Diotic and antiphasic digits-in-noise testing as a hearing screening and triage tool to classify type of hearing loss

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ABSTRACT

Objectives: The digits-in-noise test (DIN) is a popular self-test measure that has traditionally been used to screen for hearing loss by providing either a *pass* or *refer* result. Standard approaches either tested each ear monaurally or used a binaural diotic version where identical digits and noise were presented simultaneously to both ears. Recently, a dichotic, *antiphasic* version was developed, increasing sensitivity of the DIN to unilateral or asymmetric sensorineural hearing loss (SNHL) and conductive hearing loss (CHL). The purpose of this study was to determine predictors and normative ranges of the antiphasic and diotic DIN and to determine if a combination of diotic and antiphasic DIN could accurately categorize hearing into (a) normal, (b) bilateral SNHL, or (c) unilateral SNHL or CHL.

Design: The analytical sample consisted of 489 participants between the ages of 18 and 92 years with varying types, symmetry and degrees of hearing loss. Degree and type of hearing loss were determined based on standard clinical four frequency (0.5 – 4 kHz) pure tone air and bone conduction threshold averages. The sample consisted of bilateral normal hearing (*n*=293), bilateral SNHL (*n*=172), unilateral SNHL (*n*=42) and CHL (*n*=32). All participants (*n*=489) first completed an antiphasic DIN (digit stimuli 180º out-of-phase between ears), while 393 of the sample also completed a diotic DIN. Two procedures were assessed for their ability to categorize hearing into one of the three hearing groups. The first used a fixed antiphasic cut-off combined with a cut-off formed by a linear combination of antiphasic and diotic speech recognition threshold (SRT) or binaural intelligibility level difference (BILD).

Results: Poorer ear pure tone average (PTA) was the strongest predictor of antiphasic DIN score, whereas better ear PTA explained more of the variance in diotic SRT. The antiphasic DIN sensitivity and specificity was 90% and 84% respectively for detecting hearing loss, with outstanding area under the receiver operating characteristics (AUROC) values exceeding 0.93 to identify hearing loss in the poorer ear. The first fixed SRT cut-off procedure could categorize 75% of all participants correctly, while the second procedure increased correct categorization to 79%. False negative rates for both procedures were below 10%.

Conclusions: A sequential antiphasic and diotic DIN could categorize hearing to a reasonable degree into three groups of (a) normal hearing, (b) bilateral SNHL, and (c) unilateral asymmetric SNHL or CHL. This type of approach could optimize care pathways using remote and contactless testing, by identifying unilateral SNHL and CHL as cases requiring medical referral. In contrast, bilateral SNHL cases could be referred directly to an audiologist, or non-traditional models like OTC hearing aids.

Keywords: digits-in-noise, antiphasic, diotic, hearing loss, conductive hearing loss, sensorineural hearing loss, unilateral hearing loss.

INTRODUCTION

Hearing loss is often a slowly progressing chronic condition and those affected may not realize that they have it. According to the Global Burden of Disease Study (Global Burden of Disease 2016), hearing loss is one of the most common impairments, adding up to about 1.3 billion people globally. Prevalence is highest among older adults, with a third of people over 65 years affected by hearing loss of a disabling degree (World Health Organization 2020). Routine hearing screening has been suggested to bolster early uptake of intervention and increase public awareness of hearing loss (Wilson et al. 2017). The earlier a person takes up intervention, the greater the prospects of reducing the consequences, such as social isolation, depression and cognitive decline of hearing loss to a minimum (Cacciatore et al. 1999). However, only about 20% of adults seek help for hearing loss (Davis et al. 2007) and often delay help-seeking for a number of years (Davis 1995; Simpson et al. 2019). Therefore, much can be gained from routine screening and subsequent early rehabilitation. Unfortunately, adult screening programs are poorly recognized among the lay public (Lin et al. 2016) and not widely available, especially in low-and middle-income countries (Olusanya et al. 2014). In the past 15 years, there has been a shift towards more accessible screening methods, including speech recognition, that individuals can perform without a trained professional. Additionally, the desirability of remote, contactless self-screening has recently been emphasized by the Covid-19 pandemic.

Self-test measures are meant to support large scale detection of hearing loss. However, the question around continuity of care is the follow-up for a person identified with hearing loss.

Hearing screening tests usually only detect hearing loss, without discriminating types of hearing loss. Some provide information on causes and general treatment possibilities or include location-based referral to hearing aid dispensers (Swanepoel et al. 2019). However, some types of hearing loss, such as unilateral or asymmetric sensorineural hearing loss (SNHL) or conductive hearing loss (CHL), require referral to a physician (AAO-HNS 2014) according to best practice recommendations. Screening tests that can triage persons and directly refer for either diagnostic hearing assessment or medical evaluation could streamline diagnosis and treatment. Another potential problem with large scale consumer screening, especially in low- and middle-income countries, is the limited infrastructure and availability of hearing health professionals (Mulwafu et al. 2017). Even in high-income countries, diagnosis and treatment may be delayed due to high client-to-audiologist ratios (Kamenov et al. 2021). To reduce the load on overburdened healthcare systems and increase accessibility to services, over the counter (OTC) hearing aids and other amplification devices have sparked wider interest in the past few years (Humes et al. 2017). Giving precedence to cases that require standard contact-based appointments (e.g., unilateral SNHL or CHL) above those who can proceed directly with device-based intervention (e.g., age-related SNHL) is an important consideration for self-test screening.

The digits-in-noise test (DIN), which measures bottom-up speech recognition in noise, has become progressively more popular over the last 15 years. Using an adaptive procedure, the test determines the signal-to-noise ratio (SNR) at which 50% of digit-triplet recordings (e.g., 4-3-7), presented in speech-shaped masking noise, are recognized correctly (i.e., speech recognition threshold [SRT]). The DIN as a diagnostic speech-in-noise test has a steep psychometric slope and correlates highly (r = 0.86) with commonly used sentence-in-noise tests (Plomp et al. 1979; Smits et al. 2004). DIN tests are cognitively less demanding than many other speech-in-noise tests because most listeners are familiar with digits, limiting the contribution of top-down processing (Smits et al. 2013). Although factors such as cognition still factor into DIN test performance (Moore et al. 2014), the correlation between DIN and pure tone average (PTA) thresholds is higher than between PTA and other speech-in-noise tests (Jansen et al. 2010). In addition, the DIN is a robust self-test that can be conducted without calibrated equipment (Potgieter et al. 2016; Smits et al. 2004). It has, therefore, been widely implemented as an alternative to pure tone hearing screening in adults. The first DIN was released as a National Hearing Test over landline telephone in the Netherlands in 2004 (Smits et al. 2004) and had a large-scale uptake of more than 160,000 tests two and a half years after its release (Smits et al. 2005). Many more language and dialect versions of the DIN have been developed, some of which have been offered to the public as either landline or internet-based screening tests (Jansen et al. 2010; Motlagh Zadeh et al. 2020; Ozimek et al. 2009; Van den Borre et al. 2021; Watson et al. 2012). To increase global accessibility, including low-and-middle income countries, newer versions used a downloadable app where the test could be completed on iOS or Android operated smartphone or other mobile devices like the World Health Organization's official hearing test app, hearWHO (Potgieter et al. 2016; Potgieter et al. 2018; Swanepoel et al. 2019).

Though based on the original version of Smits et al. (2004), procedural differences between adaptations of the DIN exist. Some successively test each ear (Jansen et al. 2010; Smits et al. 2004; Watson et al. 2012) while others use binaural, identical stimuli presented to both ears (diotic; Potgieter et al. 2016; Potgieter et al. 2018) which is advantageous in terms of test duration. Monaural and diotic DIN SRTs agree strongly with PTA with correlations between 0.7 and 0.9 and have high sensitivity and specificity (> 80%) to detect sensorineural hearing loss (Jansen et al. 2010; Koole et al. 2016; Potgieter et al. 2018; Smits et al. 2004; Watson et al. 2012). However, diotic DIN SRTs fail to detect unilateral SNHL due to the dominance of the better ear for this task (De Sousa et al. 2020c). Furthermore, both monaural and diotic SRTs are mostly unaffected by attenuation caused by CHL when presented at suprathreshold levels (De Sousa et al. 2020b). Antiphasic presentation of the DIN has been shown to improve sensitivity to different hearing loss types (including unilateral SNHL and CHL) by using interaural 180° phase reversed speech presented in diotic noise (i.e., NoSπ; De Sousa et al. 2020b). Antiphasic presentation involves mechanisms of both binaural interaction and unmasking. Normal-hearing individuals benefit by better isolating target speech from noise and obtain about 6-8 dB lower SRTs (De Sousa et al. 2020b; Smits et al. 2016). However, peripheral hearing loss (including unilateral SNHL or CHL) significantly diminishes this antiphasic benefit (i.e., the binaural intelligibility level difference, BILD) because of disruption in interaural timing, binaural unmasking, and asynchronous neural action of the affected ears (Hartley et al. 2003; Jerger et al. 1984; Thornton et al. 2012; Welsh et al. 2004). Regression analysis predicting DIN SRT from poorer ear PTA showed steeper slopes and a higher correlation between PTA and antiphasic DIN SRTs compared to diotic DIN SRTs (De Sousa et al. 2020b). Antiphasic SRTs of listeners with hearing loss of any type were significantly higher than those of normal-hearing listeners. In contrast, diotic DIN SRTs of those of normal hearing listeners considerably overlapped with hearing loss groups consisting of bilateral SNHL, unilateral SNHL, and CHL. As a result, area under the receiver operating characteristic curve (AUROC) to detect hearing loss in the poorer ear more than 25 dB HL was considerably higher for antiphasic (94%) than diotic DIN (77%) (De Sousa et al. 2020b). Antiphasic presentation therefore provides a unique solution to improve the sensitivity of a single DIN to detect various hearing loss types and symmetries, including unilateral or asymmetric SNHL and CHL.

In a typical DIN screening procedure, the test estimates the SRT and compares the result with an established cut-off value. If the SRT is lower (better) than the cut-off, the test is a "pass" and if higher (worse), "refer". This is effective when the sole aim is to identify an affected individual. However, by following up on an initial 'referred' antiphasic test with a diotic version, according to the scheme provided in Figure 1, it could theoretically be possible to categorize the results as either (i) bilateral SNHL, or (ii) unilateral SNHL or CHL, given that diotic SRTs have been shown to be near-normal for listeners of the latter category. To investigate this hypothesis, we determined 1) the predictors and normative ranges for antiphasic and diotic DIN SRTs across degree and type of hearing loss; 2) the performance of a sequential antiphasic and diotic DIN procedure to detect and classify hearing loss type.

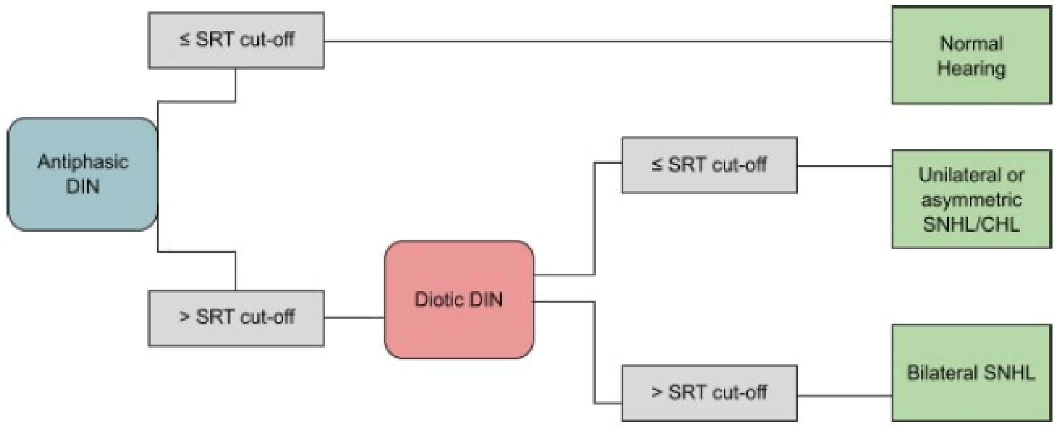

Figure 1. Screening procedure for a sequential antiphasic and diotic DIN approach. *DIN indicates digits-in-noise; SRT, speech recognition threshold; CHL, conductive hearing loss; SNHL, sensorineural hearing loss.*

METHOD

This cross-sectional study recruited 507 participants between the ages of 18 and 92 years (mean = 51 years, SD = 19 years) with varying types, symmetries and degrees of hearing loss. A convenience, non-probability sampling method was used to approach participants at clinical data collection sites. Participants were recruited from private audiology practices, a university clinic and hearing screening initiatives organized in Pretoria, South Africa. Type and degree of hearing loss was determined based on a four frequency (0.5 – 4 kHz) PTA. The sample consisted of people with bilateral normal hearing (n = 243; PTA ≤ 25 dB HL), bilateral symmetric SNHL (n = 172; PTA > 25 dB HL bilaterally), unilateral or asymmetric SNHL (n = 42; PTA > 25 dB HL in the poorer ear and ≥ 20 dB interaural PTA difference) and CHL (n = 32; air conduction PTA > 25 dB HL and ≥ 20 dB air bone gap [ABG] in the affected ears). For the unilateral or asymmetric SNHL group, only four cases were asymmetric, with the PTA in the better ear between 26 to 45 dB HL. In the CHL group, bone conduction PTA usually did not exceed 25 dB, except for one case where the bone conduction PTA in the poorer ear was 35 dB HL. Most cases of CHL were either unilateral or asymmetric (n = 21), with a smaller portion of bilaterally symmetric CHL (n = 11). A small group of mixed hearing loss (n = 18, air and bone conduction PTA ≥ 25 dB HL in the poorer ear and PTA ABG ≥ 20 dB in the affected ears) were excluded from the analytic sample. Most (n = 16) of these participants had severe or profound loss, and it was possible that false ABGs could occur due to limitations in the maximum output of the bone conductor transducer. After exclusion, the number of participants for the analyses was 489 (Table 1). Degrees of hearing were based on poorer ear PTA and categorized according to WHO grades of hearing impairment (World Health Organization 2020) as either normal hearing (PTA ≤ 25 dB HL), mild (PTA 26-40 dB HL), moderate (PTA 41-55 dB HL) or severe to profound hearing loss (PTA 56-120 dB HL).

TABLE 1. Antiphasic and diotic DIN SRTs according to degree of hearing in the poorer ear (pure tone average of 0.5, 1, 2 and 4 kHz) and hearing categories (normal, bilateral SNHL, unilateral SNHL, CHL)

			Normal (0-25 dB HL)	Mild (26-40 dB HL)	Moderate (41-55 dB HL)	Severe-Profound (56-120 dB HL)
NH & bilat SNHL (n=415)	Antiphasic	*n*	243	60	66	46
		Mean age (SD)	41 (17)	62 (11)	69 (11)	71 (13)
		Mean SRT (SD)	-17.2 (2.4)	-14.6 (2.9)	-10.2 (4.7)	-6.2 (6.8)
		Range	-21.2 to -4.2	-19.2 to -5.2	-18.2 to 11.4	-13.6 to 22.5
	Diotic	*n*	202	42	44	37
		Mean age (SD)	40 (17)	62 (11)	66 (11)	71 (13)
		Mean SRT (SD)	-10.3 (1.3)	-9.2 (1.8)	-7.6 (2.2)	-4.0 (4.9)
		Range	-16.2 to -0.2	-11.8 to -3.8	-11 to -0.4	-9.6 to 13.4
Unilat SNHL (n=42)	Antiphasic	*n*	-	3	10	29
		Mean age (SD)		60 (8)	50 (21)	46 (17)
		Mean SRT (SD)		-14.3 (1.0)	-11.1 (2.2)	-9.7 (3.9)
		Range		-15.4 to -13.4	-14.6 to -7.4	-15.0 to 6.2
	Diotic	*n*	-	3	9	26
		Mean age (SD)		60 (8)	50 (21)	46 (17)
		Mean SRT (SD)		-10.3 (1.5)	-9.5 (1.4)	-9.1 (1.4)
		Range		-12.0 to -9.0	-11.4 to -7.6	-11.6 to -6.6
CHL (n=32)	Antiphasic	*n*	-	6	7	19
		Mean age (SD)		38 (22)	40 (21)	44 (15)
		Mean SRT (SD)		-14.4 (1.5)	-12.2 (3.0)	-9.8 (1.8)
		Range		-17.0 to -13.0	-16.2 to -7.2	-14.0 to -6.2
	Diotic	*n*	-	6	6	18
		Mean age (SD)		38 (22)	40 (21)	44 (15)
		Mean SRT (SD)		-10.7 (0.8)	-9.9 (1.7)	-8.9 (1.5)
		Range		-11.6 to -9.8	-11.6 to -7.0	-11.2 to -5.2

SRT indicates speech reception threshold; PTA, pure tone average; SNHL, sensorineural hearing loss; CHL, conductive hearing loss; SD, standard deviation; SE, standard error

From this sample, 393 participants conducted both antiphasic and diotic DIN tests. They were included for hearing category classification using sequential antiphasic and diotic DIN tests. BILD was calculated by subtracting antiphasic DIN SRT from diotic DIN SRT. Defined by better and poorer ear PTAs, participants were grouped as either having: (i) normal bilateral hearing (n = 202), (ii) bilateral symmetric SNHL (n = 123), (iii) unilateral or asymmetric SNHL or CHL (n = 68). Furthermore, participants were classified based on the results of both antiphasic and diotic DIN. This classification assumed that (i) antiphasic DIN SRT ≤ cut-off indicated normal hearing; (ii) only antiphasic DIN SRT > cut-off indicated unilateral or asymmetric SNHL or CHL, and (iii) both antiphasic and diotic DIN SRTs > cut-off indicated bilateral SNHL. See Figure 1.

Procedures and equipment

The Humanities Research Ethics Committee of the University of Pretoria, South Africa approved the study protocol (number: HUM003/0120). All participants were informed of the study aims and procedures and provided written informed consent before participation.

Qualified audiologists conducted pure tone air and bone conduction audiometry at different test sites as part of a standard audiometric test battery using diagnostic audiometers calibrated to industry standards. The modified Hughson–Westlake method was used to establish thresholds (Hughson and Westlake 1994). The majority (n = 400) of the participants were tested inside a soundproof booth, while 108 normal-hearing participants were tested in a quiet office-like environment using a hearTest™ (hearX group, Pretoria South Africa) smartphone-based audiometer. The hearTest™ application ran on a Samsung J2 Galaxy smartphone (Android OS, 5.1) and connected to supra-aural Sennheiser HD280 headphones (Sennheiser, Wedemark, Germany).

The South African English DIN test (Potgieter et al. 2016) was conducted on either a Samsung Trend Neo or Samsung J2 Galaxy smartphone and coupled with manufacturer supplied wired earbuds (n = 123), Sennheiser HDA 220 (n = 242) or Sennheiser HDA 280 headphones (n = 124). The test followed the same procedure and used the same stimuli as described in De Sousa et al. (2020). Twenty-three-digit triplets were randomly selected from a list of 120 different digit triplets. Triplets were constructed with 500 ms intervals at the beginning and end of each triplet, which was presented with overlapping masking noise. Consecutive individual digits were divided by 200 ms intervals with 100 ms of jitter. Speech weighted masking noise overlapped with the digit triplets, using a fixed noise level for negative SNRs. The speech level was fixed, and the noise level varied when positive SNRs were presented to prevent clipping of the signal. Masking noise was delivered diotically and the digits were either diotic (NoSo) or antiphasic (NoSπ) between the ears. Noise "freshness" was ensured by creating a long noise file and selecting successive fragments from a random offset within the first 5s to prevent possible learning of the masking noise (Lyzenga et al. 2011). Starting at 0 dB SNR, the test used fixed step sizes of 4 or 2 dB for the first 3 steps, and 2 dB steps for the following trials (De Sousa et al. 2020b). For the first three steps, SNR became progressively lower in 4 dB steps for correct responses but increased by 2 dB per step for incorrect responses. The test tracked the SNR at which 50% of the digit triplets were correctly identified (Potgieter et al. 2016; Smits et al. 2004). A digit triplet was considered correct only when all digits were entered correctly, and the SRT was calculated by averaging the last 19 SNRs. After completing a pure-tone audiometry assessment, all participants completed either one antiphasic DIN (n=489) or antiphasic DIN and diotic DIN (n=393).

Statistical analysis

Statistical analysis was done using IBM SPSS v26.0. Multivariate linear regression analyses were used to determine the amount of variance in the diotic and antiphasic DIN SRT that could be explained by better and poorer ear PTA and age (adjusted R^2). There was linearity as assessed by partial regression plots and a plot of studentized residuals against the predicted values. There was independence of residuals (Field 2009), as assessed by Durbin-Watson statistics. There was no evidence of multicollinearity, as assessed by tolerance values greater than 0.1. There were between 1 and 7 studentized deleted residuals higher than ±3 standard deviations for antiphasic and diotic DIN SRT, which were kept in the analysis. There were no leverage values greater than 0.2, and values for Cook's distance above 1. Spearman correlations were used to determine the correlation between DIN SRT, better and poorer ear PTA because not all variables were normally distributed, as assessed by Shapiro-Wilk's test (p < 0.05). Area under the receiver operating characteristic (AUROC) analyses were conducted to determine sensitivity and specificity of the diotic and antiphasic DIN tests for different cut-off values. The targeted disorders were mild (poorer ear PTA > 25 dB HL) and moderate hearing loss (poorer ear PTA > 40 dB HL). Binomial logistic regression analyses were performed to derive AUROC curves covarying for age.

RESULTS

Antiphasic and diotic DIN SRT- PTA correlations and predictors

Figure 2 shows the distribution of antiphasic and diotic SRTs across better and poorer ear PTA. Correlations of antiphasic and diotic SRTs to poorer and better ear PTA across different types of hearing loss are presented in Figure 3. Diotic DIN SRTs of participants with hearing loss substantially overlapped with DIN SRTs of normal hearing participants, especially for CHL and unilateral or asymmetric SNHL, and for bilateral SNHL < 40 dB HL (Figure 2D; Table 1). The distinction between normal hearing and any of the hearing loss categories was better for antiphasic DIN SRT than diotic DIN SRT, suggesting greater sensitivity of the antiphasic DIN (Figure 2A & B; Table 1). For normal hearing participants, the correlation between antiphasic DIN SRT and poorer ear PTA was slightly higher than between diotic SRT and better ear PTA. For participants with bilateral SNHL, the correlations were nearly identical between better or poorer ear PTA and antiphasic or diotic DIN SRT, respectively. Because hearing losses are symmetrical for these groups of participants, differences between better and poorer ear PTA are small. However, correlations between antiphasic DIN SRT and poorer ear PTA for CHL and unilateral or asymmetric SNHL are much higher than between antiphasic DIN SRT and better ear PTA (Figure 2 & 3). On the other hand, diotic DIN SRTs of people with unilateral SNHL were more related to the performance of the better ear than poorer ear PTA (Figure 3).

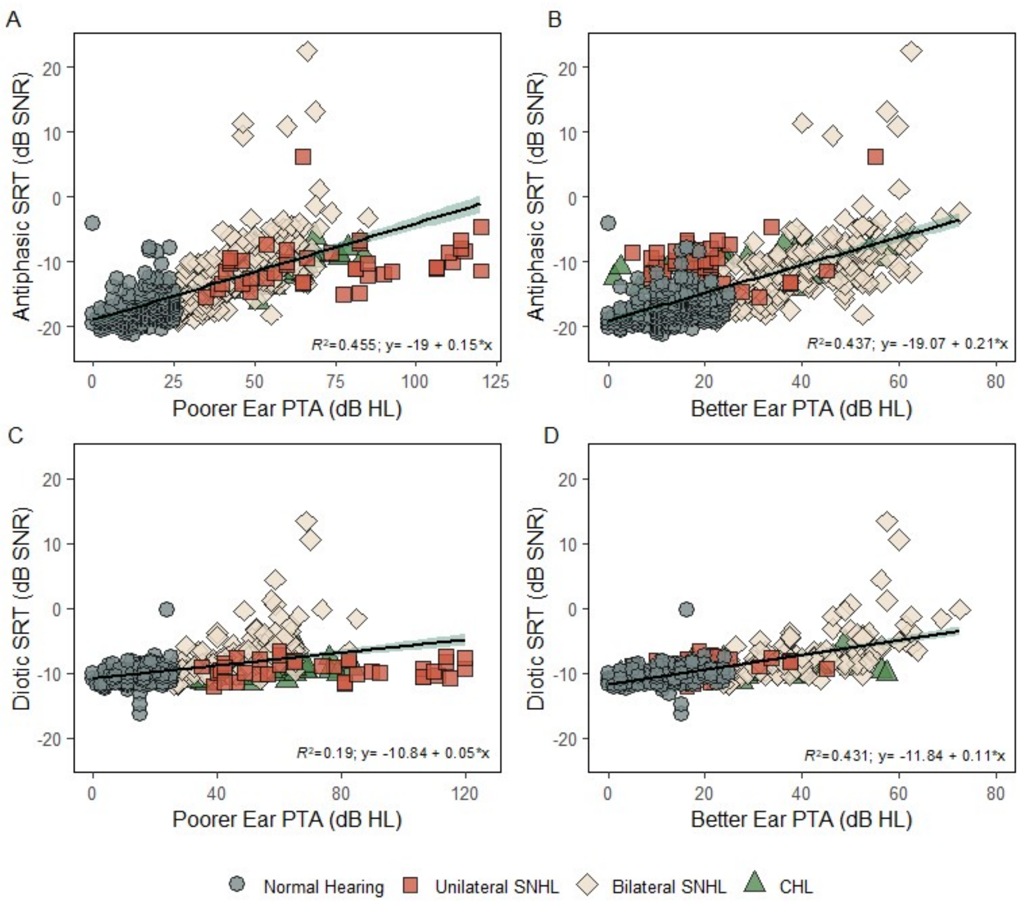

Figure 2. Relationship of the antiphasic and diotic DIN SRT to poorer and better ear PTA. *(A) Relationship of antiphasic DIN SRT to poorer ear PTA, (B) antiphasic DIN SRT to better ear PTA, (C)*

diotic DIN SRT to poorer ear PTA and (D) diotic DIN SRT to better ear PTA. Regression lines are linear fits across the entire sample, the shading indicating 95% confidence intervals. CHL indicates conductive hearing loss, dB; decibel, DIN; digits-in-noise, PTA; pure tone average, SNHL; sensorineural hearing loss, SNR; signal to noise ratio, SRT; speech reception threshold.

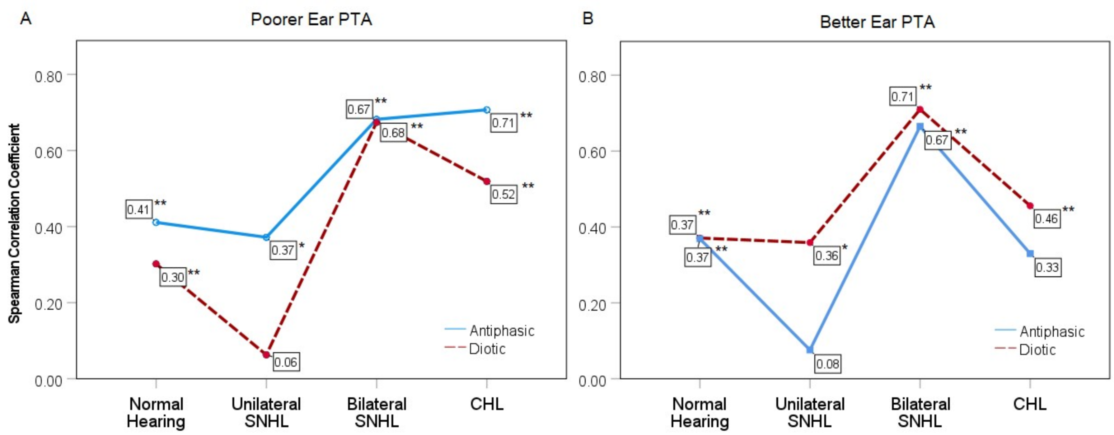

Figure 3. (A) Spearman correlations of the antiphasic and diotic DIN SRT to poorer ear PTA among different hearing categories. (B) Spearman correlations of the antiphasic and diotic DIN SRT to better ear PTA among different hearing categories. ***Indicates significant correlations at the level of 0.01. DIN indicates digits-in-noise; PTA, pure tone average; NH, normal hearing; bilat, bilateral; SNHL, sensorineural hearing loss; CHL, conductive hearing loss.*

Multiple linear regression analysis predicting antiphasic or diotic DIN SRT from better or poorer ear PTA and age are presented in Table 2. Regression models that included poorer ear PTA consistently and significantly ($p < 0.05$), predicted more of the variance (adjusted R^2) in antiphasic DIN SRT across all hearing loss groups compared to models with better ear as predictor, marginally for bilateral SNHL and unilateral or asymmetric SNHL, but considerably so for CHL. Better ear PTA explained more of the variance of diotic DIN SRT for normal hearing and bilateral SNHL; however, the proportion of variance explained by the better ear rather than poorer ear was marginal. Diotic DIN SRT for participants with unilateral or asymmetric SNHL could not be explained by either poorer or better ear PTA. Age did not contribute significantly to all models of antiphasic DIN SRT; only for participants with normal hearing and bilateral SNHL in models with better and poorer ear PTA, and for unilateral or asymmetric SNHL in the model with poorer ear PTA (Table 2). Furthermore, age only significantly contributed to models of diotic DIN SRT for participants with normal hearing.

TABLE 2. Multiple regression analysis predicting antiphasic and diotic DIN SRT from PTA and age for different categories of hearing.

		Variables in the Equation	p	Adjusted R^2	Model significance
Normal Hearing	Antiphasic SRT	Poorer ear PTA	0.061	0.208	< 0.01**
		Age	<0.01**		
		Better ear PTA	0.173	0.203	< 0.01**
		Age	<0.01**		
	Diotic SRT	Poorer ear PTA	0.085	0.139	< 0.01**
		Age	< 0.01**		
		Better ear PTA	0.034	0.146	< 0.01**
		Age	< 0.01**		
Bilateral SNHL	Antiphasic SRT	Poorer ear PTA	< 0.01**	0.359	< 0.01**
		Age	< 0.01**		
		Better ear PTA	< 0.01**	0.352	< 0.01**
		Age	< 0.05*		
	Diotic SRT	Poorer ear PTA	< 0.01**	0.360	< 0.01**
		Age	0.032		
		Better ear PTA	< 0.01**	0.379	< 0.01**
		Age	0.105		
Unilateral SNHL	Antiphasic SRT	Poorer ear PTA	0.011*	0.209	< 0.01**
		Age	< 0.01**		
		Better ear PTA	0.067	0.143	< 0.05*
		Age	0.150		
	Diotic SRT	Poorer ear PTA	0.532	0.037	0.196
		Age	0.074		
		Better ear PTA	0.127	0.089	0.073
		Age	0.222		
CHL	Antiphasic SRT	Poorer ear PTA	< 0.01**	0.476	< 0.01**
		Age	0.454		
		Better ear PTA	0.101	0.097	0.087
		Age	0.223		
	Diotic SRT	Poorer ear PTA	0.046*	0.182	0.067
		Age	0.557		
		Better ear PTA	0.013*	0.188	< 0.05*
		Age	0.412		

** Indicates significance at the level of 0.05*
*** Indicates significance at the level of 0.01*

AUROC curves were constructed from the results of logistic regression models for the detection of poorer ear PTA > 25 dB HL (Figure 4A, B) and > 40 dB HL (Figure 4C, D). The first set of ROC curves were based on DIN SRT only (Figure 4A, C), while the second set included both DIN SRT and age (Figure 4B,D). The DIN SRT cutoff values represented the point of the most optimal trade-off of sensitivity and specificity. Antiphasic DIN SRT showed a consistent larger area under the curve (AUROC) to detect hearing loss in the poorer ear than diotic DIN SRT (Table 3). Antiphasic DIN was, therefore, more sensitive and specific to hearing loss than diotic DIN. The AUROC to detect hearing loss > 25 dB HL in the poorer ear was slightly higher in antiphasic and diotic conditions when considering both SRT and age in the prediction, rather than DIN SRT alone (Table 3).

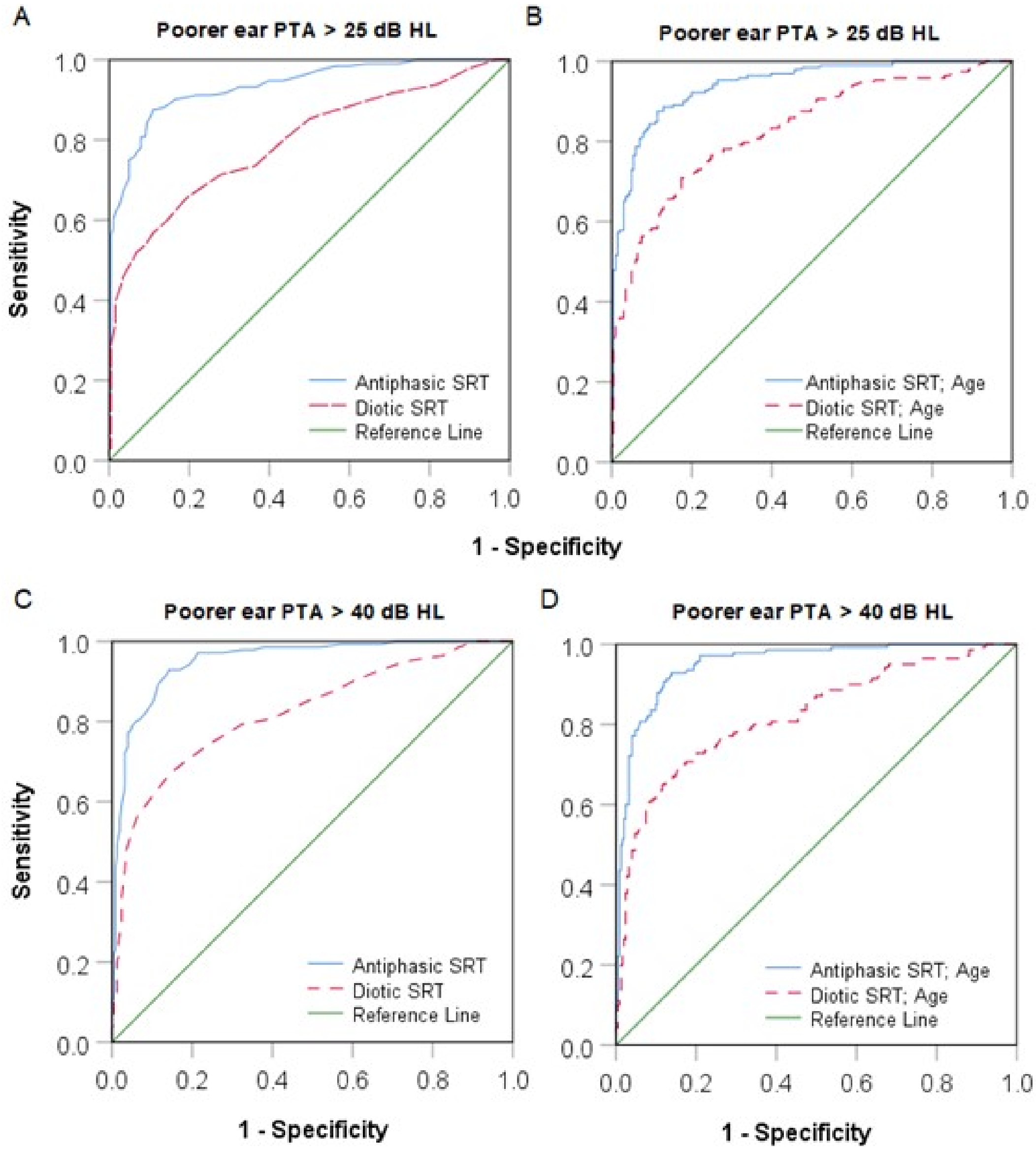

Figure 4. Receiver operating characteristic curves presenting test characteristics for the antiphasic and diotic DIN SRT for detecting poorer ear PTA > 25 dB HL and > 40 dB HL. (A) ROC curves presenting DIN SRT for the detection of poorer ear PTA > 25 dB HL, (B) DIN SRT and age for detecting poorer ear PTA > 25 dB HL, (C) DIN SRT for the detection of poorer ear PTA > 40 dB HL, (D) SRT and age for detection of poorer ear PTA > 40 dB HL. *dB indicates decibel; HL, hearing level; PTA, pure tone* average; ROC, receiver operating characteristics.

TABLE 3. Antiphasic and diotic DIN SRT logistic regression models for poorer ear PTA > 25 dB HL and > 40 dB HL						
			Antiphasic SRT			
	Predictors	Equation	AUROC (95% CI)	Cut-off	Sensitivity	Specificity
PTA > 25 dB HL	SRT	-	0.94 (0.91-0.96)	-15.7	90.1%	84.6%
	SRT, Age	p=1/ [1 + exp (-6.22 - 0.53*SRT – 0.03*age)]	0.94 (0.92-0.96)	p = 0.35	91.1%	80.1%
PTA > 40 dB HL	SRT	-	0.95 (0.93-0.97)	-13.7	90.7%	87.4%
	SRT, Age	p=1/ [1 + exp (-5.29 - 0.69*SRT – 0.01*age)]	0.95 (0.93-0.97)	p = 0.19	95.0%	80.2%
			Diotic SRT			
	Predictors	Equation	AUROC (95% CI)	Cut-off	Sensitivity	Specificity
PTA > 25 dB HL	SRT	-	0.79 (0.75-0.84)	-10.3	85.4%	49.8%
	SRT, Age	p=1/ [1 + exp (-3.61 - 0.57*SRT -0.04*age)	0.83 (0.79-0.87)	p = 0.36	80.7%	62.7%
PTA > 40 dB HL	SRT	-	0.82 (0.78-0.87)	-9.9	80.7%	60.1%
	SRT, Age	p=1/ [1+ exp (-8.19- 0.66*SRT – 0.002*age)	0.82 (0.78-0.87)	p = 0.25	80.0%	64.0%

PTA indicates pure tone average; dB, decibel; HL, hearing level; SRT, speech recognition threshold; AUROC, area under the receiver operating characteristics curve; CI, confidence interval

Antiphasic, diotic DIN and BILD categorize hearing loss groups

Figures 5 A and B each show diotic DIN SRT against antiphasic DIN SRT for : (a) Normal, (b) Unilateral or asymmetric SNHL or CHL, (c) Bilateral SNHL. Here, we explored how the whole data set fitted these categories based on the antiphasic and diotic DIN tests' combined results. Two different procedures were examined, each resulting in three areas, capturing the most participants with normal hearing (*left area of each figure*), bilateral SNHL (*upper right area*), and unilateral or asymmetric SNHL/CHL (*lower right area*). The first procedure (Figure 5A) uses an approach in which a fixed cut-off value for the antiphasic DIN (represented by a vertical line) is used to discriminate between participants with normal hearing and hearing loss and, sequentially, a second fixed cut-off value for the diotic DIN is used to discriminate between bilateral SNHL and unilateral or asymmetric SNHL/CHL (represented by a horizontal line). Using this simple method, 75% of participants were classified correctly (Table 4). Figure 5 A and Table 4 suggest that a fixed cut-off value for the diotic DIN may not optimally discriminate between bilateral SNHL and unilateral SNHL/CHL over the entire range of antiphasic DIN SRTs. Therefore, we investigated a second procedure in which three parameters (antiphasic DIN cut-off value represented by the vertical line, and slope and offset of the sloping line) were varied to maximize the percentage of correctly classified participants (see Figure 5B). The maximum achievable percentage of correctly classified participants was marginally increased to 79%. Choosing two sloping lines (not shown) did not improve the maximum achievable percentage of correctly classified participants. Note that this option would also require all participants to perform two DIN tests, whereas our approach requires only participants who fail the antiphasic DIN (right of the vertical line in Figure 5) to perform a second, diotic DIN which is practically more feasible and saves time.

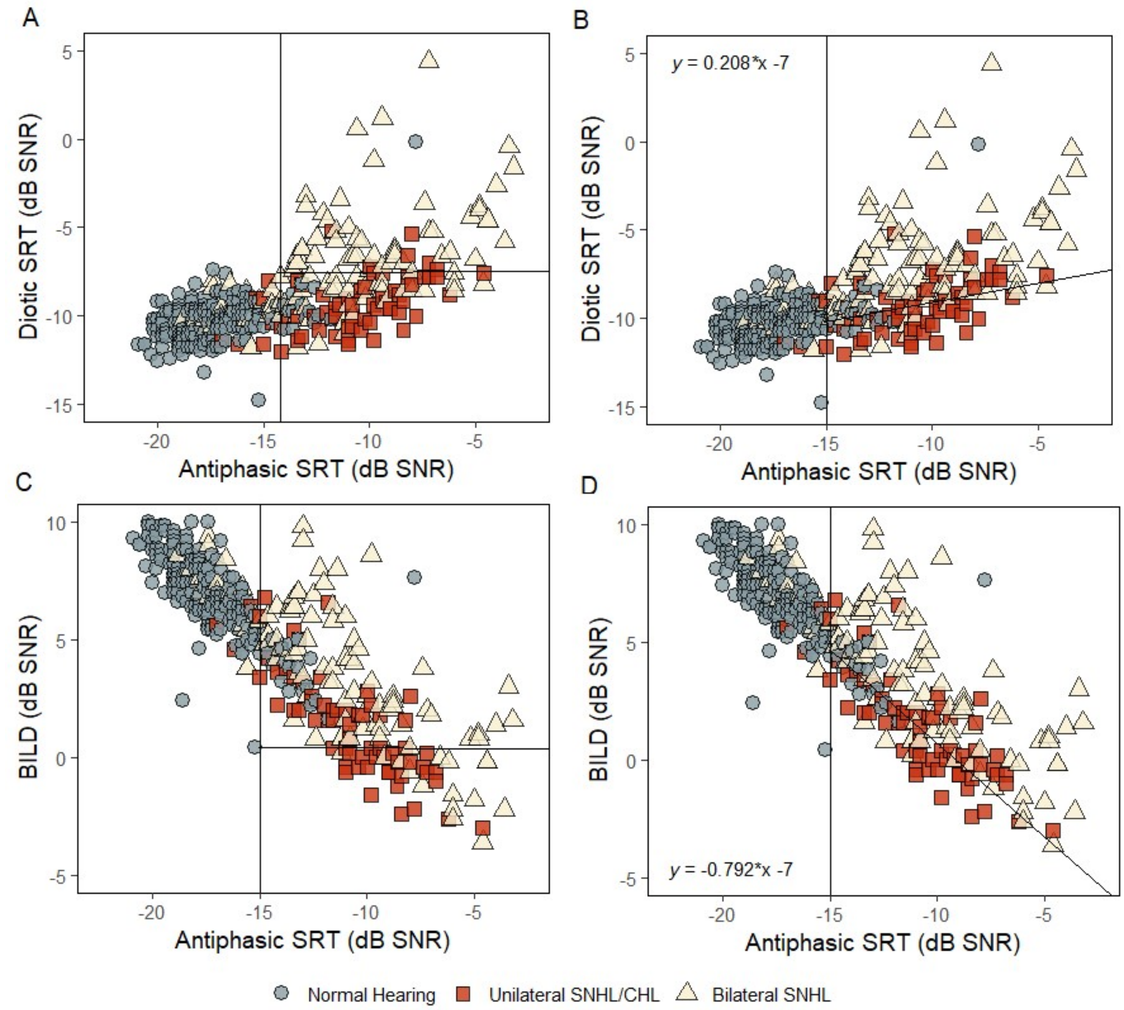

Figure 5. Hearing groups based on speech recognition threshold cut-off criteria. (A) Fixed antiphasic and diotic DIN SRT cut-off, (B) Maximum achievable percentage using fixed antiphasic and sloping diotic SRT cut-off, (C) Fixed antiphasic DIN SRT and BILD cut-off, (D) Maximum achievable percentage using fixed antiphasic DIN SRT and sloping BILD cut-off. Rectangular areas are normal hearing (*left*), bilateral SNHL (*upper right*), unilateral SNHL or CHL (*lower right*).

Although the maximum achievable percentage procedure was relatively accurate, a significant proportion of unilateral or asymmetric SNHL/CHL participants was misclassified as bilateral SNHL (35.3%). A detailed inspection of the data from the participants with bilateral SNHL and unilateral or asymmetric SNHL/CHL shows that there is considerable overlap between these groups within a range of antiphasic and diotic DIN SRTs. Of course, it is also possible to introduce a category ‘unknown’ to increase the percentages of correctly categorized participants.

TABLE 4. Percentage (number) of correctly categorized groups of hearing based on antiphasic and diotic SRTor BILD cut-offs in Figure 5 (Shaded cells = correct classification)			
	Referral category based on SRT cut-off: Antiphasic -14.2 dB SNR; Diotic -7.4 dB SNR (Fig. 5A)		
HL type based on PTA	Bilateral Normal Hearing % (*n*)	Bilateral SNHL % (*n*)	Unilateral SNHL/ CHL % (*n*)
Bilateral Normal Hearing	92.1% (186)	0.5% (1)	7.4% (15)
Bilateral SNHL	23.6% (29)	43.9% (54)	32.5% (40)
Unilateral SNHL/ CHL	10.3% (7)	8.8% (6)	80.9% (55)
	Referral category based on SRT cut-off: Antiphasic -15.0 dB SNR; Diotic 0.208 * Antiphasic SRT – 7 dB SNR (Fig.5B)		
HL type based on PTA	Bilateral Normal Hearing % (*n*)	Bilateral SNHL % (*n*)	Unilateral SNHL/CHL % (*n*)
Bilateral Normal Hearing	89.1% (180)	5.9% (12)	5.0% (10)
Bilateral SNHL	16.3% (20)	71.5% (88)	12.2% (15)
Unilateral SNHL/ CHL	4.4% (3)	35.3% (24)	60.3% (41)
	Referral category based on SRT and BILD cut-off: Antiphasic -15.0 dB SNR; BILD 0.5 (Fig. 5C)		
HL type based on PTA	Bilateral Normal Hearing % (*n*)	Bilateral SNHL % (*n*)	Unilateral SNHL/CHL % (*n*)
Bilateral Normal Hearing	89.1% (180)	10.9 % (22)	0% (0)
Bilateral SNHL	16.3% (20)	69.1% (85)	14.6% (18)
Unilateral SNHL/CHL	4.4 % (3)	51.5% (35)	44.1% (30)
	Referral category based on SRT and BILD cut-off: Antiphasic -15.0; BILD -0.792*Antiphasic SRT – 7 dB SNR (Fig 5D)		
HL Type based on PTA	Bilateral Normal Hearing % (*n*)	Bilateral SNHL % (*n*)	Unilateral SNHL/CHL % (*n*)
Bilateral Normal Hearing	89.1% (180)	5.9% (12)	5% (10)
Bilateral SNHL	16.3% (20)	71.5% (88)	12.2% (15)
Unilateral SNHL/CHL	4.4% (3)	35.3% (24)	60.3% (41)

HL indicates hearing loss; SRT, speech recognition threshold; dB, decibel; SNR, signal to noise ratio; SNHL, sensorineural hearing loss; CHL, conductive hearing loss.

In addition, we present the same two cut-off approaches based on the antiphasic DIN SRT and the derived BILD (Figure 5C & D). The overall percentage of correctly classified participants was the same as the antiphasic and diotic DIN SRT procedure when using either a fixed antiphasic and BILD cut-off (75%), or a sloping BILD cut-off (79%). As expected, the maximum achievable percentage procedure, with sloping BILD cut-off, produced the exact same categorization of participants as the antiphasic and diotic cut-off procedure (Table 4). For the fixed BILD cut-off, the cutoff value of 0.5 dB SNR demonstrated that participants with unilateral or asymmetric SNHL/CHL are expected to have minimal unmasking. However, the fixed cut-off procedure had a higher proportion of incorrectly identified unilateral or asymmetric SNHL/CHL with higher rates of correctly identified bilateral SNHL than the antiphasic and diotic DIN SRT procedure (Table 4).

DISCUSSION

The antiphasic DIN sensitivity and specificity were 90% and 85%, respectively, for detecting hearing loss in our sample of participants with different types of hearing loss, with outstanding

AUROC values of exceeding 0.94 to identify hearing loss in the poorer ear. These findings confirm the results from the initial development of the antiphasic DIN in a much larger sample (De Sousa et al. 2020b). The DIN has previously been used for detecting hearing loss with a *pass* or *refer* (Leensen et al. 2011; Potgieter et al. 2016; Smits et al. 2004; Watson et al. 2012). This study demonstrates that a combined antiphasic and diotic DIN approach could further categorize different hearing loss types with reasonable accuracy to direct patients for either audiological-, or, medical assessment.

Predictors and normative ranges of antiphasic and diotic DIN SRT

The first study objective was to determine predictors of antiphasic and diotic DIN SRT. As expected, PTA was a strong predictor of SRT across all types of hearing loss (Koole et al. 2016; Smits et al. 2004), although the relationship varied between better and poorer ear for different types of hearing loss and the different test presentations. For normal hearing and bilateral SNHL, the degree of prediction of better and poorer ear PTA for either diotic or antiphasic DIN was not expected to differ much since those groups of particpants had symmetric hearing ability. Still, better ear PTA accounted for more of the variance in diotic DIN SRT, whereas poorer ear was the main predictor of antiphasic DIN SRT. The variance explained in unilateral or asymmetric SNHL was not significant for either poorer or better ear PTA when presented diotically. In diotic conditions, a person with unilateral hearing loss will recognize digit triplets presented in the better ear (De Sousa et al. 2020b). Thus, diotic DIN SRTs closely resembled normal hearing when the loss was unilateral (Table 1). The same was seen for CHL, either unilateral or bilateral. Previous studies showed high performance of the diotic DIN to detect bilateral SNHL with AUROC of 0.93 and sensitivity and specificity of more than 80% (Potgieter et al. 2018). Monaural DIN tests also had notable AUROC between 0.86 and 0.98 (Koole et al. 2016; Smits et al. 2004; Vercammen et al. 2018). In comparison, this study had a lower diotic performance with AUROC of 0.83 and sensitivity and specificity of 82% and 56%, owing to the broad range of hearing loss types included in the sample.

Poorer ear PTA predicted only marginally more variance in antiphasic DIN SRT than the better ear for normal hearing and bilateral SNHL, but explained considerably more of the variance for unilateral or asymmetric SNHL and CHL. Studies of binaural hearing have proposed sensitivity to phase information (or temporal fine structure) as a predictor of speech in noise ability (Neher et al. 2012; Santurette et al. 2012; Strelcyk et al. 2009). Stimulus phase is determined monaurally, requiring good monaural coding fidelity, and is relayed to the auditory brainstem where the two signals are combined (Neher et al. 2012). When target speech is presented with phase differences in the presence of a diotic masker, as with the antiphasic DIN, the central auditory system can benefit from binaural cues to better detect and code speech in acoustically complex situations (Hall et al. 1995; Neher et al. 2012; Wack et al. 2012). This phenomenon, described long ago by Hirsch (1948) and Licklider (1948), is commonly known as binaural masking level- or intelligibility level difference (Hirsh 1948; Licklider 1948). The antiphasic DIN SRT is thus a measure of binaural hearing as opposed to only the function of the better ear (De Sousa et al. 2020b). Peripheral hearing loss of any type is known to degrade coding of temporal fine structure by desynchronizing the timing of action potentials (Kortlang et al. 2016). Where hearing asymmetry exists, such as unilateral SNHL, interaural coding fidelity is disrupted, and the antiphasic advantage decreases. CHL interferes with phase processing by delaying and attenuating sound passing through the affected ear (Hartley and Moore 2003). If any phase detail differs between the ears due to the CHL, coding fidelity is disrupted. The degree to which antiphasic processing is disrupted by peripheral hearing loss in the current study, was more strongly correlated to the degree of hearing loss in the poorer ear. Antiphasic DIN was, therefore, highly sensitive to detect different types of hearing loss, including unilateral or asymmetric SNHL and CHL, as opposed to diotic DIN which was insensitive to unilateral or asymmetric SNHL and CHL.

Our findings did not support a substantial influence of age since covarying for age did not improve sensitivity and specificity for either diotic or antiphasic DIN SRT significantly. However, the contribution of adding age in our analysis is complex due to the wide range of hearing loss types and symmetries included, and the interaction between age and the groups of participants (Table 1). Previous findings on the influence of age have been mixed. Koole and colleagues (2016) also found a low correlation between DIN SRT and age after controlling for PTA although their participants only included older adults between 51 to 97 years. Other reports have shown that older people tend to perform more poorly on the DIN, after controlling for PTA (Dawes et al. 2014; Moore et al. 2014; Vercammen et al. 2018), which may be attributed to declining cognitive function (Moore et al. 2014). Nonetheless, results of the current analysis did not support the requirement for age-corrected cut-off values for the diotic and antiphasic DIN. Test-retest reliability for the DIN has been confirmed in previous reports, and has shown high agreement between test repetitions for both diotic (Potgieter et al. 2016) and antiphasic DINs (De Sousa et al. 2020a). However, it is expected that the SRT of a second test would be better than for the first test for naïve listeners, due to a procedural learning effect (Smits et al. 2013). . In addition, the diotic DIN typically presents with lower measurement error (1.1 dB) than the antiphasic DIN (1.4 dB) but the between-subject variance is higher for the antiphasic DIN (De Sousa et al. 2020a). In this study, we did not include test-retest as part of our test battery, because we aimed to investigate the results as it would be implemented as a part of a sequential antiphasic and diotic DIN test procedure. In future, it may be considered to include a few training trials to minimize the effect of procedural learning

Sequential antiphasic and diotic DIN procedure to detect and categorize hearing into groups

Hearing loss could be categorized into three groups of (a) normal hearing, (b) bilateral SNHL, and (c) unilateral or asymmetric SNHL or CHL when allowing the second, diotic test for people who failed the initial antiphasic DIN. Groupings of these different antiphasic and diotic DIN SRTs, or antiphasic DIN SRT and BILDs, allowed for categorization of hearing loss types into these groups with reasonable accuracy.

The first method, using fixed diotic and antiphasic SRT cut-offs (Table 4), accurately classified normal hearing (92.1%) and unilateral or asymmetric SNHL/CHL (80.9%), but resulted in more than half (56.1%) of the participants with bilateral SNHL incorrectly classified as normal hearing, unilateral or asymmetric SNHL or CHL. Applying the same fixed cut-off procedure to the combination of antiphasic SRT and BILD accurately classified high proportions of normal hearing (89.1%) and bilateral SNHL (69.1 %); however, more than half of unilateral or asymmetric SNHL or CHL was incorrectly classified as bilateral SNHL or normal hearing. A fixed cut-off procedure for BILD may, therefore, not be an optimal procedure.

The second method, using a fixed but reduced antiphasic cut-off and a sloping diotic cut-off, captured a higher overall proportion of hearing loss (79%), including correctly categorized bilateral SNHL. However, this came at the cost of more normal hearing participants in the HL categories (10.9%) and a reduction in the proportion of correctly identified unilateral or asymmetric SNHL or CHL (20.6%). Therefore, the second method does not represent the optimal choice as a triage tool if the primary goal is to identify the maximum proportion of unilateral or asymmetric SNHL or CHL cases. Using a sloping cut-off for the BILD is essentially the same and provides the same accuracy (see Table 4). It is important to note that the majority of incorrect classifications using either a sloping BILD or diotic SRT cut-off, were people with normal hearing or milder forms of hearing loss in the poorer ear (PTA < 40 dB HL).

As a triage tool, people with bilateral SNHL could be eligible for a direct referral to a hearing aid provider or even, direct-to-consumer or over-the-counter hearing aids, while unilateral or asymmetric SNHL, CHL or mixed hearing loss are “red flag” cases indicative of potential ear disease that should be referred for full medical and audiological assessment (AAO-HNS, 2014). Ear diseases such as cholesteatoma, otitis media, or acoustic neuroma may have adverse or even life-threatening implications when diagnosis and treatment are delayed (Greenberg et al. 2001; Osma et al. 2000; Spilsbury et al. 2010; Suzuki et al. 2010). On this basis, it seems reasonable to recommend the first method (Table 4); DIN SRT screening cut-offs that most correctly categorize hearing loss types requiring medical referral (unilateral SNHL or CHL; 80.9%), even though more bilateral SNHL (32.5%) will be referred along this same path. Nevertheless, fewer than 10% of people with hearing loss are identified as having normal hearing for either cut-off method. Due to the DIN's increasing popularity as a remote self-test screening tool, these approaches could allow for self-directed first-line referrals to medical or audiological centres.

Other clinical applications and implications for future research

The COVID-19 pandemic has placed a significant strain on clinic-based models of audiological care due to the necessity for physical distancing. The need for remote care options has dramatically increased across health disciplines in the past year (Keesara et al. 2020). This sequential antiphasic and diotic DIN test procedure could act as a simple remote triage tool to identify and prioritize cases requiring traditional clinic-based audiometric testing as well as medical referral (unilateral or asymmetric SNHL and CHL) from those who can proceed with remote low-touch models of care (bilateral SNHL). Discriminating between unilateral or asymmetric SNHL and CHL based purely on DIN SRTs would not be possible as applied in the current study. However, differentiating unilateral or asymmetric SNHL/CHL could be supported by using brief case history questions (e.g., questions targetting specific information such as history of ear-pain, active drainage, bleeding from an ear, sudden onset or progressive hearing loss etc.).

Another potential application is to enable more accountable provision of hearing aids in non-traditional models like OTC. Conventionally, the only way to obtain a hearing aid was after an evaluation of the auditory system by a licensed professional. The US Food and Drug Administration (FDA), however, published a nonbinding recommendation report no longer enforcing the requirement for a medical evaluation before taking up amplification (FDA 2016). The US House of Representatives also passed the Over-the-Counter Hearing Aid Act of 2017 with the bill mandating that the FDA create a category for OTC hearing devices for people with mild-to-moderate hearing loss (The Hearing Review 2017). Although much research is still required on the regulation of these devices, sales of OTC or direct-to-consumer hearing devices will likely increase as indicated by current trends (The Hearing Journal 2021). A method to differentiate the risk of medical conditions as presented in this study could detect hearing loss deemed unsuitable for OTC hearing devices. Childhood hearing screening programs could also benefit from this approach, considering that CHL linked with otitis media is more prevalent among children than adults. The simple test paradigm using familiar digits in DIN tests allows for reliable responses in children as young as four years (Koopmans et al. 2018; Wolmarans et al. In Press), although young children may need an adult to facilitate the test procedure. Furthermore, suprathreshold testing provides the benefit of being less sensitive to ambient noise as school age-hearing screening is typically conducted outside a soundproof booth. A validation study of this DIN classification method in pediatric populations is recommended.

This report makes a unique contribution to the current DIN literature with respect to the diversity of hearing loss types examined, using both diotic and antiphasic approaches. The only other study in the literature that used the DIN to determine hearing loss type (CHL from bilateral SNHL) was from our previous work, which considered a combination of pure tone air conduction audiometry and diotic DIN (De Sousa et al. 2020a). This work used binomial logistic regression analysis to examine the combined effects of PTA, diotic DIN SRT, and age to determine the likelihood that listeners had CHL as opposed to bilateral SNHL. It showed very high accuracy to discriminate between the two hearing loss types, with an AUROC of 0.94 and provided the advantage of low-touch audiometry without bone conduction audiometry. Although the current study was the first successful attempt to discriminate bilateral SNHL from other type of hearing loss, including unilateral or asymmetric SNHL, and potential referral routes based solely on the use of DIN SRTs, it should be kept in mind that the CHL and unilateral SNHL samples were small relative to the normal hearing and bilateral SNHL samples. Ideally, the validity of the proposed test method should be evaluated in a larger cohort of listeners with CHL, unilateral SNHL, and mixed hearing loss. Although not assessed in this study, it is possible that participants with poor SRTs and BILDs that are inconsistent with the degree of hearing, may have underlying auditory processing deficits. The effect of auditory processing disorders or listening difficulty on DIN test performance could also be investigated in future studies.

CONCLUSIONS

The antiphasic DIN was confirmed as a superior screening tool to the diotic DIN to detect hearing loss across a range of hearing loss types. Poorer ear PTA was the primary predictor of antiphasic SRT, whereas better ear PTA related best to diotic DIN SRT performance. Adult age did not have a significant influence on sensitivity and specificity. Age-corrected cut-offs are thus not recommended. A two-step procedure, first an antiphasic DIN and then a diotic DIN, classified hearing into three categories of (a) normal hearing, (b) bilateral SNHL, and (c) unilateral or asymmetric SNHL or CHL with a reasonable degree of accuracy. This type of approach can optimize care pathways by identifying unilateral or asymmetric SNHL or CHL as cases requiring medical referral. In contrast, bilateral SNHL confirmed categories may be referred directly to an audiologist, or support non-traditional models like OTC hearing aids.

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