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Department of Speech-Language Pathology and Audiology

Improving the time-efficiency and reliability of the digits-in-noise hearing screening test: a comparison of four procedures

by

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Dissertation submitted in fulfilment of the requirements for the degree MA (Audiology) in the Department of Speech-Language Pathology and Audiology

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2021

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ACKNOWLEDGMENTS

- I start off in the name of my Lord, and Creator who has blessed me with the ability, knowledge, and strength to complete this study.

- I would like to thank my parents for always being there for me, I could never imagine going through any challenge without having them as my greatest supporters.

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D23 – Standard adaptive antiphasic 23-step DIN test

dB – Decibels

DC8 – Combination self-selected and adaptive 8-step DIN test

DF – Fixed SNR DIN test

DIN – Digits-in-Noise

DSS – Self-selected SNR DIN test

Hz - Hertz

LMICs – Low-and-middle income countries

SA – South Africa

SNR – Speech-to-noise Ratio

WHO – World Health Organization

FORMATTING

This research dissertation used APA 7th edition referencing style.

The formatting style of chapter three may differ from the rest of the document as the format of the journal was used to compile the submitted article.

ABSTRACT

With the rise in persons with hearing loss globally, there is an increased need to promote hearing screening which is quick and reliable to help identify persons at-risk and for timely intervention. The Digits-in-Noise (DIN) test is a speech in noise test, which was developed to determine an individual's ability to understand speech in the presence of competing noise. The DIN is usually presented in a monaural paradigm, in 2016 a binaural approach that allows both ears to be tested simultaneously was developed, allowing the test to be completed in a shorter period of time. Recently, researchers have attempted to increase the time efficiency of the smartphone DIN test by decreasing the number of presentations of the DIN. One suggestion was to use a variable step size based on the correctness of digits identified within the triplet. In contrast, another suggested using a fixed signal-to-noise ratio (SNR) presentation level for all presentations of the DIN test and producing a pass/fail result based on whether a 95% recognition level was reached. This study aimed to compare three novel DIN test procedures as a potential way to improve efficiency with acceptable reliability using smartphone technology.

One hundred and twenty participants were recruited to take part in the study. All participants were tested in two sessions in order to investigate test-retest reliability. The gold standard test utilized the adaptive antiphasic 23-step DIN test (D23) paradigm. The three novel DIN test procedures developed were, i) self-selection of SNR DIN approach (DSS), ii) a combination DIN (DC8) which utilized a self-selected SNR followed by an 8-step adaptive DIN test procedure, iii) a fixed DIN (DF) approach using a fixed SNR value of -14.5 dB SNR in all presentations to produce a pass/fail result. This research study aimed to investigate the test accuracy, test-retest reliability and time-efficiency of novel DIN approaches when compared to a validated gold standard hearing screening DIN test. The non-parametric Spearman correlation and the value of the standard error of measurement (SEM) was used to determine the test-retest reliability for quantitative variables, and Cohen's Kappa was used to test the reliability for qualitative variables. The results from the research study showed that the three novel DIN test procedures durations are significantly shorter (less than one minute) than D23. DF demonstrated a reduction of 46% in the number of presentations when compared to D23 (from 23 presentations to an average of 12.5). The DC8 test procedure had a significantly larger SEM (2.2 dB SNR) compared to the D23 (1.5 dB SNR) and weaker test reliability. However, the DC8 (rs (120) = 0.696; p < 318 0.001) showed a stronger correlation to the D23 than the DSS (rs (120) = 0.203; p < 0.001). The DSS approach showed weak test reliability and cannot be used as an accurate screening tool.

The D23 test procedure remains the most accurate and reliable DIN test that can be completed in just over 2 minutes. From the novel approaches, the DF approach is highly efficient and can be easily implemented by adjusting the cut-off value. The DC8 approach has the potential to be a time-efficient hearing screening tool, although more presentations are needed to reach the accuracy of the D23. Due to test times being less than a minute, DF and DC8 could be adjusted and validated for difficult to test populations requiring very efficient hearing screening approaches. The DSS approach cannot be used as a hearing screening tool due to the inaccurate ability to discriminate between normal and hearing-impaired listeners.

Keywords: Digits-in-Noise; hearing screening; smartphone application; time-efficiency; reliability; antiphasic

CHAPTER ONE: INTRODUCTION

Worldwide there has been an increase in the number of people affected by hearing loss. The World Health Organization (WHO) has estimated that there are currently 432 million adults with disabling hearing loss. This is expected to increase to 900 million people globally by 2050 (WHO, 2018). The expected rise in the affected number of persons with hearing loss is a global concern, as unidentified hearing loss is associated with significant negative consequences (Wilson et al., 2017). This includes social isolation due to missing out on information in everyday conversations, consequently resulting in reduced cognition and psychological distress (Wallhagen, 2010). In the elderly, this may lead to other neurological disorders such as depression, cognitive decline, or dementia. (Ciorba et al. 2012; Livingston et al., 2020; Pronk et al., 2013; Wolfgang, 2019). Early identification followed by intervention has been identified as critical to reducing the negative consequences of hearing loss (Spiby, 2014; Sabo et al., 2016). Accessible screening options to identify hearing loss in adults is an important priority to support timely identification to initiate timely treatment (Koole et al., 2016; Livingston et al., 2020; Willberg et al., 2016).

In 2004, Smits et al. (2004) developed the first telephone hearing test for the Dutch citizens, called the Digits-in-Noise (DIN) test, as a way to provide a national screening test (Smits et al., 2004). The purpose of the DIN test is to measure an individual's speech recognition ability in the presence of background noise, which indicates their hearing ability (Smits et al., 2004; Smits et al., 2013). The test uses three random digits (e.g., 3-4-8), presented in the presence of speech weighted masking noise. It implements an adaptive one up-one down tracking procedure in 2 dB steps and determines a signal-to-noise ratio (SNR) for each presentation. The SNR will either increase (become more positive) for incorrectly identified triplets or decrease (become more negative) for correctly identified triplet digits. The final SRT value is calculated by averaging the SNRs of approximately 19 presentations. The SRT obtained from DIN tests were strongly correlated to a four-frequency pure tone average (PTA) (500 – 4000 Hz) ranging from correlations of 0.77 (Smits et al., 2004) to 0.8 (Watson et al., 2012). The SRT in DIN testing is the minimum level to correctly identify speech 50% of the time in the presence of competing noise (Denys et al., 2019; Potgieter et al., 2016; Smits et al., 2004). Due to the strong relationship between the SRT and PTA, the SRT can be significant to the audiologist to interpret as it can reflect the degree of hearing loss by implementing the use of cut-off values and predefined PTA categories of hearing loss (Armstrong et al., 2020; De Sousa et al., 2020; Koole et al., 2016).

Due to the successful uptake of the Dutch DIN test and the need for a screening tool to implement early identification, other countries developed the DIN test in native languages, such as French (Jansen et al., 2010), German (Zokoll et al., 2012), American English (Watson et al., 2012), Finnish (Willberg et al., 2016), and recently in Korean (Han et al., 2020). The DIN test has thus become a widely used hearing screening test for population-based testing. After the successful development of the telephone DIN test, Smits et al. (2006) developed an internet-based DIN test in 2006 (Smits et al., 2004, Smits et al., 2006). Subsequently, with the global high uptake of smartphones, in 2016, the DIN was developed and launched as a downloadable smartphone application (hearZA) in South Africa (SA) (Potgieter et al., 2016; Swanepoel, 2017). The development of the hearZA app also aimed to provide a rapid hearing screening test by allowing both ears to be tested at the same time using a binaural diotic paradigm (Potgieter et al., 2016). This allowed test duration to be halved (≤ 3 minutes) compared to other monaural DIN tests resulting in a total test period of 6 – 8 minutes (Smits et al., 2004; Jansen et al., 2010; Potgieter et al., 2016; Watson et al., 2012). Since the hearZA's first launch in 2016, more than 30 000 persons have downloaded the smartphone application to determine their hearing status (De Sousa et al., 2020). Validation findings of the hearZA application (r = 0.79) corresponds with previous DIN tests including the Dutch (r = 0.72), American-English (r = 0.74), and French (r = 0.77) (Jansen et al., 2010; Potgieter et al., 2018; Smits et al., 2004; Watson et al., 2012). In 2018, the WHO launched its own international hearing screening app (hearWHO), which used the same test setup as hearZA (WHO, 2018). The goal of the hearWHO application was to provide a free hearing screening test for persons who are vulnerable to acquiring a hearing loss (i.e., persons who are exposed to high noise levels, hearing loss that is heredity, etc.) (WHO, 2018). The hearWHO application is available for iOS and Android devices and now also supports Spanish and Mandarin (Swanepoel et al., 2019).

Based on the number of persons who used the hearZA application in 2018, it has been determined that 37% of persons who indicated that they might have a hearing loss, only 22.4% failed the test (Swanepoel, 2018). The results obtained may be due to the binaural diotic paradigm, which represents the better ear response (De Sousa et al., 2020). To substantiate and increase the sensitivity of the DIN test without extending test time through sequential monaural assessment, De Sousa et al. (2020) introduced an antiphasic test paradigm. This approach presented the same broadband masking noise to both ears, while the phase of the speech stimuli was inverted for each ear (i.e., a 180° phase shift). The antiphasic test takes advantage of binaural integration, which showed an improved SRT value of least 6 – 8 dB in normal hearing individuals compared to the diotic approach (De Sousa et al., 2020). De Sousa et al. (2020) found higher rates of sensitivity and specificity between the PTA and the antiphasic DIN test when compared to the diotic test, furthermore, the antiphasic DIN was more accurate in determining hearing loss than the diotic. As a result, in 2019 the hearWHO application has been updated to implement the use of antiphasic stimuli (Swanepoel et al., 2019).

Although the antiphasic DIN has increased sensitivity using a binaural paradigm, it still implements a 23 presentation DIN test which takes approximately three minutes to complete (De Sousa et al., 2020). In order to make the DIN test more time-efficient, Denys et al. (2019) investigated a way to reduce the total number of presentations of the DIN to increase test efficiency (Denys et al., 2019). Denys et al. (2019) suggested using a variable step size based on the correctness of digits identified within the triplet (Denys et al., 2019). The step sizes varied between 3 dB (when all three digits were incorrect) to -1 dB (all three digits entered correctly). The number of presentations was adjusted according to a recognition probability of 79%, which showed better sensitivity and specificity to diagnose a hearing loss when compared to lower recognition probabilities (Denys et al., 2019). The SRTs obtained in this study was similar to a standard testing procedure of 27 presentations. The study allowed for a reduced number of 17 presentations indicating its ability to be as accurate as the standard procedure (Denys et al., 2019). Another recent study by Smits (2017) uses a completely different approach to the standard DIN. The study used a fixed SNR instead of an adaptive tracking method (Smits, 2017). The fixed SNR DIN test presents the same SNR in all presentations. The test will end when the ratio of the number of correct/incorrect responses to the total number of presentations reaches a specified probability, as calculated using Bayesian statistics. The end result of the test will produce either a pass (normal hearing) or refer (hearing loss) (Smits, 2017).

The DIN provides a speech-in-noise test that can be readily used by all test populations, as numbers provide basic and easy to understand stimuli. There is a need for the DIN test to be more time-efficient and accurate to increase the uptake of hearing screening and can allow for difficult to test populations (e.g. children) to be more easily screened. The current research study aimed to optimize the time-efficiency and test reliability of the DIN test by developing three novel DIN test procedures and comparing it to the validated gold standard DIN test. The standard adaptive antiphasic 23-step DIN was used as the gold standard with the novel approaches, including a DIN test procedure using a subjective method of allowing participants to self-select their perceived SNR. The second novel DIN test procedure implemented a self-selected DIN, followed by a standard adaptive antiphasic 8-step DIN. Finally, the third novel DIN test used the abovementioned fixed SNR DIN test procedure proposed by Smits (2017).

CHAPTER TWO: METHODOLOGY

2.1 Research Aims

The main aim of this research study was to compare the time efficiency and test-retest reliability of three novel versions of the DIN test to the gold standard adaptive antiphasic DIN test.

2.2 Research Design

This study employed a cross-sectional, comparative, quasi-experimental research design (Leedy & Ormrod, 2010). The data collected was used to compare whether the novel DIN tests can be a more time efficient hearing screening tool compared to the conventional DIN test. In addition, participants were retested to verify the test-retest reliability of the DIN tests.

2.3 Ethical Considerations

Connelly (2014) justified the need for reporting on ethical considerations for a research study which included ethical clearance from an institutional board, informed consent, honest reporting, and ensuring the procedures are risk-free and recruitment of participants were fair (Connelly, 2014).

Ethical clearance from the Humanities Ethics Committee, University of Pretoria, was obtained prior to the commencement of data collection for the research study (Appendix A, Protocol number: HUM011/1219).

Informed consent

According to Leedy and Omrod (2010), to ensure participants know the purpose of their participation in the study, informed consent was obtained by all participants. Due to the COVID-19 lockdown regulations at the time, the data collection procedure deviated slightly from the original proposal as participants hearing could not be evaluated diagnostically at the University of Pretoria. Participants were thus verbally made aware of the changes to the original study design and were provided with a sanitization protocol followed during the data collection procedures (Appendix C). Testing began only once an informed consent form was signed by the research participant (Appendix B). The participants were aware that their participation is voluntary, and they may withdraw from the study at any time.

Risks and benefits of the research study

Research participants were made aware that there were no physical risks involved with participating, and sanitization measures were taken to decrease the risk of spreading the COVID-19 virus (Appendix C). There were no diagnostic benefits of the research study, however, the validated standard DIN test could identify whether a participant had normal hearing status or a hearing loss. Participants who obtained a refer result on the test was referred for further evaluation (Appendix F).

Confidentiality of participants

Leedy & Omrod (2010) specified that the privacy of all participants must always be respected. All personal information of participants was kept confidential. Confidentiality of results was ensured throughout the research study by assigning the data of each participant an alpha-numeric code (e.g., C561). This code could only be accessed by the researcher and supervisors.

Data storage and sharing of results

The data from the results of the four DIN tests was stored in the application data on the internal storage of the smartphone device. This data was manually captured on a data collection sheet (Appendix E), as well as collectively entered onto an electronic Excel spreadsheet which only the researcher and supervisors have access to. The data collection sheets, completed ISO 389-1 checklists, and signed informed consent forms of participants will be archived in the Speech-Language Pathology and Audiology building at the University of Pretoria for fifteen years and can be accessed for research purposes. The results from the research study will be used to publish scientific research articles and a postgraduate dissertation and can be accessed for educational and research purposes.

Plagiarism

Plagiarism can be defined as the use of other authors writing without providing any acknowledgement to the author (Leedy & Ormod, 2010). All information obtained for the compilation of this research study has been referenced in the bibliography and cited according to APA 7th edition referencing.

2.4 Research Participants

A total of 120 participants were recruited using convenience snowball sampling based on a power analysis (statistical power of 0.8, a significance level of 0.05, and the prevalence of the population of people in SA with a hearing loss). Participants consisted of people who were known to the researcher, family and friends of the researcher were first approached, and through word-of-mouth, any volunteer participants who met the criteria were recruited. Participants were all adults between the ages of 18 to 80 years old. The average age of the participants was 42 (19.12 SD) years, and all participants were fluent in English. Sixty-two percent of participants were females and 38% male. All participants were required to complete the ISO 389-1 checklist before the testing. This checklist (Appendix D) was used to ensure otologically normal candidacy criteria was met *i.e.,* normal state of hearing health thus, participants included were free from all signs or symptoms of ear disease and from obstructing wax in the ear canal, and who had no history of excessive exposure to noise, potential ototoxic drugs, or family hearing loss. The DIN tests used in this study presented the digits using antiphasic stimuli, and thus any participant with histories of chronic ear infection was not included in this study.

2.5 Materials and Equipment

Table 2.1 provides a description of the materials and equipment used in the data collection. The researcher used 3-ply face masks and 70% isopropyl alcohol to sanitize all the equipment before and after a data collection session and sanitise the participants' hands before commencing the testing. Participants were also required to ensure they always kept their face masks on.

Table 2.1. Materials and equipment for data collection

Equipment	Rationale
ISO 389-1 checklist for otologically normal hearing individuals	Checklist for participant to complete to ensure otologically normal candidacy criteria was met.
Huawei p9 lite smartphone run by Android version 9.0 connected to Sennheiser HD 280 Pro headphones	A research application was installed to test the standard adaptive antiphasic DIN test. A version 3.0 of the research application was installed to test the three novel DIN test procedures: - *Self-selected DIN test* - *Combination self-selected and adaptive 8-step DIN test* - *Fixed SNR DIN test*

2.6 Data Collection Procedures

The initial study design included tympanometry and pure tone audiometry to assess the status of the participant's middle ear and hearing status, respectively. However, due to the COVID-19 pandemic and the inability to access the equipment, participants were only tested using a smartphone device with the four DIN test applications. This allowed data collection to proceed with all hygienic and safety measures taken by the researcher during the data collection process. Appendix C stipulated the protocol and verbal instructions used by the researcher for each participant. The participant first signed their informed consent letter (Appendix B), and thereafter completed the ISO 389-1 checklist (Appendix D).

Two Android applications were developed by the hearX Group, Pretoria, South Africa, for this research study. The one application was the previously validated standard adaptive antiphasic 23-step DIN test, and the other application ran the three novel DIN test procedures. The applications were installed onto an Android smartphone device. The research procedure consisted of two sessions that took place on the same day. Each session consisted of four DIN test procedures which were as follows:

- Test procedure 1: standard adaptive antiphasic 23-step DIN test (D23)
- Test procedure 2: self-selected SRT test (DSS)
- Test procedure 3: combination self-selected SNR and adaptive 8-step DIN test (DC8)

- Test procedure 4: fixed SNR DIN test (DF)

Thereafter, a retest of each DIN test procedure resulted in a total of eight DIN test procedures. A Latin square design of the eight procedures was utilized to determine the test order of the DIN tests and to counterbalance the DIN tests. Participants were given a break time of at least thirty minutes between the two sessions, to reduce any effects of fatigue. Data collection was retrieved at the participants home, where surrounding noise levels were kept to a minimum. Participants were asked to sit in a quiet room, with minimal noise to avoid the participant being distracted. All data obtained was logged onto the data collection sheet (Appendix E) and was electronically captured on a Microsoft Excel spreadsheet.

Test procedure 1: The standard adaptive antiphasic 23-step DIN (D23)

The South-African DIN test had been developed in South-African English with digits ranging from 1 to 9 and included 120 unique digit triplets (e.g., 8-9-2) (Potgieter et al., 2016). The participant was required to listen to and identify the three digits in the presence of competing noise (Potgieter et al., 2016). The test implemented antiphasic stimuli as suggested by De Sousa et al. (2020). This antiphasic approach presented the same broadband masking noise to both ears, while the phase of the speech stimuli altered for each ear (i.e., a 180° phase shift) (De Sousa et al., 2020). Masking noise used was shaping white noise, which matched the long-term average speech spectrum (De Sousa et al., 2020; Potgieter et al., 2016). The participant was required to first enter their birth year and gender on the screen provided. General instructions were presented on the screen of how the test works (i.e., placement of headphones and the stimuli presented). Thereafter, the participant had to indicate a comfortable listening intensity to begin the test (Potgieter et al., 2016) (Figure 2.1). The test first presented at 0 dB SNR and used a one-up one-down adaptive procedure (De Sousa et., 2020). The first three presentations the SNR were either decreased by 4 dB for correctly identified triplets or increased by 2 dB for triplet digits incorrectly recognized. The remaining 20 presentations were adapted in 2 dB step sizes, depending on the correctness of the triplet digits (i.e., increased by 2 dB for incorrectly identified digits or decreased by 2 dB for all three digits correct). The total presentations of triplet digits were 23 presentations (De Sousa et al., 2020; Potgieter et al., 2016). Triplet presentations 4 to 23 were averaged to obtain the SRT (De Sousa et al., 2020; Potgieter et al., 2016).

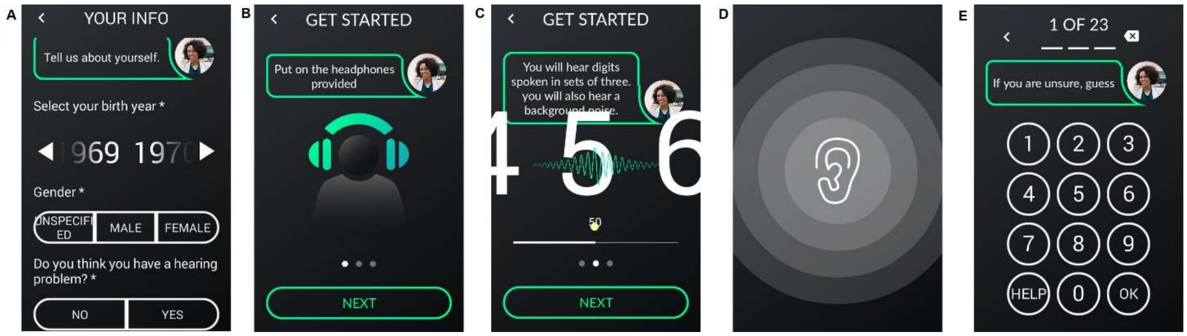

Figure 2.1. Onscreen D23 test setup from the application, A) Demographic information of participant, B) Instructions to participant, C) Setting of comfortable listening intensity, D) Three digits presented in background noise, E) Keypad to enter the three digits heard.

Test procedure 2: Self-selected SNR DIN test (DSS)

The DSS used antiphasic stimuli consisting of consecutive single digits (0-9) presented randomly and in the presence of background noise. Five blue buttons were presented on the smartphone screen, and the participant was given the following instructions at the top of the screen: "*Adjust the volume (using the slider) until you can only just hear the digits*". Each button changed the SNR of the stimuli ranging from the highest (easiest) SNR on top (number 5) to the lowest SNR (most difficult) at the bottom (number 1) (Figure 2.2). Four test screens were used; i) The first test screen used 4 dB SNR decrements between 0 dB SNR (number 5) and -16 dB SNR (number 1). ii) The second test screen used 2 dB decrements with number 5 corresponding to a 2 dB higher SNR than the selected SNR in test screen one. iii) The third and fourth test screens also used 2 dB decrements with number 5 corresponding to a 2 dB higher SNR than the selected SNR in test screen two. Thus, test screen four was similar to test screen three. On each screen, the presentations start with number 5 selected.

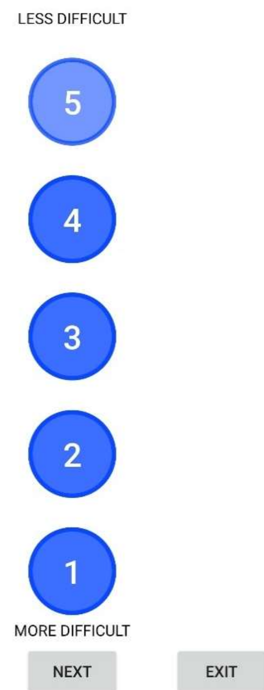

Figure 2.2. Onscreen set up of DSS slider

Test procedure 3: Combination self-selected SNR and adaptive 8-step DIN test (DC8)

The test would begin with a slider, as seen in Figure 2.2. The participant was required to select their perceived SNR ranging from – 4 dB SNR and ends at – 20 dB SNR. Once the participant selected their perceived SNR, the standard adaptive antiphasic DIN testing would begin. The test would then present three digits (e.g., 9-8-2) in the presence of background noise. This first presentation of the triplet digits would be presented at the SNR selected on the slider. The test then adapted the SNR for the first three presentations based on the correctness of the response. For the first three presentations, the SNR decreased by 4 dB for a correct response. Alternatively, the SNR would have increased by 2 dB for an incorrect response. Thereafter, the test adapted in 2 dB step sizes for the remainder presentations. The final SRT was calculated on the average of the eight presentations of the triplet digits.

Test procedure 4: Fixed SNR DIN test (DF)

This DIN test procedure made use of a fixed SNR in all presentations to determine hearing status using producing a pass (normal hearing) or fail (hearing loss) result (Smits, 2017). Unlike the other three DIN test procedures in this study, the DF test does not determine an end SRT value, as the stimuli are kept at a constant SNR presentation. Based on an antiphasic dataset, the fixed SNR was set to -14.5 dB SNR (De Sousa et al., 2020). A comfortable listening level was first set by the participant (Smits, 2017). Participants were instructed to identify antiphasic triplet digits (e.g., 7-9-2) in the presence of background noise. If they were not sure of the digits they heard, they were required to guess any three digits. The first two presentations were used for conditioning and presented at -6 dB SNR and -10 dB SNR. The conditioning presentations were not used in the calculation to estimate the probability pass/refer. The test calculated the ratio of the number of correct responses (*k*) to the total presentations (*n*) (Smits, 2017). The total number of presentations depended on whether the ratio (*k*/*n*) reached 95% recognition when the SRT was more than or less than the cut-off SNR. The number of presentations was variable because the test stopped when one of the probabilities reached a predefined value. The minimum number of presentations were eight (including the two conditional presentations).

2.7 Data Processing Procedure

Data were extracted from the Huawei p9 lite smartphone in the form of CSV files and exported to a Microsoft Excel spreadsheet. The Microsoft Excel spreadsheet was imported into the Statistic Package for the Social Sciences Version 26 (IBM SPSS v26.0, Chicago, Illinois) for analysis.

2.8 Data Analysis Procedure

The data were not normally distributed (Shapiro-Wilk *p*-values < 0.05; Field, 2017) and not perfectly symmetric, thus non-parametric statistical tests were used for the data analysis. The value of the standard error of measurement (SEM) was used in the analysis of test-retest reliability of the D23, DSS and DC8 tests. Furthermore, determining the number of total presentations of a DIN test is based on the desired test accuracy (i.e., the measurement error). The measurement error, or standard error of measurement (SEM), is inversely proportional to the square root of the number of presentations (Smits & Houtgast, 2006). The non-parametric Wilcoxon signed-rank test was used to test for significant differences between related samples, and the non-parametric Spearman correlation was used to compute correlations between variables. A Chi-square test was utilized to examine the association of results obtained when using a cut-off criterion to indicate a pass/fail result. Further analysis was conducted using GraphPad Prism and Sigmaplot to plot statistical figures.

2.9 Reliability and validity

Reliability refers to when a measurement will not alter and will remain accurate and consistent at all times. Validity refers to how accurate a test result is when compared to the gold standard. To ensure accuracy and consistency of the results, the study utilized a repeated measures design for all four versions of the DIN tests. In order to investigate the agreement between the tests, intraclass correlation coefficients between the test-retest condition was conducted. To validate whether the novel DIN test procedures were accurate in the results obtained, the novel DIN tests were compared to the gold standard D23. D23 has been validated and proven to be an accurate screening tool with high sensitivity and specificity, and which correlates well with the pure tone audiometry ($r = 0.88$) (De Sousa et al., 2020). Ideally, a study design as such would utilize pure tone audiometry to cross-check the results, but due to the COVID-19 pandemic, such testing was not accessible.

CHAPTER THREE: RESEARCH ARTICLE

Authors: Tasneem Dambha, De Wet Swanepoel, Faheema Mahomed-Asmail, Karina C. De Sousa, Marien Graham, Cas Smits.

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Keywords: Digits-in-Noise, time-efficiency, antiphasic, reliability, smartphone application, self-test

Authors:

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Conflicts of interest

There was no conflicts of interest to be disclosed.

ABSTRACT

Purpose

This study compared the test results, test-retest reliability, and test-efficiency of three novel digits-in-noise test (DIN) procedures to a conventional antiphasic 23-step adaptive DIN (D23).

Method

One hundred and twenty participants with an average age of 42 years (SD = 19) were included. Participants were tested and retested with four different DINs. Three new DIN procedures were compared to the reference D23 version: i) A self-selected DIN (DSS) to allow participants to indicate a subjective speech recognition threshold (SRT), ii) A combination DIN (DC8) which utilized a self-selected signal-to-noise ratio (SNR) followed by an 8-step adaptive DIN procedure, iii) A fixed SNR (DF) approach using a fixed SNR value of -14.5 dB SNR in all presentations to produce a pass/fail result.

Results

Test-retest reliability of the D23 procedure was better than the DSS and DC8. SRTs from DSS and DC8 were significantly higher than SRTs from D23. DSS was not accurate to discriminate between normal hearing and hearing impaired listeners. The DF, and the DC8 procedure with an adapted cut-off showed good hearing screening test characteristics.

All three novel DIN procedures durations were significantly shorter (<70 seconds) than D23. DF showed a reduction of 46% in the number of presentations when compared to D23 (from 23 presentations to an average of 12.5).

Conclusion

The fixed SNR and the DC8 DIN procedures had significantly lower test durations compared to the reference 23-step DIN, and show potential to be more time-efficient screening tools to determine normal hearing or potential hearing loss. Further studies are needed to optimize the DC8 procedure. The reference 23-step DIN remains the most reliable and accurate DIN hearing screening test.

Introduction

The World Health Organization (WHO) estimated the number of people with disabling hearing loss in 2018, and this estimate was 432 million adults. Furthermore, they projected that this number would rise to 900 million by 2050 (WHO, 2018). Accessible screening to identify hearing loss in adults is an important priority to raise awareness of a hearing loss, to support earlier treatment and to prevent associated risks, such as cognitive decline (Koole et al., 2016; Livingston et al., 2020; Willberg et al., 2016). Self-assessed hearing screening tests using a speech recognition in noise paradigm do not require calibrated and expensive equipment and can be easily accessed remotely. A popular screening test to determine the functional disability of a hearing loss is the digits-in-noise test (DIN) (Jansen et al., 2010; Moore et al., 2014; Potgieter et al., 2015; Smits et al., 2004; Van den Borre et al., 2021; Watson et al., 2012; Zokoll et al., 2012).

The test uses spoken digit-triplets, e.g., (3-4-8), mostly presented in speech weighted masking noise. The first DIN was developed as the national telephone hearing test in the Netherlands (Smits et al., 2004). Due to high uptake of the original Dutch version, other countries developed the DIN test in different languages, such as French (Jansen et al., 2010), German (Zokoll et al., 2012), Finnish (Willberg et al., 2016), and American English (Watson et al., 2012).

Advancing technology has seen the DIN landline telephone screening test with limited bandwidth signal (300 – 3400 Hz) move to broadband internet-based versions and mobile apps (Potgieter et al., 2016; Smits et al., 2004, Smits et al., 2006; Smits et al., 2013; Zokoll et al., 2012). Smartphone testing has the potential for widespread global access since 79% of the world's adult population were estimated to be smartphone owners by 2025 (GSMA, 2019).

In 2016, the first national smartphone-based DIN test was launched as a free downloadable smartphone application (*hearZA*) in South Africa. Since its launch, more than 30 000 persons have downloaded the *hearZA* application to check their hearing status (De Sousa et al., 2018). The *hearZA* app monitors hearing health and provides users with a follow-up of their hearing status by promptly reminding the user to take the hearing test at least once a year (Swanepoel, 2017). Following the successful launch of *hearZA* using smartphone DIN testing, WHO launched *hearWHO* in 2018 following the same testing procedure (Swanepoel et al., 2019; WHO, 2018).

Most standardly used DIN procedures, test each ear consecutively using an adaptive one-up, one-down procedure with a fixed step size of 2 dB to adjust the signal-to-noise ratio (SNR) and determine the speech recognition threshold (SRT). The SNR decreases by 2 dB for a triplet identified correctly and increases by 2 dB when a triplet is entered incorrectly. The SRT is determined by averaging the SNRs of the presentations from the adaptive track, omitting the first presentations' SNRs, and it represents the SNR where the listener can correctly recognize 50% of the triplets. When used for hearing screening, the SRT is compared to a predefined cut-off SNR to obtain a ‘pass’ or ‘refer’ result. Most of the current versions of the DIN are based on Smits et al. (2004; 2013) and use approximately 23 monaural or diotic presentations (Potgieter et al., 2016; Potgieter et al., 2018). The choice for this number of presentations is based on the desired test accuracy (i.e., the measurement error) and test duration. The measurement error, or standard error of measurement (SEM), is inversely proportional to the square root of the number of presentations (Smits & Houtgast, 2006), but obviously, the test duration increases with the number of presentations. By ensuring high test-retest reliability, hearing screening tests can efficiently identify even mild hearing losses which is important for persons who regularly monitor their hearing using apps like *HearZA* (Swanepoel et al., 2019). Short test time is desirable to reduce false-negative results caused by fatigue, and to promote better uptake of hearing screening tests in a consumer environment where rapid results are important (Denys et al., 2019; Potgieter et al., 2016; Swanepoel et al., 2019; Willberg et al., 2016). In this context, we call one test more *efficient* than another test if the test has the same measurement error as the other test, but the result is achieved in a shorter time; or when a higher sensitivity and specificity is achieved in the same test time.

Several ways have been proposed to reduce the test time of the DIN without compromising test accuracy. First, a diotic test paradigm has been implemented to test both ears simultaneously, instead of testing each ear sequentially (Smits et al., 2006; Potgieter et al., 2016; Potgieter et al., 2018). The diotic paradigm is time-efficient because it reduces the test duration by approximately 50%. However, the test result may represent better ear performance and is not sensitive in detecting unilateral hearing loss (De Sousa et al., 2020). Therefore, second, De Sousa et al. (2020) introduced an antiphasic test paradigm. In this approach, identical broadband masking noise is presented to both ears, while the phase of the speech stimuli is inverted between ears (i.e., a 180° phase shift). The antiphasic test takes advantage of binaural unmasking (De Sousa et al., 2020) to improve the SRT by approximately 6 to 8 dB in normal hearing individuals when compared to the diotic approach. The antiphasic DIN is also sensitive to unilateral sensorineural and conductive hearing loss without extending test time through monaural assessment. De Sousa et al. (2020) found a higher sensitivity (95%) and specificity (73%) for the antiphasic DIN than for the diotic DIN (De Sousa et al., 2020). A third method to optimize test efficiency was suggested by Denys et al. (2019). They employed a variable step size based on the number of correctly recognized digits within the triplet. When using this digit-scoring with step sizes between 3 dB (none of the three digits correctly recognized) and -1 dB (all digits correctly recognized), they found SRTs which were not significantly different from the SRTs from the reference DIN. However, the measurement error for this procedure was significantly lower than for the reference procedure with triplet-scoring (Denys et al., 2019). They estimated that a DIN with 17 presentations would be as accurate as a reference DIN procedure with 27 presentations for their procedure. Finally, a fourth method, a fixed-SNR procedure was proposed by Smits (2017). His approach was essentially different because he did not propose an adaptive procedure to estimate the SRT and then compare it to the test's cut-off value. In the procedure, all stimuli are presented at an SNR corresponding to the cut-off value (Smits, 2017). After each presentation, the probability of a pass or refer was estimated using Bayesian statistics, and the test is ended when the estimated probability of a pass or refer is higher than approximately 95%. Monte Carlo simulations showed that the DIN could theoretically be shortened to an average of approximately eight digit-triplet presentations (Smits, 2017). As far as we know, there has been no experimental data reported on the use of the fixed-SNR procedure.

This research study aimed to explore the effect of different DIN procedures on its test characteristics and efficiency as a hearing screening test. The conventional antiphasic DIN procedure was used as the reference test against which the accuracy, reliability and performace of the new DIN procedures were compared. The first new procedure explored the use of a subjective procedure to self-select the SNR using digit presentations. This method may require fewer presentations and a shorter test time.The second new procedure used a short adaptive approach to estimate the SRT, preceded by a self-selected SNR to approximate the starting SNR. Finally, the third procedure was the fixed-SNR procedure (Smits, 2017).

Method

Institutional Review Board clearance was obtained prior to data collection commencement for the research study from the Humanities Research Ethics Committee, University of Pretoria (Protocol number: HUM011/1219).

Study design and participants

A cross-sectional, comparative study, including 120 participants, was performed. Participants ages ranged between 18 to 80 years, with an average age of 42 years (SD = 19) and were all proficient in English. Sixty-two percent of participants were women, and 38% were men. All participants provided consent and completed the ISO 989-1 checklist to ensure the otologically normal candidacy criteria were met. The test-retest reliability, test characteristics, and efficiency of three different DIN procedures were compared to a conventional antiphasic 23-step adaptive DIN (D23).

Procedures and equipment

All participants completed eight different DIN procedures which including a test and retest for each condition. The eight tests were presented in counterbalanced order using a Latin square design. A thirty-minute rest period between test and retest conditions was implemented to avoid participants fatiguing. The researcher visited the participant's home with the equipment (the smartphone device, headphones, sanitization tools, and paperwork). Testing took place in a quiet room at the participant's home, and low noise levels were ensured by closing windows that could allow outside noise to interrupt. All equipment was sanitized prior and after testing the participant.

The initial study design was to include pure tone audiometry. However, due to the Covid-19 pandemic and level 5 lockdown regulations in South Africa, audiological soundproof booths and equipment could not be accessed to test participants as initially planned. The study used the national smartphone DIN test, hearZA as the reference test to compare the three novel DIN procedures. The reference test has been validated and proven to be an accurate screening tool with high sensitivity and specificity, and which correlates strongly with pure tone audiometry (r = 0.88) (De Sousa et al., 2020).

A Huawei p30 lite smartphone run by Android version 9.0 and connected to Sennheiser HD 280 Pro headphones was used for the study. An Android application was installed to test the reference DIN (hearX Group, South Africa), and an additional research Android application was installed to test the three novel DIN procedures.

The DIN tests in this study used digit triplets constructed from digits 0 to 9 spoken by a female speaker in South African English. (e.g., 8-9-2) (Potgieter et al., 2016). As described by De Sousa (2018) the noise starts 500 ms before the first digit and ends 500 ms after the last digit. The successive digits are presented with 200 ms of pause in between and a random jitter of 100 ms was applied to these pauses (Potgieter et al., 2016). The test implemented antiphasic stimuli by presenting the same-phased broadband speech-shaped white masking noise to both ears, while inverting the phase of the speech stimuli between the ears (i.e. 180°degree phase reversed) (De Sousa et al., 2020).

Antiphasic 23-step adaptive DIN (D23)

The D23 test was used as a reference test in the present study. The test first required the participant to provide general information (birth year, gender, and indicated that they do not have a hearing problem), and read the on-screen instructions of the test which was already described by the researcher before starting the test. Then, the participant was instructed to select a comfortable presentation level, by using the slider on the screen. The level increased (slide to the right) or decrease (slide to the left) when moving the slider. Next, the participant was prompted to identify the three digits in the presence of competing noise (Potgieter et al., 2016). The participant was required to type on a keypad provided on-screen the three digits they heard. If they were unsure, they had to guess. The test used fixed speech levels, and adjusted the level of the masking noise when the SNR was positive, and used fixed noise levels for negative SNRs (De Sousa et al., 2020; Potgieter et al., 2016). The first digit triplet was presented at 0 dB SNR. The test followed a one-up one-down adaptive procedure to estimate the SRT (De Sousa et al., 2020). The SNR of the initial three presentations were adjusted by either decreasing by 4 dB for a correct response or increasing by 2 dB for an incorrect response. The remaining 20 SNRs were adapted in 2 dB steps. The last 19 SNRs were averaged to obtain the SRT (De Sousa et al., 2020; Potgieter et al., 2016). In total there were 23 triplet presentations (De Sousa et al., 2020; Potgieter et al., 2016). Appendix A, figure A.1 provides screenshots of the D23 test described above.

Self-selected DIN (DSS)

The self-selected DIN used a continuous sequence of random consecutive antiphasic digits (0-9) presented in the presence of background noise (e.g., 1 – 4 – 7 – 9 – 5 – 3, etc.). Note that, unlike the other procedures, single digits were used. The digits were also constructed with 500 ms silences before and after each digit, and the masking noise was presented with the presentation of the digits. Five buttons were presented on the smartphone screen, and the participant was instructed with the text: "*Adjust the volume (using the buttons below) until you can only hear the digits*". Each button changed the SNR ranging from the highest (easiest) SNR on top to the lowest SNR (most difficult) at the bottom. Once the participant made their selection, they were required to press “Next” to proceed to the following adjustment trial. Four adjustment trials were used and each adjustment trial used a different adjustment senstivity; i) The first adjustment trial used 4 dB SNR decrements between 0 dB SNR (top button) and -16 dB SNR (bottom button). ii) The second adjustment trial used 2 dB decrements with the top button corresponding to a 2 dB higher SNR than the selected SNR in the first adjustment trial. iii) The third and fourth adjustment trials also used 2 dB decrements with the top button corresponding to a 2 dB higher SNR than the selected SNR in the second adjustment trial. Thus, the fourth adjustment trial was similar to the third. For each adjustment trial, the presentations start with the top button selected. Appendix A, figure A.2 shows a screenshot of the adjustment trial of the DSS test. The third adjustment trial SRT value was used in the data analysis.

Combination self-selected and adaptive 8-step DIN (DC8)

The DC8 procedure had two phases. The first phase followed the same procedure as for the DSS DIN to allow the participant to self-select the SNR. However, just one adjustment trial with five buttons was used to bring the presentation level to roughly approximate the SRT quickly. The adjustment trial presented in the first phase used 4 dB SNR decrements between -4 dB SNR (top button) and -20 dB SNR (bottom button). Phase two of the DC8 procedure was a short antiphasic adaptive DIN, similar to the D23 procedure, with 8 presentations which started at the self-selected SNR. For the first three presentations, the SNR decreased by 4 dB for a correct response and increased by 2 dB for an incorrect response. The remaining 5 presentations followed a 2 dB step size, and the final SRT was based on an average of these last 5 presentations. Appendix A, figure A.3 is a display of phase one and two of the DC8 test.

Fixed SNR DIN (DF)

As proposed by Smits (2017), this test procedure used a fixed SNR , corresponding to the cut-off value of -14.5 dB SNR established by De Sousa et al. (2020). The participant was instructed to select a comfortable presentation level, by using a slider to increase (slide to the right) or decrease (slide to the left) the SNR of the digit triplets and choose ‘Next’. Then, a dummy presentation was presented at -6.0 dB SNR and at -10.0 dB SNR to get used to the test. These presentations were not used in determining the test result. Then the actual test started. The minimum number of presentations was set at 6, and the total number of presentations was variable. After each presentation, the proportion of correct responses was calculated and the probability that the true SRT was better than the cut-off value (pass) or worse than the cut-off value (refer) was estimated using Bayesian statistics. When the estimated probability for a pass or refer was higher than 95%, or the maximum number of presentations was reached, the test stopped. Otherwise, another stimulus was presented, and the calculations were repeated. Appendix A, figure A.4 shows the test setup of the screenshots from the DF test.

Statistical analysis

All data was analyzed using the Statistical Package for the Social Sciences (SPSS) program (IBM SPSS v26.0). Because the data were not normally distributed, even after transformation, non-parametric tests were used on the unaltered data. Non-parametric Spearman correlation coefficients were calculated between the SNRs obtained for the four different adjustment trials of the DSS method and D23. The strongest correlations with D23 were found for the third and fourth adjustment trial (nearly identical values); therefore, the SNRs from the third level were used in the analyses. The non-parametric Wilcoxon signed-rank test was used to test for significant differences between mean SRTs for each test method. The non-parametric Spearman correlation was used to compute correlations between variables, and to determine the test-retest reliability for quantitative variables. The test-retest reliability for qualitative variables were tested for using Cohen's kappa. The standard error of measurement was determined from the differences between the test- and retest SRT estimates obtained from each participant. Logistic regression was used to create pass-rate functions for different DIN procedures, and sensitivity and specificity were also calculated for the different DIN procedures. The sensitivity of each new DIN test procedures was calculated by dividing the number of correctly identified partipicants with hearing loss by each procedure by the total number of participants with hearing loss. Likewise, the specificity was calculated by dividing the number of correctly identified participants without hearing loss by the total number of participants wihout hearing loss. Hearing loss was defined as a reference DIN SRT (D23) greater than -14.5 dB SNR (De Sousa et al., 2020).

Results

Test-retest reliability

The scatter plots in Figure 1 show test vs retest data for the reference DIN (D23), the self-selected DIN (DSS) and the combination DIN (DC8). Test-retest differences, represented by scatter around the line of equality, are generally smaller for D23 and largest for DSS. Table 1 shows the mean SRTs (SD) for test-retest conditions and other characteristics for the three novel DIN procedures. It shows that D23 has the strongest correlation between test and retest SRTs and the smallest SEM. The DC8 test procedure shows a significant improvement of retest SRTs of 0.6 dB, indicative of a learning effect.

Test-retest reliability of the fixed-SNR procedure (DF), assessed by Cohen's kappa, is $\kappa = 0.630$, $p < 0.001$ indicating a substantial agreement (McHugh, 2012).

Table 1. Mean SRTs (SD) for test-retest conditions and other characteristics across three DIN procedures

DIN test	Mean SRT (SD) *test*	*retest*	**Difference (sig.)*	Spearman correlation (sig.)	SEM [dB]
D23	-14.8 (5.4)	-14.8 (5.4)	*z*=-.006, *p* = 0.995	0.748 (*p* < 0.001)	1.5
DSS	-9.0 (5.2)	-9.1 (4.8)	*z*=-.320, *p* = 0.749	0.409 (*p* < 0.001)	3.7
DC8	-13.5 (3.9)	-14.1 (4.4)	*z*=-2.103, *p* = 0.035	0.536 (*p* < 0.001)	2.2

Note. SRT values measured in dB SNR; D23 = standard adaptive 23-step DIN; DSS = Self-selected Speech Recognition Threshold; DC8 = Combination self-selected and adaptive 8-step DIN; SD = Standard deviation; SEM = Standard Error of Mean; *Difference between test and retest measured using the Wilcoxon signed-rank test

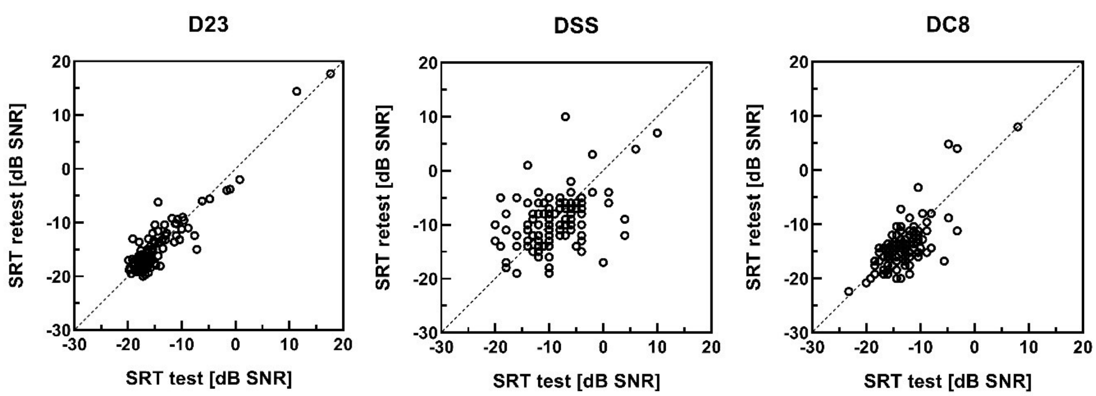

Figure 1. Bivariate plots of the retest SRT against the initial test SRT for three different DIN procedures. A small amount of jitter was added to each data point in the middle panel to avoid overlap.

Relationships between results from the new DIN procedures and the reference DIN procedure

The average of test and retest SRTs was calculated and used to explore the different procedures' relationships. Figure 2 shows the mean SRT from the DSS against D23, and the mean SRT from the DC8 against D23. Clearly, the self-selected SRTs are generally higher than the D23 SRTs because almost all data points lie above the line of equality (left panel of Figure 2).

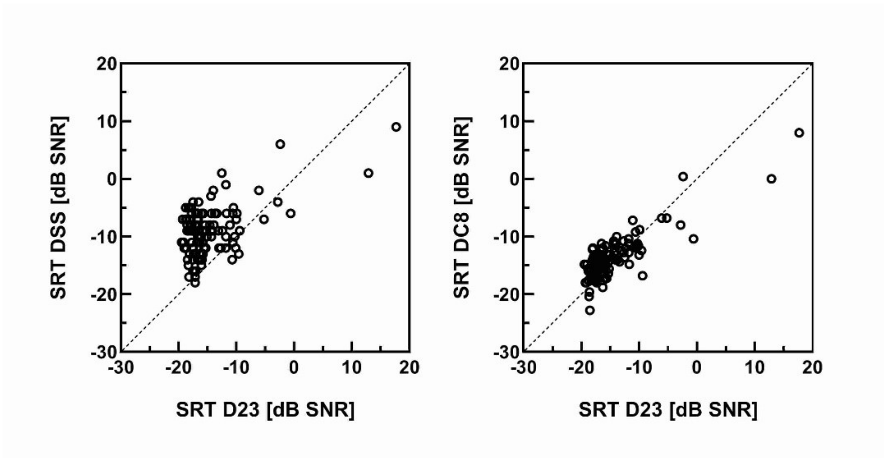

Figure 2. Bivariate plots of mean SRTs from new DIN procedures against mean SRTs from the reference DIN procedure.

The correlation between DSS SRT and D23 SRT (*rs* (120) = 0.203; $p < 0.001$) is weaker than the correlation between DC8 SRT and D23 SRT (*rs* (120) = 0.696; $p < 0.001$). The DSS SRTs are significantly higher than the D23 SRTs (mean difference of 5.8 dB; $z = 8.539$; $p < 0.001$), and the DC8 SRTs are also significantly higher than the D23 SRTs (mean difference of 0.99 dB; $z = 5.134$; $p < 0.001$). Thus, different cut-off values are needed when using the DSS, DC8 or D23 procedures for hearing screening.

Screening characteristics of the different DIN procedures

The reference D23 DIN has previously shown high sensitivity and specificity to detect hearing loss and showed a strong correlation with pure tone average thresholds ($r = 0.88$) (De Sousa et al., 2020). The cut-off value of the reference D23 DIN is -14.5 dB SNR. Thus, ideally, each test should discriminate between participants with SRTs above and below this value. Therefore, we used this standard cut-off value to evaluate screening characteristics. To take into account the systematic difference of 5.8 dB between DSS SRT and D23 SRT, and 0.99 dB between DC8 SRT and D23 SRT, we also adapted cut-off values of -8.7 dB SNR (-14.5 + 5.8) and -13.5 dB SNR (-14.5 + 0.99) for the DSS and DC8 procedure, respectively. Figure 3 shows the proportion of the tests resulting in 'pass', as a function of the mean SRT of the D23 procedure. The solid lines represent the pass-rate functions which are logistic functions fitted to the data. The mean D23 SRT was rounded and results were grouped according to the round SRT. Note that test and retest SRTs for the DSS and DC8 procedure were not averaged but treated as independent measures. For each procedure, the raw data were fitted with a logistic function through a maximum-likelihood procedure represented by solid lines in Figure 3.

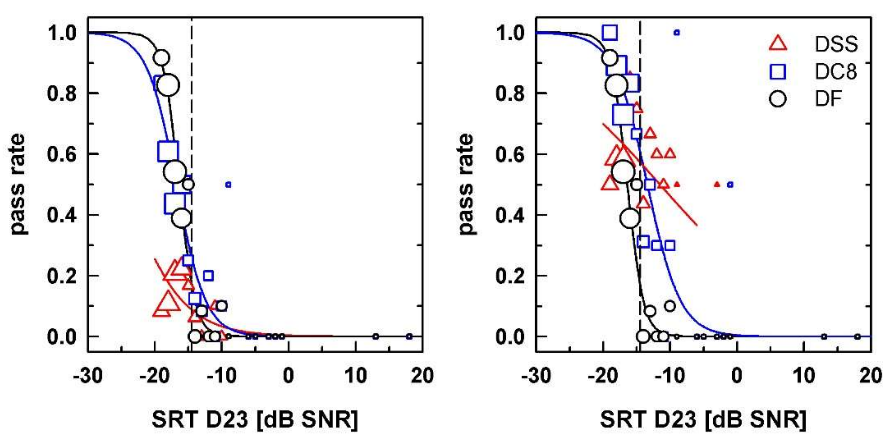

Figure 3. Proportion of the new DIN procedures which result in 'pass' as a function of the mean SRT of the D23 procedure. The left panel shows the results when using the cut-off value of -14.5 dB for all procedures and the right panel shows the results when using the adapted cut-off values.

Table 2 provides details of the pass-rate functions, and sensitivity and specificity of different DIN procedures.The slope of the pass-rate function indicates the region of SRTs where the pass rate drops from high to low values. The pass-rate function of the

DF procedure has the steepest slope and demonstrates the smallest region of SRTs where the accuracy of the test in discriminating between pass and fail is poor. The test-characteristics of the DSS procedure are poor. Using an adjusted cut-off value improves the balance between sensitivity and specificity, but the resulting values are near chance level (= 0.50) for this procedure. Using an adjusted cut-off value for the DC8 procedures improves the specificity of the test but, of course, at the cost of lower sensitivity.

Table 2. An overview of the test characteristics of the pass-rate functions and sensitivity and specificity of different DIN test procedures

Test procedure	Slope of pass-rate function (dB^{-1})	Correctly classified (%)	Sensitivity (1 – FNR)	Specificity (1 – FPR)
Standard cut-off = -14.5 dB SNR				
Fixed SNR (DF)	-0.21	74	0.97	0.64
Self-selected SNR (DSS)	-0.06	41	0.97	0.16
Combination (DC8)	-0.11	65	0.91	0.54
Adjusted cut-off values				
Self-selected SNR (DSS)	-0.02	61	0.54	0.64
Combination (DC8)	-0.10	80	0.73	0.83

Test time and number of presentations of the different DIN procedures

Figure 4 shows violin plots of the test durations of the different procedures. The average test duration of the reference D23 procedure was 136 sec. The three novel DIN procedures all have significantly shorter test durations than the reference D23 test with average test durations of 68, 57 and 47 seconds for the DF ($z = -7.744$, $p < 0.001$), DSS ($z = -9.150$, $p < 0.001$) and DC8 ($z = -9.192$, $p < 0.001$) procedure, respectively.

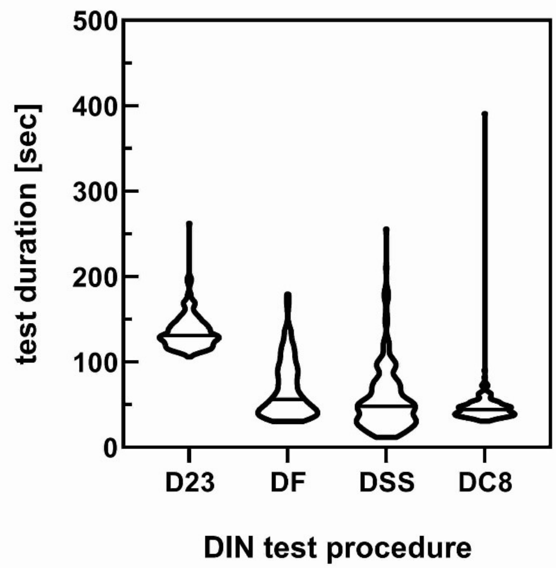

Figure 4. Violin plot showing the test duration of the different DIN procedures. Horizontal solid lines depict median values.

The DF procedure varies in the total number of presentations with an average of 12.5 presentations, including the two dummy presentations, (SD = 5.6; *Range* = 8 – 27) to produce a pass/fail result. Fifty-one percent of the tests were completed after a minimum of 8 presentations. The bubble plot in Figure 5 shows the number of presentations per test as a function of the average D23 DIN with the size of the bubbles corresponding to the number of tests. The shape of the calculated distribution is as expected (Smits, 2017), with the highest number of presentations for participants with SRTs near the cut-off SNR (represented by the vertical dashed line) (Smits, 2017).

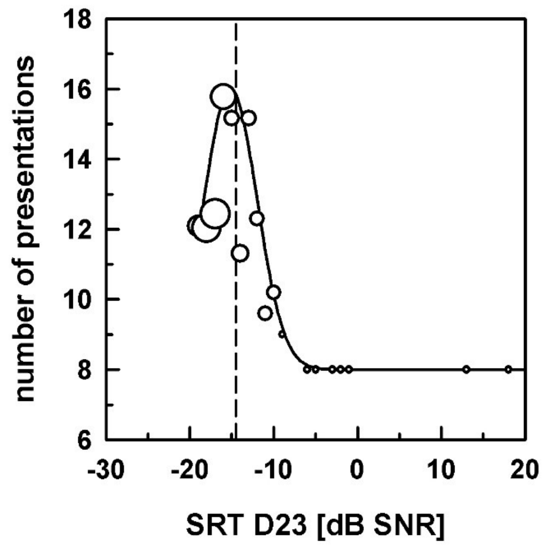

Figure 5. Bubble plot showing the number of presentations for the DF procedure. The sizes of the bubbles correspond to the number of tests. The solid line serves as a guide to the eye.

Discussion

The main aim of this study was to compare the test-retest reliability, test characteristics and efficiency of three DIN procedures to a reference DIN test. Overall, all three novel DIN procedures had significantly shorter test durations of less than one minute, which was better than the average duration of more than two minutes of the reference D23 test.

The conventional D23 method had the lowest SEM (1.5 dB SNR) calculated from the test – retest differences, indicating the best test-retest reliability. The SEM is very similar to the reported SEM for the same test in the study by De Sousa et al. (2020).

Self-selected DIN (DSS)

The procedure DSS was based on a completely subjective measurement of how an individual perceives speech in the presence of background noise. Although the test is quick, it is not useful as a screening test because of the poor test characteristics. Differences between test and retest SRT are large yielding an SEM of 3.7 dB SNR (see Table 1 and Figure 1). Even more clear are Figure 3 and Table 2, which show that the test performs almost at chance level. Changing the cut-off value does not improve its performance as a screening test. The self-selected SNRs are much higher than the SRTs from the D23 DIN, demonstrating that participants choose very favourable SNRs where recognition probabilities are high. A similar test that allows the individual to self-select their perceived SNR is the Perceptual Performance Test (PPT) which was developed and validated as a tool to measure discrepancies between objective and subjective measures of speech recognition in noise. The test compares the “perceived” SRT and the “measured” SRT (Saunders & Cienkowski, 2002; Saunders et al., 2004). In line with the study by Saunders et al. (2004), we found a significantly higher (z = -8.264, p < 0.001) mean subjective (DSS, M = -9.0 dB SNR) compared to measured SRT (D23, M = -14.8 dB SNR).

Combination self-selected and adaptive 8-step DIN (DC8)

Our results suggest that a combination test procedure could potentially be used for efficient hearing screening. However, the current implementation with 8 presentations following the self-selected SNR, has a larger SEM (2.2 dB) and weaker correlation between test and retest SRT than the reference D23 DIN (SEM = 1.5 dB). Second, the average DC8 SRTs are significantly higher than the D23 SRTs. Given the linear relationship between SEM and the inverse square root of the number of presentations, it can be estimated that approximately 17 presentations would be needed for the combination test procedure (DC8) to reach the SEM of 1.5 dB SNR from the D23 procedure. Obviously, the implication of increasing the number of presentations of the DC8 would be an increase of the test duration. A possible reason for the higher average DC8 SRTs than the average D23 SRTs is that some of the participants self-selected a relatively high SNR. Then, the first presentation of the adaptive procedure was too far above the SRT, which causes a bias in the estimated SRT (Smits & Houtgast, 2006).

Fixed SNR DIN (DF)

The test characteristics for the DF procedure are excellent and show high sensitivity, a short test time and a low number of presentations. (Figure 3 and Table 2). The data are an experimental confirmation of Smits (2017) simulations and demonstrate that the number of presentations can be reduced significantly when the aim of the screening test is solely to discriminate between normal hearing and hearing-impaired participants (Smits, 2017). A disadvantage of the procedure is that it does not provide direct information about the severity of the hearing loss as the other test procedures do. The DF's average number of presentations was 12.5 presentations, which showed a 45.7% decrease in presentations compared to the D23. The average number of presentations is higher than the value of 8.3 from Smits (2017) simulations, but the minimum of presentations in the present implementation of the procedure was set at 8 and included two dummy presentations (Smits, 2017). When taking these differences into account, the estimated number of presentations in our experimental study and in the simulations from Smits (2017) are very similar (Smits, 2017). Of course, the average number of presentations also depends on the distribution of the SRTs.

Study limitations

One limitation of this study is the lack of pure tone audiometry thresholds. We used the average of two DIN SRTs (D23) as a reference. This can be considered a valid method to compare the quality of the different test procedures to differentiate participants with SRT above or below a cut-off SNR. However, because the reference SRT is not error-free the true test characteristics are expected to be somewhat better than reported here.

Usually, pure tone audiometry is used as a reference measure when evaluating DIN tests. The reference DIN test, D23, as used in this present study has previously been validated as accurate and reliable screening tool (De Sousa et al., 2020). It shows a high correlation with PTA ($r = 0.88$), and good sensitivity and specificity in detecting hearing loss. Further, a speech-in-noise test allows for a better understanding of a persons hearing ability when compared to pure tone audiometry, as it is a representation of hearing in everyday. Other research studies have supported the use of speech-in-noise tests due to its ability to better depict hearing loss over pure tone audiometry (Bergaman, 1971; Vermiglio et al., 2012). Other DIN tests have also shown good correlations with PTA, and thus can be justified as a stand-in test for pure tone audiometry (Jansen et al., 2013; Potgieter et al., 2016; Smits et al., 2004; Van den Borre et al., 2021).

The end goal of smartphone-based DIN testing is to have a self-administered, easy to comprehend screening test. In line with our study, it was noted in the initial uptake of the SA DIN (*hearZA*) that the median age was 37 years old (Swanepoel, 2018, p. 51). Overall, more younger persons downloaded the initial *hearZA* app compared to older adults (Swanepoel, 2018, p. 51). A reason for this and for future teleaudiology practice is the concern that older adults do not have strong computer literacy skills, which may reflect overall limited uptake of healthcare technologies (Moore et al., 2015; Swanepoel, 2018, p. 51). For this study, the researcher was present to give the participants clear instructions on how to navigate the test. However, the complexity of having two different test phases in the DC8 may compromise the reliability when testing children and older adults who do not readily understand the test procedure. The interpretation of the test instructions for the DSS may differ between listeners, as some may choose the SNR at which they can clearly understand the digits instead of "barely understanding" the digits presented in background noise.

Conclusion

Overall, the reference DIN procedure (D23) provides the most reliable and accurate test result. When implemented as a hearing screening tool, it can be easily accessed using a smartphone device and, on average, requires just over 2 minutes to complete.

The fixed-SNR (DF) DIN is highly efficient and can be easily implemented because the cut-off SNR from the reference DIN can be used. The DC8 procedure shows potential as a time-efficient procedure, although more presentations than used in the current implementation are needed to reach the same accuracy as the D23 procedure. Consequently, the test time will increase. Further the average DC8 SRT is higher than the D23 SRT; thus, a different cut-off SRT must be determined. Finally, the self-selected DIN (DSS) procedure is not useful as a screening test because of its poor test characteristics.

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Appendices

APPENDIX A

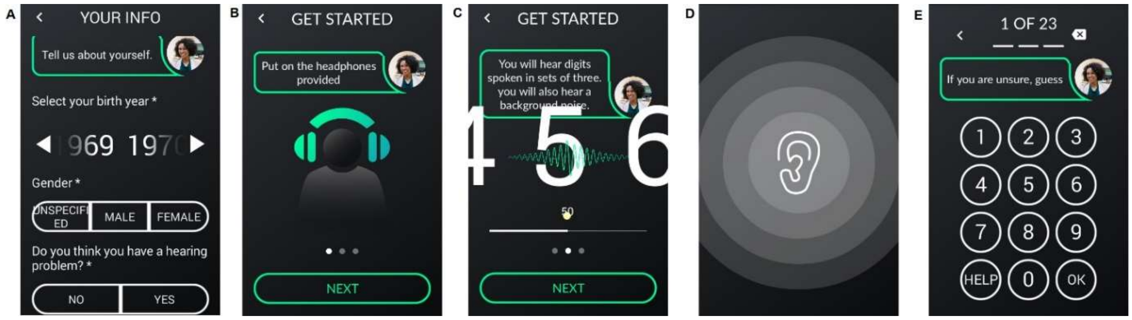

Figure A.1. Onscreen D23 test setup from the application, A) Demographic information of participant, B) Instructions to participant, C) Setting of comfortable listening intensity, D) Three digits presented in background noise, E) Keypad to enter the three digits heard.

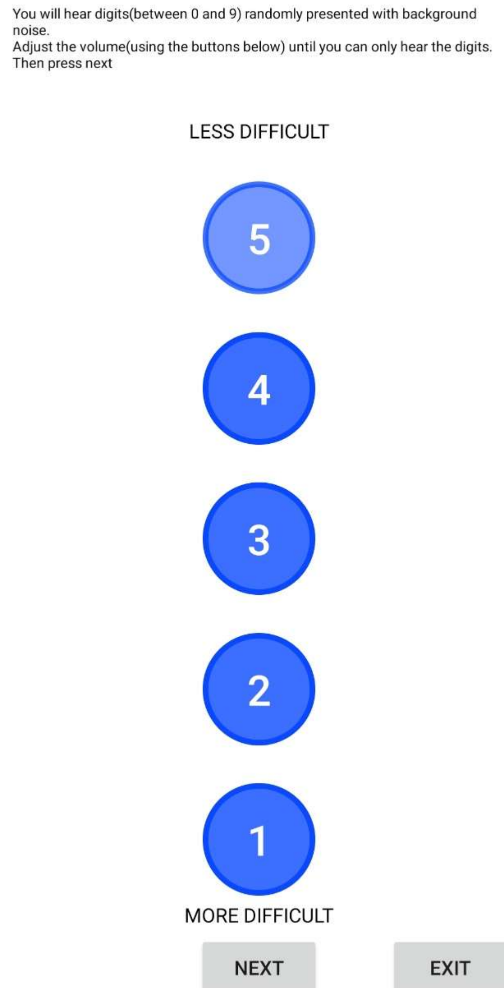

Figure A.2. Onscreen set up of DSS slider

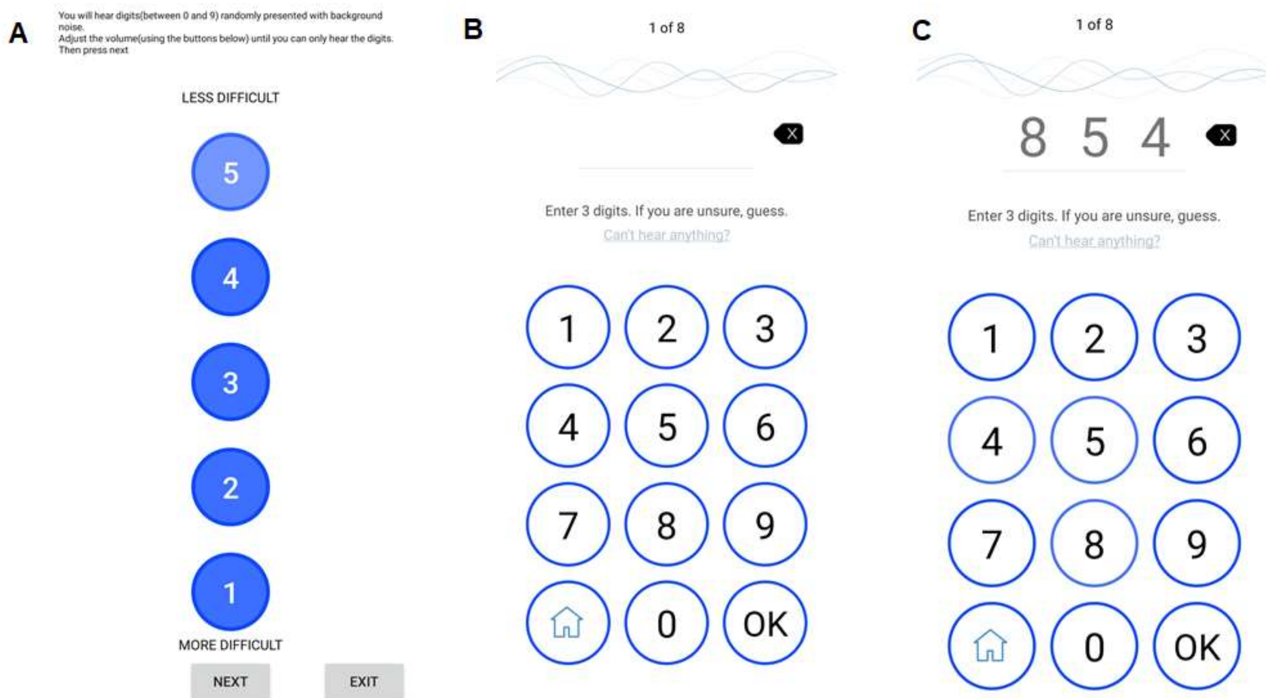

Figure A.3. Onscreen DC8 test setup from the application. Phase one is depicted by A) Participant is instructed adjust the volume using the buttons labelled 1 – 5 until they can only hear the digits, then press next. Phase two: B) Three digits presented in background noise, C) Participants type in the three digits heard.

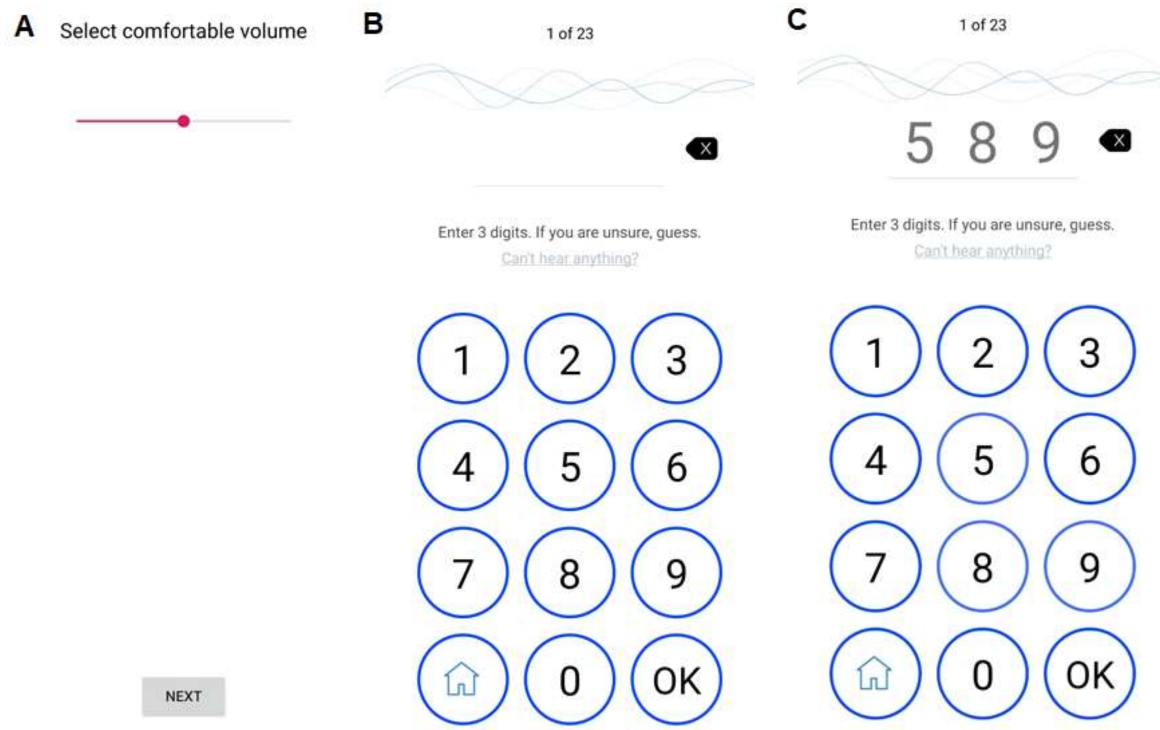

Figure A.4. Onscreen DF test setup from the application. A) Setting of comfortable listening intensity (right to increase, left to decrease), B) Three digits are presented in background noise, C) Participant types in the three digits heard on the keypad provided.

CHAPTER FOUR: DISCUSSION AND CONCLUSION

4.1 Discussion of Results

The DIN test is a popular hearing screening tool that has been developed in various languages and on different platforms to allow for easier access to hearing screening and to promote early intervention of hearing loss (Han et al., 2020; Jansen et al., 2010; Potgieter et al., 2016; Potgieter et al., 2018; Smits et al., 2004; Watson et al., 2012; Zokoll et al., 2012). The formerly established telephone DIN test can now be easily accessed on any device that has internet access (i.e., computers, tablets, or smartphone devices) (Denys et al., 2019; Han et al., 2020; Folmer et al., 2017; Potgieter et al., 2016; Smits et al., 2013). Despite the fact that the DIN test can be readily accessed, the currently validated DIN tests still take several minutes to complete depending on whether both ears are tested sequentially or simultaneously. This research study aimed to investigate novel procedures of the DIN test by altering the methodologies, improving the test efficiency, and investigating the test-retest reliability thereof.

Comparing the test-retest reliability of novel DIN test procedures

As highlighted in the study by Denys et al. (2019), the test reliability must not be compromised when shortening the total test duration (Denys et al., 2019). Thus, the test-retest reliability was carefully considered to determine the potential of the novel DIN test procedures as compared to the gold standard D23 approach.

A Cohen's Kappa test showed a substantial degree of agreement between the test and retest results of the DF approach. To further substantiate, the DF approach showed excellent test characteristics (Figure 3 and Table 2) to achieve whether a person has normal hearing or a hearing impairment by utilizing a pass/fail criterion. When comparing the three novel DIN test procedures, the DF approach had the highest sensitivity and specificity compared to the DC8 and DSS. The DF approach also had the steepest slope from the other two novel DIN tests, demonstrating the smallest region of SRTs where the accuracy of the test in discriminating between pass and fail was poor. Due to the lack of an SRT value in the DF test procedure, assumptions about the degree of hearing loss cannot be determined or compared to SRTs of the other DIN approaches.

Although the test-retest reliability was lower of the DC8 approach compared to the D23, the results showed a much stronger correlation than the DSS (Figure 1). The one major advantage of the DC8 approach compared to the other two novel DIN tests was the ability of the test to alter the SNR presented based on the correctness of previously entered three digits. All previous research studies that developed and validated the DIN test used the adaptive method of testing due to its ability to accurately confirm the SRT by altering the SNR ratio based on the correct or incorrect identification of the triplet pairs (Denys et al., 2019; Han et al., 2020; Jansen et al., 2010; Potgieter et al., 2016; Potgieter et al., 2018; Smits et al., 2004; Watson et al., 2012; Zokoll et al., 2012). The DC8 approach implemented both a subjective and objective method of DIN testing. The participant must first select their perceived SNR, and thereafter the adaptive DIN test begins at the SNR selected. It would be assumed that the final "true" SRT will be reached sooner if the participant correctly selected their SNR. In this study, we found that the DC8 approach had a larger SEM and weaker correlation between the test and retest SRTs when compared to the D23 (Table 1). One possible explanation for this difference can be that participants first selected a high (more positive) SNR which is the first presentation of the adaptive procedure, and thus caused the final SRT to be worse than the actual SRT, as it is based on the average of the total presentations (Smits & Houtgast, 2006). It was determined using the linear relationship between the SEM and inverse square root of the number of presentations that the DC8 procedure would need to increase the number of presentations needed to achieve the same SEM as the D23. The DC8 approach would need approximately 17 presentations to reach the SEM of 1.5 dB SNR from the D23 procedure.

The DSS test procedure was designed to allow for a completely subjective measurement of a participant's SNR. The DSS approach had a significantly higher average SRT compared to the D23 (Table 1). The mean difference between the means of the DSS and D23 was 5.8 dB, which demonstrated that participants overall underestimated their true hearing ability. The average age of participants in this research study was 42 years old, and it was noted that older persons would select higher SNRs compared to younger participants. This is indicative that participants chose more favourable SNRs to attain higher recognition probabilities. Furthermore, the correlation between the DSS and D23 was weaker than the SRT correlation of the DC8 and D23 (Figure 3.2). In addition to comparing the DSS to D23, the results obtained indicated that the DSS approach did not have good test-retest reliability. There was a significant difference between the test-retest results of the DSS approach, resulting in the highest SEM of 3.7 dB SNR compared to the other DIN tests (Table 1). The weak correlation between the SRTs of the DSS and D23, and low test-retest reliability, shows that this study's subjective procedure of selected SNR DIN testing is not viable to be used as a screening test to determine hearing status.

Comparing the time-efficiency of three novel DIN test procedures

This research study implemented antiphasic stimuli in a binaural paradigm for all the DIN test procedures compared to other DIN studies. Binaural presentation already results in more time-efficient DIN testing as both ears are tested simultaneously (De Sousa et al., 2020; Potgieter et al., 2016; Potgieter et al., 2018).

The DC8 approach had the shortest test procedure with an average test duration of 47 seconds (Table 4.1), which showed a 65.4% reduction in test duration compared to the D23. The DC8 approach was much shorter than D23, but it did not have the same test performance as D23. The SEM of the DC8 approach (2.2 dB SNR) was larger than the D23 (1.5 dB SNR), and the difference between the average SRT test and retest means were significantly higher for the DC8 approach. Thus, using the linear relationship between the SEM and inverse square root of the number of presentations, it was calculated that the DC8 would need a total of 17 presentations to reach the same SEM value as D23. Although the DSS approach was a shorter test compared to the D23, with an average of 57 seconds, the test fell short on its accuracy and test-retest reliability.

The DF test procedure had the longest test duration compared to the other two novel DIN test procedures; however, the difference between the total average test duration between the DF and the DC8 was only 18.72 seconds (Table 4.1). The main difference between the DF and DC8 test procedures is the fixed number of total presentations set for the DC8 approach. The DF approach implemented a fixed SNR of the model suggested by Smits (2017). According to Smits (2017), theoretically, the DIN test could be shortened to approximately 8 triplet presentations to determine pass or refer (Smits, 2017). The DF approach had a 45.7% reduction in presentations compared to the D23 (from 23 to 12.5 presentations). Although the average amount of presentations (12.5) was higher than the average 8 presentations found in the simulations by Smits (2017), it should be considered that for this study, the minimum number of presentations that were pre-programmed for the DF test procedure was eight presentations and included two trial conditioning tests.

Table 4.1. Duration (measured in seconds) of the D23 test and three novel DIN test procedures

DIN test procedure	Mean Duration in seconds (SD)		Range (min – max)	
	Initial test	*Retest*	*Initial test*	*Retest*
D23	139.06 (22.70)	132.37 (15.42)	(111.68 - 262.63)	(105.87 - 195.77)
DF	*70.58 (32.32)	65.91 (33.37)	(32.21 - 179.76)	(30.67 - 171.60)
DSS	*66.41 (39.31)	51.76 (35.42)	(13.43 - 215.49)	(14.02 - 260.99)
DC8	*51.86 (33.10)	42.93 (74.59)	(30.75 - 391.30)	(30.81 - 72.45)

Note. D23 = Standard adaptive antiphasic 23-step DIN; DF = Fixed SNR DIN; DSS = Self-selected SNR DIN; DC8 = Combination self-selected SNR and adaptive 8-step DIN; SD = Standard deviation; WSR (*z*) = Wilcoxon signed rank test which displays the median difference (z) between the test and retest conditions
* A Wilcoxon signed-rank test showed a statistically significant difference between the D23 and DF (z = -9.425, $p < 0.001$), DSS (z = -9.15, $p < 0.001$), and DC8 (z = -9.192, $p < 0.001$) respectively.

Overall, all three novel DIN tests had significantly shorter test durations approximating one minute than a 3-minute average of the conventional D23 procedure (De Sousa et al., 2020). Thus, there is the potential of novel DIN tests, the DC8 and DF, to provide a more time efficient test compared to the D23. However, further research is needed to optimize the accuracy and reliability of the tests. The DC8 approach shows the potential to be a more time-efficient DIN, but more presentations would be needed (approximately 17) to reach the accuracy of the D23. The DSS approach was the least accurate and reliable DIN test, and thus is not a suitable screening tool. The conventional D23 procedure had the lowest SEM (1.5 dB SNR), indicating the best test-reliability, The D23 test procedure has also previously shown to be highly correlated with four-frequency PTA (r = 0.88) (De Sousa et al., 2020). This study showed that the D23 could be completed in just over 2 minutes (136 seconds) (Table 4.1).

4.2 Clinical Implications

This research study found that the DIN test has the potential to be reduced to less than one minute, which may prove to be a useful tool to conduct hearing screenings quickly. Using a fixed SNR, this study showed that participants needed a minimum of

8 presentations to determine hearing status. This was in line with the theoretical research paper by Smits (2017), which showed that the DIN could be reduced to 8 presentations. Furthermore, the DC8 approach also shows the potential to become an accurate and reliable hearing screening test if we alter the number of presentations to 17 presentations which as in line with what Denys et al. (2019) reflected in their study. Persons at home can either take the test independently or be screened by clinicians, nurses, or even teachers at schools. Moreover, the use of smartphone DIN testing allows the audiologist to rapidly conduct hearing screenings, and the equipment needed is minimal compared to standard pure tone audiometry. The DIN test is an excellent hearing screening tool in schools and communities because children can easily understand the presentation of numbers especially in South Africa with multilingual and second-language speakers (Wolmarans et al., 2021). By promoting hearing screening using time efficient smartphone technology, persons who refer can obtain the necessary intervention. This all compliments and promotes the key goal of early intervention (Swanepoel, 2019).

The DIN tests used in this study implemented antiphasic stimuli, which allowed for better specificity in determining whether hearing loss is unilateral, conductive, or purely sensorineural (De Sousa et al., 2020). This study showed that the DF and the DC8 could provide a potential DIN hearing test that takes less than one minute to complete, and by using antiphasic binaural stimuli, both ears are tested at the same time. This study highlighted the use of smartphone hearing screening tests, specifically the antiphasic DIN, which can make efficient audiological testing possible in situations such as the COVID-19 pandemic where minimal patient contact is desired.

4.3 Critical Evaluation

A critical evaluation was included to assess the strengths and limitations of the research study.

Strengths of the study

A power analysis was conducted to determine the minimum sample size needed to achieve the desired level of significance ($p < 0.05$). The minimum sample size of 40 males and 40 females was based on the sensitivity and specificity of at least 0.8 and the prevalence of adults with hearing loss in Sub-Saharan Africa (4.55%) (WHO, 2018). This research study managed to recruit a total of 120 participants (46 males, and 74 females). A retest condition for each DIN test allowed for within-subject comparisons and a cross comparison of the results of each DIN test procedure. Furthermore, this research study included a wide range of adults (18 – 80 years old) with an average age of 42. Studies have shown the importance of early detection of hearing loss in persons from the age of 50 (Spiby, 2014; WHO, 2018).

Participants were tested in their homes and in a natural environment which is the usual test environment that persons will use to perform the smartphone DIN testing. This presented results that were ecologically valid. The use of smartphone testing provided an easy and quick setup of equipment, and each DIN test procedure was short test durations (less than two minutes). This allowed for more participants to be tested per day.

A Latin square design was used to counterbalance the eight test conditions (including the retest of the four DIN tests), which ensured that that test order was not biased. The thirty-minute rest period between the test and retest sessions ensured that the participants did not feel fatigued after being tested with four different DIN tests, this further ensured that participants did not lack concentration towards the end of the testing. Although pure tone audiometry was not conducted, inter-test reliability could be determined by comparing the three novel DIN tests to the D23. The D23 test procedure has previously been validated and showed a good correlation with four-frequency PTA (r = 0.88) (De Sousa et al., 2020) and thus was used as the gold standard of comparison in this study.

Limitations of the study

Although this study used a validated DIN test as a gold standard, it should be worth mentioning that the lack of pure tone audiometry thresholds is a study limitation, as true sensitivity and specificity values could not be determined and compared to the novel DIN test procedures. Due to the Covid-19 pandemic and level 5 lockdown regulations in South Africa, access to audiological soundproof booths and equipment could not be used to test participants. When compared to other studies, the SRT values obtained in the novel DIN test procedures could not be correlated to the pure tone audiometry results, which could determine the sensitivity and specificity of the tests (De Sousa et al., 2020; Denys et al., 2019; Potgieter et al., 2018).

4.4 Future Research

The DIN tests investigated in this research study all used antiphasic stimuli, which is proven to be sensitive to unilateral, conductive, or purely sensorineural hearing loss (De Sousa et al., 2020). Future research should utilise the DF and the DC8 in younger test populations, such as children. Children are most vulnerable to conductive hearing loss, and by encouraging a shorter DIN test and implementing smartphone technology, school-based hearing screenings can be made easier as minimal equipment is required and hearing screenings are conducted quickly. This may increase uptake, which promotes early detection and intervention (Swanepoel, 2018). Furthermore, children have a short attention span, and thus by using a quick hearing screening test allows for more accurate and reliable results. By implementing smartphone technology, the DIN test allows for any persons to elicit the hearing screening test and is not dependent on an audiologist. Thus, teachers at schools who have access to the DIN smartphone application can help identify learners at risk of hearing loss (Swanepoel et al., 2019).

When compared to the gold standard D23 test procedure, the DC8 approach fell short in terms of its reliability and accuracy, thus we found that future research should alter the test procedure of the DC8 to 17 presentations instead of eight and be tested against the D23 and pure tone thresholds. Denys et al. (2019) also showed that the DIN could be reduced to 17 presentations to provide accurate and reliable results (Denys et al., 2019). The DF approach should be investigated and validated using the cut-off value from the D23; this can then provide a shortened DIN testing compared to other DIN test paradigms.

For future research it would be highly beneficial to include pure tone audiometry to the research test procedure, as pure tone audiometry can diagnose the degree of hearing and determines a person's true hearing thresholds. This can help to categorize the spread of participants into categories of normal hearing and hearing loss. Furthermore, the four-frequency PTA can be used to compare the SRTs obtained from the novel DIN test procedures and can also be used to determine the sensitivity and specificity of the novel DIN test procedures. In addition to this, this research study used antiphasic stimuli in all four DIN test procedures. Due to its high sensitivity to detect conductive hearing loss, it would be recommended for bone conduction audiometry to be utilized in the future research to determine the presence of conductive hearing loss. This can further be confirmed using tympanometry testing.

4.5 Conclusion

The DIN test has been developed worldwide and in several different languages to provide accessible hearing screening for early identification and intervention. This study investigated three novel DIN test procedures to provide a more time-efficient and reliable DIN test option compared to the gold standard D23 test procedure. These novel DIN test procedures were more time-efficient but did not provide results with reliability on par with the conventional D23 approach. The DF approach was the most time efficient novel DIN test, which can be easily implemented by adjusting the cut-off value. The DC8 approach has potential to be a time-efficient hearing screening tool, although more presentations are needed to reach the accuracy of the D23. Overall, the DSS approach cannot be used as a hearing screening tool due to its poor test characteristics of SRT values that differed significantly from the conventional D23 approach, and it had a longer average test duration compared to the other two novel DIN tests.

CHAPTER FIVE: REFERENCES

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CHAPTER SIX: APPENDICES

6.1 APPENDIX A: Ethical clearance from the Faculty of Humanities

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Humanities 100.
1919 - 2019
Research Ethics Committee

12 February 2020

Dear Miss T Dambha

Project Title:	Improving the Time Efficiency and Reliability of a Digits-in-Noise Test
Researcher:	Miss T Dambha
Supervisor:	Dr F Mahomed Asmail
Department:	Speech Language Path and Aud
Reference number:	16051743 (HUM011/1219)
Degree:	Masters

I have pleasure in informing you that the above application was **approved** by the Research Ethics Committee on 30 January 2020. 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.

We wish you success with the project.

Sincerely

Prof Maxi Schoeman
Deputy Dean: Postgraduate and Research Ethics
Faculty of Humanities
UNIVERSITY OF PRETORIA
e-mail: PGHumanities@up.ac.za

Fakulteit Geesteswetenskappe
Lefapha la Bomotho

6.2 APPENDIX B: Informed consent letter for participant

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

INFORMED CONSENT:

I, Tasneem Dambha, am a final year audiology student at the Department of Speech-Language Pathology and Audiology, University of Pretoria. I would like to invite you to participate in my undergraduate research project titled: *Improving the time efficiency and reliability of a Digits-in-Noise test.* The Digits-in-Noise (DIN) test is an important hearing screening tool that measures a person's ability to detect speech in background noise. The purpose of this research study is to compare the time efficiency and reliability of four versions of the DIN test (three novel DIN tests and the standard adaptive DIN test).

Before you agree to take part in this study you should fully understand what is involved. We ask that you read this form and ask questions should you have any before agreeing to participate in the study.

Volunteers
Male or female individuals who are 18 years and older.

Procedures
The test assessment will be conducted at the Department of Speech-Language Pathology and Audiology, University of Pretoria. The testing will take place in two sessions, and you will be allowed a thirty-minute break in between the sessions:

- Session one (± 25 minutes):
    1. Tympanometry will be conducted to ensure normal middle ear functioning and to rule out a conductive component.

    2. Pure tone audiometry will be conducted using the *HearTest* application to obtain hearing thresholds.

3. South African DIN hearing test

   This will involve listening and identifying three digits in the presence of background noise which will vary in loudness as the test proceeds.

4. Experimental Optimized DIN tests

   This will involve listening and identifying three digits in the presence of background noise. The signal will alter according to the test protocol and will differ for the three versions of the DIN test procedures.

- Session two will take place thirty minutes after the initial test. Testing will include a retest of the four different DIN tests and will take approximately ten minutes.

Rights as a volunteer

Your refusal to participate or withdrawal from the study will not influence or impact any of the services that you are receiving at the Department of Speech-Language Pathology and Audiology.

Confidentiality

All of your personal information will be kept confidential. Confidentiality of results will be ensured throughout the project as an alpha-numeric code (eg. C561) will be allocated to each participant. This code will only be known to the researcher and supervisors.

Risks and benefits

There are no risks involved during this study and you will not be negatively influenced in any way. You will benefit from this study by obtaining a free hearing screening. If necessary, you will be referred for further medical or audiological intervention.

Data storage

The results from your participation will be stored at the Department of Speech-Language Pathology and Audiology at the University of Pretoria for 15 years for research and archiving purposes.

Should you require any additional information, or clarification on the information stated above, please feel free to contact Tasneem Dambha, 082 698 5331.

If you agree to participate in this study, please sign the attached consent form to follow.

Thank you for your interest and participation in this study.

Kind regards,

Tasneem Dambha
Audiology student
Tel: 082 698 5331
Email: tasneem.dambha@gmail.com

Main supervisor: Dr. F Mahomed-Asmail

Co-supervisor: Prof. De Wet Swanepoel

Co-supervisor: Mrs. K DeSousa

PARTICIPANT ID CODE: [ ]

Consent to participate in the following study entitled:

Improving the time efficiency and reliability of a Digits-in-Noise test

Please complete the following:

SURNAME:

NAME:

DATE OF BIRTH:

I, ____________________________________ hereby understand the purpose and procedure of this research study and I agree to participate in the research project titled: *Improving the time efficiency and reliability of a Digits-in-Noise test*. I am aware of any potential risks and benefits. I acknowledge that the results obtained may be used for research purposes. I am aware that participation is voluntary and that I may withdraw my participation from this research project, at any time.

______________________________ ______________

SIGNATURE OF PARTICIPANT DATE

______________________________ ______________

SIGNATURE OF RESEARCHER DATE

6.3 APPENDIX C: Verbal instructions to participants

PROTOCOL FOR DIN RESEARCH STUDY

- ❖ The researcher will first sanitize all equipment before reaching the participant's home.
- ❖ The researcher and participant will first sanitize their hands using a 70% alcohol sanitizer.
- ❖ Both the researcher and participant will always have on their face masks.
- ❖ The researcher will maintain a safe distance from the participant.
- ❖ The participant volunteers to participate at his/her own risk.
- ❖ The participant can stop the research testing at any time.
- ❖ The participant will be made aware that the two tests that was initially included in the study, tympanometry and pure tone testing, had to be removed due to the inaccessible equipment during Covid-19 pandemic.
- ❖ The researcher will explain the test procedure of each DIN testing before the participant can start with the test, if the participant is not sure, the researcher re-explains and uses the app screens to show the participant what to look for or which buttons needs to be pressed.
- ❖ Once the participant has completed his/her testing, all equipment will be sanitized by the researcher before leaving.

The following information will be verbally instructed to the participants for the three novel DIN tests:

<u>The DSS test</u>

1. You will hear random numbers in the presence of background noise.
2. Please select a number, ranging from 1 – 5 on this slider, to indicate where you can barely hear the digits with the noise. Number 1 is the loudest, and number 5 is the softest level.
3. Once you have selected the number, please press ***Next***.
4. There are four test sliders in total.

The DC8 test

1. The test begins with a slider ranging from 1 – 5, where number 1 is the loudest and number 5 is the softest level.
2. You will hear random numbers in the presence of background noise.
3. Please select a number where you can barely hear the digits with the noise.
4. Once you have selected the number, please press ***Next***.
5. You will then see a screen with a keypad.
6. You will hear three numbers and background noise.
7. Please type in the three numbers that you hear, if you are unsure, please guess.
8. Click the ***Next*** button once you have typed in the three numbers.

The DF test

1. First you will need to adjust the volume to where you can hear the numbers clearly, if you move to the left it will become softer, and to the right it will become louder.
2. Once you have selected your comfortable level, please press ***Next***.
3. You will then see a screen with a keypad.
4. You will hear three numbers and background noise.
5. Please type in the three numbers that you hear, if you are unsure, please guess.
6. Click the Next button once you have typed in the three numbers.

6.4 APPENDIX D: ISO 389-1 checklist

Questionnaire for hearing tests

1.	**Name:**		**Date of birth:** **Gender:**
2.	**Have you ever had trouble with your hearing (for example, infections, ear noises, drainage, etc.?)**		
	Yes	No	If yes, please detail:
3.	**Have you ever had an operation in your ear?**		
	Yes	No	If yes, please detail:
4.	**Have you ever taken drugs, tablets or been given injections that affected your hearing?**		
	Yes	No	
5.	**Have you worked for several years in a place that was very noisy, i.e. where it was difficult to communicate?**		
	Yes	No	If yes, please detail:
6.	**Did you wear any hearing protector at that time?**		
	Yes	No	
7.	**Do you attend pop/rock concerts or discotheques?**		
	Never	Once a year	More than once a year
8.	**Do you play any musical instrument?**		
	Yes	No	If yes, please specify:
9.	**Do you listen to personal wearable players?**		
	Never	Less than 2 hours per week	More than 2 hours per week
10.	**Have you been exposed to any loud sounds from, e.g. motorbikes, chain-saws, gunfire, fire-crackers or explosions?**		
	Yes	No	If yes, what kind and how often:
11.	**Does/did anyone in your immediate family have a hearing disorder?**		
	Yes	No	If yes, please specify:
12.	**Have you ever had a hearing test before?**		
	Yes	No	If yes, when and where:
I agree to the storage of my data and their use in connection with the threshold measurements			
Date:			Signature:

6.5 APPENDIX E: Data collection form

RESEARCH DATA COLLECTION SHEET

"Investigating the time-efficiency and reliability of a Digits-in-Noise test"

Name: ___________________ Participant number: [ ]

Date: ____________

DOB: ___________

Native Language: _____________

TYMPANOMETRY

	Left ear	**Right ear**
Type		
Middle ear pressure (daPa)		
Static Compliance (ml)		
Ear canal volume (ml)		

PURE TONE THRESHOLDS:

	Left ear (dB)	**Right ear (dB)**
500Hz		
1000Hz		
2000Hz		
4000Hz		
Pure tone average (PTA)		

STANDARD DIGITS-IN-NOISE TEST:

	SNR	Time taken to complete test (msec)
Test		
Retest		

OPTIMIZED TEST 1 – FIXED SNR DIN TEST:

	PASS/REFER	Time taken to complete test (msec)
Test		
Retest		

OPTIMIZED TEST 2 – SELF-SELECTED DIN TEST:

	SNR	Time taken to complete test (msec)
Test		
Retest		

OPTIMIZED TEST 3 – COMBINATION 8-STEP DIN TEST:

	SNR	Time taken to complete test (msec)
Test		
Retest		

Additional comments:

6.6 APPENDIX F: Referral form

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology and Audiology

Date: ________________

To whom it may concern,

A hearing screening was conducted on _____________ 20__ on the following patient, ________________________at the Department of Speech-Language Pathology and Audiology, at the University of Pretoria.

During the evaluation it was noted that the patient should be referred for further assessment. For this reason, we would like to refer him/her to:

Professional person:	
	Audiologist
	Ear-nose-and-throat specialist/ General Practitioner

Reason:	
	Referral on hearing screening: Further hearing evaluation recommended
	Excessive wax in ear
	Negative pressure in the middle ear
	Other

Thank you for assessing and treating the patient.

____

Postgraduate student:

____

Prof. De Wet Swanepoel, Dr. F Mahomed-Asmail, Mrs. K De Sousa