Speech Recognition in Noise Using Binaural Diotic and Antiphasic Digits-in-Noise in Children: Maturation and Self-Test Validity

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Abstract

Background: Digits-in-noise (DIN) tests have become popular for hearing screening over the past 15 years. Several recent studies have highlighted the potential utility of DIN as a school-aged hearing test. However, age may influence test performance in children due to maturation. In addition, a new antiphasic stimulus paradigm has been introduced, allowing binaural intelligibility level difference (BILD) to be measured by using a combination of conventional diotic and antiphasic DIN.

Purpose: This study determined age-specific normative data for diotic and antiphasic DIN, and a derived measure, BILD, in children. A secondary aim evaluated the validity of DIN as a smartphone self-test in a subgroup of young children.

Research Design: A cross-sectional, quantitative design was used. Participants with confirmed normal audiometric hearing were tested with a diotic and antiphasic DIN. During the test, arrangements of three spoken digits were presented in noise via headphones at varying signal-to-noise ratio (SNR). Researchers entered each three-digit spoken sequence repeated by the participant on a smartphone keypad.

Study Sample: Overall, 621 (428 male and 193 female) normal hearing children (bilateral pure tone threshold of ≤ 20 dB hearing level at 1, 2, and 4 kHz) ranging between the ages of 6 and 13 years were recruited. A subgroup of 7-year-olds ($n = 30$), complying with the same selection criteria, was selected to determine the validity of self-testing.

Data Collection and Analysis: DIN testing was completed via headphones coupled to a smartphone. Diotic and antiphasic DIN speech recognition thresholds (SRTs) were analyzed and compared for each age group. BILD was calculated through subtraction of antiphasic from diotic SRTs. Multiple linear regressions were run to determine the effect of age on SRT and BILD. In addition, piecewise linear regressions were fit across different age groups. Wilcoxon signed-rank tests were used to determine differences between self- and facilitated tests.

Results: Age was a significant predictor, of both diotic and antiphasic DIN SRTs ($p < 0.05$). SRTs improved by 0.15 dB and 0.35 dB SNR per year for diotic and antiphasic SRTs, respectively. However, age effects were only significant up to 10 and 12 years for antiphasic and diotic SRTs, respectively. Age significantly ($p < 0.001$) predicted BILD, which increased by 0.18 dB per year. A small SRT advantage for facilitated over self-testing was seen but was not significant ($p > 0.05$).

Conclusions: Increasing age was significantly associated with improved SRT and BILD using diotic and antiphasic DINs. DIN could be used as a smartphone self-test in young children from 7 years of age with appropriate quality control measures to avoid potential false positives.

Keywords: age; children; diotic; antiphasic; speech recognition threshold; binaural intelligibility level difference

More than 34 million children globally are estimated to have disabling hearing loss.[1] Unidentified childhood hearing loss has a pervasive impact on academic achievement, self-esteem, behavior and energy, socioemotional ability, and vocational opportunity.[2] [3] [4] [5] [6] Newborn infants should be screened for hearing after birth, but due to poor adherence to or the absence of neonatal hearing screening,[7] [8] loss to follow-up,[9] [10] and progressive or acquired hearing loss,[11] childhood hearing loss is not adequately assessed or managed, even in high-income countries. Concerns around noise-induced hearing loss have also increased due to the use of personal audio devices among the youth,[12] [13] which has been identified in children as young as 7 years.[14]

Periodic hearing screenings in schools are often the first point of access for children who are not screened at birth[15] and is a valuable strategy to identify late onset and acquired childhood hearing loss. Current protocols for school-aged screening recommend pure tone audiometry (PTA).[16] While pure tone testing is an accurate method for detection of hearing loss, it is reliant on trained personnel and expensive audiometric equipment that must be calibrated regularly to industry standards. More recently, speech-in-noise tests have become available to the public on self-test platforms like the World Health Organization's (WHO's) hearWHO app.[17] The digits-in-noise (DIN) test, which measures the ability to accurately recognize 50% of digit triplets (e.g., 3–4–7) presented in speech-weighted masking noise (speech recognition threshold [SRT]), was introduced in 2004 in the Netherlands.[18] The test is known for its robustness because it can be used without calibrated equipment, can be self-administered, and is less sensitive to ambient noise than traditional pure tone testing.[18] [19] More importantly, the DIN test is quick and can be administered through technology that most people already have.[17] Furthermore, the test correlates favorably with pure tone average thresholds and has high specificity and sensitivity (>90%) to detect sensorineural hearing loss in adults.[20] [21] Consequently, the DIN was first developed for landline telephone[18] and later for mobile[21] [22] and Internet platforms.[17] [23]

The first downloadable Internet app-based version of the DIN test was released in 2016 as South Africa's national hearing test[21] and has had wide-ranging uptake since its release.[24] Although the test was primarily intended for adults, it has been proposed to be a viable test for children[25] [26] since digits are easily understood, even by listeners with low linguistic competence (Kaandorp et al, 2016). The use of simple closed-set digits limits the contribution of top-down processing. Furthermore, a study by Koopmans et al[26] showed that when facilitated by a test administrator, the test can accurately be conducted in children as young as 4-years old. However, when unassisted, young children tend to perform poorly.[25] In a review of the characteristics of people who used the South African app-based DIN test, it was found that over 1,200 children between 5 and 15 years of age were tested in a 2-year period despite the app indicating use for adults only.[24] It, therefore, seems that there is a parental interest in mobile tools to screen their children's hearing.

Children often listen to speech in acoustically demanding situations where there is a dependence on their ability to separate speech from noise using binaural and other cues.[26] Besides good peripheral hearing, cognitive factors such as working memory, attention, and auditory processing (e.g., temporal processing) also play a role in the ability to accurately recognize speech in noise.[27] [28] Speech recognition in noise is, therefore, a developmental process where performance improves with increasing age in childhood. Buss et al[29] investigated masked sentence recognition in children, young adults, and older adults using various maskers. They found that SRTs were better for young adults (19–30 years) than children (5–16 years) for both speech-shaped noise and two-talker speech maskers. The development of language and vocabulary can arguably result in better performance for young adults in sentence recognition, yet maturation effects on closed-set word recognition in stationary speech-shaped noise have also been shown in children between 5 and 13 years of age.[30] Supportive of these findings, Koopmans et al[26] found that there was a significant age effect in the performance of children between 4 and 12 years of age using the DIN, highlighting a need for age-specific child norms.

There are several versions of the DIN, differing in either language, test procedure, or both. In previous landline and computer-based versions, DIN thresholds were measured sequentially in each ear[18] [19] [31] or measured binaurally,[21] where identically phased speech is presented to both ears simultaneously in the presence of masking noise. Although the binaural diotic version is time efficient, with a typical test completed within 3 minutes,[20] [21] it lacks sensitivity to unilateral hearing loss because the SRTs reflect the performance of the better ear.[22] Furthermore, suprathreshold tests like the DIN, either monaural or diotic, do not detect conductive hearing loss.[22] The most common hearing loss in young children is conductive, related to otitis media[32] and wax impaction.[33] To enable accurate hearing loss detection, the test would have to be sensitive to these types of hearing loss.

Recently, the interaural 180-degree phase-inverted (antiphasic) digits were used to increase sensitivity of the DIN to a wider variety of hearing losses.[17] [22] [34] If a stimulus is phase inverted with a diotic masker, the ability to detect target stimuli improves. This phenomenon was described long ago,[35] [36] with the combination of diotic and antiphasic low-frequency tone stimulus presentation used to determine the binaural masking level difference (BMLD) or binaural intelligibility level difference (BILD) when using speech stimuli. BILD is a measure of the ability both to spatially segregate speech from noise and to understand speech-in-noise, relying on both accurate coding of interaural phase in the auditory brainstem, and decoding and identification of speech in the auditory cortex.[35] [36] Interaural phase inversion of the digits produces asynchronous neural coding in the brainstem,[37] [38] [39] improving recognition threshold of the digits. Research has demonstrated that in the inferior colliculus, both single and populations of neurons have lower masked thresholds to $NoS\pi$ than to NoSo.[40] Therefore, different populations of neurons are responsible for tone detection in these two conditions. In-phase (So) signals were detected by an increased discharge rate while phase-reversed ($S\pi$) signals were detected by a decreased discharge. Single neuron response to binaural unmasking signals was consistent with their sensitivity to the interaural delay of the tones and noises. Furthermore, the decrease in discharge rate indicating the presence of $S\pi$ signals was caused by a desynchronization of the activity due to the masking noise at the brain stem coincidence detectors.[40]

Impairments in either the ear (sensorineural or conductive hearing loss) or the brainstem (e.g., auditory neuropathy) disrupt the use of the phase difference between noise and digits, leading to reduced binaural unmasking.[37] [38] [39] Thus, by implementing antiphasic speech to the DIN test, De Sousa et al[22] could improve the sensitivity of a rapidly conducted binaural DIN test to bilateral sensorineural, unilateral sensorineural, and conductive hearing loss. The DIN had larger areas under the Receiver Operating Characteristic curve for detection of hearing loss (>25 decibels in hearing level [dB HL]) for antiphasic (0.94) than for diotic (0.77) presentation.[22] By completing both a standard diotic and antiphasic DIN, the BILD can be determined simply by subtracting the antiphasic from the diotic SRT.

The BMLD or BILD, when using speech stimuli as described by Hirsh[35] and Licklider,[36] could improve one's ability to detect target stimuli. Recently, a group of researchers[17] [22] [34] investigated this phenomenon by utilizing interaural 180-degree phase-inverted (antiphasic) digits to increase sensitivity of the DIN to a wider variety of hearing losses. This interaural phase inversion of the digits produces asynchronous neural coding in the brainstem,[37] [38] [39] improving recognition threshold of the digits. Although the antiphasic DIN is considered to be a sensitive hearing screening measure in adults and is used in the WHO hearscreen app,[17] there is no consensus on how BILD (derived from the antiphasic SRT) develops with age.[41] Research shows BILD does not significantly differ between adults and children.[42] [43] Other studies have found that BILDs increase with increasing age.[44] Some studies report that spatial release of masking is adult-like at a young age (e.g., 4–6 years)[45] [46] [47] while others show a developmental trajectory.[26] [48] [49]

Practically, age-specific normative criteria should be available for the diotic and antiphasic DIN, to relate the results of children tested to that of their peers. Determining normative criteria is a large undertaking because many children in different age groups should be tested to accurately reflect mean test scores and confidence intervals.[26] This study, therefore, investigated diotic and antiphasic DIN SRTs and the derived BILD in a large sample of school-going children between 6 and 13 years of age. A secondary objective was to determine the validity of self-testing on a smartphone compared with facilitated testing in a subgroup of 7-year-old children.

Method

Institutional review board approval was obtained from the Humanities Research Ethics Committee, University of Pretoria (protocol number: HUM020/0119), prior to data collection. The schools and caregivers/parents were informed of the study's aims and provided consent. Furthermore, children provided assent before data collection procedures began.

Participants

Initially, 661 participants were purposively sampled from 4 English private schools in the City of Tshwane, South Africa, and stratified according to age. However, only 621 met the inclusion criteria of normal hearing (bilateral PTA ≤ 20 dB HL at 1, 2, and 4 kHz),[50] and normal outer and middle ear function (428 male and 193 female). Included participants were in grades 1 to 7 and ranged in age from 6 to 13 years (mean, 9.6; standard deviation [SD], 2.1). Participants were categorized into English first language ($n = 556$) and English additional language (EAL; $n = 65$) groups. A subgroup of 7-year-olds ($n = 30$) was selected to determine the validity of self-testing on a smartphone compared with facilitated testing of diotic and antiphasic SRTs.

Material and Apparatus

A Welch Allyn PocketScope™ was used to examine the ear canal and tympanic membrane for any abnormalities. A calibrated tympanometer (MAICO ERO•SCAN® Pro) was used to determine the participant's middle ear functioning to rule out a conductive component.

A Type 4 screening audiometer (hearScreen™, hearX group, Pretoria, South Africa) connected to calibrated circumaural headphones (Sennheiser HD280 Pro, Germany) was used to identify normal hearing children. Prior to data collection, the circumaural headphones were calibrated according to prescribed standards (ANSI/ASA S3.6–2010). The protocol defined a screening failure as the inability to detect 20 dB HL at one or more frequencies (1, 2, and 4 kHz) in either ear. The DIN application ran on a smartphone (Samsung SM-J200H) with circumaural headphones (Sennheiser HD280 Pro). Calibration is not required since the DIN is presented suprathreshold, and headphone type has been shown to not have a significant effect on SRT.[21]

Procedures

Screening audiometry, tympanometry, and otoscopy were conducted on all children to ensure only those with normal hearing, and outer and middle ears were included in the study sample. Participants with abnormalities in outer or middle ear results or those who failed the screening were excluded from the study and referred for further intervention.

Participants who passed the initial hearing screening underwent DIN testing. The current DIN used the same procedure as described in De Sousa et al.[22] The stimuli were diotic and antiphasic South African English digits from 0 to 9, spoken by a female native speaker.[22] [24] The application used the equalized digit material from Potgieter et al.[21] There the speech recognition function of each digit was determined using a logistic function and maximum likelihood procedure, and the signal-to-noise ratio (SNR) corresponding to 50% correct was determined. Level corrections were applied to ensure that each digit had a 50% chance of being recognized correctly at the same SNR. The diotic test paradigm (NoSo) presented identically phased digits and masker simultaneously to both ears, whereas antiphasic presentation (NoSπ) presented digits with a 180° phase shift between the ears in the presence of a diotic masker.[22] [26] [34] A single DIN test consisted of 23-digit triplets that were randomly selected from a list of 120 different digit (0–9) triplets.[21] Digit triplets were compiled with 200 ms silent intervals and 100 ms of uniform jitter between single digits to add some uncertainty in the listening task about when the next digit will be presented.[21] Before and after each triplet, there were 500 ms silent intervals. Speech-shaped masking noise had the same spectrum as the long-term average speech spectrum of the digits without any silences.[21] [51] A fixed noise level and varying speech level were used when triplets with negative SNRs were presented. However, to ensure a relatively constant overall level of the stimuli, the noise level varied and the speech level was fixed once the SNRs became positive.[21] This procedure prevents clipping of the signal and provides a comfortable listening experience to the user. The test started at 0 dB SNR and followed a one-up, one-down adaptive procedure, tracking where 50% of digit triplets could be recognized correctly. The first three steps were reduced in 4dB SNR for correct triplets, and increased in 2dB for incorrect triplets. After the first three triplets, the test continued in fixed 2dB steps. A triplet was only considered correct when all three digits were entered correctly. The final SRT was calculated as the average SNR of the last 19 triplets.[21] [22]

The tests were conducted by the researcher in a quiet room to avoid noise disturbances and minimize possible distractions. The order of the diotic and antiphasic conditions was counterbalanced across participants to counteract test order bias. The researcher explained the procedure before testing, and the participants were instructed to listen to the digit triplet and repeat them once they were heard. Whenever participants were uncertain, they were instructed to guess. The test operator entered the participant's responses (the digits) on the smartphone keypad.

To determine the validity of self-testing compared with facilitated testing, l 30 of the children aged 7 years also self-registered their responses. Four DIN tests were done, with a self-test and facilitated test in each condition (antiphasic and diotic). The DIN test procedure was counterbalanced for both diotic and antiphasic stimuli, and self- and facilitated testing. Self-administered testing required participants to listen to the digit triplets and enter them on the smartphone keypad. Whenever they were uncertain of what they heard, they were instructed to guess. During facilitated testing, a researcher entered the child's verbal responses into a smartphone keypad. The facilitated and self-reported responses were collected in the same set of trials.

Data Analysis

Raw data were captured onto a Microsoft Excel spreadsheet and analyzed using statistical software (Statistical Package for the Social Sciences, IBM SPSS, v25; Chicago, Illinois). Descriptive statistics included means, standard deviations, and percentages. After inspecting skewness, kurtosis values, and boxplots, multiple outliers were identified. Outliers ($n = 16$ diotic; $n = 18$ antiphasic) were judged as unreliable if the ceiling SNR was reached (i.e., a positive SNR of 22.5 dB SNR) or in the case of high SD from the mean SRT (≥2 SD). Linear regressions were run to determine the effect of age, gender, and EAL on diotic and antiphasic SRT and BILD. Furthermore, piecewise linear regressions were run across different age groups. Wilcoxon signed-rank tests were run to determine the difference between self- and facilitated DIN testing since not all variables were normally distributed (Shapiro-Wilk $p < 0.05$).

Results

The distribution of diotic and antiphasic DIN SRTs is presented in [Tables 1] and [2], respectively. It is, however, important to note that inter-subject variability is always larger in antiphasic than in diotic conditions. The linear regression indicated a negative association between age and SRT in both the diotic and antiphasic conditions (see [Fig. 1]). That is, younger children tended to have higher (i.e., poorer) SRTs than older children. Age was the only factor that significantly ($p < 0.001$) predicted diotic (F[3.601] = 23.756; adj. $R^2 = 0.10$) and antiphasic SRTs (F[3.599] = 49.598; adj. $R^2 = 0.20$). A 1-year increase in age was associated with a 0.15 dB decrease in diotic SNR (95% confidence interval [CI]: –0.188 to –

0.116) and a 0.35 dB decrease in antiphasic SNR (95% CI: –0.404 to –0.291). Piecewise linear regressions were fit across different ages to determine where age no longer significantly predicted antiphasic and diotic SRTs ([Fig. 1]). Age significantly ($p < 0.001$) predicted antiphasic SRT up to 9.9 years (F[1.337] = 14.175; adj. $R^2 = 0.038$; [Fig. 1A]) and diotic SRT up to 11.9 years (F[1.488] = 21.764; adj. $R^2 = 0.041$; [Fig. 1B]). From 10 and 12 years onward, for antiphasic (p = 0.062) and diotic (p = 0.194) SRTs respectively, age was not a significant predictor anymore. Additionally, linear regressions were done to investigate whether age, gender, and EAL predicted BILD. Across participants, only age significantly ($p < 0.001$) predicted BILD (F[1.169] = 24.560; adj. $R^2 = 0.037$). A 1-year increase in age was associated with a 0.17 dB increase in BILD (95% CI: 0.111–0.256). The distribution of BILD across age groups is shown in [Table 3]. In addition, piecewise linear regressions were fit across different ages to determine where age no longer significantly predicted BILD ([Fig. 2]). Age only significantly predicted BILD up to 9.9 years (F[1.335] = 4.04; adj. $R^2 = 0.01$; $p < 0.05$). From 10 years up, age was not a significant predictor (p = 0.888).

Table 1 Distribution of the average diotic SRT across age groups, standard deviation of the mean, range, and 90th percentile range (5th–95th percentiles)

Age in years	*n*	Mean (SD): dB SNR	Minimum: dB SNR	Maximum: dB SNR	5th–95th percentiles
6.0–6.9	74	−8.8 (0.8)	−10.6	−7.0	−10.2 to −7.5
7.0–7.9	82	−8.9 (1.0)	−11.2	−6.8	−10.6 to −7.2
8.0–8.9	92	−9.0 (0.9)	−11.2	−6.8	−10.5 to −7.0
9.0–9.9	87	−9.1 (0.9)	−11.0	−7.0	−10.4 to −7.4
10.0–10.9	75	−9.2 (0.9)	−11.0	−7.2	−10.6 to −7.6
11.0–11.9	78	−9.4 (1.0)	−11.8	−7.2	−11.0 to −7.8
12.0–12.9	83	−9.7 (1.1)	−12.4	−7.0	−11.6 to −8.0
13.0–13.9	34	−9.8 (1.0)	−11.6	−7.8	−11.5 to −8.1
Total	605	−9.2 (1.0)	−12.4	−6.8	−10.8 to −7.5

Abbreviations: dB, decibel; SD, standard deviation; SNR, signal-to-noise ratio; SRT, speech recognition threshold.

Table 2 Distribution of the average antiphasic SRT across age groups, standard deviation of the mean, range, and 90th percentile range (5th–95th percentiles)

Age in years	*n*	Mean (SD): dB SNR	Minimum: dB SNR	Maximum: dB SNR	5th–95th percentiles
6.0–6.9	79	−15.4 (1.6)	−18.6	−11.2	−17.4 to −12.4
7.0–7.9	81	−15.6 (1.5)	−19.4	−11.8	−18.4 to −13.0
8.0–8.9	93	−15.7 (1.6)	−20.0	−12.2	−18.0 to −12.8
9.0–9.9	87	−16.3 (1.5)	−19.8	−12.8	−19.2 to −14.1
10.0–10.9	72	−17.0 (1.3)	−19.8	−14.0	−19.1 to −14.3
11.0–11.9	74	−17.0 (1.4)	−20.4	−13.6	−19.6 to −14.5
12.0–12.9	83	−17.3 (1.4)	−20.6	−14.0	−19.8 to −14.8
13.0–13.9	34	−17.5 (1.4)	−19.4	−14.0	−19.3 to −14.6
Total	603	−16.4 (1.6)	−20.6	−11.2	−19.0 to −13.6

Abbreviations: dB, decibel; SD, standard deviation; SNR, signal-to-noise ratio; SRT, speech recognition threshold.

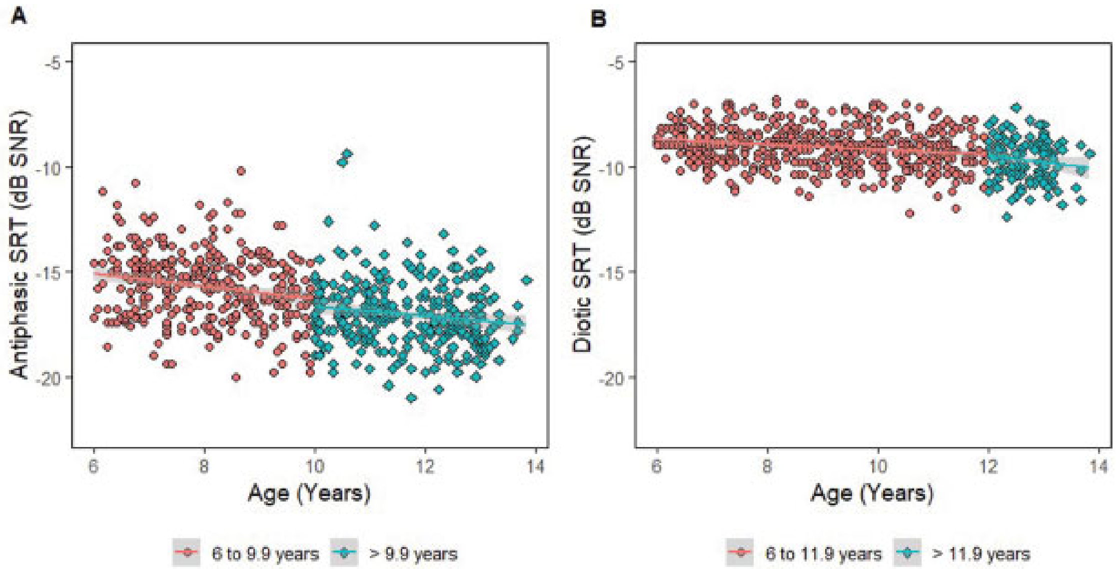

Fig. 1 (A) Antiphasic SRT according to age, with piecewise regressions fit to 6 to 9.9-years old and >9.9-years old. (B) Diotic SRT according to age, with piecewise regressions fit to 6 to 11.9-years old and >11.9-years old. SRT, speech recognition threshold; dB, decibel; SNR, signal-to-noise ratio.

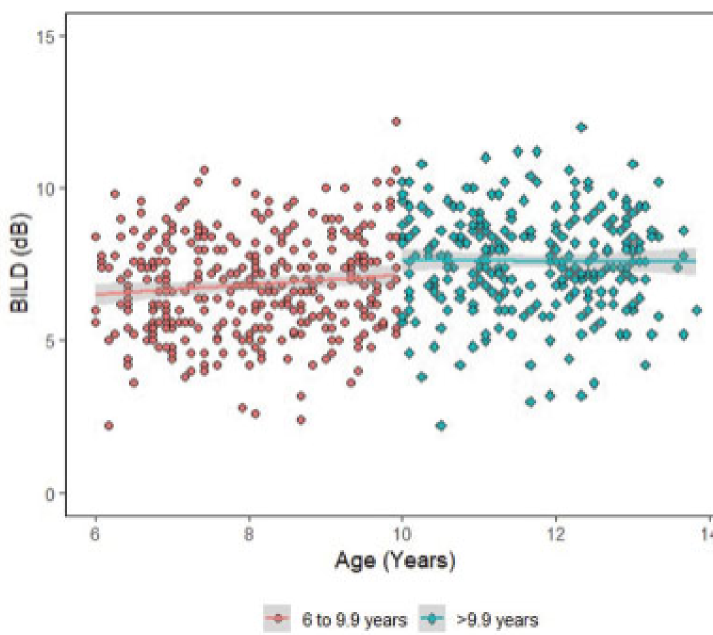

Fig. 2 Binaural intelligibility level difference (BILD) correlation with age (*n* = 593). BILD outliers excluded (*n* = 28/4.5%). Regressions are piecewise regressions fit to 6 to 9.9 years and >9.9 years.

Table 3 Distribution of the average BILD scores across age groups, standard deviation of the mean, range, and 90th percentile range (5th–95th percentiles)

Age in years	*n*	Mean (SD): dB SNR	Minimum: dB SNR	Maximum: dB SNR	5th–95th percentiles
6.0–6.9	73	6.8 (1.4)	3.6	9.8	4.7–9.3
7.0–7.9	81	6.6 (1.7)	2.8	10.6	4.0–9.6
8.0–8.9	81	6.7 (1.5)	2.6	9.8	4.3–9.3
9.0–9.9	87	7.2 (1.8)	3.6	12.2	4.7–10.2
10.0–10.9	72	7.7 (1.6)	3.8	10.8	4.7–10.1
11.0–11.9	74	7.6 (1.6)	3.0	11.2	4.8–10.3
12.0–12.9	81	7.7 (1.5)	3.6	12.0	5.2–10.2
13.0–13.9	34	7.7 (1.5)	4.2	10.8	5.0–10.4
Total	593	7.2 (1.6)	2.6	12.2	4.6–9.9

Abbreviations: BILD, binaural intelligibility level difference; dB, decibel; SD, standard deviation; SNR, signal-to-noise ratio.

Validity of Self-Testing

[Fig. 3] shows the diotic and antiphasic SRTs for self-test versus facilitated test. Two outliers deviating more than 2 SD from the mean were identified and excluded from the analysis. Mean diotic facilitated and self-test DIN SRTs were –9.1 (SD, 1.1) dB SNR and –8.7 (SD, 1.6) dB SNR, respectively. Antiphasic facilitated and self-test DIN showed mean SRTs of –15.6 (SD, 1.4) dB SNR and –14.8 (SD, 1.9) dB SNR, respectively. On average, facilitated testing was better than self-testing by 0.4 dB and 0.8 dB for diotic and antiphasic DIN, respectively. However, the difference was not significant for either diotic ($p = 0.218$) or antiphasic DIN ($p = 0.07$).

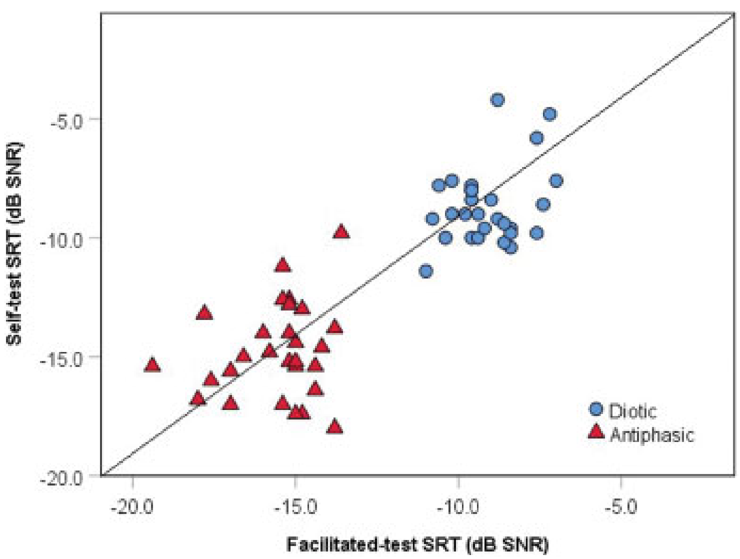

Fig. 3 Diotic and antiphasic SRTs according to facilitated test and self-test with outliers excluded (*n* = 2/6%). The diagonal line is a reference line. SRT, speech recognition threshold; dB, decibel; SNR, signal-to-noise ratio.

Discussion

The first objective of this study was to evaluate antiphasic and diotic SRTs in children between 6 and 13 years of age. Age-related effects were evident on both conditions, with an improvement of 0.15 dB SNR and 0.35 dB SNR per year in diotic and antiphasic conditions. However, age effects were only significant up to 10 and 12 years for antiphasic and diotic SRTs, respectively. De Sousa et al[22] used the same diotic and antiphasic DIN in normal hearing adults and showed mean antiphasic SRTs of –17.5 dB SNR and –10.4 dB SNR. These SRTs were only slightly better than the diotic SRT for children older than 12 years (–9.8 dB SNR) and antiphasic SRT for children older than 10 years (–17.2 dB SNR) in the current study. This suggests that the diotic and antiphasic DIN SRTs become adult-like between 10 and 12 years of age. The age effects of the SRTs are an important consideration to identify precise referral criteria in the context of child or school-age screening.

Previous DIN research also investigated speech recognition in children. Denys et al,[25] for example, used the DIN in a monaural setup, which showed a 0.2 dB decrease in SRT per year among children aged 9 to 16 years. Koopmans et al[26] investigated speech recognition abilities in children compared with adults using a similar diotic and antiphasic DIN to the current study. Children between 4 and 12 years were grouped according to age, and together with the adult group, results showed a significant effect of age on diotic and antiphasic SRTs.[26] Children from 10 years onward, however, performed comparable to adults in both conditions. These results are consistent with the current study showing age-related improvement of DIN SRTs, as are results from other studies investigating speech recognition in noise using different test materials.[26] [49] [52] [53] [54] [55] Furthermore, this study confirms that BILD, derived from the diotic and antiphasic DIN, improves with age, as reported previously for Dutch children.[26] A study conducted by Moore et al[56] did not find a significant age effect on BILD. This could be attributed to the lower sample size and the fact that they used tonal stimuli to determine BMLD.[56]

Previous researchers have attributed the high SRTs in young children to both auditory and nonauditory aspects, or a combination of the two.[26] [56] Specifically, these age-related improvements may be due to the maturation of the auditory system and ongoing development of binaural processing.[57] Other research suggests that linguistic and cognitive skills, attention, and working memory may also play a role in these developmental differences. For example, McCreery et al[58] showed that better working memory and selective attention skills were linked to better masked sentence recognition in two groups of children aged 5 to 6 years and 9 to 10 years. However, these nonauditory factors were not assessed in the current study.[59] Furthermore, it must be considered that the DIN was created to minimally rely on nonauditory factors. For example, nearly 99% of 6-year-old children can accurately recall three digits in forward direction.[60] Therefore, when Koopmans et al[26] compared a pediatric version of the DIN using single digits to the standard DIN using triplets, they did not find a significant difference between the two procedures, even when including children as young as 4-years old. On that account, it is unlikely that memory had a significant effect on DIN test performance and the use of a simpler pediatric version of the test can be considered unnecessary. Furthermore, minimum linguistic skills are required to complete the DIN and the effect of nonnative language is small in adults.[61] This study similarly did not find a significant effect of EAL speakers on SRT, but the notably smaller sample size in this group should be considered. Cognition is presumably another factor that can influence test performance. The degree to which cognition contributes to children's DIN test performance is still unclear. Moore et al[62] found a significant relation between measures of cognition and

DIN SRT in 40 to 70-year-old adults. On the other hand, Talarico et al[63] found that children with higher cognitive abilities do not perform significantly better than children with lower cognitive abilities on speech recognition tasks in speech-shaped noise. It should be noted, however, that the participants in the study reported here were recruited from mainstream private schools, with no obvious cognitive deficits or severe academic underachievement noted.

The secondary objective of this study evaluated the validity of a self-test DIN compared with a facilitated DIN test in younger children on a smartphone. Although there were no statistically significant differences between the self-test and facilitated test (diotic and antiphasic), the slightly lower SRTs in the self-test condition may be clinically significant in some cases. Including quality control measures, such as retesting by a facilitator when children fail a self-test DIN, may avoid false positives while capitalizing on the advantages of self-screening, for example, less human resource requirements. Increasing proficiency with mobile technology among children, even for those living below the poverty threshold, suggests that self-testing on a smartphone may become more widely accepted in the future.[64] [65] The relatively small SRT difference between self- and facilitated testing seen in this study can be explained by the fact that children seemed well adept at using touchscreen smartphones. A limitation of the study was that self-test reliability was not measured since a repetition of self- and facilitated testing was not completed. Previous studies have, however, reported evidence supporting reliable DIN testing even in young children. For example, Koopmans et al[26] conducted facilitated DIN among children aged 4 to 12 years and found that, after a practice run, there was no significant difference between test and retest. The measurement error was 1 dB, which corresponds well with the measurement error for adults.[51]

Denys et al[25] measured reliability by dividing the SNRs in the adaptive track by 2. Per child participant, the signed sample-based SD was taken into account for SRT measured during the first and second half of the DIN. The test reliability across participants was defined as the SD of these individual reliability estimates.[18] [25] Smits et al[18] and Denys et al[25] also found the DIN to be reliable across children between 9 and 16 years of age.

This study was able to confirm age-related improvements in diotic and antiphasic DIN SRTs, and BILD performance. Normative age-specific SRTs could, therefore, be determined. Furthermore, the DIN proved valid as a self-test for children 7 years and older. However, some remarks can be made regarding our analysis. We excluded participants who deviated more than 2 SD from the mean DIN scores as possible unreliable responses (~4.5%). All participants had normal hearing sensitivity, but it is possible that some of these outliers may have underlying deficits in memory, attention, or auditory processing. Although not assessed in this study, participants with poor BILDs (that can be derived from the diotic and antiphasic DIN) may have a possible auditory processing deficit. Further investigation into children with normal peripheral hearing, but abnormal DIN results will be informative and should be investigated in the future.

Conclusion

The current study suggests that children's speech recognition in noise abilities develop well into adolescence. Age-dependent normative data for the DIN test are required up to at least 10 and 12 years of age, for diotic and antiphasic conditions, respectively. A combined diotic and antiphasic DIN screening approach can provide two tests to determine pass/fail outcomes along with a derived BILD as an indicator of children's ability both to spatially segregate speech from noise and to understand speech-in-noise. Furthermore, the test can be used as a self-testing option on a smartphone for children from 7 years of age. Quality control measures that require children who fail a self-test to be rescreened by a facilitator could avoid potential false positives while improving efficiencies related to self-testing.

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Conflict of Interest

The authors David R. Moore and De Wet Swanepoel have a relationship with the hearX™ Group (Pty) Ltd, which includes equity, consulting, and potential royalties. The authors report no other conflicts of interest.

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