretoria). The sites and institutions provided written informed consent to participate in the research study.

2.7.2.1. Study I: Data collection procedures

The developmental phase of the digits-in-noise test included the following procedures:

- A female N South African English speaker was used for the voice recording.
- Recorded digits were equalized with respect to their recognition probability. Digits were equalized by applying level corrections to the digits ensuring that each digit had a 50% chance of being recognized correctly at the same SNR.
- Four lists of 100 digits were created and presented on a laptop computer using a headphone set (Sennheiser HD 201).
- Each list consisted of 10 digits combined with the masking noise at fixed SNR's (-2, -4, -6, -8, -10, -12, -14, -16, -18 and -20 dB SNR). Each digit (0 – 9) appeared once at each SNR in a list.
- The order of the SNR was fixed; the digits appeared in random order at each SNR. The masking noise was fixed at 70 dB SPL.
- The presentation started with the easiest SNR (-2 dB) and progressed to the most difficult SNR (-20 dB) in 2 dB steps.
- The noise started 500ms before the digit started and ended 500ms after the digit ended.

- Two lists of digits were presented to the left ear and two lists to the right ear. The lists alternated between the ears, always presenting to the right ear first.
- The subjects had to listen to each digit and enter their response on the laptop computer keyboard.
- The next digit was presented after the subject responded by entering the digit on the keyboard. When the subject was unable to identify the digit, they had to guess the digit.
- Each subject's responses were stored.

The following procedures were followed to generate triplets with an adaptive test procedure:

- A list of triplets was stored in the Android app containing 120 unique digit-triplets (Smits et al, 2013).
- Sound-files of the digits 0 to 9 were stored separately in OGG format in the app.
- When the test starts a digit-triplet is randomly selected from the list of 120 different digit-triplets.
- The program assembled the triplet by concatenating the appropriate digits with silent intervals of 500ms at the beginning and end of each triplet.
- Subsequent digits were followed by 200ms silences with 100ms of jitter in between.
- The test operated with a fixed noise level and a varying speech level when triplets with negative SNRs were presented. When triplets with positive SNRs were presented the speech level became fixed and the noise level varied. This procedure ensures that the overall level of the signal was kept

approximately constant (i.e., triplet mixed with the noise), preventing clipping of the signal and providing a comfortable listening experience to the user.

2.7.2.2. Study II: Data collection procedures

- An otoscopic examination was conducted to observe the external ear canal for inflammation, foreign objects, growths and cerumen that may have caused obstruction. Tympanic membrane structures that were observed included the pars flaccida, pars tensa, the manubrium of the malleus, the umbo and the cone of light (Martin & Clark, 2003).
- A tympanometer was used to determine the external ear canal volume, middle ear pressure and tympanic membrane compliance (Martin & Clark, 2003).
- A calibrated clinical audiometer was operated to determine hearing sensitivity at 250-8000 Hz. All the audiometric data was recorded on an audiogram. Codes were assigned to all subjects.
- A non-standardized self-reported rating questionnaire for English language competence was completed by each subject. The questionnaire consisted of three questions.
    - The first question asked each subject to indicate how many languages they are competent in.
    - Secondly, the subject listed the languages from most competent to least competent.
    - The final question asked the subjects to rate their English competence for speaking according to everyday communication.

- A simple scoring method was used in the form of a rating scale that varied between 1 (not competent at all) to 10 (perfectly competent) for the English speaking category.

- The digits-in-noise hearing screening test was conducted in English. The results were recorded on a database according to a code assigned to each subject.

2.7.2.3. Study III: Data collection procedures

- An otoscopic examination was conducted to observe the external ear canal for inflammation, foreign objects, growths and cerumen that may have caused obstruction. Tympanic membrane structures that were observed included the pars flaccida, pars tensa, the manubrium of the malleus, the umbo and the cone of light (Martin & Clark, 2003).
- A tympanometer was used to determine the external ear canal volume, middle ear pressure and tympanic membrane compliance (Martin & Clark, 2003).
- A calibrated clinical audiometer was operated to determine hearing sensitivity at 250-8000 Hz. All the audiometric data was recorded on an audiogram. Codes were assigned to all subjects.
- Speech testing was presented with live voice in Afrikaans or English. SRS dB was obtained across intensities by administering the *Afrikaanse Foneties Gebalanseerde Woordelys* (a phonetically balanced word list) to Afrikaans speaking subjects (Laubscher & Tesner, 1966). The *University of Pretoria, English Phonetically Balanced Word List* was used to obtain SRS dB in N English speakers. A list of 25 phonetically balanced words was presented 30 dB HL above the 4FPTA) at three different intensities (maximum intensity 90 dB).

Normal SRS dB scores were classified with 100% word discrimination at intensities ≤40 dB HL. The best ear maximum SRS dB was used in the analysis.

- The digits-in-noise hearing test was conducted in English. The results were recorded on a database according to a code assigned to each subject.

2.8. Statistical analysis

A detailed summary of the statistical analysis utilized for studies I, II and III is provided in Table 2.5.

Table 2.5. Statistical analysis

Study	I	II	III
Title	Development and validation of smartphone-based speech-in-noise hearing screening test in South African English.	The South African English smartphone digits-in-noise hearing test: Effect of age, hearing loss and speaking competence.	Evaluating a smartphone digits-in-noise test as part of the audiometric test-battery.
Statistical analysis	• The mean, standard deviation and median was calculated for all listeners. • Speech recognition function for each digit was determined by fitting a logistic function to the raw data using a maximum likelihood procedure. The SNR corresponding to 50% correct for each digit was determined from the fitted function. A correction factor was calculated by subtracting this SNR from the average SNR of all digits (Vlaming, MacKinnon, Jansen & Moore, 2014). The correction factors were applied to the digits to align the 50% correct recognition probabilities for all the digits. • SRTs were averaged across subjects. • A repeated measures analysis of variance (ANOVA) was conducted to compare the effect of headphones on the SRT. • The raw data of the SRT measurements (n=20) for the five headphones were fitted with a logistic function to determine speech recognition functions. • The normal-hearing cut-off value was determined through the upper 95th percentile point for SRT scores (n=186).	• The mean, standard deviation and median was calculated for all subjects. • A linear regression model was used to determine predictive variables for the digits-in-noise SRT for subjects with best ear 4FPTA >25 dB HL and a second linear regression model for listeners with best ear 4FPTA ≤25 dB HL. The linear regression models were constructed for continuous variables (age and 4FPTA) and categorical variables (gender, self-reported English speaking competence) to determine the contribution of these variables to the digits-in-noise SRT. • A two-way analysis of covariance (ANCOVA) was used to evaluate differences in the digits-in-noise SRT for listeners with best ear 4FPTA ≤25 dB HL for N and NN listeners with self-reported English speaking competence rating of ≥6/10, and NN listeners with self-reported English speaking competence rating of ≤5/10 (NN ≤5). Age and best ear 4FPTA were selected as covariates. • A cross-tabulation analysis was conducted to show the distribution of subjects over English language speaking scores and age. • Logistic regression models were used to determine the screening characteristics of the digits-in-noise SRT.	• A Spearman correlation coefficient was explored to assess the relationship between the best ear 4FPTA, maximum SRS dB and the digits-in-noise SRT. • A comparison was conducted to analyse the relationship between the best ear 4FPTA and maximum SRS dB. • The accuracy of the South African English smartphone digits-in-noise test was determined by comparing the SRT to the best ear 4FPTA and maximum SRS dB. • Descriptive statistics, frequencies and proportions were determined for these variables. • The sensitivity and specificity, positive predictive value (PPV) and negative predictive value (NPV) were calculated as an indication of the accuracy of the method for determining a hearing loss. • The AUROC was determined to provide a further indication of the accuracy between the variables. • Descriptive statistics indicating the mean, range and standard deviation for aided and unaided hearing aid digits-in-noise SRTs were determined.

		• Receiver operator characteristic curves (ROC) were determined from the results of the logistic regression analyses for N and NN listeners' scores ≥6 (self-reported English speaking competence scores ≥6) and NN listeners' scores ≤5 (self-reported English speaking competence scores ≤5) separately. The first set of ROC curves were based on the SRT of the subjects; the second set of ROC curves were based on the SRT and age of the subjects.	• A correlation was conducted to analyse the relationship between the aided and unaided hearing aid digits-in-noise SRTs.
Chapter in Thesis	3	4	5

CHAPTER 3

DEVELOPMENT AND VALIDATION OF A SMARTPHONE-BASED DIGITS-IN-NOISE HEARING TEST IN SOUTH AFRICAN ENGLISH

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3.1. Abstract

Objective

The objective of this study was to develop and validate a smartphone-based digits-in-noise hearing test for South African English.

Design

Single digits (0 – 9) were recorded and spoken by a N English female speaker. Level corrections were applied to create a set of homogeneous digits with steep speech recognition functions. A smartphone app was created to utilize 120 digit-triplets in noise as test material. An adaptive test procedure determined the SRT. Experiments were performed to determine headphones effects on the SRT and to establish normative data.

Study Sample

Participants consisted of 40 normal-hearing subjects with thresholds ≤15 dB across the frequency spectrum (250 – 8000 Hz) and 186 subjects with normal-hearing in both ears, or normal-hearing in the better ear.

Results

The results show steep speech recognition functions with a slope of 20%/dB for digit-triplets presented in noise using the smartphone app. The results of five headphone types indicate that the smartphone-based hearing test is reliable and can be conducted using standard Android smartphone headphones or clinical headphones.

Conclusion

A digits-in-noise hearing test was developed and validated for South Africa. The mean SRT and speech recognition functions correspond to previous developed telephone-based digits-in-noise tests.

3.2. Introduction

Approximately 360 million people across the world suffer from a permanent disabling hearing loss (WHO, 2013a). Developing countries in regions such as sub-Saharan Africa, Asia Pacific and South Asia have the highest estimated prevalence of hearing loss in people over 65 years in the world (WHO, 2013a). An estimated 44% of adults older than 65 years of age have a disabling hearing loss in sub-Saharan Africa (WHO, 2013a). According to WHO (WHO, 2013b) estimates for sub-Saharan Africa, more than 3 million adults in South Africa suffer from a disabling hearing loss (STATSSA, 2013; WHO, 2013b).

Despite the high prevalence of hearing loss in sub-Saharan Africa, ear and hearing health care services are mostly unavailable (WHO, 2013a; Fagan & Jacobs, 2009). A major contributor to poor ear and hearing care access is the severe shortage of audiologists and otolaryngologists in the region (Fagan & Jacobs, 2009). According to WHO (2013a) sub-Saharan Africa has a particularly dire shortage of audiology services, with typically one audiologist to every million people (WHO, 2013a). Even though South Africa has significantly more ear and hearing health care providers than the rest of sub-Saharan Africa, the country also has a shortage that is exacerbated by an unequal distribution across rural and urban areas and between private and public health care sectors (Fagan & Jacobs, 2009; Theunissen & Swanepoel, 2008).

Geographic accessibility and proximity to health care clinics have a direct influence on the development of health care services (Arcury et al., 2005; Buor, 2003; Gething et al., 2004; Tanser et al., 2006). In South Africa, the temporal and spatial coverage

by public transport is sporadic, unreliable and expensive. In rural areas walking is often the primary mode of transportation (Tanser et al, 2006; Tanser et al, 2001). Access to audiological services and hearing screening is difficult for most of the people living in rural areas in South Africa because local ear and hearing health care services are unavailable. People often have to travel long distances to urban centers where services may be available at hospitals, but often with long waiting lists (Fagan & Jacobs, 2009).

To improve access to hearing loss detection, many high-income countries have resorted to using telephone-based digits-in-noise screening tests. These speech-in-noise tests measure the SNR where a listener recognizes 50% of the digit-triplets (i.e., 4-7-2) correctly (i.e., SRT). During the past ten years, the telephone-based digit-triplet speech-in-noise hearing screening tests have been developed for several countries including the USA, United Kingdom, Australia, Germany, Poland, Switzerland and France (Watson et al., 2012; Jansen et al., 2010; Zokoll et al., 2012). Smits, Kapteyn and Houtgast (2004) reported the first telephone-based digit-triplet speech-in-noise screening test, employed as the National Hearing Test in the Netherlands (Smits et al., 2004; Smits et al., 2006b). Within the first 4 months after the digit-triplet speech-in-noise hearing screening test was launched, 65 000 people dialed the test. After two and a half years close to 160 000 people used the screening test (Smits & Hougast, 2005). After mailing a questionnaire to the people who completed the test, Smits et al. (2006b) found that 50% of callers, who failed the screening test, obtained a diagnostic hearing test. After the National Hearing Test was developed, Smits, Goverts and Festen (2013) also developed the digits-in-noise

test (DIN). The DIN was developed for diagnostic speech-in-noise hearing testing to determine hearing loss for speech recognition in noise (Smits et al., 2013).

Based on the successful implementation of the digit-triplet speech-in-noise hearing screening tests in these developed countries, it could be an affordable and accessible alternative for developing countries. The test may overcome access barriers to first line hearing screening services and save the costs of administering a hearing screening program (Linssen, Anteunis & Joore, 2015; Jansen et al., 2010; Fagan & Jacobs, 2009; Smits & Houtgast, 2005; Smits et al., 2004).

An important advantage of this hearing screening test is that it uses highly familiar spoken words, digit-triplets, as speech material. In a country like South Africa where there are 11 official spoken languages, digit-triplets may be more suitable than standard words or sentences because they depend on low linguistic demands and use a “closed-set” pattern (Smits et al., 2013; STATSSA, 2011). In addition, numerous South Africans from different linguistic backgrounds use English numerals within their own African language (Branford & Claughton, 2002). Additionally, the users themselves can administer the speech-in-noise hearing screening test, the test is fully automated, and it can be conducted in a few minutes. Furthermore, the digits-triplet speech-in-noise hearing screening test is ecologically valid since it approximates everyday speech-in-noise environments and it has been demonstrated to be sensitive to detect hearing loss (Jansen et al., 2010; Smits et al., 2004; Zokoll et al., 2012; Smits et al., 2013).

Apart from the advantages of this telephone-based hearing test a significant barrier in regions like sub-Saharan Africa is the poor landline penetration. In South Africa a National Household Survey indicated that 79.5% of South Africans have access to only a mobile phone, 0.3% of South Africans have access to only a landline telephone and 13.9% of South Africans have access to both a mobile phone and landline telephone (STATSSA, 2013). Whilst mobile phone penetration is much better, sound quality has been demonstrated to be poorer in mobile phones compared to landline telephones (Smits & Houtgast, 2005). Furthermore, mobile phone call costs are likely to be prohibitively expensive. An alternative platform for implementing the digit-triplet speech-in-noise hearing test for countries like South Africa may be to offer it as a downloadable app for use on smartphones. Using a smartphone app can allow for an accessible user-friendly interface for self-testing by those with access to these devices. An important advantage of using an app is the possibility to use high fidelity, broadband, test signals where standard telephone networks use bandwidth limited signals.

In 2013, there were already approximately 5 billion mobile phones in the world, of which more than 1.08 billion are estimated to be smartphones. The mobile industry advanced to such an extent that approximately half of the adult population currently own a mobile phone (Martinez-Pérez, de la Torre-Diéz & López-Coronado, 2013; IC4D, 2012; The Economist, 2015a; The Economist, 2015b). By 2020 it is estimated that 80% of the adult population globally will own a smartphone (The Economist, 2015a; The Economist, 2015b). Penetration of these mobile phones in Africa has also seen an unprecedented increase to approximately 778 million mobile subscribers by the end of June 2013. An estimate of 1.2 billion mobile phones will be

used by 2018 in Africa, of which 412 million will be smartphones (Reed, Jotischky, Newman, Mbongue & Escofet, 2014).

The increasing penetration of smartphones means that a smartphone-based digits-in-noise hearing test in a country like South Africa may provide widespread access to hearing screening in rural and urban areas and across different socio-economic strata. To date, there has been no reported smartphone-based app for a digits-in-noise based national hearing test. The aim of this study was to develop and validate a South African English smartphone-based digits-in-noise hearing test. The study consisted of three phases. Phase I involved the recording, processing and equalization of the speech material. Phase II included the smartphone app development, methods for triplet generation, and the adaptive test procedures. Finally, normative data were gathered, and the effect of five different headphone types on the SRT of the smartphone digits-in-noise hearing test were examined in phase III.

The Research Ethics Committee of the University of Pretoria approved the research study before the study commenced.

3.3. PHASE I: Recording and equalization of digits

3.3.1. Recording and processing the speech material

South African English mono- and bi-syllabic digits (0 – 9) were selected as speech material. Single digit recordings were made for two N South African English female speakers in a sound-proof booth and recorded on video-camera (Panasonic P2 X250). A carrier phrase “the number” was said before pronouncing each digit to

allow natural intonation. A microphone (Sennheiser e815s) was held approximately 5cm from the speakers' mouth during recordings. Speakers were asked to read out four lists of digits where each digit appeared four times in random order. The recordings were sampled at 48 000 Hz with a 16 bit resolution. Each digit was formatted separately using the Final Cut Pro 7 editing software. The digits were Root Mean Square equalized and stored in WAV format.

Five speech-language therapists rated the two female voices according to naturalness, articulation, voice quality, intonation and speed of production. The female voice with the best average rating was selected. The five speech-language therapists then rated the four recordings of each digit for the selected female speaker according to the naturalness, articulation, voice quality, intonation and speed of production (Theunissen & Swanepoel, 2008). The final list of digits was compiled using the best rated digits for digits 0 to 9 for the selected female speaker.

The masking speech noise was generated by shaping white noise to match the long-term average speech spectrum of the digits. The level of the masking noise was equal to the average level of the digits without any silences (Smits et al., 2013).

3.3.2. Equalization of speech material

Digits were equalized with respect to their recognition probability. Equalizing digits by applying level corrections to the digits ensured that each digit had a 50% chance of being recognized correctly at the same SNR.

3.3.3. Methods

3.3.3.1. Subjects

Twenty normal-hearing subjects participated in the listening study. Mean age of subjects was 20 years (SD=3.5 yrs), ranging from 18 to 32 years. All subjects were female. Pure-tone thresholds were equal to or better than 15 dB HL at each octave frequency from 250 to 8000 Hz (ISO 389-1, 1998).

3.3.3.2. Equipment and Measurements

A clinical audiometer (GSI 61, Grason-Stadler, Milford, New Hampshire, USA) was used to conduct a pure-tone audiogram in a sound-proof booth.

Measurement software was developed in Matrix Laboratory for presenting digits in noise. Four lists of 100 digits were created and presented on a laptop computer using a headphone set (Sennheiser HD 201). Each list consisted of 10 digits combined with the masking noise at fixed SNR's (-2, -4, -6, -8, -10, -12, -14, -16, -18 and -20 dB SNR). Each digit (0 – 9) appeared once at each SNR in a list. The order of the SNR was fixed; the digits appeared in random order at each SNR. The masking noise was fixed at 70 dB SPL. The presentation started with the easiest SNR (-2 dB) and progressed to the most difficult SNR (-20 dB) in 2 dB steps. The noise started 500ms before the digit started and ended 500ms after the digit ended. Two lists of digits were presented to the left ear and two lists to the right ear. The lists alternated between the ears, always presenting to the right ear first. The subjects had to listen to each digit and enter their response on the laptop computer keyboard. The next digit was presented after the subject responded by entering the

digit on the keyboard. When the subject was unable to identify the digit, they had to guess the digit. Each subject's responses were stored.

3.3.3.3. Results

The group average for correct identification of each digit at each SNR is shown in Figure 3.1. The speech recognition function for each digit was determined by fitting a logistic function to the raw data using a maximum likelihood procedure. The SNR corresponding to 50% correct for each digit was determined from the fitted function. A correction factor was calculated by subtracting this SNR from the average SNR of all digits (Vlaming et al., 2014). The correction factors were applied to the digits to align the 50% correct recognition probabilities for all the digits. The level corrections were very small with the largest value for digit 1 (+0.4 dB).

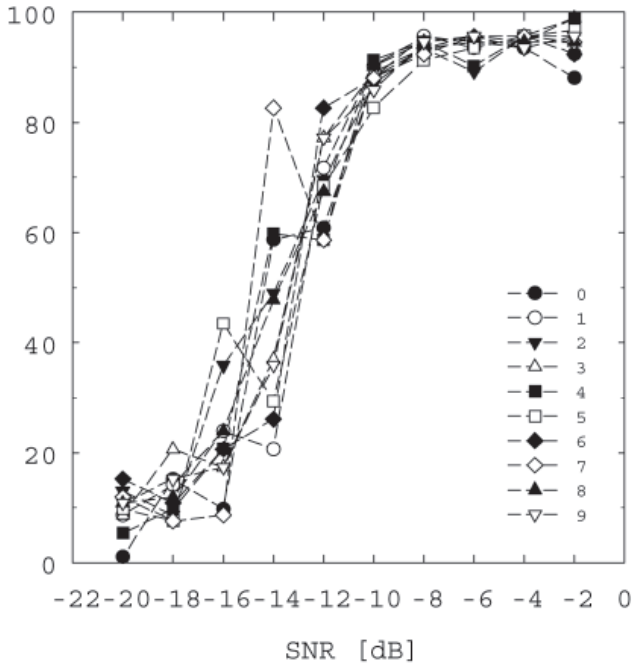

Figure 3.1. The average speech recognition probabilities for single digits-in-noise before equalization.

3.4. PHASE II: Development of the smartphone application test procedures

3.4.1. Smartphone application

A smartphone app (the South African smartphone digits-in-noise test) was designed using Android studio (version 0.6.0, created by Google) written in Java (Java development kit version 8.0, created by Oracle). The smartphone app was designed to be used on any Android smartphone. When the app is launched, a tutorial screen appears to instruct the subject how to use the app. The next screen instructs the subject to choose his/her gender. After the subject chooses his/her gender the “date-of-birth” is selected. The third screen instructs the subject to put on the smartphone headset and listen to digit-triplets being repeated. The subject uses a scroll-bar to adjust the intensity of the digit-triplets to a comfortable listening intensity. The final screen allows the subject to enter his/her initials and surname. A “Start Test” button allows the subject to begin testing. When the test starts, digit-triplets are presented diotically. A pop-up keypad appears after the subject listened to the digits to allow the subject to enter the response. Supplementary material provides screenshots of the smartphone app and is available in the online version of the journal (Appendix M).

3.4.2. Triplet generation and adaptive test procedure

A list of triplets was stored in the Android app containing 120 unique digit-triplets (Smits et al., 2013). Sound-files of the digits 0 to 9 were stored separately in OGG format in the app. When the test starts a digit-triplet is randomly selected from the list of 120 different digit-triplets. The program assembles the triplet by concatenating the appropriate digits with silent intervals of 500ms at the beginning and end of each

triplet. Subsequent digits are followed by 200ms silences with 100ms of jitter in between. The test operates with a fixed noise level and a varying speech level when triplets with negative SNRs are presented. When triplets with positive SNRs are presented the speech level becomes fixed and the noise level varies. This procedure ensures that the overall level of the signal is kept approximately constant (i.e., triplet mixed with the noise), prevents clipping of the signal and provides a comfortable listening experience to the user.

The adaptive test procedure was similar to the test procedure used by Smits et al. (2004) and is as follows:

- Before triplets are presented, the subject is instructed to select a comfortable listening intensity.
- Based on the subject's selected listening intensity, the first triplet is presented.
- When the response is entered the next triplet will be presented at a 2 dB higher SNR for an incorrect response or at a 2 dB lower SNR for a correct response.
- A triplet is judged to be correct when all digits are entered correctly.
- The SRT is calculated as the average SNR of the triplets presented (4 to 23).

3.5. PHASE III: Smartphone digits-in-noise test headphone types, effects and norms

3.5.1. Effect of different headphones on the smartphone digits-in-noise test

The purpose of this study component was to determine if different headphones would differentially affect the digits-in-noise test results. A repeated measures design was followed to compare the SRT of five different headphones.

3.5.2. Method

3.5.2.1. Subjects

Twenty normal-hearing students from the University of Pretoria, Department of Speech-Language Pathology and Audiology participated in the study. The mean age of the subjects was 19 years (SD= 0.9 yrs) ranging from 18 to 21 years. All subjects were female. Pure-tone thresholds were equal to or better than 15 dB HL at each octave frequency from 250 to 8000 Hz (ISO 389-1, 1998) for all subjects, except for three subjects who had a 20 dB threshold at one frequency (250 Hz, 8000 Hz and 2000 Hz) and one subject who had 20 dB HL threshold at two frequencies (1000 Hz and 8000 Hz).

3.5.2.2. Equipment and Measurements

A clinical audiometer (GSI 61, Grason-Stadler, Milford, New Hampshire, USA) was used to conduct a pure-tone audiogram in a sound-proof booth.

Five smartphones (1 Samsung Trend, 4 Vodafone Smart Kicka) were used to administer the South African smartphone digits-in-noise test. Five different headphones were used to listen to the digits-in-noise test. The first three

headphones are examples of intraconchal earphones accompanying an entry-level smartphone (Vodafone Smart Kicka), a mid-range smartphone (Samsung S4 mini) and a top-end smartphone (Samsung S5). Two supra-aural headphone types were used consisting of a Sennheiser HD 202 II headphone and a TDH 50-P audiometric headphone. Supplementary material provides photographs of the five different headphones and is available in the online version of the journal (Appendix M).

Each subject conducted a trial digits-in-noise test on a smartphone to negate for a learning effect. After the subjects completed the trial digits-in-noise test they performed one test with each headphone type. The order of the headphone types was counterbalanced to avoid order effects.

3.5.2.3. Results

SRTs of the 20 subjects were averaged across subjects per headphone. The highest average SRT was found for the TDH 50-P headphones (-11.4 dB) and the lowest average SRT was found for the Sennheiser HD 202 II headphones (-11.7 dB), see Table 3.1. An ANOVA was conducted to compare the effect of headphones on SRT. The main effect was not significant $F(4,76)=.354$, $p=.84$, indicating that the effect of headphone type on the measured SRT were statistically non-significant.

Table 3.1. Descriptive statistics for the SRT SNRs (n=20) for five headphone types

Headphone/Earphone type	Range (dB)	Minimum (dB)	Maximum (dB)	Mean (dB)	Std. Deviation (dB)
Intraconchal (S5)	2.8	-12.8	-10	-11.6	0.75
Intraconchal (S4 mini)	2.2	-12.4	-10.2	-11.5	0.49
intraconchal (Voda)	2.4	-12.6	-10.2	-11.5	0.72
Supra-aural (HD202II)	2.2	-13	-10.8	-11.7	0.64
Supra-aural (TDH50P)	2.6	-12.8	-10.2	-11.4	0.85

S5 = Samsung S5 earphones; S4 mini = Samsung S4 mini earphones; Voda = Vodaphone Kicka earphones; HD202II = Seinnheiser headphone; TDH50P = Audiometric headphone

The raw data of the SRT measurements for the five headphones were fitted with a logistic function to determine speech recognition functions and the results are shown in Figure 3.2. The average speech recognition function has a slope of 20%/dB.

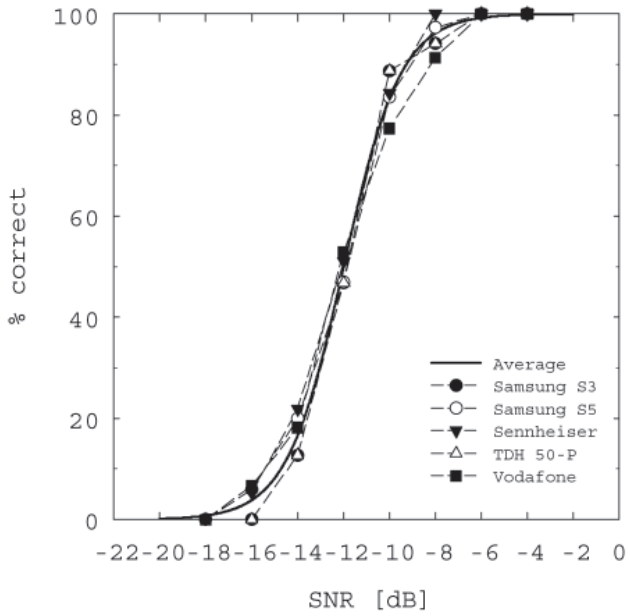

Figure 3.2. The average speech recognition probabilities for digit-triplets at each SNR conducted using five different headphone types presented using the smartphone app.

3.5.3. Normative data for the digits-in-noise hearing test

The purpose of this component was to describe the normative range for the smartphone digits-in-noise test. The cut-off values for normal-hearing in both ears or normal-hearing in the better ear were determined (i.e., normal-hearing in at least one ear).

3.5.4. Method

3.5.4.1. Subjects

Two groups of subjects from private audiology practices and governmental hospitals in Gauteng participated in this study. The first group consisted of 96 N South African English subjects with a PTA equal to or better than 15 dB HL for the better ear. The PTA was calculated as the average pure-tone hearing threshold for 500, 1000, 2000 and 4000 Hz. The “worst-ear” average PTA was 8.2 dB HL, range= -2.5 to 58.8 dB HL, for this group. The mean age of the subjects was 24 years (SD=13 yrs) ranging from 16 to 74 years. Twenty-four of the subjects were male and 72 were female. The second group consisted of 90 N South African English speaking subjects with PTAs equal to or better than 15 dB HL in both ears. The mean age of these subjects was 22 years (SD=10 yrs) ranging from 13 to 64 years. Twenty-two of the subjects were male and 68 were female.

3.5.4.2. Equipment and measurements

Clinical audiometry was conducted with standard clinical audiometers to measure a pure-tone air conduction audiogram in a sound-proof booth by certified audiologists. Octave frequencies between 250 and 8000 Hz were tested. After the pure-tone air conduction audiogram was determined each subject conducted the South African digits-in-noise hearing test. The digits-in-noise hearing test was performed on a smartphone (Vodaphone Smart Kicka or Samsung Trend) with a headphone (intraconchal Vodaphone Kicka earphones or Seinnheiser HD 202 supra-aural headphones) in a quiet room.

3.5.4.3. Results

The normal-hearing cut-off value was determined through the upper 95th percentile point for SRT scores for the two groups of N South African English subjects with normal-hearing or mild hearing losses. The mean SRT for the 96 subjects with normal-hearing in one ear was -10.6 dB (SD=1.0 dB). The mean SRT for 90 subjects with normal-hearing in both ears was -10.7 dB (SD=0.9 dB). The cut-off values for "pass/refer" were determined at -8.4 dB for adult subjects with normal-hearing in the better ear and -8.9 dB for adult subjects with normal-hearing in both ears (Table 3.2).

Table 3.2. Distribution of the SRT SNRs recorded with the South African English digits-in-noise hearing test for group 1 (n=96) and group 2 (n=90) N South African English subjects

	Group 1 (Best ear ≤15 dB PTA)	**Group 2 (Both ears ≤15 dB PTA)**
Average SRT SNR (SD)	-10.6 (1.0)	-10.7 (0.9)
Min	-12.4	-12.4
Max	-6.6	-7.4
95 Percentile	-8.4	-8.9

3.6. Discussion

A smartphone-based digits-in-noise hearing test was developed and validated for South African English to provide widespread access to hearing screening across rural and urban areas. The smartphone app can be used with standard headphones or earphones, and results can be obtained within a few minutes. Unlike the bandwidth limited signals in telephone digit-triplet screening tests, the signal produced by the smartphone is a broadband signal of digital audio output quality.

In phase I of this study the South African smartphone-based digits-in-noise hearing test was developed following similar procedures as the Dutch and French digits-in-noise hearing tests (Smits et al., 2013). The average slope steepness for the speech

recognition function of the South African smartphone-based digits-in-noise hearing test (broadband signal) (20%/dB) agreed well with the Dutch (20%/dB), French (20%/dB) and German (18%/dB) bandwidth limited telephone digits-in-noise tests (Smits et al., 2004; Jansen et al., 2010; Zokoll et al., 2012).

The measured average diotic digit-triplet SRT for the normal-hearing subjects or subjects with a mild hearing loss was -10.6 dB SNR conducted using the smartphone app. The measured average SRT for the Dutch, French and German digits-in-noise tests by telephone ranged between -6.4 to -6.9 dB SNR (Smits et al., 2004; Zokoll et al., 2012). The lower SRT value for the South African smartphone test can be attributed to the digital signal quality afforded by the smartphone as opposed to the restricted bandwidth on landlines used by the other studies. The South African digits-in-noise hearing test produces a digital signal that covers a bandwidth of 30 to 20, 000 Hz which represents the human voice more accurately and therefore improves speech intelligibility (Bonello, 2015). When headphones were used to conduct the Dutch, French and German digits-in-noise tests, the SRT scores (-9.3 to -11.2 dB SNR) compared more favourably to the SRT of the South African test (Zokoll et al., 2012).

Since smartphones can be coupled to different headphones we evaluated whether the type and quality of headphones influenced the SRT. In phase III the effect of five headphones (3 intraconchal earphone and 2 supra-aural headphones) were investigated. No statistically significant difference between the average SRTs were found. The digits-in-noise test is therefore accurate using different headphones making it uniquely suited to serve as a smartphone-based hearing test that could be

downloaded by persons across South Africa and administered using standard headphone sets (Culling, Zhao & Stephens, 2005). The average SRTs in the headphone-comparison study were approximately 0.8 dB lower (better) than the average SRT in the normative data. This difference can be attributed to a learning effect that is found for the first test for naïve listeners (Smits et al., 2013) when administering multiple tests. A trial test was conducted in the headphone-comparison study to eliminate the learning effect.

The rapid evolution of the mobile industry makes it easy for any person in South Africa to obtain a mobile phone but the effect of the South African English digits-in-noise test on South African English additional language speakers needs to be determined. Potential factors that could influence the performance of English additional language speakers on the hearing test may include auditory memory, cognition and the linguistic complexity of test material (van Wijngaarden, Steeneken & Houtgast, 2002; Zokoll et al., 2013). Smits et al. (2013) however concluded that the digits-in-noise test depend minimally on top-down processing (e.g. linguistic skills) and can be utilized to test subjects with normal to profound hearing losses, including children and cochlear implant candidates (Smits et al., 2013). A comparison between sentence-in-noise and the digits-in-noise test performance has also shown that both tests measured approximately the same speech recognition ability and vocabulary size and educational level did not have a major effect on performance (Kaandorp, Smits, Merkus, Goverts & Festen, 2015). Various studies indicate that participants who speak English as a second language perform worse on competing signal speech tests compared to N English speakers (Tabri, Smith Abou Chacra & Ping, 2011; van Wijngaarden et al., 2002; Zokoll et al., 2013), although the

effect of non-nativeness on digit-triplet recognition in noise is small (Kaandorp et al., 2015). It is therefore important that different norms should be investigated for the South African English digit-in-noise hearing test as South Africa consists of a multilingual population.

3.7. Conclusion

A South African digits-in-noise hearing test was successfully developed and validated as a self-test on a smartphone via a smartphone app using standard and clinical headphones. The mean SRT and speech recognition functions for the smartphone-based hearing test correspond well to previous developed telephone-based digits-in-noise tests (Smits et al., 2004; Jansen et al., 2010). Results were independent of headphone type and the app can be used with any Android smartphone. The South African smartphone digits-in-noise hearing test could increase access to hearing services across South Africa if made available on online App-stores. The issue of the potential performance differences for participants who speak English as a second language needs to be investigated in the context of the multiple languages commonly used throughout South Africa.

CHAPTER 4

THE SOUTH ARICAN ENGLISH DIGITS-IN-NOISE HEARING TEST: EFFECT OF AGE, HEARING LOSS AND LANGUAGE SPEAKING COMPETENCE

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4.1. Abstract

Objective

This study determined the effect of hearing loss and English speaking competency on the South African English digits-in-noise hearing test to evaluate its suitability for use across N and NN speakers.

Design

A prospective cross-sectional cohort study of N and NN English adults with and without sensorineural hearing loss compared pure-tone air conduction thresholds to the SRT recorded with the smartphone digits-in-noise hearing test. A rating scale was used for NN English listeners' self-reported competence in speaking English. This study consisted of 454 adult listeners (164 male, 290 female; range 16 – 90 years), of which 337 listeners had a best ear 4FPTA of ≤25 dB HL.

Results

A linear regression model identified three predictors of the digits-in-noise SRT namely 4FPTA, age and self-reported English speaking competence. The NN group with poor self-reported English speaking competence (≤5/10) performed significantly ($p<0.01$) poorer than the N & NN (≥6/10) group on the digits-in-noise test. Screening characteristics of the test improved with separate cut-off values depending on English speaking competence for the N & NN (≥6/10) group and NN (≤5/10) group. Logistic regression models, that include age in the analysis, showed a further improvement in sensitivity and specificity for both groups (AUROC .962 and .903 respectively).

Conclusions

Self-reported English speaking competence had a significant influence on the SRT obtained with the smartphone digits-in-noise test. A logistic regression approach considering SRT, self-reported English speaking competence and age as predictors of best ear 4FPTA >25 dB HL showed that the test can be used as an accurate hearing screening tool for N and NN English speakers. The smartphone digits-in-noise test therefore allows testing in a multilingual population familiar with English digits using dynamic cut-off values that can be chosen according to self-reported English speaking competence and age.

4.2. Introduction

An important part of maintaining health and wellbeing for older adults is to screen for and treat hearing loss (Bushman, Belza & Christianson, 2012). Nevertheless adult hearing screening programs are very scarce. Hearing screening tests will become increasingly important as the adult population is continuously growing and life expectancy escalates. It is expected that the world's adult population aged 60 years and older will almost double from 12% to 22% by 2050 (WHO, 2015). The incidence of hearing loss increases as the adult population ages with approximately one-third of adults aged 65 years and older affected by a disabling hearing loss (WHO, 2013a). The latest Global Burden of Disease study (GBD, 2016) indicates that 1.33 billion people suffer from hearing loss making it the 2nd most common impairment evaluated. Unfortunately, only about 20% of adults with hearing loss seek help (Smits et al., 2006a; Davis et al., 2007).

An untreated hearing loss negatively impacts communication abilities and cognitive, physical and psychological functioning and general quality-of-life (Nachtegaal et al., 2009; Lin, 2011; Davis et al., 2016). Communication difficulties related to hearing loss can lead to poor social engagement resulting in restricted socialization, impaired relationships with friends and family with loneliness as a consequence, especially in the elderly (Davis et al., 2016). Persons with hearing loss demonstrate greater cognitive decline that may be associated with an increased risk of dementia (Lin, 2011, Lin & Ferrucci, 2012; Davis et al., 2016). Hearing loss is also related to physical impairment in older adults with an increased likelihood to fall due to impaired auditory and vestibular cues that limit environmental awareness, attention and postural control (Lin & Ferrucci, 2012). The communication, physical and

cognitive effects of hearing loss have also been linked to psychological impairments and feelings of depression, anxiety, frustration and fatigue resulting in poor quality-of-life (Davis et al., 2007). The physical impairments associated with a hearing loss can furthermore cause an added financial burden on the elderly due to increased health care costs (Simpson et al., 2016).

Early hearing loss intervention and counselling are important services that may prevent or forestall cognitive decline, dementia, the negative psychological and physical effects associated with hearing loss and save future health related costs (Simpson et al., 2016). Hearing screening programs are important for early detection of hearing loss to maximize hearing rehabilitation and quality-of-life outcomes. Various hearing screening tests exist of which standard hearing screening options usually include self-administered questionnaires and pure-tone audiometry. Self-administered questionnaires are an affordable method to detect hearing loss and could be utilized by any health care professional (Swanepoel et al., 2013). In recent years more accessible hearing screening methods have been developed that individuals can access directly without a health care professional. Many countries which include the Netherlands, United States of America, Australia, Germany, Poland, Switzerland and France now offer landline telephone hearing screening tests based on the recognition of digits in noise. These self-administered tests measure the SNR where a listener recognizes 50% of the digit-triplets correctly (i.e., SRT) (Jansen et al., 2010; Smits et al., 2004; Zokoll et al., 2012; Watson et al., 2012). These digits-in-noise hearing screening tests are fully automated which makes the tests appealing because they can be self-administered. The tests are also quick to administer and can be completed in only a few minutes. Furthermore, the digits-in-

noise hearing screening tests mimic everyday speech-in-noise environments and are sensitive to detect hearing loss (Jansen et al., 2010; Smits et al., 2004; Zokoll et al., 2012; Smits et al., 2013, Williams-Sanchez et al., 2014).

In countries like South Africa, where landline telephone penetration is less than 13% of households (STATSSA, 2013) a digits-in-noise hearing test over the landline telephone is inadequate to reach the general population. To provide access to ear and hearing health care services an alternative platform was considered. A smartphone-based digits-in-noise hearing test for end-users was developed and validated in South African English (Potgieter , Swanepoel, Myburgh, Hopper & Smits, 2016). The test can be downloaded in South Africa (www.hearZA.co.za) as an application and on a smartphone or other iOS or Android device. Low-cost smartphone penetration is approaching 80% of households, making widespread access to the test possible for people living in rural and urban areas (Potgieter et al., 2016; Ericsson Mobility Report, 2015). The test enables users to conduct a self-test in the comfort of a home setting using the app downloaded to a smartphone. The smartphone-based digits-in-noise hearing test provided equivalent results across earphones and headphone types. Contrary to landline telephone hearing tests that are limited to the bandwidth of the telephone network (approximately 300 - 3400 Hz) the app-based smartphone test uses broadband digital quality signals (30 – 20,000 Hz) (Potgieter et al., 2016).

Employing an English-based smartphone digits-in-noise hearing test in South Africa presents its own challenge considering the multilingual population, with 11 official languages. Estimates indicate that only 9.6% of the population is N English speaking

(STATSSA, 2011). NN language listeners typically perform worse on standard speech-in-noise tests compared to N listeners (van Wijngaarden et al., 2002; Zokoll et al., 2013). The speech material may contain unfamiliar vocabulary and complex grammatical structures which influence NN language listeners' performance on speech recognition tasks (van Wijngaarden et al., 2002; Zokoll et al., 2013). In addition to age of NN language acquisition, amount of NN language use and linguistic background, age itself may also influence speech recognition (Rogers, Lister, Febo, Besing & Barams, 2006; Rimikis, Smiljanic & Calandruccio, 2013).

An English-based digits-in-noise test has several advantages compared to speech-in-noise tests that are based on open set sentence or word recognition that makes this test more amenable for use in a multilingual setting. Firstly, digits-in-noise tests employ simple speech material with low linguistic demands. Secondly, the speech material is presented as a closed set (i.e., digits between 0 and 9). Thirdly, English digits are mostly familiar and often used by speakers of other languages (Branford & Claughton, 2002). Finally, Kaandorp et al. (2016) have shown that normal-hearing NN listeners only needed a 0.8 dB higher SNR than N listeners to recognize 50% of digit-triplets correctly. These advantages provide the potential for an English-based smartphone digits-in-noise hearing screening test to be used as a national screening test in a multilingual country like South Africa.

The aim of this study was to evaluate the South African digits-in-noise hearing test's suitability for use as a hearing screening test. The study hypothesis posited that the digits-in-noise SRT would be poorer in non-native listeners with poor English speaking competence than in native listeners or non-native listener with good

English speaking competence, but would be sufficiently accurate for screening purposes.

4.3. Materials and methods

4.3.1. Listeners

Three private hearing health care practices, three public hospital audiology units and the University clinic at the Department of Speech Language Pathology and Audiology, University of Pretoria were involved in data collection. A convenience non-probability sampling procedure was followed with participants at clinical data collection sites who were available and willing to participate in the research study. All listeners provided written informed consent to participate. The group of listeners comprised of participants who represented all 11 official languages in South Africa (Table 4.1). The 11 official languages in South Africa are English, Afrikaans, Northern Sotho, Zulu, Sotho, Tswana, Xhosa, Tsonga, Swazi, Ndebele and Venda (STATSSA, 2011). A total of 458 listeners (166 male, 292 female) participated in this study. Four listeners with a mixed hearing loss were excluded from all analyses, resulting in 454 adult listeners (164 male, 290 female). Eleven of the 454 listeners did not have an English speaking competence score. The 11 listeners were excluded in analyses where the English speaking competence scores were used. The mean age was 36 years (±22 years) with a range of 16 – 90 years (Table 4.1).

Table 4.1. Characteristics of subjects according to their N language, gender and age

Native Language	Subjects (n)	Male (n)	Female (n)	Age Range (years)	Mean Age (years)	Standard Deviation
English	134	43	91	16 – 89	35	24
Afrikaans	109	40	69	16 - 90	49	24
Northern Sotho	60	23	37	16 - 79	34	19
Zulu	32	9	23	16 - 63	34	18
Sotho	25	15	10	16 - 67	33	17
Tswana	22	6	16	16 - 46	19	8
Xhosa	20	13	7	16 - 83	24	16
Tsonga	18	7	11	16 - 64	30	18
Swazi	10	5	5	16 - 25	18	3
Ndebele	9	1	8	19 - 59	29	16
Other	15	2	13	16 - 65	27	13

4.3.2. Material and apparatus

Test procedures included otoscopy, diagnostic pure-tone air and bone conduction audiometry, the South African English smartphone-based digits-in-noise test and a self-administered English language competence questionnaire. An otoscopic evaluation was performed for observation of any obstruction in the external auditory meatus. Excessive cerumen was removed by a qualified audiologist or medical practitioner before testing commenced.

4.3.3. Procedures

At all test sites calibrated audiometers with supra-aural headphones or insert earphones were used to conduct standard audiometry. Bone conduction audiometry was additionally conducted on participants with average thresholds at 500, 1000, 2000 and 4000 Hz (4FPTA) of more than 25 dB HL. The modified Hughson-Westlake method was used to seek pure-tone air and bone conduction thresholds (Hughson and Westlake, 1944). The hearing loss was categorised as conductive or

mixed when the difference between the air and bone conduction 4FPTA was >15 dB in the best ear (Margolis & Saly 2007).

The digits-in-noise test was administered binaurally on Vodafone Kicka smartphones or a Samsung Trend smartphone. Intraconchal Vodafone earphones were used to present the stimuli from the Vodafone Kicka smartphones and a HD202II Sennheiser supra-aural headphone was used with the Samsung Trend smartphone. A study conducted by Potgieter et al. (2016) observed no difference between the digits-in-noise SRTs for these headphone types. The digits-in-noise hearing test consisted of 5 screens. The first screen opened to a quick tutorial screen which instructed the listener on how to use the app. The second screen allowed the listener to select his/her gender. The third screen asked the listener to select his/her date of birth. The fourth screen instructed the listener to place either earphones into the ears or supra-aural headphones on the ears. The listener was presented with digits being repeated. A scroll bar allowed the listener to adjust the volume to a comfortable level. On the final screen the listener entered his/her initials and surname. A “start test” button commenced the test.

The test material is selected from a list of 120 unique digit-triplets stored in the app (Potgieter et al., 2016). In the app the sound files for the digits 0 to 9 were stored separately in OGG format (Potgieter et al., 2016). The bi-syllabic digits 0 and 7 were also used as speech tokens to minimize a possible learning effect (Smits et al., 2013; Smits, 2016). When the test started, the digit-triplets were assembled by concatenating the appropriate digits with silent intervals of 500ms at the beginning and end of each triplet. Subsequent digits were followed by 200ms silences with

100ms of uniform jitter between each digit to add some uncertainty in the listening task for when the next digit will be presented. The digit-triplet files were mixed with broadband speech-shaped noise at the required SNR to form a stimulus. When triplets with negative SNRs were presented the test operated with a fixed noise level and a varying speech level. The speech level became fixed and the noise level varied when triplets with positive SNRs were presented. By following this test procedure, a nearly constant overall level of the stimuli was ensured (i.e., digit-triplet mixed with the noise). The digits were pronounced by a female N speaker of South African English. When the test started, the first stimulus set was presented at the listener's self-chosen comfortable listening level. A pop-up keypad appeared to allow the listener to enter the response. If the digit-triplet was entered 100% correctly the next stimulus was presented at a 2 dB lower SNR than the previous digit-triplet. When the digit-triplet was entered incorrectly the next stimulus was presented at a 2 dB higher SNR than the previous digit-triplet. Each test used 24 digit-triplets to estimate the SNR corresponding to the 50% correct recognition probability (i.e., SRT). All stimuli were presented binaurally. See Potgieter et al. (2016) for further details.

A non-standardized self-reported rating scale for English language competence was completed by each listener. A facilitator/translator was present to assist illiterate listeners or listeners with poor English language competence to complete the questionnaire. The questionnaire consisted of one simple question. The question asked the listeners to rate their English speaking competence in everyday communication. A simple scoring method was used in the form of a scale between 1 (not competent at all) and 10 (perfectly competent).

4.4. Results

The sample of 454 listeners represented a range of self-reported English speaking competences across language groups and ages (Figure 4.1). For illustrative purposes, the listeners were categorized into three groups with approximately the same amount of listeners in each group (30% N English, 24% Afrikaans and 46% other languages). Figure 4.2 illustrates the effect of age on hearing loss for these three groups.

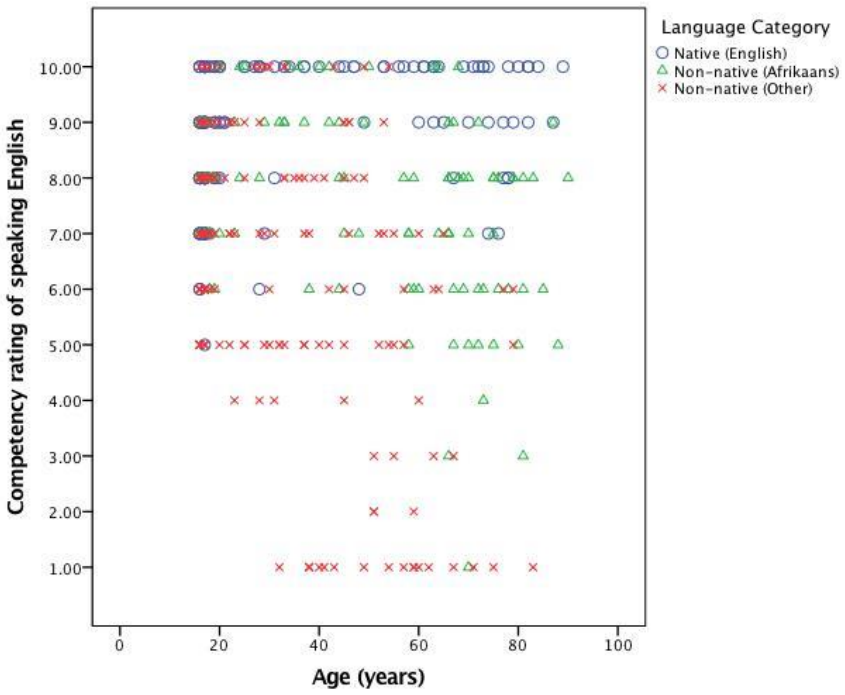

Figure 4.1. English speaking competence across age and language categories (N English, Afrikaans and all other languages) of listeners.

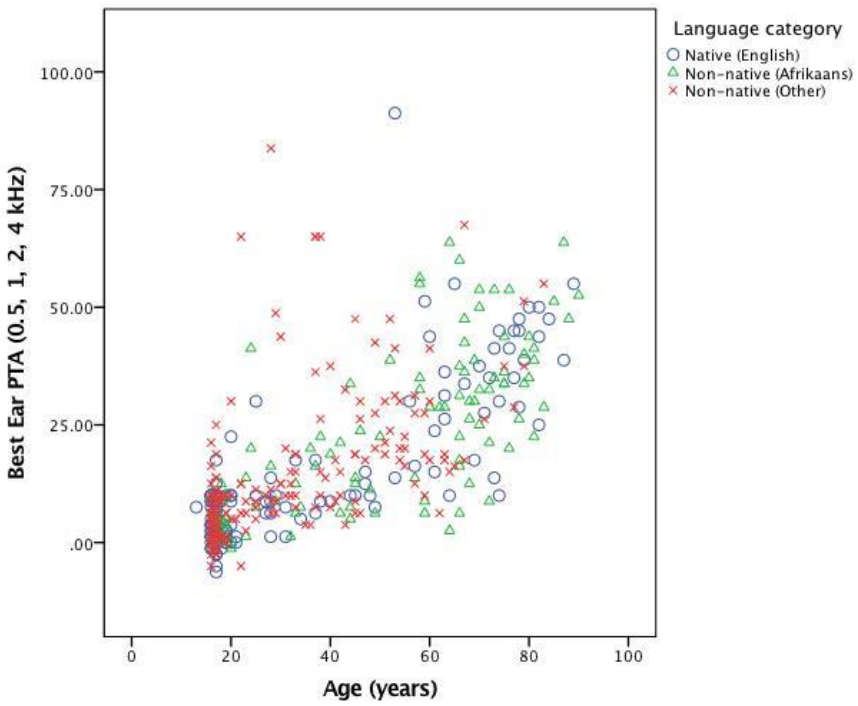

Figure 4.2. Best ear 4FPTA (0.5, 1, 2 and 4 kHz) across age and language categories (N English, Afrikaans and all other languages).

4.4.1. Predictive variables of the digits-in-noise SRT

Linear regression models were constructed for continuous variables (age and best ear 4FPTA) and categorical variables (gender, English speaking competence) to test whether these variables significantly predicted the digits-in-noise SRT. Final model selection was based on backward elimination of non-significant variables ($p>0.05$). The relative quality of the models was measured by the Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC). The AIC and BIC are measures used to assess model fit. These measures are based upon the likelihood function of the model, and can be used to compare the fit of non-tested models for the same dataset (Hox, 2002). A linear regression model for normal-hearing listeners with best ear 4FPTA ≤25 dB HL indicated that English speaking competence (beta -0.210; 95%CI -0.287 to -0.134; $p<0.001$) and age (beta 0.042; 95%CI 0.033 to 0.051;

p<0.001) were significant predictors of the digits-in-noise SRT for normal-hearing listeners. The linear regression model for listeners with best ear 4FPTA >25 dB HL indicated that English speaking competence (beta -0.294; 95%CI -0.553 to -0.036; p<0.001) was a significant predictor of the digits-in-noise SRT. Age (beta 0.018; 95%CI -0.028 to 0.064; p=0.44) however was not a significant predictor of the digits-in-noise SRT. Gender was not a significant predictor of the digits-in-noise SRT in both linear regression models.

4.4.2. English competence groups

Listeners were grouped based on the self-reported English speaking competence score to allow an even distribution of listeners in each group to determine comparisons in the analysis. The average SRT for normal-hearing (best ear 4FPTA ≤25 dB HL) N listeners was compared to the average SRT of normal-hearing NN listeners within each group of self-reported English speaking competence (scores 1 to 10) using t-tests (no multiple comparison corrections). Significant differences in SRTs were observed between N listeners and the 5 groups of NN listeners with English speaking competence scores ≤5 (all p-values <0.01). No significant differences in SRTs were observed between N listeners and the 5 groups of NN listeners with English speaking competence scores ≥6 (p-values between 0.116 and 0.589). As such NN listener groups were categorised into NN with English speaking competence scores of ≤5 and ≥6.

Next, a two-way ANCOVA was used to evaluate differences in the digits-in-noise SRT for groups of listeners with best ear 4FPTA ≤25 dB HL based on their English speaking competence rating. Age and best ear 4FPTA were selected as covariates.

A significant difference was observed ($p<0.01$; $F(4)=154.91$; $R^2=0.579$) between the digits-in-noise SRT (corrected for age and best ear 4FPTA) for N listeners (adjusted mean -9.5 dB; SE: 0.17; 95%CI -9.8 to -9.2 dB), NN ≥6 (adjusted mean: -9.3 dB; SE: 0.13; 95% CI: -9.5 to -9.0 dB) and NN ≤5 (adjusted mean: -7.9 dB; SE: 0.24; 95% CI: -8.4 to -7.4 dB). Pairwise comparisons only demonstrated a significant difference ($p<0.01$; Bonferroni corrected) between the NN ≤5 and the two other groups. There was no significant difference between the N and NN ≥6 groups. Thus N and NN ≥6 were grouped (N & NN ≥6) and the NN ≤5 were kept as a separate group for further analyses.

The digits-in-noise SRT and best ear 4FPTA correlation was significant ($p<0.01$) for the N & NN ≥6 listeners group (0.763; Pearson correlation) and for the NN ≤5 listeners group (0.690; Pearson correlation), see Figure 4.3.

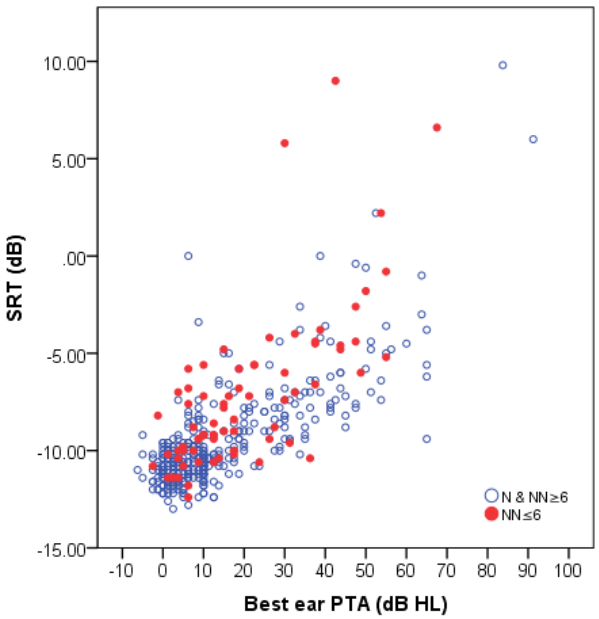

Figure 4.3. Smartphone digits-in-noise SRT correlation with best ear 4FPTA (0.5, 1, 2 and 4 kHz) for N & NN ≥6 (r=.763) and NN ≤5 (r=.690).

4.4.3. Reference scores

Reference scores were determined from normal-hearing listeners (best ear 4FPTAs ≤25 dB HL). Table 4.2 shows the mean, range and standard deviation of the SRT for the whole group of listeners and for the N & NN ≥6 group and NN ≤5 group separately. The average normal-hearing SRT in the N & NN ≥6 group is approximately 1.7 dB better (lower) than in the NN ≤5 group.

Table 4.2. Demographics and performance summary for normal-hearing according to self-reported English speaking competence (best ear 4FPTA ≤25 dB HL) *N – Native speakers; NN – non-native speakers*

Description	All Lang	N&NN≥6*	NN≤5*
Subjects (n)	337	291	46
Mean Age (yrs)	27	26	36
Age Range(yrs)	16 to 81	16 to 81	16 to 67
StDev Age(yrs)	16	14	17
SRT Range (dB)	0.0 to -13.0	0.0 to -13.0	-4.8 to -12.4
Mean SRT(dB)	-10.2	-10.4	-8.7
StDev SRT(dB)	1.6	1.5	1.9

** "How competent are you in speaking English?" Rating scale (1 = no competence; 10 = perfect competence)*

4.4.4. Screening characteristics

To determine the screening characteristics of the test, logistic regression models were used to determine equations to discriminate between listeners with best ear 4FPTA ≤25 dB HL and best ear 4FPTA>25 dB HL. Logistic regression models were constructed for all listeners grouped together and for the subgroups N & NN ≥6 and NN ≤5 separately. The SRT was used as predictor and the additional value of using age as a predictor was determined (Table 4.3). Highest test accuracy was obtained by including age and SRT for both groups. In both groups, the addition of age as predictor increased the specificity of the test.

Table 4.3. Logistic regression models for N & NN ≥6 and NN ≤5 listeners.

	Predictors	Equation	AUROC	Cut-off value	Sensitivity	Specificity
All subjects	SRT	-	.925	SRT=-9.55 dB	.94	.77
N&NN≥6	SRT	-	.943	SRT=-9.55 dB	.95	.83
	SRT, age	p=1/[1+exp(-0.562 ·SRT-0.080·age)]	.962	p=0.149	.95	.87
NN≤5	SRT	-	.873	SRT=-7.50 dB	.84	.74
	SRT, age	p=1/[1+exp(-0.478 ·SRT-0.054·age)]	.903	p=0.263	.84	.77

The ROC was determined from the results of the logistic regression analyses for N & NN ≥6 and NN ≤5 separately. The first set of ROC curves were based on the SRT of the listeners; the second set of ROC curves were based on the SRT and age of the listeners. The ROC curves were used to determine the AUROC, the cut-off values and the sensitivity (proportion correctly identified listeners with a hearing loss among the listeners with a hearing loss) and specificity (proportion correctly identified listeners with normal-hearing among the listeners with normal-hearing) of the digits-in-noise test. Figure 4.4 shows the ROC curve based on all listeners as one group and Figure 4.5 shows the ROC curves for the subgroups with SRT as predictor and with SRT and age as predictors.

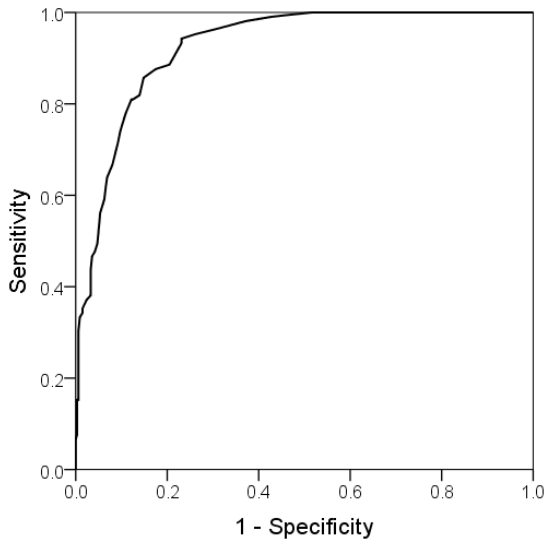

Figure 4.4. ROC curve for all listeners with SRT as predictor.

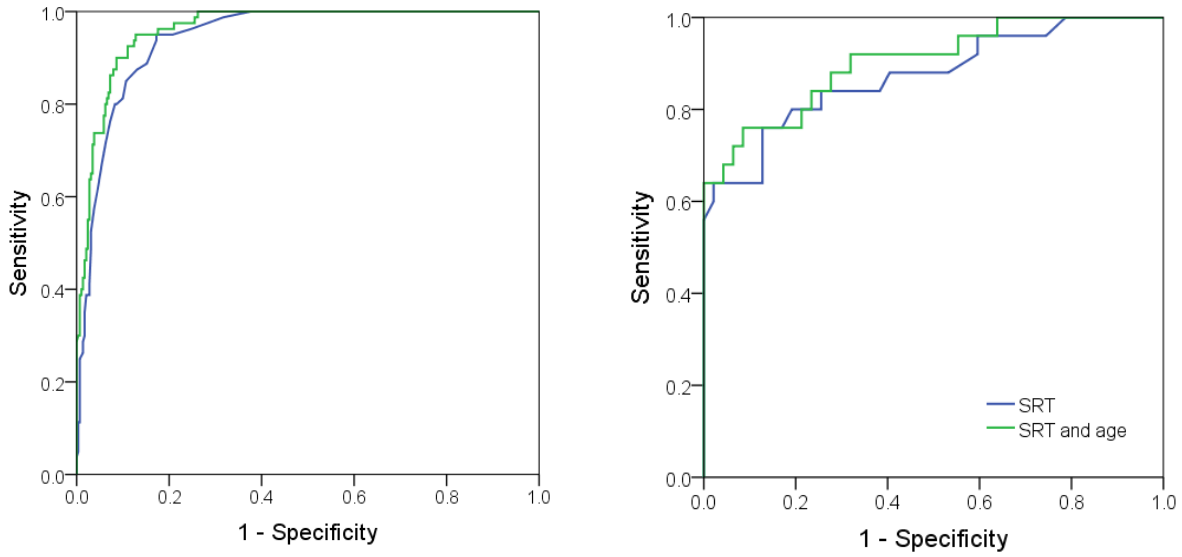

Figure 4.5. ROC curves for N & NN ≥6 (left) and NN ≤5 (right). The improvements of test characteristics are illustrated by the shift of the curves to the upper left corner with the inclusion of age as a predictor.

4.5. Discussion

The recently developed English smartphone digits-in-noise test (Potgieter et al., 2016) promises widespread access to hearing screening in a country like South Africa where smartphone penetration is approaching 80% of households (Ericsson Mobility Report, 2015). Because of the multilingual population in South Africa, it is important to consider the effect of NN listeners' performance on the digits-in-noise test. This study determined the performance of NN English listeners on the South African English smartphone digits-in-noise hearing test, compared to N English listeners.

The smartphone digits-in-noise SRTs and the best ear 4FPTA were significantly correlated (r=0.76 for N & NN ≥6; r=0.69 for NN ≤5). The correlation for the N & NN ≥6 group agrees with previous results reported for the Dutch (r=0.72), French

(*r*=0.77) and American-English (*r*=0.74) landline telephone digits-in-noise hearing screening tests (Smits et al., 2004, Jansen et al., 2010, Watson et al., 2012). The smartphone digits-in-noise test was conducted binaurally whilst the Dutch, French and American-English tests were ear specific. Another difference, compared to previous reports, is the inclusion of 70.4% NN listeners (n=320) in this study. These findings indicate that comparable correlation between digits-in-noise SRTs and best ear 4FPTAs can be obtained in a sample where the majority of listeners are NN English listeners with some degree of self-reported English speaking competency.

The results of the linear regression models indicated that English speaking competence is a significant predictor of the digits-in-noise SRT; age is only a significant predictor for listeners with best ear 4FPTA ≤25 dB HL. A contributing factors could be the difference in distribution of age and hearing loss between listeners with best ear 4FPTA ≤25 dB HL and listeners with a best ear 4FPTA>25 dB HL. Results also support findings by Moore et al. (2014) who indicated that age may possibly have an effect on the digits-in-noise SRT. They showed that a decline in cognitive functioning, associated with age, has an effect on the digits-in-noise SRT. Koole et al. (2016) found a low correlation between age and the digits-in-noise SRT after controlling for pure-tone thresholds. In light of the above, it is important to consider age when determining the result of the digits-in-noise test in normal-hearing listeners because it may contribute to the accuracy of the screening test outcome. Accuracy of the smartphone digits-in-noise test was evaluated by determining the AUROC, sensitivity and specificity of the test to discriminate between listeners with best ear 4FPTA >25 dB and those with best ear 4FPTA ≤25 dB, for N and NN English listeners. Logistic regression models and ROC curve analysis demonstrate

that subgroups based on English speaking competence and including age as predictor increases the AUROC, sensitivity and specificity of the test.

Test performance improved in the N & NN ≥6 group (AUROC=0.962) when self-reported English speaking competence and age were considered. The sensitivity (0.95) and specificity (0.87) for N & NN ≥6 English listeners (best ear 4FPTA >25 dB HL) compared well to the Dutch (0.91 and 0.93 respectively) and American-English (0.80 and 0.83 respectively) digits-in-noise tests (Smits et al. 2004; Watson et al. 2012). The sensitivity and specificity was poorer for the NN ≤5 group than for the N & NN ≥6 group. Possible reasons for this finding might be the fact that the NN ≤5 group was more heterogeneous in English speaking competence; the group included a smaller number of listeners; and varying distributions of hearing loss degrees may have influenced the calculated test characteristics. Self-reported English speaking competence was a significant predictor of the digits-in-noise SRT. Results by Kaandorp et al. (2015) also indicated that NN listeners did not perform as well as N Dutch listeners on the Dutch digits-in-noise test. Vocabulary size and educational level had a small effect (0.8 dB SNR increase) on the performance of NN listeners on digits-in-noise recognition (Kaandorp et al., 2015). This small difference in the performance between N listeners and NN listeners was measured to re-validate that digits-in-noise depend minimally on top-down processing (e.g., linguistic skills) (Smits et al., 2013).

ROC curve analysis was used to determine cut-off SNR values for “pass” (4FPTA ≤25 dB HL) and “refer” (4FPTA >25 dB HL) for hearing loss for N and NN English listeners. The cut-off SNR value for “pass” or “refer” for hearing loss for N & NN ≥6

English was -9.55 dB and -7.50 dB for NN ≤5 English listeners. The higher cut-off SNR for NN ≤5 English listeners can be expected as the linear regression model demonstrates that English speaking competence has a negative effect on the digits-in-noise SRT, and the mean SRT for normal-hearing listeners is higher for the NN ≤5 group than for the N & NN ≥6 group (Table 4.2). The mean SRT of the normal-hearing N & NN ≥6 English listeners (-10.4 dB) is similar to the diotically measured average SRT for the Dutch and American-English digits-in-noise test (-10.0 and -11.2 dB SNR respectively) (Smits et al., 2016). This comparison indicates that the digits-in-noise test provides close comparisons across NN listeners with good language proficiency (Smits et al., 2016).

The current study demonstrates that a smartphone application provides an opportunity to use the English digits-in-noise hearing test as a national test for South Africans. The fact that English digits are often used by speakers of other languages in South Africa (Branford & Claughton 2002) allows for the possibility to accommodate non-native listeners by adjusting reference scores based on a self-reported English speaking competence. More representative data from diverse language groups and English competence levels would be useful to improve the validity of the test as a nationally used screening tool. The smartphone application could be programmed to report the test results in a listener's native language to allow for correct interpretation of test results across non-native listeners. The result of this study also indicates that age could be included when determining the screening test result of the digits-in-noise SRT, thereby increasing the accuracy of the screening test in normal-hearing listeners. Providing these adjustments can ensure adequate test performance across native English and non-native English

listeners. It is important to note that this study was limited to a small group (15.9%; 72/454 listeners) of non-native English listeners with poor self-reported English speaking competence (scores ≤5/10). Future studies should aim to expand data on this group of listeners.

CHAPTER 5

EVALUATING A SMARTPHONE DIGITS-IN-NOISE TEST AS PART OF THE AUDIOMETRIC TEST-BATTERY

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5.1. Abstract

Background

Speech-in-noise tests have become a valuable part of the audiometric test-battery providing an indication of a listener's ability to function in background noise. A simple digits-in-noise test could be valuable to support diagnostic hearing assessments, hearing aid fittings and counselling for both paediatric and adult populations.

Objective

The objective of this study was to evaluate the smartphone digits-in-noise test's performance as part of the audiometric test-battery.

Design

This descriptive study evaluated 109 adult subjects (43 male, 66 female) with and without sensorineural hearing loss by comparing pure-tone air conduction thresholds, SRS dB and the digits-in-noise SRT. An additional nine adult hearing aid users (4 male, 5 female) was utilized in a subset to determine aided and unaided digits-in-noise SRTs.

Results

The digits-in-noise SRT is strongly associated with the best ear 4FPTA (r=0.81) and maximum SRS dB (r=0.72). The digits-in-noise test had high sensitivity and specificity to identify abnormal pure-tone (0.88 and 0.88 respectively) and SRS (0.76 and 0.88 respectively) results. There was a mean signal-to-noise ratio SNR improvement in the aided condition that demonstrated an overall benefit of 0.84 SNR dB.

Conclusion

The digits-in-noise SRT was significantly correlated with the best ear 4FPTA and maximum SRS dB. The digits-in-noise SRT provides a useful measure of speech recognition in noise that can evaluate hearing aid fittings, manage counselling and hearing expectations.

5.2. Introduction

5.2.1. Background

One of the major problems persons with hearing loss experience is communication in the presence of background noise (Taylor, 2003). Amplification options such as hearing aids, cochlear implants and assistive listening devices could improve hearing abilities, but most hearing impaired listeners still find it difficult to understand conversation in background noise (Smits et al., 2013). Speech-in-noise tests have become an important asset to the diagnostic audiometric test-battery as pure-tone air conduction testing and speech recognition scores are not able to determine or mimic the everyday challenge of listening to speech-in-noise (Taylor, 2003).

By the late 1970's speech-in-noise tests became popular due to Plomp & Mimpen's (1979) pioneering work with the development of the standard Dutch speech-in-noise test. The standard Dutch speech-in-noise test was able to reliably determine the SRT for sentences. Many variations of the standard Dutch speech-in-noise test were developed in several languages because of the test's strong validity, reliability, sensitivity and specificity (Theunissen, Swanepoel & Hanekom, 2009; Plomp & Mimpen, 1979). Examples of such tests include the HINT, MHINT and the German sentence test (Nilsson, Soli & Sullivan, 1994; Wong, Soli, Liu, Han & Huang, 2007; Kollmeier & Wesselkamp, 1997).

Today speech-in-noise tests are primarily used in the clinical setting to determine a person's ability to function in a general communication environment by evaluating the speech understanding handicap caused by the hearing loss (Smits et al., 2013). Speech-in-noise tests possess additional clinical value since information on speech

understanding in noise can support adjustment and monitoring of hearing aid and cochlear implant fitting parameters (Smits et al., 2013). Speech-in-noise tests have also played an important role in counselling hearing aid or cochlear implant users to understand their hearing disability, manage expectations and implement intervention approaches (Smits et al., 2013; Kaandorp et al, 2015).

Most speech-in-noise tests use meaningful sentences as speech material because sentences are representative of daily conversation. Even though speech-in-noise sentence tests are able to determine hearing loss for speech, the appropriateness of such a test may be limited (Smits et al., 2013; Theunissen et al., 2009). To administer a speech-in-noise sentence test the listener must be able to understand a whole sentence correctly at a comfortable SNR. Most listeners with a hearing loss perform poorly on speech recognition tasks due to the severity of the hearing loss or language competence, especially in non-native English listeners (Smits et al., 2013; Potgieter, Swanepoel, Myburgh & Smits, 2017). Therefore, listeners with poor English language competence, cochlear implant users, children and people with severe hearing losses are not able to conduct a speech-in-noise sentence test (Smits et al., 2013; Potgieter et al., 2017).

More recently the DIN was developed for diagnostic and clinical purposes (Smits et al., 2013). This test, using digit-triplet (i.e., 1-6-5) material, was demonstrated to be suitable as speech material in a diagnostic digits-in-noise test by comparing it to the gold standard Dutch sentence test developed by Plomp & Mimpen (1979). This study concluded that the digit-triplets test demonstrated no learning effect and an accurate SRT could be determined (Smits et al., 2013). The DIN also had high criterion

validity and the steepness of the slope for the speech recognition function compared positively to the Dutch sentence test (Smits et al., 2013). Additionally, the DIN could be conducted by normal-hearing persons up until persons with a profound hearing loss. The simplicity of the DIN test even allows children to conduct the test (Smits et al., 2013).

Because of the successful development of the DIN, the South African smartphone-based digits-in-noise hearing test was developed in 2016 (Smits et al., 2013; Potgieter et al., 2016). Following a similar development and validation procedure as the Dutch DIN test (Smits et al., 2013; Potgieter et al., 2016) the South African digits-in-noise test was developed using South African English digits (0 – 9) as speech material. The noise level was fixed for negative SNRs, whereas the speech was fixed for positive SNRs. An adaptive test procedure was followed where a triplet was presented 2 dB higher (correct response) or 2 dB lower (incorrect response) based on the subject's response. The SRT was calculated as the average SNR of the triplets presented. A cut-off value was determined at -9.55 dB to indicate "pass" or "refer" for hearing loss in N or NN English speakers with a high level of self-reported English speaking competence (Potgieter et al., 2017; Smits et al., 2013).

Potgieter et al. (2017) demonstrated that the South African digits-in-noise test could accommodate NN listeners by adjusting the "pass" or "refer" criteria based on self-reported English speaking competency. The South African digits-in-noise test therefore ensures an accurate test result across N and NN South African English listeners (Potgieter et al., 2017). Additionally, the increased use of smartphones in South Africa allows the digits-in-noise test to be available to increasing numbers of

South Africans living in rural and urban areas (Potgieter et al., 2016; Potgieter et al., 2017).

Based on the successful implementation of the South African digits-in-noise test as a screening test (available on a smartphone app) it's suitability for clinical use in an audiology clinic required investigation. Smits et al. (2013) reported that the diagnostic DIN test could be an important asset to the audiometric test-battery for the following two reasons. Firstly, in South Africa, no standardised or validated recorded speech materials for spondee or phonetically balanced word lists exist. A diagnostic version of the South African digits-in-noise test can provide additional information on a listener's hearing impairment for speech recognition in noise. The digits-in-noise test is validated and consist of recorded speech material with low linguistic demands suitable to test normal to profound hearing losses (Smits et al., 2013; Potgieter et al., 2016) Secondly, the test could assist in counselling and management of a listener's hearing aid expectation as well as assessing hearing aid benefit (Smits et al., 2013).

5.2.2. Objective

Given the potential benefit of a diagnostic version of the South African digits-in-noise test, this study aimed to compare the digits-in-noise test alongside standard diagnostic audiology tests in clinical practice. A comparison was conducted between pure-tone audiometry, SRS dB and the digits-in-noise SRT. The digits-in-noise test was also utilized in a subset of participants to determine the potential benefit for use with hearing aid listeners by determining aided and unaided digits-in-noise SRTs.

5.3. Methodology

The institutional review board of the University of Pretoria approved the research study before data collection commenced.

5.3.1. Subjects

A comparative and correlational descriptive research design was followed. Various audiometric practices in the Gauteng region assisted with data collection. Each audiologist was supplied with a smartphone to conduct the South African English smartphone-based digits-in-noise test on subjects in their own private practice or at the public health hospital audiology clinic. A convenience non-probability sampling procedure was followed with selected subjects as they were available and willing to volunteer to take part in the research study at clinical data collection sites. The subjects were assessed with a comprehensive audiometric test-battery and the smartphone digits-in-noise test in a single test session lasting approximately one hour.

5.3.2. Methods and Materials

An otoscopic evaluation was performed to allow observation of any obstruction in the external auditory meatus. Any ear canal obstructions were removed by ‘n qualified audiologist or health care provider before testing commenced.

A variety of calibrated clinical audiometers were used to conduct pure-tone air conduction, bone conduction and speech recognition testing. Air conduction and speech audiometry was done in a sound-proof booth using supra-aural or insert earphones. A bone oscillator was used to conduct bone conduction audiometry. Air

conduction thresholds across octave frequencies from 250 to 8000 Hz were determined, while bone conduction thresholds were determined from 500 to 4000 Hz. The modified Hughson-Westlake method was used to seek pure-tone air and bone conduction thresholds (Hughson & Westlake, 1944). The 4FPTA was calculated to categorize the severity and configuration of the hearing impairment according to the Jerger criteria (Jerger & Jerger, 1980). Normal-hearing was categorized as normal if the best ear 4FPTA was ≤25 dB HL. A mixed hearing loss was determined by calculating the pure-tone and bone conduction averages (500, 1000, 2000 and 4000 Hz) for both ears. The hearing loss was categorised as conductive or mixed when the average threshold difference was >15 dB HL (Margolis & Saly, 2007).

Speech recognition testing was presented with live voice in Afrikaans or English. Currently no standardized recorded phonetically balanced word lists exist in Afrikaans or South African English. Speech recognition testing was therefore limited as live voice presents variation in speech production and articulation (Hood & Poole, 1980). SRS were obtained across intensities by administering the *Afrikaanse Foneties Gebalanseerde Woordelys* (a phonetically balanced word list) to Afrikaans speaking subjects (Laubscher & Tesner, 1966). The *Univeristy of Pretoria, English Phonetically Balanced Word List* was used to obtain SRS dB in N English speakers. A list of 25 phonetically balanced words was presented 30 dB HL above the 4FPTA at three different intensities (maximum intensity 90 dB). English additional language speakers could choose whether they would like speech recognition testing to be presented in Afrikaans or English. Normal maximum SRS dB was classified as a 100% word discrimination score at intensities ≤40 dB HL. The best ear maximum

SRS dB was used in the analysis. The 50% SRS dB was not available for all subjects. Various sites were involved in data collection, thereby not using the same methods for determining SRS dB scores.

The South African smartphone digits-in-noise app instructed the subject to enter his/her gender, date of birth, initials and surname. The subject placed the smartphone earphone set into the ears and listened to digits being repeated. A scroll bar allowed the subject to adjust the volume of the digits being repeated to a comfortable listening intensity. A “start test” button presented the test. The subject entered the digit responses on the smartphone keypad.

Once the digits-in-noise hearing screening test started the test operates by varying the noise intensity level while having a fixed speech level when triplets with negative SNRs are presented. When triplets with positive SNRs are presented the speech level becomes fixed and the noise level varies. The noise starts 500 ms before and after triplet presentation. The digits were pronounced by a female speaker with natural intonation, for example 6-9-0, spoken as six-nine-zero. The first digit-triplet set was presented based on the subject’s comfortable listening intensity. The subject responded to the triplet set by entering the digit-triplet set on a pop-up keypad. The next digit are presented 2 dB higher (incorrect response) or 2 dB lower (correct response) based on the subject’s response.

The subgroup of nine hearing aid users was asked to perform an additional digits-in-noise test using their hearing aids. The digits-in-noise test was presented using free-field speakers in a sound-proof booth. The subjects were placed seated 1 meter from

the speaker facing the speaker at 0˚. The subjects entered their response using the smartphone app.

5.3.3. Data analysis

A Spearman correlation coefficient was determined to assess the relationship between the best ear 4FPTA, maximum SRS dB and the digits-in-noise SRT. A paired sample t-test was conducted to analyse the relationship between the best ear 4FPTA and maximum SRS dB.

The performance of the South African English smartphone digits-in-noise test was determined by comparing the SRT to the best ear 4FPTA and maximum SRS dB. Descriptive statistics, frequencies and proportions were determined for these variables. The sensitivity and specificity, PPV and NPV were calculated as an indication of the accuracy of the method for determining a hearing loss. Additionally, the AUROC from a ROC analysis was determined to provide a further indication of the accuracy between the variables.

Descriptive statistics indicating the mean, range and standard deviation for aided and unaided hearing aid digits-in-noise SRTs were determined.

5.4. Results

A total of 109 adult subjects (43 male, 66 female) participated in this study. The mean age was 55 years (20 SD) with a range of 16 – 89 years. An additional subset of nine adult subjects (4 male, 5 female) with an average age of 72 year (7.2 SD; 63 to 84 yrs range) participated in this sub-study.

5.4.1. Comparing digits-in-noise speech reception threshold, pure-tone audiometry and maximum speech recognition monaural performance score intensity.

Significant correlations (Figure 5.1) were evident between the best ear 4FPTA and maximum SRS dB (r=0.87; n=111; p<0.001), and the best ear 4FPTA and digits-in-noise SRT (Figure 5.2) (r=0.81; n=120; p<0.001) and the maximum SRS dB and digits-in-noise SRT (Figure 5.3) (r=0.72; n=111; p<0.001). The strongest correlation was between the best ear 4FPTA and maximum SRS dB and the weakest correlation was between the maximum SRS dB and the digits-in-noise SRT. A comparison between the best ear 4FPTA (28.8 Mean; 17.9 SD) and SRS dB (53.6 Mean; 18.9 SD) showed a significant difference between the two variables.

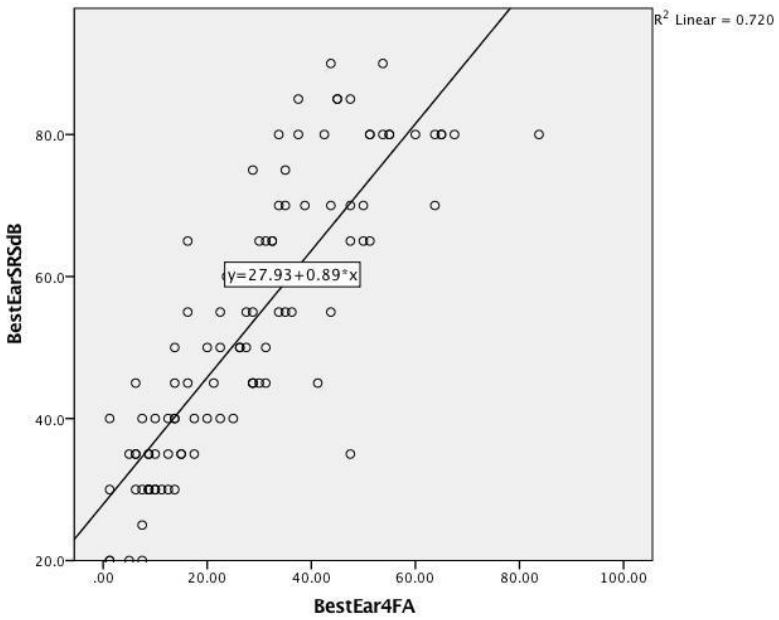

Figure 5.1. Scatterplot indicating the correlation between the best ear 4FPTA and maximum SRS dB

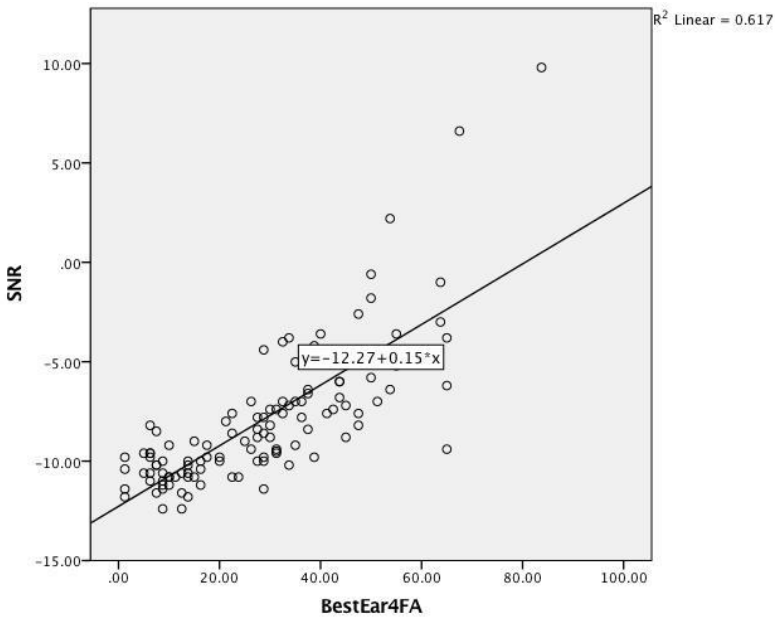

Figure 5.2. Scatterplot indicating the correlation between the best ear 4FPTA and digits-in-noise SNR (signal-to-noise ratio)

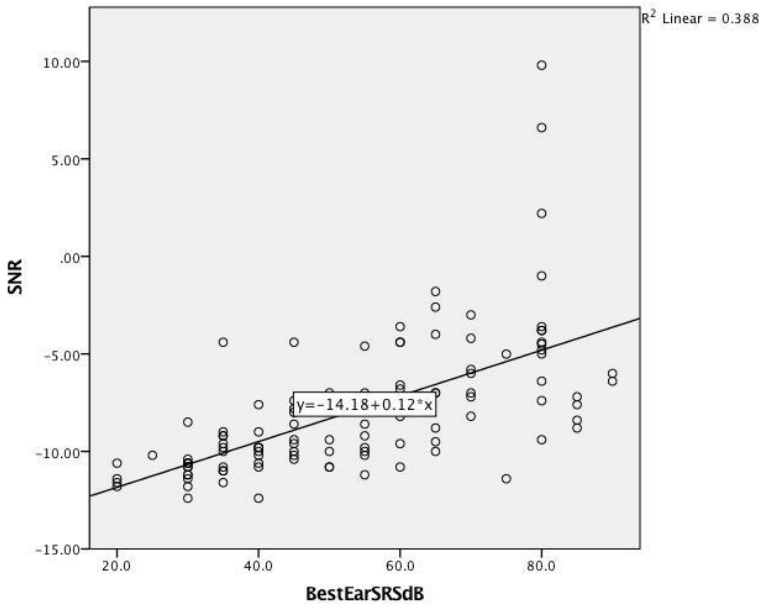

Figure 5.3. Scatterplot indicating the correlation between the best ear maximum SRS dB and digits-in-noise SNR (signal-to-noise ratio)

High sensitivity and specificity were obtained when comparing the digits-in-noise SRT to the maximum SRS dB HL (Table 5.1). The PPV of the digits-in-noise SRT was 91.5% and NPV was 66% to identify subjects with and without an abnormal maximum SRS dB result (≤100% word discrimination score at ≥40 dB HL).

The digits-in-noise SRT had a high sensitivity and specificity to identify subjects with an abnormal 4FPTA result (Table 5.1). The PPV of the digits-in-noise SRT was 89.8% and NPV was 86% to identify subjects with and without an abnormal 4FPTA result.

The best ear maximum SRS dB predicted normal and abnormal best ear 4FPTA, with a high sensitivity and specificity (Table 5.1). The PPV of the maximum SRS dB HL was 98.3% and the NPV was 75.5% to identify subjects with and without an abnormal 4FPTA result.

Table 5.1. Performance of digits-in-noise SRT and maximum SRS dB to predict normal and abnormal best ear 4FPTA (SNR cut-off = -9.5 dB SNR)

	HL[‡] (n)	NH[§] (n)	Sens	Spec	AUROC
BE[ł] SRT predicting BE 4FPTA	50	59	0.883	0.878	0.941
Maximum SRS dB predicting BE 4FPTA	60	49	0.831	0.974	0.937
BE SRT predicting BE SRS dB	59	50	0.76	0.868	0.884

[ł]*BE = Best ear*
[‡]*HL = Hearing loss*
[§]*NH = Normal-hearing*

A comparison between aided hearing aid digits-in-noise SRTs (-7.2 Mean; 2.1 SD; -3.2 to -9.4 range) and unaided hearing aid digits-in-noise SRTs (-6.4 Mean; 2.6 SD; -2 to -9.4 range) showed a small increase in SRT with hearing aids (0.8 Mean; 1.5

SD). There was significant individual variability between subjects in the aided condition (-3.2 to -9.4 range) and unaided condition (-2 to -9.4 range) (Table 5.2).

Table 5.2. Descriptive statistics for aided and unaided hearing aid digits-in-noise SRTs (n=9)

	Mean	Range	Standard Deviation
Age	72	63 to 84	7.2
Best ear 4FPTA	37.6	26.2 to 47.5	8.1
Digits-in-noise SRT (aided)	-7.2	-9.4 to -3.2	2.1
Digits-in-noise SRT (unaided)	-6.3	-9.4 to -2	2.6
Digits-in-noise SRT difference	-0.84	-3.6 to 1.6	1.5

5.5. Discussion

An English smartphone digits-in-noise test was successfully developed in 2016 to provide widespread hearing screening in South Africa (Potgieter et al., 2016). Smits et al. (2013) implemented a diagnostic version of the DIN to support the diagnostic audiometric test-battery in determining the speech recognition impairment in noise for listeners (Smits et al., 2013). In order to determine the South African English digits-in-noise hearing test's applicability as a diagnostic tool the digits-in-noise SRT was compared to the audiometric 4FPTA (best ear) and maximum SRS dB (best ear) in the current study.

The smartphone digits-in-noise SRT and the best ear 4FPTA was significantly correlated (r_s=0.81) in line with previous results reported for the Dutch (r=0.72), French (r=0.77) and American English (r=0.74) landline telephone digits-in-noise hearing screening tests (Smits et al., 2004, Jansen et al., 2010, Watson et al., 2012). A good relationship between the digits-in-noise SRT and maximum SRS dB was demonstrated (r_s=0.72) and corresponded to previous results comparing the

Northwestern University Auditory Test No. 6 in quiet to the Words-in-Noise Test (R_s =0.61) (Wilson, 2011). The AUROC for the digits-in-noise SRT and best ear 4FPTA comparison (0.941) in this study compared well to the AUROC for the Dutch (0.974) landline digits-in-noise test (Smits et al., 2004).

The sensitivity and specificity of the digits-in-noise test provides an indication of the digits-in-noise SRT's ability to correctly identify listeners with or without a hearing loss. The sensitivity and specificity of the digits-in-noise SRT compared to the best ear 4FPTA (0.88 and 0.88 respectively) related well to the Dutch (0.91 and 0.93 respectively) and American English (0.80 and 0.83 respectively) landline digits-in-noise tests (Smits et al., 2004; Watson et al., 2012). A high sensitivity (0.76) and specificity (0.87) were also found when comparing the digits-in-noise SRT to the maximum SRS dB. The poorest correlation was between the digits-in-noise SRT and maximum SRS dB. Unsurprisingly, these tests are very different in what they measure with the SRS dB being a supra-threshold speech test in quiet whilst the digits-in-noise test is a threshold test in noise (Taylor, 2003; Lucks Mendel, 2008; Wilson, 2011). The tests therefore complement each other within a clinical test-battery. The SRS dB would always remain a fundamental part of the audiometric test-battery as it is a method to crosscheck the pure-tone threshold and provides information on speech processing, sensitivity to speech stimuli and understanding speech at supra-threshold levels in quiet (Lucks Mendel, 2008). The digits-in-noise test reflects a person's speech recognition ability in noise and provides an indication of loss for speech-in-noise ability (Taylor, 2003; Wilson, 2011; Smits et al., 2013). The digits-in-noise test can therefore inform counselling and hearing aid expectation management (Taylor, 2003; Wilson, 2011; Smits et al., 2013).

Pure-tone thresholds forms an essential part of the audiometric test-battery as the measurement provides information regarding a listener's degree, type and configuration of hearing loss (Kramer, Kapteyn, Festen & Tobi, 1996). Pure-tone thresholds however are unable to provide insight into speech recognition abilities in background noise (Kramer et al., 1996; Smits et al., 2004). Speech-in-noise tests (i.e., the digits-in-noise test) are most valuable in diagnosing a listener's speech recognition impairment in noise (Smits et al., 2013; Taylor, 2003). The results from the comparison between the digits-in-noise SRT and best ear 4FPTA show a strong relationship between these measures. The digits-in-noise SRT is therefore strongly associated with the 4FPTA but provides complementary information on speech recognition impairment in noise. Additionally, the digits-in-noise test can be an applicable asset to the diagnostic audiometric test-battery for the following reasons. Firstly, the digits-in-noise test is easy to administer and takes a few minutes to conduct (Potgieter et al., 2016). Secondly, simple speech material is used requiring low linguistic demands (Potgieter et al., 2016; Smits et al., 2004). Thirdly, the digits-in-noise test can be conducted from normal-hearing to profound hearing losses. Fourthly, the test is user friendly and can be utilized to test children (Smits et al., 2013). Finally, NN English listeners with poor English language speaking competence are able to conduct the digits-in-noise test (Potgieter et al., 2017).

A small sample (n=9) of hearing aid users were evaluated with the digits-in-noise test with and without hearing aid amplification. The mean SNR improved in the aided condition and demonstrated an overall benefit of 0.84 SNR dB. There was significant individual variability between subjects in the aided condition (-3.2 to -9.4 SNR dB) and unaided condition (-2 to -9.4 SNR dB). The digits-in-noise test can be valuable in

a clinical audiology setting to provide individualised performance measures for hearing aid users in background noise (Taylor, 2003). A measure of speech-in-noise ability is a valuable clinical addition for counselling and demonstrating hearing aid benefit in the presence of background noise (Taylor, 2003). Counselling informed by the digits-in-noise SRT could assist hearing aid users to understand their hearing impairment and provide important information regarding the communication difficulties that may persist (Taylor, 2003; Smits et al., 2013). The hearing aid could also be adjusted according to the hearing aid user's needs as reflected on the digits-in-noise SRT (Taylor, 2003). The limitation of this study included the small sample of hearing aid users evaluated with and without hearing aid amplification using the digits-in-noise test and the lack of data for 50% SRS dB scores.

5.6. Conclusion

The digits-in-noise SRT is strongly associated with the best ear 4FPTA and maximum SRS dB and could therefore provide complementary information on speech recognition impairment in noise. The digits-in-noise test had high sensitivity and specificity to identify abnormal pure-tone and SRS dB results. The digits-in-noise SRT and best ear 4FPTA was significantly correlated with previously developed landline telephone digits-in-noise tests. The digits-in-noise SRT can also demonstrate benefit for hearing aid fittings. The test is quick to administer and provides information on the SNR loss. The digits-in-noise SRT could therefore be used as a counselling tool to evaluate hearing aid fittings, manage counselling and hearing expectations.

CHAPTER 6

DISCUSSION, CLINICAL IMPLICATIONS AND CONCLUSION

Despite the prevalence of hearing loss, age-related hearing loss has been underdiagnosed and left untreated due to its slow and progressive onset (ASHA, 2011). Screening programs at health care facilities aim to identify people who could potentially benefit from hearing intervention (ASHA, 2011). Hearing screening programs have not been successfully implemented in South Africa due to several challenges. One of the major challenges is gaining access to health care clinics. In South Africa it is often difficult for people living in rural areas to travel to health care clinics as transport are expensive and unreliable (Tanser et al, 2006; Tanser et al, 2001).

The development of mobile technology and mobile penetration (80% of households in South Africa) across South Africa has offered new ways of providing access to affordable health care services (Ericsson Mobility Report, 2015). This study therefore investigated three aims. Firstly, a South African English smartphone digits-in-noise hearing test was developed and validated as a downloadable smartphone app to provide widespread access to hearing screening to people living in rural and urban areas. Secondly, the performance of NN English listeners on the South African English smartphone digits-in-noise hearing test was determined and compared to N English listeners. Lastly, the South African English digits-in-noise hearing test was evaluated for its clinical application as part of the standard audiology diagnostic test-battery in a diagnostic clinical setting.

6.1. Summary of findings

The continual increase in smartphone penetration in South Africa means that a smartphone-based digits-in-noise hearing test in a country like South Africa may provide widespread access to hearing screening in rural and urban areas and across different socio-economic strata. To date, this study reported the first smartphone-based app for a digits-in-noise based national hearing test.

The digits-in-noise hearing screening test development and characteristics were reported in study I and study II. Study I involved three phases for the development of the smartphone app. Phase I involved the recording, processing and equalization of the speech material. Phase II included the smartphone app development, methods for triplet generation, and the adaptive test procedures. Finally, normative data were gathered, and the effect of five different headphone types on the SRT of the smartphone digits-in-noise hearing test were examined in phase III. Study II investigated the performance of NN English listeners on the South African English smartphone digits-in-noise hearing test, compared to N English listeners.

Study I (phase I & II) followed similar procedures as the landline telephone-based Dutch and French digits-in-noise hearing tests (Smits et al., 2013). This study's average slope steepness for the speech recognition function of the South African smartphone-based digits-in-noise hearing test (broadband signal) (20%/dB) corresponded closely with the Dutch (20%/dB), French (20%/dB) and German (18%/dB) bandwidth limited telephone digits-in-noise tests (Smits et al., 2004; Jansen et al., 2010; Zokoll et al., 2012).

A lower SRT value (-10.6 dB SNR) for the South African smartphone test was found compared to Dutch, French and German landline telephone-based digits-in-noise tests (range -6.4 to -6.9 dB SNR) (Smits et al., 2004; Zokoll et al., 2012). The lower SRT value can be attributed to the digital signal quality afforded by the smartphone as opposed to the restricted bandwidth on landlines used by the other studies.

Phase III of study I investigated whether the type and quality of headphones would influence the digits-in-noise SRT. No statistically significant difference between the average SRTs for 5 different headphone sets (entry level to top-end quality headphone sets) was found. The digits-in-noise test is therefore accurate using different headphones making it uniquely suited to serve as a smartphone-based hearing test that could be utilized across rural and urban areas in South Africa (Culling et al., 2005).

Study II investigated the performance of NN English listeners on the South African English smartphone digits-in-noise hearing test, compared to N English listeners. This study demonstrated a good correlation between the digits-in-noise SRT and best ear 4FPTA (r=0.76 for N & NN ≥6; r=0.69 for NN ≤5) which compared well to correlations found for the Dutch, French and American English landline telephone-based digits-in-noise tests (Smits et al., 2004, Jansen et al., 2010, Watson et al., 2012). A high sensitivity and specificity (0.95 and 0.87 respectively) was found for the N & NN ≥6 (language proficiency score ≥6) group which compared well to the sensitivity and specificity of the Dutch and American English landline telephone-based digits-in-noise tests (Smits et al., 2004; Watson et al., 2012). The NN ≤5

(language proficiency score ≤5) group obtained a lower sensitivity and specificity compared to the N & NN ≥6 group.

Results from study II further demonstrated that the linear regression models indicated that self-reported English speaking competence is a significant predictor of the digits-in-noise SRT; age is only a significant predictor for listeners with a best ear 4FPTA ≤25 dB HL. A higher cut-off value for “pass/refer” for hearing loss was found for the N & NN ≥6 group (-9.55 dB HL) than for the NN ≤5 group (-7.50 dB HL). Even though these results indicate that poor English language proficiency has a negative effect on the digits-in-noise SRT an accurate hearing screening test could still be conducted. In order to accommodate listeners with poor self-reported English speaking competence adjustments to the smartphone hearing test should be considered.

Study III investigated the clinical application of the South African smartphone digits-in-noise test as part of the audiometric test battery. The smartphone digits-in-noise SRT and the best ear 4FPTA was significantly correlated (r_s=0.81) in line with previous results reported for the Dutch (r=0.72), French (r=0.77) and American English (r=0.74) landline telephone digits-in-noise hearing screening tests (Smits et al., 2004, Jansen et al., 2010, Watson et al., 2012). A strong relationship between the digits-in-noise SRT and maximum SRS dB was obtained (r_s=0.72) and correlated well to results comparing the Northwestern University Auditory Test No. 6 in quiet to the Words-in-Noise Test (R^2=0.61) (Wilson, 2011). The AUROC for the digits-in-noise SRT and best ear 4FPTA comparison (0.941) related well to the AUROC for the Dutch (0.974) landline digits-in-noise test (Smits et al., 2004).

The sensitivity and specificity of the digits-in-noise SRT compared to the best ear 4FPTA (0.88 and 0.88 respectively) related well to the Dutch (0.91 and 0.93 respectively) and American English (0.80 and 0.83 respectively) landline digits-in-noise tests (Smits et al., 2004; Watson et al., 2012). A high sensitivity (0.76) and specificity (0.87) was also found when comparing the digits-in-noise SRT to the maximum SRS dB. This comparison relates well to the sensitivity and specificity for the digits-in-noise SRT compared to the best ear 4FPTA (0.88 and 0.88 respectively). The poorest comparison was between the digits-in-noise SRT and maximum SRS dB.

A small sample (n=9) of hearing aid users was investigated to evaluate the digits-in-noise test in subjects with and without hearing aid amplification. The mean SNR improvement in the aided condition and demonstrated an overall benefit of 0.9 SNR dB.

6.2. Clinical implications

6.2.1. The South African smartphone-based digits-in-noise test's suitability as a hearing screening

This study developed a valid South African digits-in-noise hearing test that functions as a self-test on a smartphone via a smartphone app. The smartphone digits-in-noise test is a suitable option as a hearing screening test due to the following qualities. Firstly, the smartphone digits-in-noise test provides an accurate hearing screening test result with high sensitivity and specificity. Secondly, the results of this study indicates that age could be included in a logistic regression function when

determining the screening test result of the digits-in-noise SRT, thereby increasing the accuracy of the screening test in normal-hearing subjects.

As a smartphone app the digits-in-noise test can be used by any person in possession of a smartphone as the app does not make use of a 3G or 4G connection apart from perhaps downloading the app onto a smartphone. This way the digital audio files reside on the smartphone and ensure that the quality of the sound files is not affected by the quality of a mobile phone connection. In fact, the test can be conducted without a mobile phone connection. The downloaded app can be accessed on the smartphone without the need of a mobile connection.

A high quality digital signal is produced by the smartphone as opposed to the restricted bandwidth on landline telephones used by previous reported studies. The South African digits-in-noise hearing test produces a digital signal that covers a bandwidth of 30 to 20 000 Hz which represents the human voice more accurately and therefore improves speech intelligibility (Bonello, 2015). Results were independent of headphone type and the app can be used with any Android smartphone. The digits-in-noise test is therefore accurate using different headphones making it uniquely suited to serve as a smartphone-based hearing test that could be downloaded by persons across South Africa and administered using standard headphone sets (Culling et al., 2005).

A smartphone app allows for possibilities to accommodate NN listeners to also use the hearing screening test by adjusting reference scores based on a self-reported English speaking competency scale that can be incorporated into the app.

Furthermore, the smartphone app could be programmed to report the test results in a subject's N language to allow for correct interpretation of test results across NN listeners. Providing these adjustments can ensure good test performance across N English and NN English listeners.

6.2.2. Clinical application of the South African smartphone-based digits-in-noise hearing test

The results from this study indicated that the digits-in-noise hearing test can be appropriate for the clinical audiometric setting as the digits-in-noise SRT is strongly associated with the 4FPTA, but provides complementary information on speech recognition impairment in noise. Additionally, the digits-in-noise test can be an applicable asset to the diagnostic audiometric test battery for the following reasons. Firstly, the digits-in-noise test is easy to administer and takes a few minutes to conduct (Potgieter et al., 2016). Secondly, simple speech material is used requiring low linguistic demands (Potgieter et al., 2016; Smits et al., 2004). Thirdly, the digits-in-noise test can be conducted from normal-hearing to profound hearing losses. Fourthly, the test is user friendly and can be utilized to test children (Smits et al., 2013). Finally, NN English listeners with poor English language speaking competence are able to conduct the digits-in-noise test (Potgieter et al., 2017).

The digits-in-noise SRT and maximum SRS dB measures are very different with SRS being a supra-threshold speech test in quiet compared to the digits-in-noise test which is a threshold test in noise. The SRS provides an indication of a person's ability to recognise words in quiet whilst the digits-in-noise test reflects a person's speech recognition ability in noise. In this study we used the maximum SRS dB

compared to the digits-in-noise SRT. In retrospect, using the 50% SRS dB, which is a lower supra-threshold score than the maximum SRS dB, would have been more appropriate and more closely aligned to the digits-in-noise SRT. Nonetheless, using the maximum SRS dB showed that these tests complement each other within a clinical test battery and can inform counselling and hearing aid expectation management.

Furthermore, the digits-in-noise test can be valuable in a clinical audiology setting to provide individualised performance measures for hearing aid users in background noise (Taylor, 2003). The digits-in-noise SRT can therefore be a valuable clinical addition for counselling and demonstrating hearing aid benefit in the presence of background noise (Taylor, 2003). Counselling informed by the digits-in-noise SRT could assist hearing aid users to understand their hearing aid impairment and provide powerful information regarding the communication difficulties that persist. The hearing aid could also be adjusted according to the hearing aid user's needs as reflected on the digits-in-noise SRT (Taylor, 2003).

6.3. Study limitations

Limitations of this research study include the following:

- This study followed a convenience sampling approach and therefore had no control over the number of listeners from each language group that participated in the study. The convenience sampling approach resulted in an underrepresentation of listeners for some of the language groups which is not entirely representative of the South African population.

- A comparatively small sample of NN listeners with poor self-reported English speaking competence participated in this study. Evaluating a larger sample of NN listeners with poor self-reported English speaking competence would allow a better representation of the South African population and increase the test performance accuracy for persons with poor English competence.
- In study III (Chapter 5), a small sample of hearing aid users evaluated with and without hearing aid amplification used the digits-in-noise test. A larger sample of hearing aid users is required to indicate statistical trends for the benefit of using hearing aid amplification.
- No children aged <16 years were included in this study. Smits et al. (2013) indicated that the digits-in-noise test can be used to test children as the test makes use of simple linguistic demands (digits) compared to previously developed speech-in-noise test (Smits et al., 2013). The applicability of the digits-in-noise test in the testing of children should be explored in the South African context.

6.4. Recommendations for future research

The following recommendations should be considered when conducting future research in this field of study.

- A stratified sampling approach should be followed. This approach could be beneficial to follow as it would allow control over the subjects that best represent the study population and minimize the over- or underrepresentation of a study sample (de Vos et al., 2011).
- A large sample of subjects with poor self-reported English speaking competence should be investigated to provide a better representation of the

South African population. In the current study, a 10 point rating scale for self-reported English speaking competency was used when evaluating English NN speakers. A simpler rating scale (e.g., rating according to “very poor, poor, good, excellent”) for self-reported English speaking competence could perhaps be trailed. The question could also be adapted to enquire about listeners understanding of English as opposed to English speaking competence.

- Future research should determine the performance of children on the smartphone digits-in-noise test. The digits-in-noise test makes use of simple linguistic demands (digits), is quick to administer and provides an accurate SRT result. The test might be suitable to test children as it could simplify the test procedures used to evaluate hearing ability in children, thereby obtaining an accurate test result in a short period of time.
- The smartphone digits-in-noise test’s clinical value could be determined in a cochlear implant clinic. The test could be administered using a smartphone app, therefore different connectivity options are possible (direct or wireless streaming). This type of testing would allow the cochlear implant user to conduct the test at home.
- Only a small sample of hearing aids users were tested with the digits-in-noise test in study III (Chapter 5). A larger sample could investigate whether there are associations between the SNR benefit in hearing aid outcomes.

6.5. Conclusion

This study demonstrated that a smartphone app provides the opportunity to use the English digits-in-noise hearing test as a national test for South Africans. The smartphone app can accommodate NN listeners by adjusting reference scores based on a self-reported English speaking competence rating. The inclusion of age when determining the screening test result increases the accuracy of the screening test in normal-hearing listeners. Providing these adjustments can ensure adequate test performance across N English and NN English listeners. Furthermore, the digits-in-noise SRT is strongly associated with the best ear 4FPTA and maximum SRS dB and could therefore provide complementary information on speech recognition impairment in noise in a clinical audiometric setting. The digits-in-noise SRT can also demonstrate benefit for hearing aid fittings. The test is quick to administer and provides information on the SNR loss. The digits-in-noise SRT could therefore be used as a counselling tool to explain a listener's hearing impairment and assist in satisfying hearing aid fitting outcomes.

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APPENDICES

APPENDIX A

Letter of approval for the Postgraduate Research Ethics Committee, Faculty of Humanities, University of Pretoria

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UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Research Ethics Committee

25 April 2014

Dear Prof Swanepoel

Project:	**Development and validation of a South African English smartphone-based speech-in-noise hearing test**
Researcher:	**J-M Potgieter**
Supervisor:	**Prof D Swanepoel**
Department:	**Speech-Language Pathology and Audiology**
Reference number:	**26029822**

Thank you for the well written application that was submitted for ethics review.

I am pleased to be able to inform you that the above application was **approved** by the **Research Ethics Committee** on 24 April 2014. Data collection may therefore commence.

Please note that this approval is based on the assumption that the research will be carried out along the lines laid out in the proposal. Should the actual research depart significantly from the proposed research, it will be necessary to apply for a new research approval and ethical clearance.

The Committee requests you to convey this approval to the researcher.

We wish you success with the project.

Sincerely

Prof Karen Harris
Acting Chair: Postgraduate Committee &
Research Ethics Committee
Faculty of Humanities
UNIVERSITY OF PRETORIA
e-mail:Karen.harris@up.ac.za

Research Ethics Committee Members: Dr L Blokland;Prof Prof M-H Coetzee; Dr JEH Grobler; Prof KL Harris (Acting Chair); Ms H Klopper; Dr C

APPENDIX B

Letter of approval for the Postgraduate Research Ethics Committee, Faculty of Health Science, University of Pretoria

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The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.
- FWA 00002567, Approved dd 22 May 2002 and Expires 20 Oct 2016.
- IRB 0000 2235 IORG0001762 Approved dd 22/04/2014 and Expires 22/04/2017.

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Health Sciences Research Ethics Committee

31/07/2014

Approval Certificate
New Application

Ethics Reference No.: 232/2014

Title: Development and validation of a South African English smartphone-based speech-in-noise hearing test

Dear Miss Jenny-Mari Potgieter

The **New Application** as supported by documents specified in your cover letter for your research received on the 27/06/2014, was approved, by the Faculty of Health Sciences Research Ethics Committee on the 30/07/2014.

Please note the following about your ethics approval:
- Ethics Approval is valid for 3 years.
- Please remember to use your protocol number (**232/2014**) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, or monitor the conduct of your research.

Ethics approval is subject to the following:
- The ethics approval is conditional on the receipt of 6 monthly written Progress Reports, and
- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

Dr R Sommers; MBChB; MMed (Int); MPharMed.
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health).

♦ Tel:012-3541330 ♦ Fax:012-3541367 Fax2Email: 0866515924 ♦ E-Mail: fhsethics@up.ac.za
♦ Web: //www.healthethics-up.co.za ♦ H W Snyman Bld (South) Level 2-34 ♦ Private Bag x 323, Arcadia, Pta, S.A., 0007

THE STUDY WILL BE CONDUCTED AT:	
• Steve Biko Academic Hospital	✓
• Tshwane District Hospital	✓

APPENDIX C

Letter of approval for the Junior Tukkies, Postgraduate Research Ethics Committee, Faculty of Humanities, University of Pretoria

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UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Research Ethics Committee

05-Jun-2015

Dear Prof Daniel Swanepoel,

Project: JuniorTukkie Hearing Screening Programme

Researcher: Daniel Swanepoel

Supervisor (incl. other investigators): Swanepoel, Daniel DCD~

Department: Speech-Language Pathology and Audiology

Reference number/s: GW20150511HS

Thank you for the application that was submitted for ethical consideration.

I am pleased to inform you that the above application was **approved** by the **Faculty of Humanities Research Ethics Committee** on **05-Jun-2015**. Data collection may therefore commence.

Please note that this approval is based on the assumption that the research will be carried out along the lines laid out in the proposal. However, should the actual research depart significantly from the proposed research, a new research proposal and application for ethical clearance will have to be submitted for approval.

The Committee requests you to convey this approval to the researcher.

We wish you success with the project.

Sincerely

Prof Karen Harris
Acting Chair: Postgraduate Committee and Research Ethics Committee
Faculty of Humanities
UNIVERSITY OF PRETORIA
e-mail:Karen.harris@up.ac.za

Kindly note that your original signed approval certificate will be sent to your supervisor via the Head of Department. Please liaise with your supervisor.

Research Ethics Committee Members: Prof KL Harris (Acting Chair); Dr L Blokland; Dr JEH Grobler; Prof B Hofmeyr; Ms H Klopper; Dr C Panebianco-Warrens; Dr C Puttergill, Prof GM Spies; Dr Y Spies; Prof E Taljard

APPENDIX D

Letter of approval for the Fezi Ngubentombi Hospital

Department of
Health
FREE STATE PROVINCE

Date	20 August 2014	File no	
To	Dr D Motau Head of Department: Free State Department of Health	From	ME Letshokgohla Acting District Director Fezile Dabi District

RE: REQUEST FOR APPROVAL OF THE AUDIOLOGY RESEARCH PROJECT FOR FEZILE DABI DISTRICT

1. **Purpose:**

To obtain approval to conduct the audiology research project on the development of and validation of a South African English smartphone based speech-in-noise hearing test at Fezi Ngubentombi Hospital in Fezile Dabi District as of September 2014.

2. **Background/Motivation**

2.1. Due to the scarcity of audiology staff and the high turnover of the officials in the public sector, Fezile Dabi District currently has no audiologist in the District to assist with early detection and management of hearing loss.

2.2. In order to address the gap and allow for service rending to the community the District approached the Universities in close proximity to request the possibility of using students to close the gap with supervision and support by lecturers. In response the University of Pretoria suggested that we be assisted by Ms Jenni-Mari Potgieter who needs to do hearing tests on various clients to develop and assess validity of a new hearing screening tool.

2.3. The official sent her research proposal and the plan will be to assess the clients on our waiting list that is close to a 100 already. The official will do this with the students that act as research assistants to perform the tests, assist us with prescription of the correct devices, make the moulds and fit the hearing aids that we have available.

2.4. We shall ask for permission to present the finding at the Provincial Research day on completion to allow for development of staff.

2.5. The service will be free of charge and they understand that they will foot the bill for traveling.

2.6. The audiology equipment at Fezi Ngubentombi Hospital will be used during the exercise to validate the findings of the new test. The process will be coordinated by the community service speech therapist at the complex.

3. **Financial implications:**

3.1. The use of the staff for the project will imply that we will not have to pay for the audiology service at Pelonomi Hospital as was indicated in a recent communication from their unit manager, Ms J Jensen.

3.2. Clients can be assisted without waiting for a space on the commuter to Bloemfontein or an appointment at Pelonomi for assessment – saving cost on transport

3.3. Hearing devices are available but the prescription and fitting needs to be done by an audiologist in line with HPCSA requirement – this will ensure effective use of funds spent on devices and align us with the national requirement in terms of waiting times for services when dealing with assistive devices.

4. **Personnel implications:**

4.1. Improve access to services in an area that is considered a scarce skill and increase the ability to render patient care.

4.2. Expose students to the area as a possible placement site for community service.

5. **Communication/Consultation:**

Mrs NS Malinga – CEO Fezi Ngubentombi/Parys Hospitals
University of Pretoria School of Speech Therapy, Language Pathology and Audiology

6. **Authority/Delegation:**

Approval of the transfer is vested in the Head: Health.

7. **Recommendations:**

It is recommended that the approval be granted for the audiology research project to be conducted at Fezi Ngubentombi Hospital, Fezile Dabi District to start as of 1 September 2014.

Submitted by: Ms A Brits Acting Manager: Human Resource Fezile Dabi District Date: 20/8/2014	**Supported /~~not supported~~ by:** Mr ME Letshokgohla Acting District Manager Fezile Dabi District Date: 28/08/2014
~~Recommended/not recommended~~ by: Matela MMed (Psed) Dr S Matela District Health Service Chief Directorate Department of Health Date: 01/09/2014	**Approved/~~not~~ approved by:** Dr D Motau Head: Department Health Date: 1/09/2014

APPENDIX E

Letter of approval for the Tshwane District Hospital

232/2014.

Permission to do Research and access Records / Files / Data base at the Tshwane District Hospital

To: Chief Executive Officer/Information Officer **From:** The Investigator

Tshwane District Hospital

Dr. N. Soe Ms. Jenni-Mari Potgieter

Re: Permission to do the following research at Tshwane District Hospital

The principal investigator, Ms. Jenni-Mari Potgieter, and her research supervisor, Prof. De Wet Swanepoel are researchers working at the Department of Speech-Language Pathology and Audiology at the Hatfield Campus of the University of Pretoria. I, Jenni-Mari Potgieter, requesting permission on behalf of all of us to conduct a study on the Tshwane District Hospital grounds that involves access to patient records.

The title of the study is: Development and validation of a South African English smartphone-based speech-in-noise hearing test.

We intend to publish the findings of the study in a professional journal and/ or at professional meeting like symposia, congresses, or other meetings of such a nature.

We furthermore request in terms of the requirements of the Promotion of Access to Information Act. No. 2 of 2000 that we be granted access to clinical records, files and databases.

We undertake not to proceed with the study until we have received approval from the Faculty of Health Sciences Research Ethics Committee, University of Pretoria.

Yours sincerely

JM Potgieter

Signature of the Principal Investigator

Permission to do the research study at this hospital and to access the information as requested, is hereby approved.

Chief Executive Officer

TDH Hospital

Dr S Nkosi

P.P.

Signature of the CEO

38

Tshwane District Hospital
Private Bag X179
PRETORIA 0001

2014 -07- 01

Hospital Official Stamp

Tshwane Distrik Hospitaal
Privaatsak X179
PRETORIA 0001

APPENDIX F

Data collection approval for the Sandton and Constantia Park private practices

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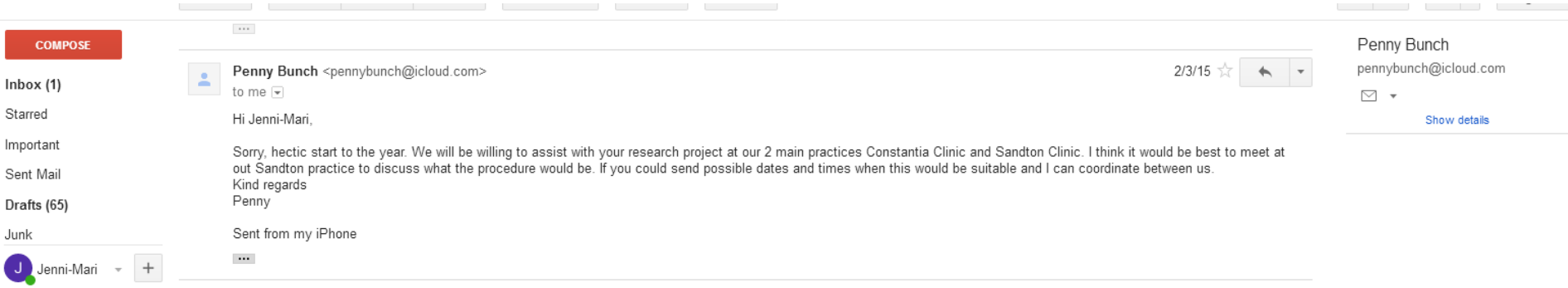

COMPOSE
Inbox (1)
Starred
Important
Sent Mail
Drafts (65)
Junk
Jenni-Mari
Penny Bunch <pennybunch@icloud.com>
to me
2/3/15
Hi Jenni-Mari,
Sorry, hectic start to the year. We will be willing to assist with your research project at our 2 main practices Constantia Clinic and Sandton Clinic. I think it would be best to meet at out Sandton practice to discuss what the procedure would be. If you could send possible dates and times when this would be suitable and I can coordinate between us.
Kind regards
Penny
Sent from my iPhone
Penny Bunch
pennybunch@icloud.com
Show details

APPENDIX G

Letter of informed consent to participants

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities

Department of Speech Language

Date:

Researcher: Jenni-Mari Potgieter

Tel: 082 551 4938

To Whom It May Concern:

Thank you for showing interest in this research project being conducted at **[hospital/practice name]**. The title of the research project is: *Development and validation of a South African English smartphone-based speech-in-noise hearing test.*

The study involves a questionnaire, a speech-in-noise hearing test and a series of audiological tests that is completely harmless and non-invasive. Participation in the study is voluntary and you may withdraw at any time. If you do participate the following procedures will apply to you:

- An otoscopic examination, followed by tympanometry measurements, will be conducted. Your outer ear canal, eardrum and middle ear functioning will be examined while you sit quietly. During tympanometry measures a small probe will be placed in your ear. These procedures do not require any response from you and will take approximately 5 minutes.

- You will then undergo a standard hearing evaluation (pure-tone air and bone conduction behavioural audiometry, speech audiometry), where you are required to respond to the presence of a sound. You will also be asked to repeat a list of words as intensity decreases. This procedure takes approximately 20 minutes.

- A computer based speech-in-noise hearing test will be administered. You will respond to a series of recorded digits in noise. Respond to each digit-set by entering the digits on the computer keyboard. This procedure takes approximately 5 minutes.

- You will complete a short questionnaire indicating your perception on your hearing status.

All the audiological test procedures are non-invasive and only the behavioural (pure-tone air and bone conduction, speech audiometry) and speech-in-noise hearing test procedures require responses from you. It is also important to note that all information will be treated ***strictly confidential***. The results will be used for research purposes as part of a dissertation and possibly future articles, or presentations. At no point in time will any names or identifying information be made available. The data will be stored for archiving and research purposes at the University of Pretoria for at least 15 years.

By agreeing to participate in this study you acknowledge that future research using the acquired data may be conducted at a later stage. ***You are free to withdraw from the study at anytime*** without any negative consequences.

Should you require any further information, you are welcome to contact us.

Sincerely,

Jenni-Mari Potgieter

Researcher

Prof. De Wet Swanepoel

Supervisor

Prof. Bart Vinck

HEAD OF DEPARTMENT: Speech Language Pathology and Audiology

University of Pretoria
Department Communication Pathology: Audiology

INFORMED CONSENT FORM

Development and validation of a South African English smartphone-based speech-in-noise hearing test

Please complete the following:

Clinic: _____

Surname: _____

Name: _____

Age: _____

Participation Number: _____

I, hereby agree to participate in this project and acknowledge that the data may be used for research purposes. I am aware that I can withdraw from this project, at any time, should I want to.

_____ _____

Signature Date

APPENDIX H

Hospital and private practice data collection request letter

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities

Department of Speech Language

Date:

TO: [Hospital Name]

RE: DEVELOPMENT AND VALIDATION OF A SOUTH AFRICAN ENGLISH SMARTPHONE-BASED SPEECH-IN-NOISE HEARING TEST

We would like to inform you of a research project we are engaging to enquire whether your hospital would be willing to participate in collecting data.

What is this research project about?

The project entails the development of a speech-in-noise smartphone-based hearing test for adults. The smartphone-based hearing test may offer a way to provide widespread access to identify patients at risk for a hearing loss at an early stage providing underserved populations across different socio-economic levels the opportunity to have a hearing screening.

What will be required if the hospital participates?

If the hospital decides to participate in this project, your assistance would be required to ask a prospective client to consider participating in the study. If they agree to participate they will have to sign the provided letter of informed consent. Participating clients will be required to complete a brief 5-minute questionnaire as well as the speech-in-noise smartphone-based hearing test, which takes approximately 5 minutes. You will also be asked to make the audiometry assessment results (e.g. pure-tone audiometry, SRT etc.) of the specific client available for the research project. The client informed consent letter will make this clear to them also.

What will be required of my clients if they participate?

Each client who agrees to participate in this research project will need to sign the informed consent letter (See Appendix A). Apart from their routine audiological assessment, they need to complete a 5-minute questionnaire and conduct the additional 5-minute speech-in-noise smartphone-based hearing test.

How will this research project benefit the hospital?

You will have the opportunity to be among the first hospitals to be exposed to the new speech-in-noise smartphone-based hearing test. You will be provided with the speech-in-

noise smartphone-based hearing test (including phone and headset) used during the data collection process for your own use after the project is completed. The speech-in-noise hearing test is also in the process to be validated for diagnostic purposes, and may be used to assist in hearing aid counselling in the near future since it will provides a patient-specific signal-to-noise ratio.

What is required by the University of Pretoria if the hospital decides to participate?

Data from a minimum of 100 clients will be required. All data will be treated confidentially and codes will be assigned to each patient to ensure identifying information is kept anonymous. Processed data will be used towards completion of a doctorate degree in audiology for Ms Jenni-Mari Potgieter and may also be used for teaching purposes, conference presentations, or published in article format. Data will be archived for a minimum of 15 years according to University of Pretoria regulations for archiving and research purposes. Ethical clearance will be required before any data collection may commence.

We hope that the hospital could serve as a centre where normative data collection could take place. If you require any information or have additional queries, please do not hesitate to contact us at 012 420 4280 (Prof. De Wet Swanepoel) and 082 551 4938 (Ms. Jenni-Mari Potgieter).

Kindly provide a signed letter of agreement if you are willing to participate as a data collection hospital and would like to participate as data collection site for this research project.

Sincerely,

_____

Ms Jenni-Mari Potgieter

Doctoral student

_____

Prof De Wet Swanepoel

Research Supervisor

_____

Prof Bart Vinck

Head of Department: Speech Language Pathology and Audiology

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities

Department of Speech Language

Date:

TO: [Private Audiology Practice Name]

RE: DEVELOPMENT AND VALIDATION OF A SOUTH AFRICAN ENGLISH SMARTPHONE-BASED SPEECH-IN-NOISE HEARING TEST

We would like to inform you of a research project we are engaging to enquire whether your practice would be willing to participate in collecting data.

What is this research project about?

The project entails the development of a speech-in-noise smartphone-based hearing test for adults. The smartphone-based hearing test may offer a way to provide widespread access to identify patients at risk for a hearing loss at an early stage providing underserved populations across different socio-economic levels the opportunity to have a hearing screening.

What will be required if my practice participates?

If your practice decides to participate in this project, your assistance would be required to ask a prospective client to consider participating in the study. If they agree to participate they will have to sign the provided letter of informed consent. Participating clients will be required to complete a brief 5-minute questionnaire as well as the speech-in-noise smartphone-based hearing test, which takes approximately 5 minutes. You will also be asked to make the audiometry assessment results (e.g. pure-tone audiometry, SRT etc.) of the specific client available for the research project. The client informed consent letter will make this clear to them also.

What will be required of my clients if they participate?

Each client who agrees to participate in this research project will need to sign the informed consent letter (See Appendix A). Apart from their routine audiological assessment, they need to complete a 5-minute questionnaire and conduct the additional 5-minute speech-in-noise smartphone-based hearing test.

How will this research project benefit my practice?

You will have the opportunity to be among the first audiology practices exposed to the new speech-in-noise smartphone-based hearing test. You will be provided with the speech-in-

noise smartphone-based hearing test (including phone and headset) used during the data collection process for your own use after the project is completed. The speech-in-noise hearing test is also in the process to be validated for diagnostic purposes, and may be used to assist in hearing aid counselling in the near future since it will provides a patient-specific signal-to-noise ratio.

What is required by the University of Pretoria if your practice decides to participate?

Data from a minimum of 30 clients will be required. All data will be treated confidentially and codes will be assigned to each patient to ensure identifying information is kept anonymous. Processed data will be used towards completion of a doctorate degree in audiology for Ms Jenni-Mari Potgieter and may also be used for teaching purposes, conference presentations, or published in article format. Data will be archived for a minimum of 15 years according to University of Pretoria regulations for archiving and research purposes. Ethical clearance will be required before any data collection may commence.

We hope that your practice could serve as a centre where normative data collection could take place. If you require any information or have additional queries, please do not hesitate to contact us at 012 420 4280 (Prof. De Wet Swanepoel) and 082 551 4938 (Ms. Jenni-Mari Potgieter).

Kindly provide a signed letter of agreement if you are willing to participate as a data collection practice and would like to participate as data collection site for this research project.

Sincerely,

_____

Ms Jenni-Mari Potgieter

Doctoral student

_____

Prof De Wet Swanepoel

Research Supervisor

_____

Prof Bart Vinck

Head of Department: Speech Language Pathology and Audiology

APPENDIX I

Audiogram

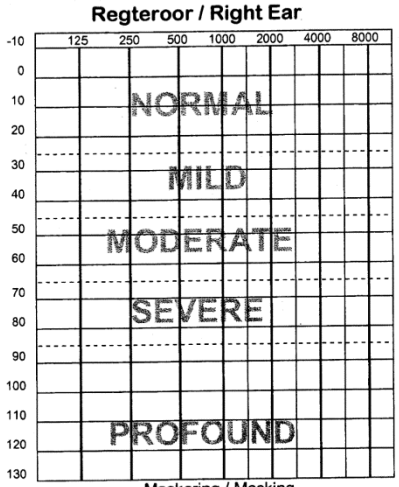
Universiteit van Pretoria / University of Pretoria
Spraak-Taalpatologie en Oudiologie / Speech-Language Pathology and Audiology
Tel: (012) 420-2816 / (012) 420-2491

Naam / Name: _____ **Datum / Date:** _____

GEB / DOB: _____ **Oudioloog / Audiologist:** _____ **Student / Student:** _____

Suiwertoonoudiogram / Pure Tone Audiogram

Regteroor / Right Ear

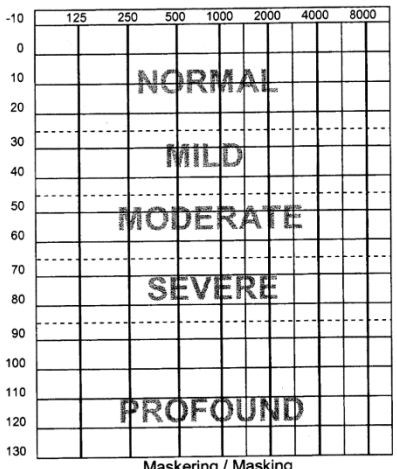


Maskering / Masking

LG/AC							
BG/BC							

% Gehoorverlies / % Hearing Loss: R _____ L _____ B _____

Linkeroor / Left Ear



Maskering / Masking

LG/AC							
BG/BC							

Pediatriese toetsprotokol / Pediatric test protocol:

BOA	VRA	CPA

Weber

250	500	1000	2000	4000

Rinne

R	L

Bing

R	L

Otoskopiese Ondersoek / Otoscopic Examination

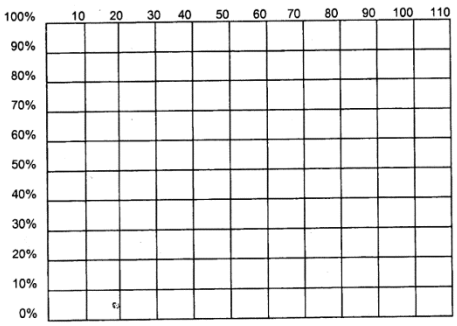
R

L

Oorvormer / Transducer:

Insert oorfone / Insert earphones
Oorfone / Earphones
Vryeveld / Free field

Spraakoudiogram / Speech Audiogram



Maskering / Masking L R

Spraak stimuli gebruik / Speech stimuli used:

Live voice	Vooraf opgeneem / Pre-recorded

	R	L
STD / PTA		
SOD / SRT		
SOD gemaskeer / SRT masked		
Disk % Disc.		
MGL / MCL VP / UCL		
Spraakdeteksie / Speech Detection		

Akoestiese Immittansie / Acoustic Immittance

	R	L
Timpanogram / Tympanogram		
Middeloordruk / Middle Ear Pressure		
Statiese / Static Compliance		
Oorkanaal Volume / Ear Canal Volume		

Akoestiese Refleks / Acoustic Reflex

Refleks Drempel / Reflex Threshold R Kontra / Contra	R Ipsi	PTT / STD	Verskil / Difference	Refleks Verstarwing / Reflex Decay	Frekwensie / Frequency	Refleks Drempel / Reflex Threshold L Kontra / Contra	L Ipsi	PTT / STD	Verskil / Difference	Refleks Verstarwing / Reflex Decay
					250 Hz					
					500 Hz					
					1 kHz					
					2 kHz					
					4 kHz					
					BBN					

Toetsbetroubaarheid / Test reliability:

Goed / Good	Gemiddeld / Average	Swak / Poor

Oor / Ear	Ongemaskeerde lug / Unmasked Air	Ongemaskeerde Been / Unmasked Bone	Gemaskeerde Lug / Unmasked Air	Gemaskeerde Been / Masked Bone	Geen Respons / No Response	Vrye Veld / Sound Field	VP / UCL	Versterkte drempel / Aided threshold
R	O	<	△	[	↓	S	⊓	A
L	X	>	□	]				

APPENDIX J

Language speaking competence questionnaire

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech Language
Pathology and Audiology

Date: _____
Name and Surname: _____
Date of Birth: _____
Age: _____

Participant number: _____

Questionnaire: Language competence

1. In how many languages are you competent?_____

2. Please list the languages from most competent to least competent.
   a. _____
   b. _____
   c. _____
   d. _____
   e. _____
   f. _____

3. Please rate your **English** competence according to a scale out of 10.
   (10 being excellent)
   a. Speaking /10
   b. Writing /10
   c. Reading /10

APPENDIX K

Proof of article acceptance from the International Journal of Audiology

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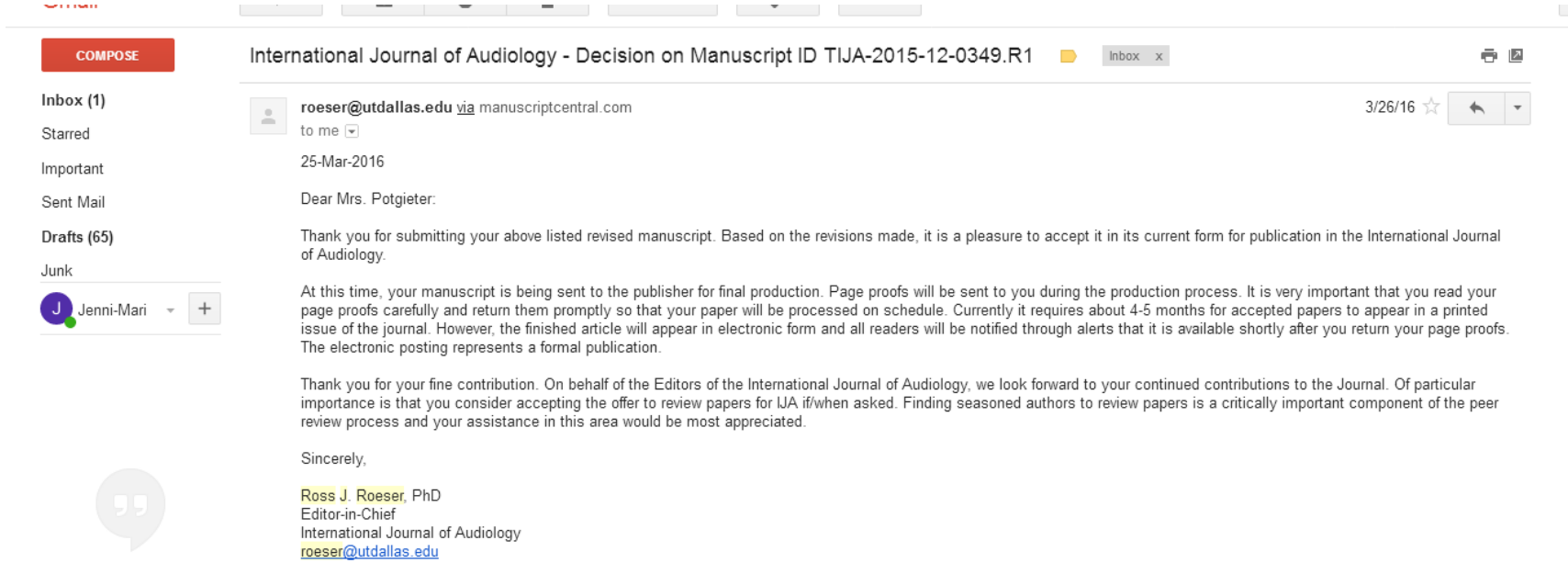

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roeser@utdallas.edu via manuscriptcentral.com

to me

3/26/16

25-Mar-2016

Dear Mrs. Potgieter:

Thank you for submitting your above listed revised manuscript. Based on the revisions made, it is a pleasure to accept it in its current form for publication in the International Journal of Audiology.

At this time, your manuscript is being sent to the publisher for final production. Page proofs will be sent to you during the production process. It is very important that you read your page proofs carefully and return them promptly so that your paper will be processed on schedule. Currently it requires about 4-5 months for accepted papers to appear in a printed issue of the journal. However, the finished article will appear in electronic form and all readers will be notified through alerts that it is available shortly after you return your page proofs. The electronic posting represents a formal publication.

Thank you for your fine contribution. On behalf of the Editors of the International Journal of Audiology, we look forward to your continued contributions to the Journal. Of particular importance is that you consider accepting the offer to review papers for IJA if/when asked. Finding seasoned authors to review papers is a critically important component of the peer review process and your assistance in this area would be most appreciated.

Sincerely,

Ross J. Roeser, PhD
Editor-in-Chief
International Journal of Audiology
roeser@utdallas.edu

APPENDIX L

Proof of article acceptance from Ear and Hearing

RE: EANDH-D-16-00325R3, entitled "The South African English Smartphone Digits-in-noise Hearing Test: Effect of Age, Hearing Loss and Speaking Competence"

Dear Dr. Swanepoel,

I am pleased to inform you that your work has now been accepted for publication in Ear and Hearing. All manuscript materials will be forwarded immediately to the production staff for placement in an upcoming issue.

OPEN ACCESS
If you indicated in the revision stage that you would like your submission, if accepted, to be made open access, please go directly to step 2. If you have not yet indicated that you would like your accepted article to be open access, please follow the steps below to complete the process:
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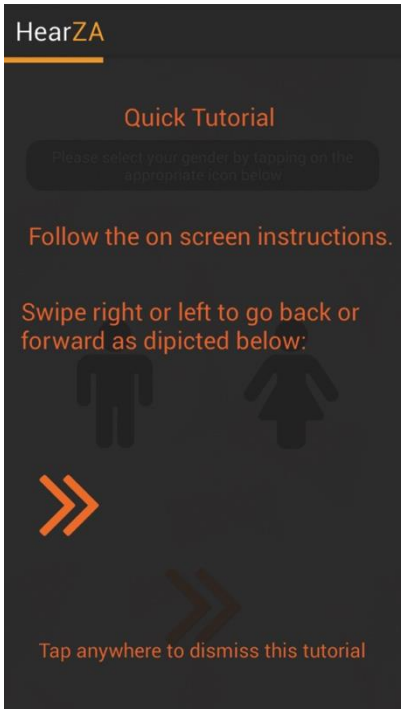
a. Article Title - The South African English Smartphone Digits-in-noise Hearing Test: Effect of Age, Hearing Loss and Speaking Competence
b. Manuscript Number - EANDH-D-16-00325R3

APPENDIX M

Smartphone application screenshots

SUPPLEMENTARY MATERIAL

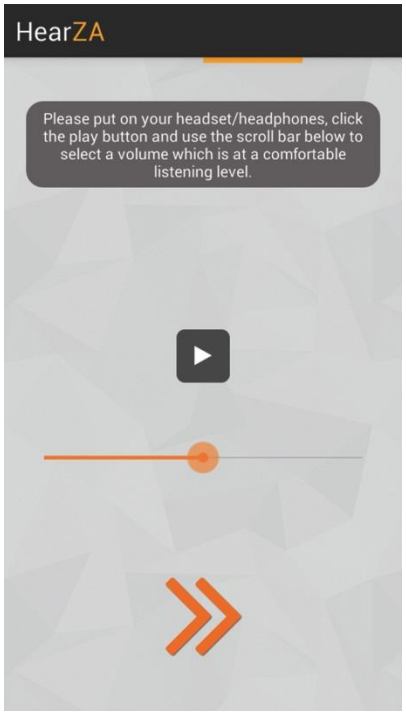
Supplementary Material 1



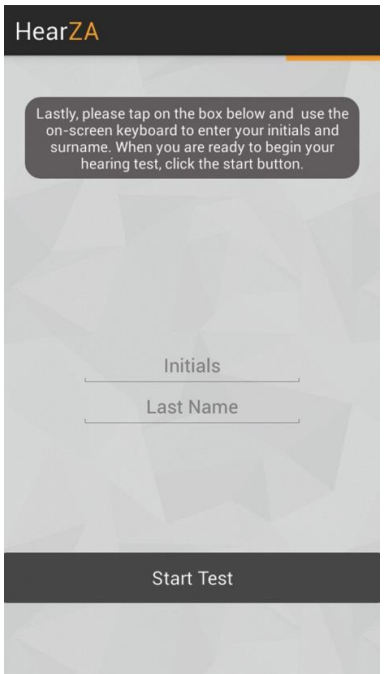
Supplementary material 1a. A tutorial screen instructs the subject on how to use the application

Supplementary material 1b. Gender is selected by tapping on the appropriate icon

Supplementary material 1c. The year of birth is selected by scrolling up or down and tapping on the appropriate year



Supplementary material 1d. The subject is instructed to put on the smartphone headset and listen to digit-triplets being repeated. The subject uses a scroll-bar to adjust the intensity of the digit triplets to a comfortable listening intensity



Supplementary material 1e. The initials and surname are entered. The “Start Test” button allows the subject to begin testing

Supplementary Material 2

Supplementary material 2a. Intrachonchal earphones accompanying the Vodaphone Smart Kicka entry-level smartphone

Supplementary material 2b. Intrachonchal earphones accompanying the Samsung S4 mini mid-level smartphone

Supplementary material 2c. Intrachonchal earphones accompanying the Samsung S5 top-end smartphone

Supplementary material 2d. Sennheiser HD 202 II supra-aural headphones

Supplementary material 2e. TDH 50-P audiometric supra-aural headphones

APPENDIX N

Proof of article submission from the South African Journal of Communication Disorders

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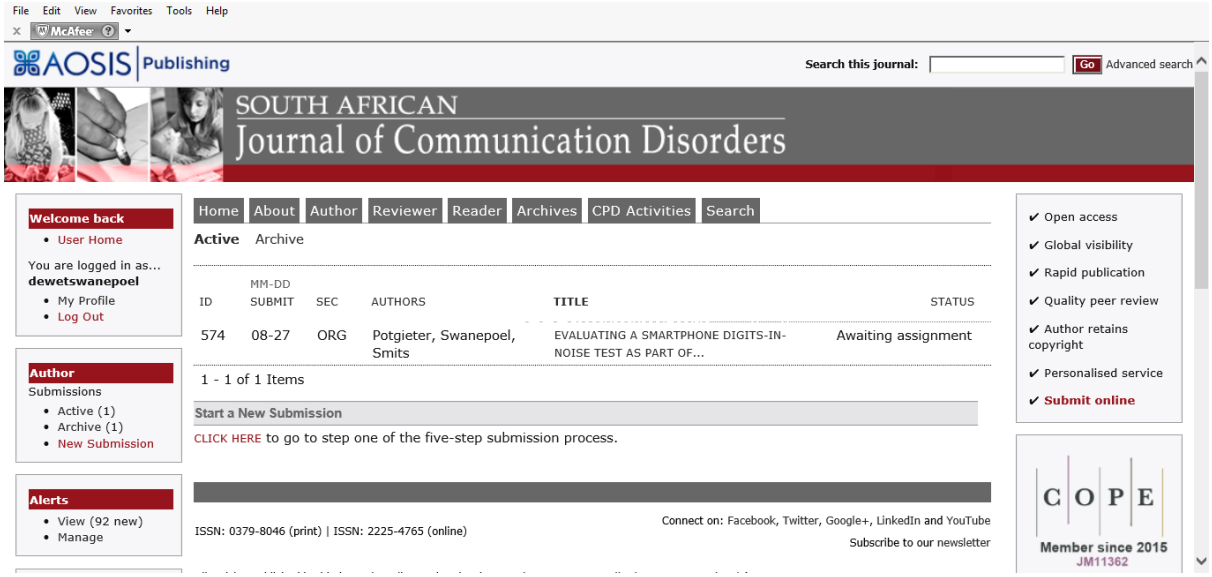
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