Remote monitoring of adult cochlear implant recipients using digits-in-noise self-testing

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Conflict of interest:
The relationship between De Wet Swanepoel and the hearX Group includes equity, consulting, and potential royalties. All other authors have declared that no competing interests existed at the time of publication.

Abstract

Purpose: The COVID-19 pandemic has accelerated the uptake and scope of telehealth. This study determined the accuracy and reliability of a smartphone digits-in-noise (DIN) test when conducted by adult CI recipients in a simulated home environment compared to a clinic setup. Perceptions of remote monitoring using speech-in-noise (SIN) testing were also explored.

Method: Thirty-three adult CI recipients between 18 and 78 years of age (M = 46.7, SD = ±20.4) conducted the DIN test in a simulated home environment and a clinic setup. Test-retest reliability across the two environments and comparisons between test settings were evaluated. A survey explored the perceptions of adult CI recipients regarding remote monitoring and use of the DIN self-test.

Results: Mean aided SRTs in the clinic and simulated home environment test conditions and clinic and simulated home environment retest conditions did not differ significantly. Mean test-retest SRTs in the clinic and simulated home environment were significantly different ($p < .05$). High intraclass correlation coefficient (ICC) and low standard error of measurement (SEM) scores reflected good and excellent reliability between test-retest measures and between clinic and simulated home environment measures. Most participants were positive about the possibility of using the DIN test at home to self-assess speech perception although some test adjustments such as including training items and a less adverse starting SNR may be required.

Conclusions: Adult CI recipients can use the smartphone DIN test to self-assess aided speech-in-noise performance in a home environment with accuracy and reliability relatively similar to clinic testing.

Introduction

The COVID-19 pandemic has exceeded 251 million confirmed cases in less than two years, with more than 5 million deaths globally (Dong et al., 2020). As a result, governments and authorities were forced to implement preventive measures such as social distancing, lockdowns, self-isolation, and quarantine to contain the spread of the virus (Shah et al., 2020). The need for physical distancing and the communicable nature of COVID-19 has led to a significant increase in demand for telehealth options (Blandford et al., 2020). COVID-19 has compelled healthcare systems, including the

audiology industry (Swanepoel & Hall, 2020), to be innovative in the way in which services are delivered to patients (Cassar et al., 2021).

Telehealth has been recommended to overcome some of the current audiological service delivery challenges amid the pandemic (Swanepoel & Hall, 2020; Manchaiah et al., 2021). Traditionally the goal of telemedicine was to enable individuals who reside in underserved or remote regions to access medical services and care. However, the target audience of telemedicine has seen a dramatic change during COVID-19, with safety becoming the primary driver (Zeng, 2020). The technology-driven nature of audiology regarding hearing assessment and intervention further offered unique opportunities to deliver remote care (Swanepoel & Hall, 2020). Telefitting of cochlear implant (CI) devices and hearing aids (HAs) have received limited attention until the COVID-19 pandemic (Swanepoel & Hall, 2010; Zeng, 2020), but the feasibility thereof has been described in several studies (Ramos et al., 2009; Wersag et al., 2010; Eikelboom et al., 2014; Schepers et al., 2019; Luryi et al., 2020; Kim et al., 2021). Most recently, a study by Meeuws et al. (2020) demonstrated that with audiologist supervision, it is possible to remotely fit CIs when supported by artificial intelligence.

Telehealth has been used with great success with CI recipients in terms of CI device programming (Ramos et al., 2009; McElveen et al., 2010; Rodríguez et al., 2010; Wasowski et al., 2010; Eikelboom et al., 2014; Samuel et al., 2014; Slager et al., 2019), intraoperative testing (Shapiro et al., 2008) and objective tests such as electrode impedance testing and the measurement of electrically evoked compound action potential (ECAP) thresholds (Goehring et al., 2012; Hughes et al., 2012). Studies have demonstrated that remote fitting of CI devices is safe, effective, and accepted by most CI recipients and health professionals (Ramos et al., 2009; McElveen et al., 2010;

Wesarg et al., 2010; Eikelboom et al., 2014; Kuzovkov et al., 2014; Samuel et al., 2014; Schepers et al., 2019). Slager et al. (2019) confirmed that the amount of time required to complete remote versus in-office CI device programming is similar.

Previous studies have found that CI recipients' and audiologists' experience using telemedicine services is highly positive (Rodríguez et al., 2010; Swanepoel & Hall, 2010; Wasowski et al., 2010; Wesarg et al., 2010; Eikelboom et al., 2014; Kuzovkov et al., 2014; Goehring & Hughes, 2017; Slager et al., 2019; Eikelboom et al., 2021). According to Cullington et al. (2016), adult CI recipients who wear their devices during every waking hour are open to the idea of making telehealth part of their device management routine. Similarly, a study by Cullington and Aidi (2017) indicated that most adult CI recipients could administer a remote speech perception test in a simulated home environment and indicated a preference for the above clinic tests.

Remote CI device programming and testing have demonstrated feasibility and preference in some cases, but certain CI recipients may still need or prefer the clinic. During initial CI device activation, clinicians usually determine magnet strength, measure the length of the speech processor cable, explain CI device use and demonstrate how batteries should be changed (Buckman & Fitzharris, 2020). These interactions require the clinician and CI recipient to be at the same location (Buckman & Fitzharris, 2020). In addition, as part of the audiological protocol, CI recipients' speech perception abilities are routinely assessed at the clinic, as improved speech understanding is usually the primary goal of cochlear implantation (Cullington & Aidi, 2017).

Speech-in-noise (SIN) tests are clinically valuable for CI recipients as it allows the monitoring, comparison, and adjustment of CI settings (Smits et al., 2013; Kaandorp et

al., 2015). Recently, Davidson et al. (2021) demonstrated a direct relationship between SIN tests and increased hearing aid (HA) satisfaction. Stimuli routinely used during speech perception testing for adult CI recipients include sentences, monosyllabic words or digits presented through the sound field in quiet (de Graaff et al., 2018) or in the presence of background noise (Brown et al., 2019). As a SIN test, the Digit-in-Noise (DIN) test has an essential role in the counselling and follow-up of CI recipients during rehabilitation (Smits et al., 2013; Kaandorp et al., 2015). In a recent study from Maruthurkkara et al. (2021), adult CI recipients successfully used the DIN as part of the *Remote Check* application to self-assess hearing in a home environment.

The DIN test is a widely used and preferred test due to its reliability, validity, user-friendly self-test applications, time-efficiency and low linguistic demands (Kaandorp et al., 2015; Cullington & Agyemang-Prempeh, 2017; Cullington & Aidi, 2017; Potgieter et al., 2018; Swanepoel et al., 2019; De Sousa et al., 2020). The World Health Organization has also adopted this test approach for their widely used smartphone-based self-test application (hearWHO app) for hearing screening (Swanepoel et al., 2019). The DIN test is highly correlated with sentence-in-noise tests and has a low measurement error (Smits et al., 2013) and has therefore been successfully applied to HA and CI recipients in evaluating hearing ability (Kaandorp et al., 2015; Cullington & Agyemang-Prempeh, 2017; Cullington & Aidi, 2017; Van den Borre et al., 2021). The DIN test has also been shown to produce robust results across various sound field transducers (Brown et al., 2019) using a smartphone DIN test, which makes home-based monitoring possible.

We investigated if the DIN test can be used by CI recipients as an alternative speech test. The DIN test is a self-test that can be administered at home and test results can give an indication if face-to-face device programming is required. The need for a self-

test arose during the COVID-19 pandemic when alternative ways to reach patients were explored. The objective of this study was to describe the accuracy and reliability of an aided DIN test for CI recipients to evaluate SIN performance in a simulated home environment. A secondary objective was to explore adult CI recipients' perceptions of remote monitoring using SIN testing.

Method and materials

Institutional review board approval from the Research Ethics Committee of the University of Pretoria (HUM016/0721) was obtained prior to data analysis.

Research design

As a result of the impact of the COVID-19 pandemic on hearing health care service delivery, the Pretoria Cochlear Implant Unit (PCIU) explored alternative means to serve their CI patients. Hence, SIN testing using the DIN test was added to the standard routine audiological protocol for adult CI recipients. This study investigated DIN test outcomes by employing an explorative, within-subjects repeated measures design. The adapted PCIU audiological protocol involved the DIN test in two listening environments, namely a simulated home environment and a clinic setup, which was the study's first phase. The DIN test was administered twice in each condition to evaluate test-retest reliability. The test environments were counterbalanced to avoid first-order carryover effects and control the two listening environments (Brown et al., 2019).

The second phase of the study included a survey completed by the adult CI recipients to investigate their perceptions of remote monitoring using the DIN test. The DIN test and survey results provided information about remote CI monitoring. This already obtained DIN test and survey data were analysed and reported retrospectively.

Participants

Thirty-three adult CI recipients with a mean age of 46.7 years (SD = ±20.4; range: 18–78 years) who attended routine postoperative CI device programming/ follow-up appointments at the PCIU between April 2021 and August 2021 were included. CI recipients were pre- or postlingually deafened and unilateral, bilateral, or bimodal CI users. None of the participants made use of electro-acoustic stimulation (EAS) systems and all were oral communicators. Adult CI recipients with single-sided deafness were excluded. The participants were English first-language speakers (21.2%) and English second language users (78.8%). Table 1 describes the sample population.

Table 1. Characteristics of adult cochlear implant recipients (n=33)

	All participants % (n)
Onset of hearing loss	
Prelingual deafness	39.4% (13)
Postlingual deafness	60.6% (20)
Age at study (years)	
Mean (SD)	46.7 (20.4)
Range	18 - 78
Gender	
Male	42.4% (14)
Female	57.6% (19)
Hearing device(s)	
Bilateral cochlear implants	27.3% (9)
Unilateral cochlear implant[1]	42.4% (14)
Bimodal[2]	30.3% (10)
Age at onset of severe - profound hearing loss (years)	
Mean (SD)	21.8 (23.0)
Range	0 - 61
Duration of severe - profound hearing loss prior to cochlear implantation[3] (years)	
Mean (SD)	11.3 (11.8)
Range	0.25 - 44
CI experience[4] (years)	
Mean (SD)	10.9 (8.0)
Range	0.3 - 28
Implant type	
Cochlear	78.8% (26)
MedEl	18.2% (6)
Advanced Bionics	3% (1)
Speech processor model	
Cochlear Nucleus 7 (CP 1000)	48.5% (16)
Cochlear Nucleus 6 (CP910 and CP920)	18.2% (6)
Cochlear Nucleus 5 (CP810)	3% (1)
Kanso 2	9.1% (3)
Medel Sonnet 2	12.1% (4)
Medel Rondo 2	6.1% (2)
Naida CI Q70 (Advanced Bionics)	3% (1)
DIN testing starting environment	
Clinic	48.5% (16)
Simulated home environment	51.5% (17)

[1] Not using hearing aid in non-implanted ear
[2] Unilateral cochlear implant, using hearing aid in non-implanted ear
[3] Time-lapse (years) between onset of (severe) hearing loss and (first) cochlear implantation
[4] Time-lapse between activation of (first) CI device and DIN testing (data collection)

Data collection material and equipment

Phase I – Cochlear implant aided DIN test accuracy and reliability in a simulated home environment

Smartphone DIN test

A binaural diotic (in-phase) stimulus paradigm with South African English digits was used on the smartphone (Android OS) DIN test research application (hearDigits™, hearX Group, South Africa) (Potgieter et al., 2016, 2018). During this test, three bi- and monosyllabic digits (0-9) were presented in the presence of speech-weighted masking noise from a list of 120 available digit triplets (Potgieter et al., 2016, 2018). The triplet is assembled by the program by concatenating the appropriate digits with 500 ms silent intervals at the beginning and end of every triplet. The following digits are presented in 200 ms silences with 100 ms jitter in between (Potgieter et al., 2016). An adaptive signal-to-noise ratio (SNR) one-up one-down procedure was used (4 dB for the first 3 steps, thereafter, continuing in 2 dB steps), which measured the SNR at which the listener correctly identified 50% of the digit triplets. During the first three steps, incorrect responses resulted in a 2 dB SNR increase per step, and correct responses decreased the SNR by 4 dB per step. Only if all the digits were entered correctly was the digit triplet regarded as correct. Each DIN test contained 23 combinations of three digits (digit triplets), and the last 19 SNRs were averaged to work out the Speech Reception Threshold (SRT) (De Sousa et al., 2020). A lower SRT (dB SNR) score indicated a better speech recognition in noise result and a higher SRT (dB SNR) score referred to poorer speech recognition in noise (Cullington & Agyemang-Prempeh, 2017).

Test environments and setup

DIN testing in the simulated home environment was administered in an office at the Department of Speech-Language Pathology and Audiology, University of Pretoria, South Africa. The office was in the same building where the PCIU is situated. This office was selected to imitate a home environment with background noise, reverberation, and some distraction. Participants were seated at a table, with the Bluetooth speaker positioned one meter between eye-level and 45° from eye-level on the table (Figure 1B). A portable JBL Flip 4 speaker was connected to the Samsung Trend Neo smartphone through a Bluetooth connection to present the DIN in the sound field. An audiologist assisted with the test setup, but the participant completed the test using the smartphone application independently and without any assistance.

In the clinic setup, DIN testing was conducted in the PCIU audiometric booth through a single loudspeaker (ADAM A7X). The Samsung smartphone was connected to the Interacoustics AC40 clinical audiometer by a 3.5 mm x 5-metre audio cable. The length of the cable allowed the smartphone to reach the participant seated in the audio booth. In the audio booth, participants were positioned at 0° azimuth and one metre from the loudspeaker (see Figure 1A). The audiologist assisted with the test setup, but each participant held the smartphone to type in their response independently and without any assistance.

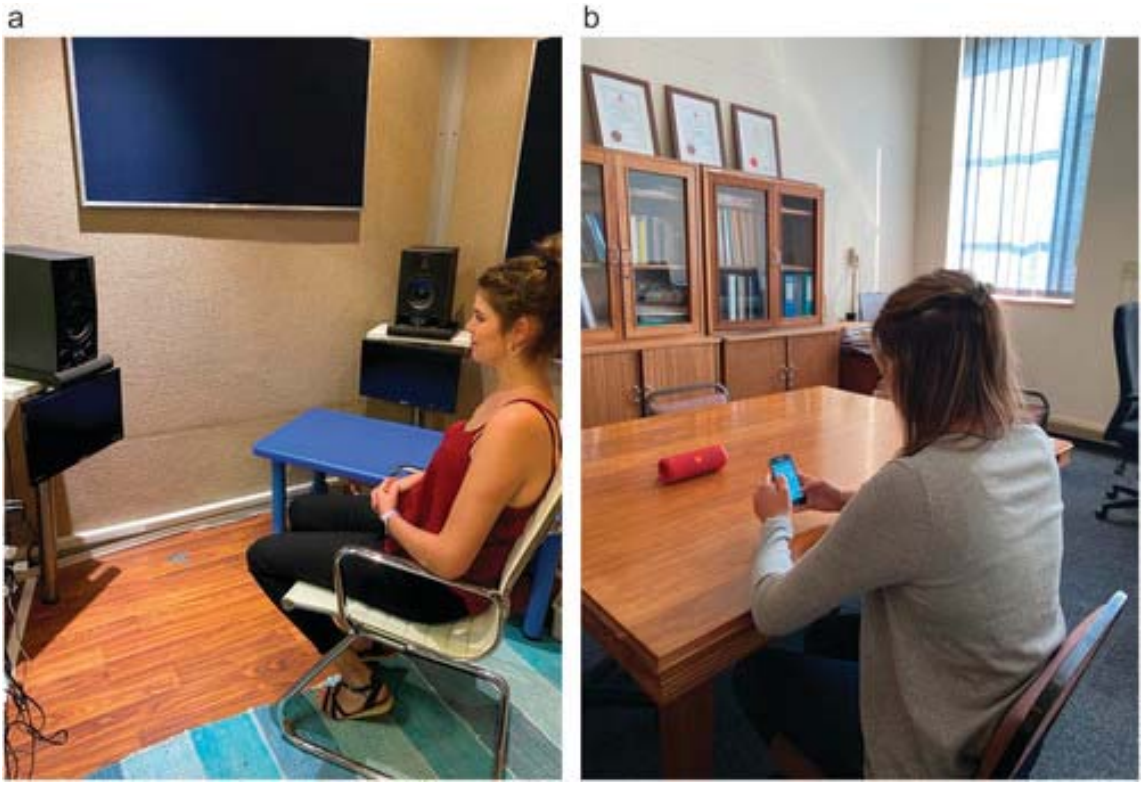

Figure 1. Participant and speaker positioning during (A) clinic setup and (B) simulated home environment digits-in-noise testing.

Phase II – Survey on perceptions of remote monitoring

Perceptions of remote monitoring survey

A self-administered survey was developed for this study to explore adult CI recipients' perceptions of remote monitoring (Supplemental material 1). Items from several existing surveys were considered, adapted, and used to compile the survey used in this study (Cullington & Agyemang-Prempeh, 2017; Cullington & Aidi, 2017; de Graaff et al., 2019; Ayas et al., 2020). Adaptations were made to ensure the questions encompass the COVID-19 pandemic theme and refers to the specific smartphone DIN test utilised in this study.

The survey determined how participants experience the DIN test in the simulated home environment. The survey included a total of ten questions. In addition to the four questions that related to the DIN testing, five questions related to the COVID-19 pandemic and the possibility to receive CI related services at home. A five-point Likert scale was used as a rating scale (from strongly agree to strongly disagree) in which participants rated their level of agreement to the nine statements. Participants were also provided with one open-ended question to comment on their experiences of the DIN test.

Data collection procedures

Clinical audiologists at the PCIU identified adult CI recipients who attended routine postoperative CI follow-up appointments at the PCIU that adhered to the inclusion criteria. After the audiologist completed routine CI device programming and postoperative audiological testing in the audiometric booth (aided pure tone and speech perception testing), DIN testing proceeded.

In the case of bilateral CI users, CI recipients were required to use their better hearing (dominant) ear for testing purposes. In the case of bimodal CI users, CI recipients were required to remove the hearing aid in the non-implanted ear and only use their CI's speech processor during testing (Cullington & Aidi, 2017; Philips et al., 2018; Kropp et al., 2020). CI recipients were instructed to use the program and volume setting of their CI speech processor that they use in everyday situations.

In the clinic setup, the Samsung smartphone was connected to the audiometer to start with the South African DIN test in the sound field. Adult CI recipients were seated one metre from the loudspeaker at 0° azimuth (Figure 1A).

For both test environments, once the application (hearDigits™, hearX Group, South Africa) was opened, the audiologist was required to type in the CI recipient's name, surname, year of birth, code, and home language. The following DIN test application screen required participants to rate their English proficiency on a scale of 1-10, in line with the study by Potgieter et al. (2018). Thereafter, a three-step tutorial screen provided instructions on how the application works. The audiologist also provided uniform and consistent verbal instructions informing each CI recipient that the digits will be presented in the presence of background noise, which the CI recipient should try to ignore. The CI recipient was made aware that the test will start immediately, is adaptive (i.e., the noise will become louder and softer), requires careful listening and might be perceived as difficult. In both test environments, three practice digits (e.g., 5,3,1) read by a female voice in English were presented without the presence of background noise. The CI recipients were asked to indicate when the practice digits were perceived at a comfortable listening level in the clinic set-up. The audiologist adjusted the intensity on the audiometer (in dBHL) until a comfortable listening level was reached. Once a comfortable listening level was reached, the audiologist tapped on the "NEXT" icon on the application screen for testing to commence. The three digits without background noise were presented through the Bluetooth speaker in the simulated home environment to allow CI recipients to select a comfortable listening level. This was achieved by CI recipients dragging the volume control on the application screen to a preferable level. CI recipients tapped on the "NEXT" icon on the application screen for testing to commence as soon as a comfortable listening level was reached.

The CI recipient was required to listen and identify three digits in the presence of broadband speech-shaped noise (Potgieter et al., 2016; Potgieter et al., 2018). Once

identified, the CI recipient was required to type the three digits into the digits-in-noise application (hearDigits™, hearX Group, South Africa). In both environments the CI recipients were required to enter the digits in the keypad themselves. If CI recipients were unsure of the digits, they were instructed to guess.

After performing the DIN test in both environments, CI recipients were asked to complete a hard copy survey about their perceptions of remote monitoring.

Data analysis

Retrospective DIN test results were retrieved from the research Android OS application and retrospective survey data from the hard copy surveys. DIN test and survey data were coded into MS Excel 2013 and then analysed using the Statistical Package for the Social Sciences Version 26.0 (IBM SPSS, Chicago, Illinois) (SPSS). SPSS was used to generate the graphs demonstrating survey data. DIN testing data (SNRs), data from clinical files (demographic information) and survey data were captured on the Excel sheets. Descriptive statistics were used to define the sample population (Table 1). Means, average SNR, and standard deviations of both environments in the test and retest stages of the study were analysed using descriptive statistics. The Shapiro–Wilk's normality test ($p < 0.05$) indicated that the data were not normally distributed. Therefore, non-parametric analysis was used to compare the mean SNRs between the clinic and simulated home environment in the test and retest stages of the study. A Wilcoxon signed-rank test was conducted to verify whether there was a statistically significant mean difference between the SNRs when comparing the initial test to the retest ($p < 0.05$) in each environment and when comparing the SNRs between the two

environments. A two-way mixed-effects model was used to assess reliability using the intraclass correlation coefficient (ICC). The ICC and standard error of measurement (SEM) also reflected the degree of agreement and degree of correlation amongst measurements.

Results

Cochlear implant aided DIN test accuracy and reliability in a simulated home environment

All participants completed the DIN test twice in both test environments, with the test environments counterbalanced (Table 2). There were no significant mean SRT differences for either the initial clinic and simulated home test ($p = .254$; $z = 1.14$), or between the clinic and simulated home retest conditions ($p = .224$; $z = 1.22$). However, there was a statistically significant improvement between the clinic test and retest of 3.2 dB SNR ($p = .037$) as well as an improvement of 1.8 dB SNR ($p = .014$) between the simulated home environment test-retest (Figure 2). There were five outliers (four in the clinic and one in the simulated home environment) who performed poorly on the initial test instead of the retest in each condition (Figure 3). The SEM (Table 2) indicated the agreement between measures with lowest SEM for simulated home test-retest. The ICCs in both the clinic and simulated home environment test-retest measures were high (Table 2), reflecting good and excellent reliability, respectively (Portney & Watkins, 2000). In addition, there was good to excellent agreement (Portney & Watkins, 2000) between the initial test of the clinic and simulated home environment, as well as between the clinic and simulated home retests (Table 2).

Table 2. Characteristics of digit-in-noise speech recognition thresholds and comparisons between clinic and home test and test-retest (n=33). ***IQR – interquartile range; ICC – intraclass correlation coefficient; SEM – standard error of measurement***

	Mean (SD)	Range	IQR	ICC (95% CI)	SEM
DIN scores					
Clinic #1	7.6 (11.1)	-9.4 – 22.5	22.8	-	-
Clinic #2	4.4 (10.2)	-7.8 – 22.5	17.7	-	-
Home #1	8.2 (10.9)	-8.8 – 22.5	22.5	-	-
Home #2	6.4 (10.5)	-7.4 – 22.3	20.7	-	-
DIN comparisons (difference scores)					
Clinic test-retest	3.2 (7.0)	-7.8 – 22.3	8.7	0.861 (0.694 - 0.934)	1.2
Home test-retest	1.8 (4.0)	-8.4 – 10.8	4.8	0.957 (0.900 - 0.980)	0.7
Clinic #1 vs Home #1	7.9 (10.7)	-7.7 – 22.2	23.7	0.957 (0.912 - 0.979)	1.9
Clinic #2 vs Home #2	5.4 (9.6)	-7.2 – 22.2	16.7	0.850 (0.691 - 0.926)	1.7

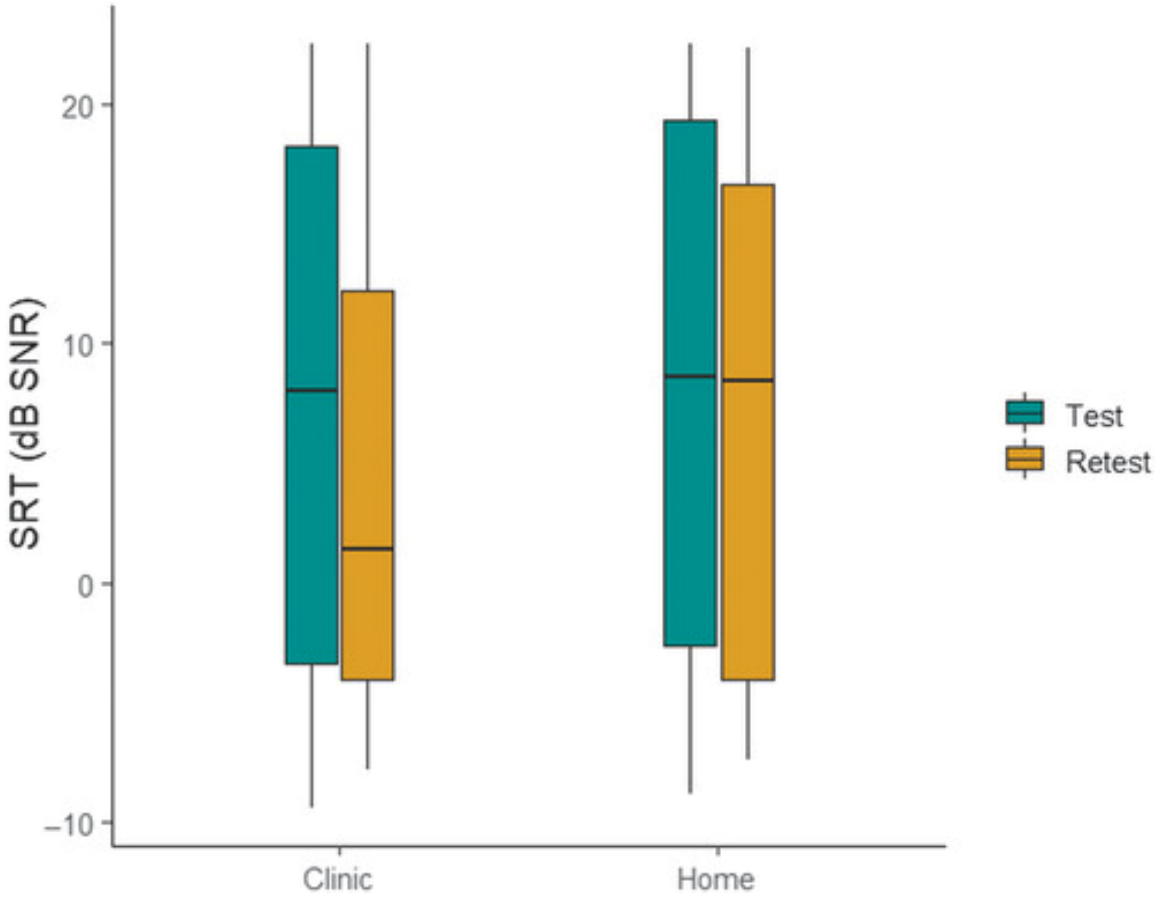

Figure 2. Box plots representing test versus retest scores measured in dB signal-to-noise ratio (SNR) of the digits-in-noise (DIN) test conducted in the clinic environment (left) and in the simulated home environment (right). The box displays the portion of the distribution falling between the lower and upper quartiles (25th and 75th percentiles). The median is represented by the horizontal line. The vertical lines outside the box (whiskers) include the smallest and largest values that are not classified as extreme values or outliers. A lower speech reception threshold (SRT; dB SNR) score represents a better result and a higher SRT (dB SNR) score represents a poorer result.

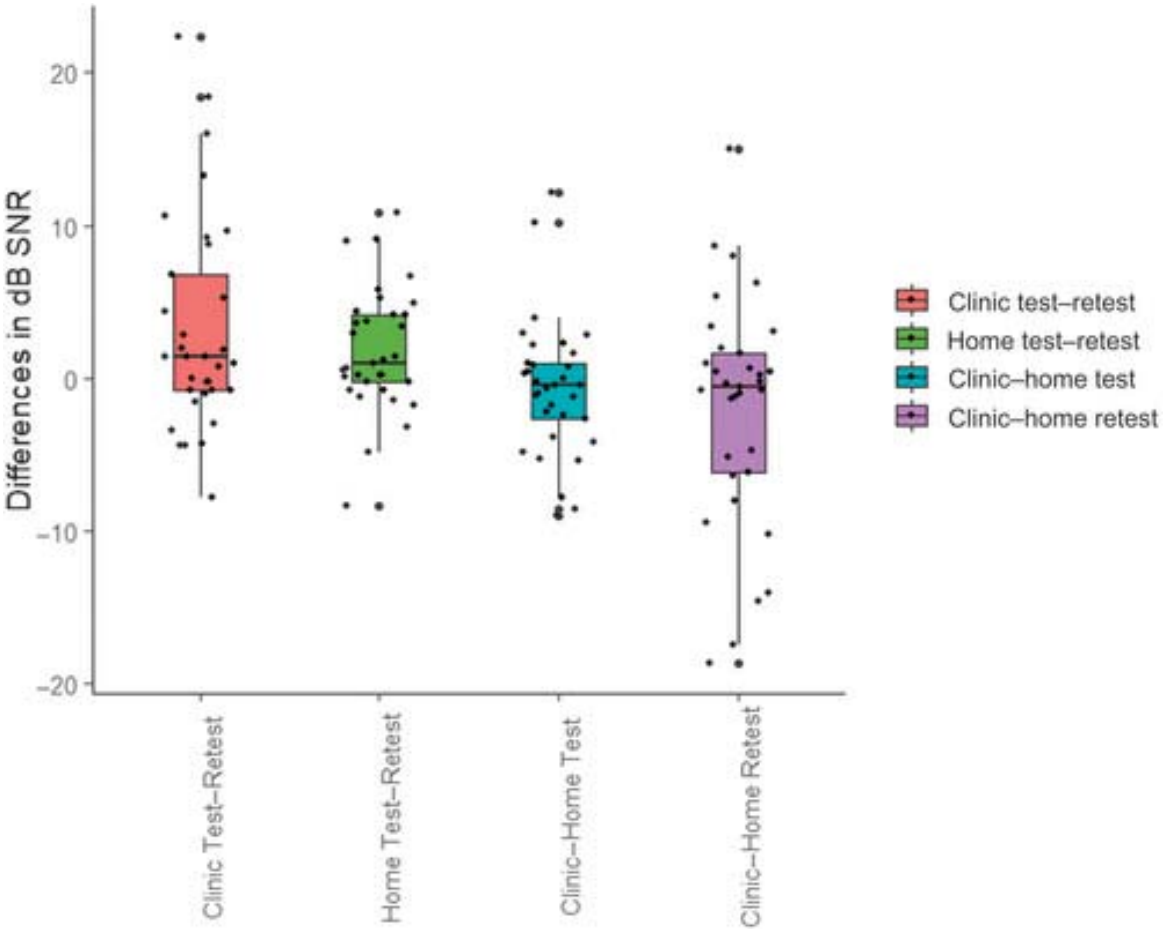

Figure 3. Box plots indicating the intrasubject variability in dB SNR within (left and second from left) and between (right and second from right) the test environments. The dots above and below the box plots are deemed as outliers by SPSS due to its positions more than 1.5 box lengths below the lower quartile and above the upper quartile. A lower SRT (dB SNR) score represents a better result and a higher SRT (dB SNR) score represents a poorer result.

No significant difference between the prelingually deafened and postlingually deafened groups were identified in the simulated home environment (p = .196) and in the clinic (p = .182). The mean test duration in the clinic was 3.49 minutes (1.42 SD) and in the simulated home environment 3.48 minutes (1.47 SD).

Perceptions of remote monitoring

All participants (n=33) agreed or strongly agreed that they could perform the DIN test in both DIN test environments. Most participants agreed or strongly agreed (90.9%) that they would feel comfortable using the DIN test to self-test speech perception abilities with their CI at home and responded positively (78.7%) to the possibility of receiving regular CI services from their home. Most participants however agreed or strongly agreed (93.9%) that they were comfortable attending a face-to-face appointment with their audiologist during COVID-19 pandemic. Most participants agreed or strongly agreed (81.9%) that they struggle to hear speech in the presence of background noise with their CI(s), but they agreed or strongly agreed (78.8%) that the quality of the speech testing conducted in the simulated home environment was similar to the quality of the speech testing conducted in the clinical environment (Figure 4 and 5).

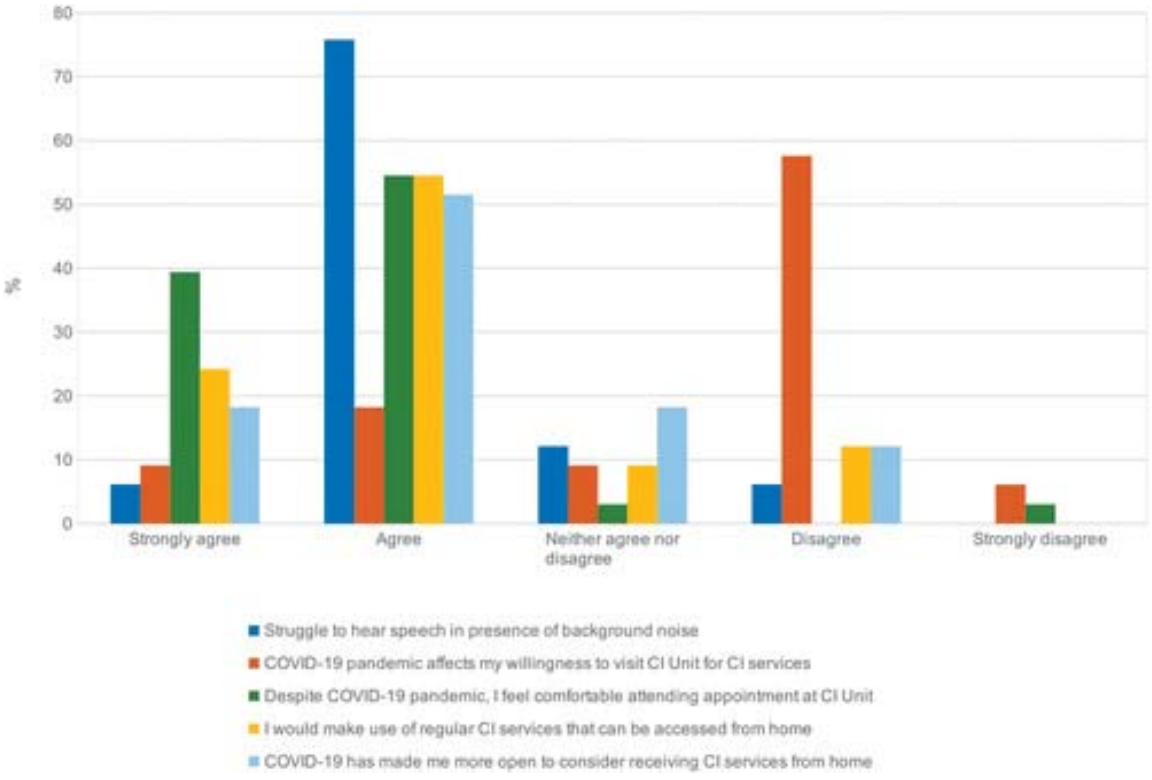

Figure 4. Results of survey items related to remote services for cochlear implant (CI) patients (*N* = 33).

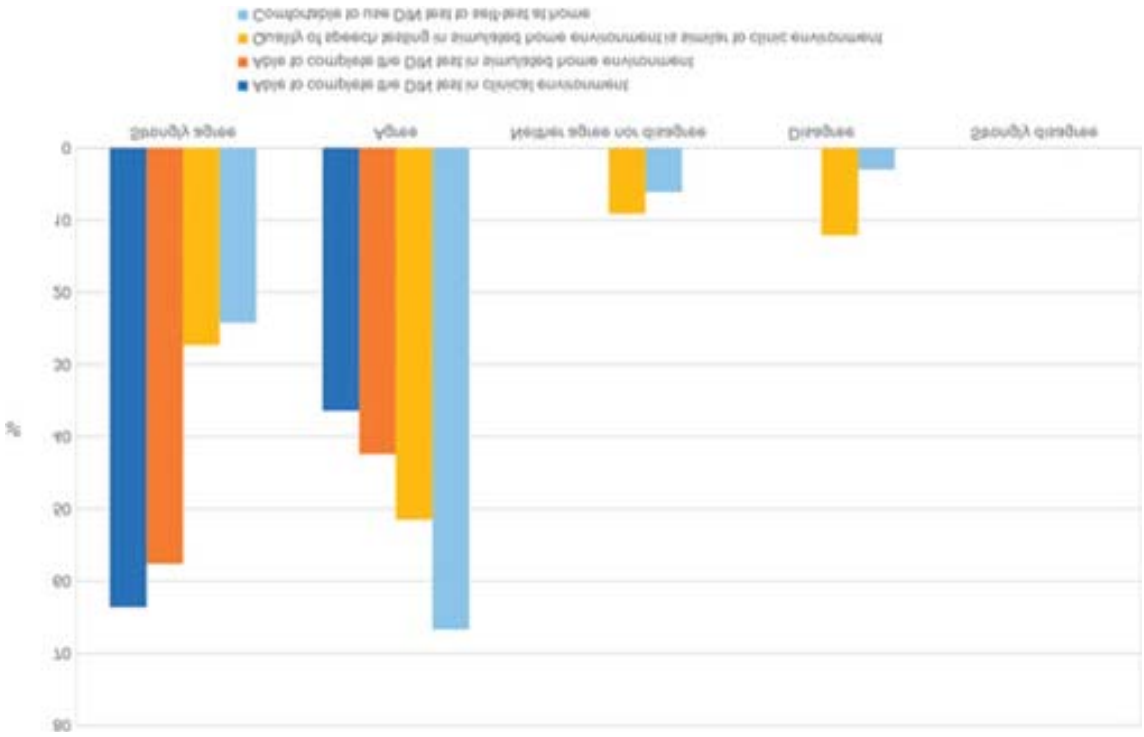

Figure 5. Results of survey items related to the digits-in-noise (DIN) test (*N* = 33).

The free text section of the survey for participants' experiences of the DIN test was analysed thematically with two themes identified as indicated in Table 3.

Table 3 Thematic analysis of participant reported experiences of using the Digits-in-Noise (DIN) test

Themes	Examples
Positive test experiences	*"The DIN test was enjoyable"* *"An interesting test"* *"An amazing test"* *"An excellent test"* *"A good test to use"*
Test concerns	*"The test was somewhat difficult"* *"The test was hard"* *"Sometimes hearing the digits well but sometimes struggling to hear the digits"* *"The test is more difficult in the simulated home environment"* *"The lack of delay at the start of the test caused confusion"*

Discussion

This explorative study determined the accuracy and reliability of an aided DIN self-test for adult CI recipients to evaluate SIN performance in a simulated home environment. All CI recipients were able to complete the DIN self-test in both environments. The mean SRTs between the clinic and simulated home environment were not significantly different, indicating that adult CI recipients can conduct the smartphone DIN test in a home environment with reliability and accuracy relatively similar to the clinic (via loudspeaker in the audiometric booth). De Graaf et al. (2018) found similar results where a strong correlation was identified between clinician-led audio booth testing and home testing, although a connection with an audio cable was used to perform the DIN test instead of a loudspeaker in the home environment.

In contrast to previous DIN studies that used a direct connection (audio cable) between the CI sound processor and computer/ tablet to (Cullington & Agyemang-Prempeh, 2017; de Graaff et al., 2018; Philips et al., 2018), the present study was conducted in the sound field. Although an audio cable connection eliminates or reduces the background noise, sound field testing with a loudspeaker enables the clinician to assess the entire hearing pathway (Cullington & Aidi, 2017) and allows testing without specialised equipment. In addition, direct connection prevents the functional assessment of the speech processor microphone(s) since dirty microphone covers may negatively affect speech perception (de Graaff et al., 2018). More favourable speech perception results may be obtained with an audio cable, resulting in an inaccurate reflection of actual speech perception in daily life (de Graaff et al., 2018; Sevier et al., 2019). Although Brown et al. (2019) did not identify any significant difference in DIN test results when comparing different speakers in a quiet environment, the influence of

loudspeaker quality in a noisy home environment is yet to be investigated. Wireless streaming for a device to the CI sound processor recently became a possibility for remote testing and should be explored in future studies as an alternative to direct audio input and loudspeaker testing in the home environment (van Wieringen et al., 2021).

Significantly better ($p < .05$) DIN results were recorded for retest instances within each environment. Several studies (Kaandorp et al., 2015; de Graaff et al., 2018; Kropp et al., 2020) have also reported a procedural learning effect between test and retest in the DIN test. In the study by Kropp et al. (2020), some participants overcame the learning effect using a third test. However, despite administering a practice list, Kaandorp et al. (2015) still identified a small learning effect between test and retest (of 0.3 dB) between the second and third test lists in adult CI recipients. In this study, large test-retest differences were identified in some participants, similar to a study by Kaandorp et al. (2015). Despite this effect, the SEM values were comparable to the values of 1.7 (DIN administered with loudspeakers) and 1.2 (audio cable connection to conduct DIN) in a study by de Graaff et al. (2018) and 1.1 in a study by Kaandorp et al. (2015). The current study calculated the SEM and ICC for both environments and demonstrated a good agreement level and high reliability for the test overall (Table 2). More importantly, the SEM and ICC values indicated that the simulated home environment test-retest values are comparable to the test-retest reliability obtained in the clinic. Furthermore, the lower SEM allows the DIN test to be compared in various conditions such as CI only versus bimodal situations, CI or HA settings, or bilateral versus unilateral conditions (Kaandorp et al., 2015). According to Philips et al. (2018), when CI recipients conduct the DIN test in a home environment, familiarity with the test reduces the learning effect, and fatigue would have a minor effect on outcomes.

In the current study, an average improvement of 1.8 dB between test and retest was found in the simulated home environment, and a greater test-retest improvement of 3.2 dB was seen in the clinic environment. These results support the need for at least one training list, especially for CI recipients who often experience difficulty with listening in noisy environments (Gifford et al., 2008; Dorman & Gifford, 2017; Willberg et al., 2021). The test and retest SRT scores for both test instances range from -9.4 to 22.5 dB in the clinic and -8.8 to 22.5 dB in the simulated home environment, indicating a wider range of results than the SRT range of -6.6 to 12.4 dB SNR in the study by Kropp et al. (2020) and the −2.55 and 12 dB range in the study by Cullington and Aidi, (2017). The current study's DIN test setup used a starting SNR of 0 dB which was intended to differentiate normal hearing from hearing loss and not for CI recipients who already have a significant SNR loss (Smits et al., 2004; Potgieter et al., 2016; De Sousa et al., 2020). More than half of the CI participants in this study had SRTs that were higher than the starting SNR of 0 dB. This starting SNR is likely to be too adverse for CI recipients as a starting intensity and could be adjusted in addition to a training list to be administered prior to testing.

All adult CI recipients, except those with SSD, were included in this study, which reflected the wide-ranging speech perception abilities and performance of adult CI recipients (Kropp et al., 2020). The CI experience of participants at the time of data collection ranged from three months to 28 years, also reflecting the heterogeneity of the study sample. Patient-related variables were controlled for by using a within-subjects design (Maruthurkkara et al., 2021). In addition, test environments were counterbalanced. Although numerous factors have been investigated to explain the wide-ranging speech perception outcomes in CI recipients, a large part of the variance

is yet to be explained (Roditi et al., 2009; Lazard et al., 2012; Blamey et al., 2013). The variety of factors influencing speech perception performance in adult CI recipients is well recognised, for example, the position of the electrodes (Finley et al., 2008; Lazard et al., 2012), duration of severe to profound hearing loss prior to implantation (Blamey et al., 1996, 2013; Budenz et al., 2011; Holden et al., 2013; Mosnier et al., 2014; Roditi et al., 2009), residual hearing, and preoperative speech recognition (Leung et al., 2005; Lazard et al., 2012). Studies by Taylor et al. (2020) and Potgieter et al. (2018) demonstrated the potential influence of language abilities on DIN test performance. In addition, Van Wijngaarden et al. (2002) and Zokoll et al. (2013) stated that cognition, auditory memory, and linguistic complexity of the test material could potentially affect the performance of English second language speakers. However, the DIN relies minimally on top-down processing (e.g., linguistic skills) (Smits et al, 2013), English digits are used in a variety of languages and the self-reported English competence of non-native listeners can be used to adjust reference scores to accommodate this population.

Participant feedback indicated that most (69.7%) were more open to the possibility of receiving regular CI related services that can be accessed from home as a result of COVID-19. The majority of participants responded positively to the possibility of using the DIN test at home to self-assess speech perception (90.9%) and possibly receiving regular CI services from home (78.7%). All participants stated being able to perform the DIN test in both test environments without any difficulties. The time taken to complete the DIN test was fast (3.5 minutes per test in each environment) and is consistent with the DIN test times of 2 to 3 minutes reported by Kropp et al. (2020). SIN testing through a Bluetooth speaker enables CI recipients to perform the DIN test easily and quickly at home without any additional specialised equipment. Testing of speech perception

abilities in noise with the DIN test allows clinicians to evaluate and optimise the fitting parameters of CIs and use the DIN test for rehabilitation follow-up purposes (Smits et al., 2013; Kaandorp et al., 2015; Van den Borre et al., 2021). Although DIN test speech material is restricted and sentence tests might be more representative of real-life listening conditions, the DIN test may be more useful than the sentence test for the evaluation of cochlear implant fitting (Smits et al., 2013). Numerous studies have demonstrated a high correlation between the DIN test and other sentences-in-noise tests in CI recipients (Kaandorp et al., 2015, 2016, 2017; Cullington & Aidi, 2017; Willberg et al., 2021). A study by van Wieringen et al. (2021) indicated the DIN in the home environment proved to be more useful than the sentences-in-noise to identify ear-specific changes in auditory performance and monitor progress at regular intervals. In contrast to the sentences-in-noise test, the DIN can be administered repeatedly without a clinician.

A limitation of the current study was the relatively small sample size. It is important to keep in mind that the DIN test was not originally developed to evaluate the hearing ability of individuals with severe to profound hearing loss (Smits et al., 2004) and the results of this population cannot be compared to those with normal hearing as almost all of them would obtain perfect scores (Cullington & Aidi, 2017). Another potential limitation may be the difficulties related to home testing as opposed to testing in a simulated home environment. Test accuracy can be compromised by problems with internet connectivity, technical competence, and noisy testing environments. However, recent studies indicate that reliable results can be obtained for home-based testing despite less control over sound level and quality (Swanepoel & Hall, 2010; Molander et

al., 2013; Masalski et al., 2014). In the present study the audiologist assisted with the setup in both environments. Although a self-setup may empower participants to be able to independently perform the setup in their home, an initial explanation or demonstration of the setup by the audiologist may still be necessary. Due to the ease of the setup, the explanation can be done remotely. Numerous studies have however noted the value of patient-site facilitators in providing optimal and efficient services (Hughes et al., 2012; Wesarg et al., 2010; Crowell et al., 2011; Eikelboom et al., 2014).

Future recommendations for the DIN test in CI recipients would be to include training items and a less adverse SNR to create a more beneficial starting level for this population, which could decrease the test-retest differences obtained in this study.

Conclusions

The results of this explorative study have demonstrated that although various factors may influence remote testing, the DIN test can be conducted by adult CI recipients in a home environment with accuracy and reliability relatively similar to clinic testing. As a result of the COVID-19 pandemic, CI recipients are more inclined to use remote CI services and tests such as the DIN test to self-assess speech perception at home. With minor changes to testing procedures, the DIN test could possibly be used by clinicians as part of the standard test battery as a reliable and accurate SIN test for adult CI recipients.

Acknowledgments

No funding was received to conduct this research. The authors would like to thank the Pretoria Cochlear Implant Unit for their assistance with this project.

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