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

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KEYWORDS

Digits-in-noise, speech-in-noise, hearing test, hearing loss, smartphone, hearing screening.

ABREVIATIONS

DIN:	Digits-in-noise test
ISO:	International Standards Organization
PTA:	Pure tone average
SNR:	Signal-to-noise ratio
SD:	Standard deviation
SRT:	Speech reception threshold
STATSSA:	Statistics South Africa
WHO:	World Health Organization

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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 first language English female speaker. Level corrections were applied to create a set of homogeneous digits with steep speech recognition functions. A smartphone application 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.

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 application. 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.

INTRODUCTION

Approximately 360 million people across the world suffer from a permanent disabling hearing loss (World Health Organization [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 (Statistics South Africa [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 signal-to-noise ratio (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 et al (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, 2006). 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 (2006) found that 50% of callers, who failed the screening test, obtained a diagnostic hearing test. After the National Hearing Test was developed, Smits et al (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 et al, 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 application for use on smartphones.

Using a smartphone application can allow for an accessible user-friendly interface for self-testing by those with access to these devices. An important advantage of using an application 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 et al, 2013; Information and Communication for Development, 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 et al, 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 application 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 application 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.

PHASE I: RECORDING AND EQUALIZATION OF THE DIGITS

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 native 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).

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.

Methods

Subjects

Twenty normal-hearing subjects participated in the listening study. Mean age of subjects was 20 years (Standard Deviation [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 (International Standards Organisation [ISO] 389-1, 1998).

Equipment and Measurements

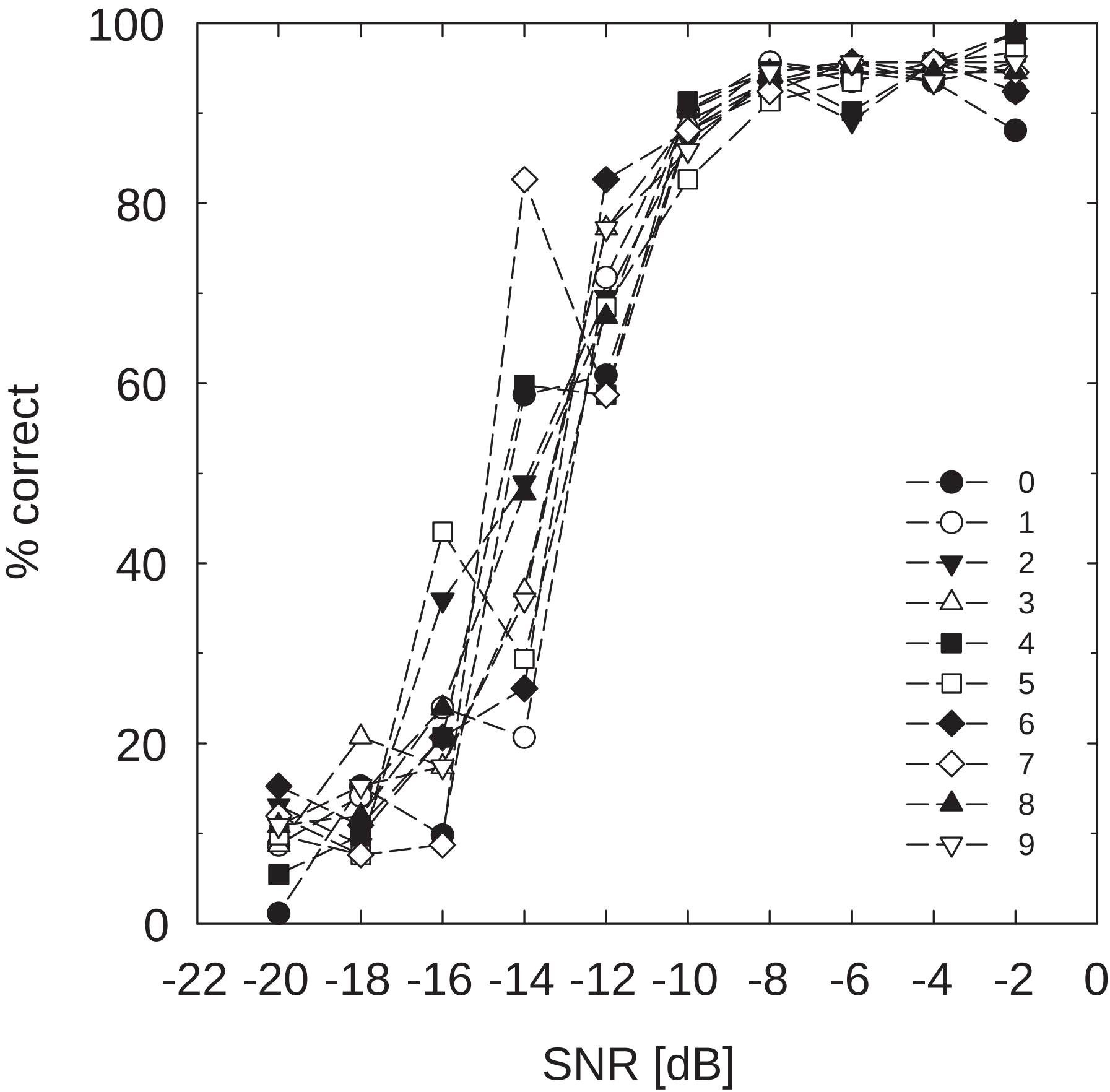
A clinical audiometer (GSI 61, Grason-Stadler, Milford, New Hampshire, USA) was used to conduct a pure-tone audiogram in a sound-proof booth.

Measurement software was developed in Matrix Laboratory (Matlab) 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.

Results

The group average for correct identification of each digit at each SNR is shown in Figure 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

Figure 1. The average speech recognition probabilities for single digits-in-noise before equalization.



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).

PHASE II: DEVELOPMENT OF THE SMARTPHONE APPLICATION AND TEST PROCEDURES

Smartphone Application

A smartphone application (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 application was designed to be used on any Android smartphone. When the application is launched, a tutorial screen appears to instruct the subject how to use the application. 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 application and is available in the online version of the journal.

Triplet generation and adaptive test procedure

A list of triplets was stored in the Android application 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 application. 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).

PHASE III: SMARTPHONE DIGITS-IN-NOISE TEST HEADPHONE TYPES EFFECT AND NORMS

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.

Method

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).

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.

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.

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 I. A repeated measures analysis of variance (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 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 2. The average speech recognition function has a slope of 20%/dB.

Figure 2. The average speech recognition probabilities for digit-triplets at each SNR conducted using five different headphone types presented using the smartphone application.

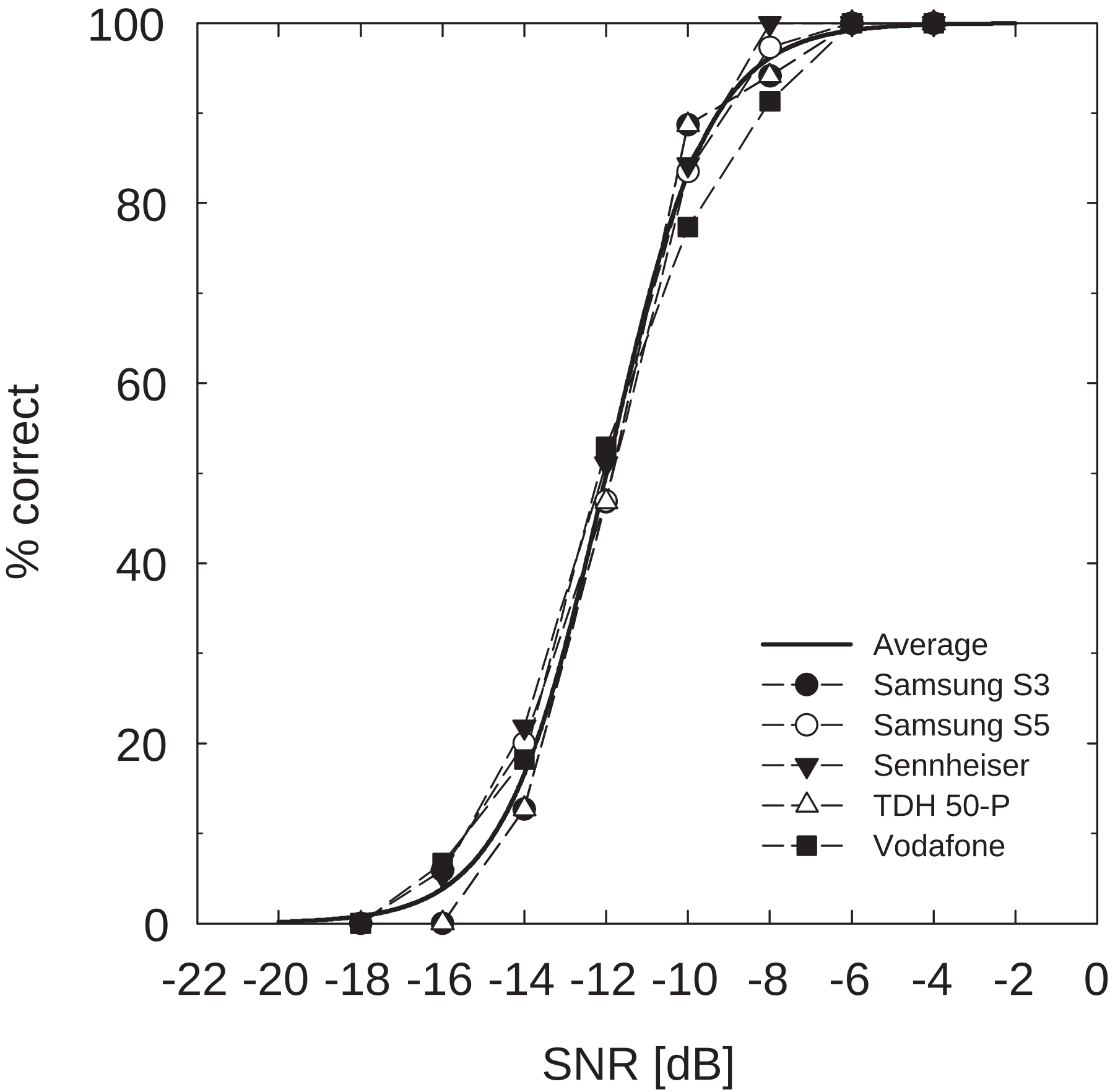


Table 2. Distribution of the SRT SNRs recorded with the South African English digits-in-noise hearing test for group 1 (n=96) and group 2 (n=90) native South African English subjects.

	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

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).

Method

Subjects

Two groups of subjects from private audiology practices and governmental hospitals in Gauteng participated in this study. The first group consisted of 96 native 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 native 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.

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.

Results

The normal-hearing cut-off value was determined through the upper 95th percentile point for SRT scores for the two groups of native 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.

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 application 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 application. 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 n.d.). 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 et al, 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 et al, 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 et al, 2015). Various studies indicate that participants who speak English as a second language perform worse on competing signal speech tests compared to native-English speakers (Tabri et al, 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.

CONCLUSION

A South African digits-in-noise hearing test was successfully developed and validated as a self-test on a smartphone via a smartphone application 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 application 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..

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation under the grant number 88803.

DECLARATION OF INTEREST

The University of Pretoria will be exploring the commercialisation of the developed test to ensure its availability to the public.

REFERENCES

Arcury, T.A., Gesler, W.M., Preisser, J.S., Spencer, J. & Perin, J. 2005. The effect of geographic and spatial behavior on health care utilization among the residents of a rural region. *Health Serv Res,* 40, 135-155.

Bonello, I.O. n.d. *Tutorial abouth the VQR (Voice Quality Restoration) technology*. Available from: <http://www.solidynepro.com/download/VQR%20Tutorial%20ENG.pdf> [2015, August].

Branford, W. & Claughton, J.S. (2002). 10 Mutual lexical borrowings among some languages of southern Africa: Xhosa, Afrikaans and English in *Language of South Africa*. R. Mestherie (ed.). Cambridge University Press, 199.

Buor, D. 2003. Analysing the primacy of distance in the utilization of health services in the ahafo-ano south district. Ghana. *Int J Health Plann Manage,* 18, 293-311.

Culling, J.F., Zhao, F. & Stephens, D. 2005. The viability of speech-in-noise audiometric screening using domestic audio equipment. *Int J Audiol,* 44, 691-700.

Fagan, J.J. & Jacobs, M. 2009. Survey of ENT services in Africa: Need for a comprehensive intervention. *Glob Health Action,* dio:10.3402/gha.v2i0.1932.

Gething, P.W., Noor, A.M., Zurovac, D., Atkinson, P.W., Hay, S.I. et al. 2004. Empirical modeling of government health service use by children with fevers in Kenya. *Acta Trop,* 91, 227-237.

Information and Communication for Development 2012. *Maximizing Mobile*. The World Bank.

International Standards Organization 1998. *Acoustics - Reference zero for the calibration of audiometric equipment - Part 1: Reference equivalent threshold sound pressure levels for pure tone and supra-aural earphones.* ISO 389-1, Geneva.

Jansen, S., Luts, H., Wagener, K.C., Frachet, B. & Wouters, J. 2010. The French digit triplet test: A hearing screening tool for speech intelligibility in noise. *Int J Audiol,* 49, 378-387.

Kaandorp, M.W., De Groot, A.M.B., Festen, J.M., Smits, C. & Goverts, S.T. 2015. The influence of lexical-access ability and vocabulary knowledge on measures of speech recognition in noise, *Int J Audiol*, DOI:10.3109/14992027.2015.1104735.

Linssen, A.M., Anteunis, L.J.C. & Joore, M.A. 2015. The Cost-Effectiveness of Different Hearing Screening Strategies for 50- to 70-Year-Old Adults: A Markov Model. Value Health*,* 560-569.

Martinez-Péres, B., de la Torre-Diéz, I. & López-Coronado, M. 2013. Mobile health applications for the most prevalent conditions by the World Health Organization: Review and Analysis. *J Med Internet Res,* 14, March 2014. Available from: <http://www.jmir.org/2013/6/e120/>.

Reed, M., Jotischky, N., Newman, M., Mbongue, T., Escofet, G. 2014. Africa Telecoms Outlook 2014: Maximizing digital service opportunities. *Informa Telecoms & Media*, United Kingdom.

Smits, C., Goverts, T. & Festern, J.M. 2013. The digits-in-noise test: Assessing auditory speech recognition abilities in noise. J *Acoust Soc Am,* 133, 1693-1706.

Smits, C. & Houtgast, T. 2005. Results from the Dutch speech-in-noise screening test by telephone. *Ear Hear,* 26, 89-95.

Smits, C., Kapteyn, T.S. & Houtgast, T. 2004. Development and validation of an automatic speech-in-noise screening test by telephone. *Int J Audiol,* 43, 15-28.

Smits, C., Merkus, P. & Houtgast, T. 2006. How we did it: The Dutch functional hearing-screening tests by telephone and internet. *Clin Otolaryngol,* 31, 436-455.

Statistics South Africa 2013. *General Houshold Survey.* Available from: <http://www.statssa.gov.za/publications/P0318/P03182013.pdf> [2015, May].

Statistics South Africa 2011. *Census in brief, South Africa.* Available from: <http://www.statssa.gov.za/publications/P03014/P030142011.pdf> [2015, May].

Tabri, D., Smith Abou Chacra, K.M. & Ping, T. 2011. Speech perception in noise by monlingual, bilingual and trilingual listeners. *Int J Commun Disord,* 46, 411-422.

Tanser, F., Gijsbertsen, B. & Herbst, K. 2006. Modelling and understanding primary health care accessibility and utilization in rural South Africa: An exploration using a geographical information system. *Soc Sci Med,* 63, 691-705.

Tanser, F., Hosegood, V., Benzler, J., Solarsh, G. 2001. New approaches to spatially analyse primary health care usage patterns in rural South Africa. *Top Med Int Health,* 6, 826-838.

The Economist 2015a. 28 February 2015-last update. *Smartphones: Planet of the Phones*. Available from: <http://www.economist.com/news/leaders/21645180-smartphone-ubiquitous-addictive-and-transformative-planet-phones> [2015, March].

The Economist 2015b. 28 February 2015-last update. *Telecoms and Society: The truly personal computer*. Available from: <http://www.economist.com/news/briefing/21645131-smartphone-defining-technology-age-truly-personal-computer> [2015, March].

Theunissen, M. & Swanepoel, D.W. 2008. Early hearing detection and intervention services in the public health sector in South Africa. *Int J Audiol,* 47, S23-S29.

van Wijngaarden S.J., Steeneken, H.J.M. & Houtgast, T. 2002. Quantifying the intelligibility of speech in noise for non-native listeners. *J Acoust Soc Am,* 1906-1916.

Vlaming, M.S.M.G., MacKinnon, R.C., Jansen, M., Moore, D.R. 2014. Automated Screening for High-Frequency Hearing Loss. *Ear Hear,* 35. 667-679.

Watson, C.S., Kidd, G.R., Miller, J.D., Smits, C., Humes, L.E. 2012. Telephone screening tests for functionally impaired hearing: Current use in seven countries and development of a US version. *J Am Acad Audiol,* 23, 757-767.

World Health Organization 2013a. *Mutli-country assessment of national capacity to provide hearing care.* Available from:

<http://www.who.int/pbd/publications/WHOReportHearingCare_Englishweb.pdf?ua=1> [2015, May].

World Health Organization 2013b. *Millions of people in the world have hearing loss that can be treated or prevented.* Available from: <http://www.who.int/pbd/deafness/news/Millionslivewithhearingloss.pdf?ua=1> [2015, April].

Zokoll, M., Hochmuth, S., Warzybok, A., Wagener, K.C., Buschermöhle et al. 2013. Speech-in-noise tests for multilingual hearing screening and diagnostics. *Am J Audiol,* 22, 175-178.

Zokoll, M.A., Wagener, K.C., Brand, T., Buschermöhle, M., Kollmeier, B. 2012. Internationally comparable screening tests for listening in noise in several European languages: The German digit-triplet test as an optimization prototype. *Int J Audiol,* 51, 697-707.

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.