Research Article

Comparison of the Ling-6 Sound Test with Warble Tone Stimuli in Audiometry of Hearing-Impaired Children Using Hearing Aids Considering Different Prescriptions and Normal-Hearing Children

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Highlights

- Unaided/aided thresholds can be traced with Ling-6 sound test
- Be aware of audibility of the phonemes after the hearing aid fitting
- This results can be used as an evidence-based tool for speech detection

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ABSTRACT

Background and Aim: Speech is a vital stimulus and the ultimate goal of hearing aid fitting to make the speech an audible signal. The purpose of this research was to investigate whether it is possible to track the threshold with speech phonemes and which of the two fitting methods of Desired Sensation Level version 5.0 (DSL v5.0) and National Acoustic Laboratories-Nonlinear 2 (NAL-NL2) provide better audibility for the phonemes.

Methods: In this cross-sectional study, the unaided thresholds of 18 normal-hearing children and the aided thresholds of 15 hearing-impaired children aged 5-8 years were evaluated with two types of stimuli. DSL v5.0 and NAL-NL2 methods were used for hearing aid fitting in hearing-impaired children.

Results: There was a significant relationship between the unaided and aided thresholds of each phoneme and the warble tone threshold at the corresponding frequency ($p<0.01$), except for the phoneme /s/. The results showed a significant difference between the aided thresholds of each phoneme and the upper limit of the speech banana in the corresponding frequency for each method ($Z=-4.99$, $p\leq0.001$).

Conclusion: The results showed that phonemes could be used to assess unaided and aided thresholds. In the first fit, both methods estimated the amount of amplification that caused the average aided thresholds for these six phonemes for moderate to severe hearing loss to be positioned within the speech banana range, except for the average aided thresholds for the /s/ phoneme in the NAL-NL2 method that was placed outside the range.

Keywords: Ling-6 sound test; pediatric audiometry; desired sensation level version 5.0; national acoustic laboratories-nonlinear 2

Introduction

Hearing is a vital sense and one of the main methods to establish communication among humans [1]. The hearing system can be negatively affected by heredity, loud sound exposure, trauma, ototoxic drugs, and aging, leading to hearing loss. The loss can be caused by damage to any part of the auditory periphery and/or central pathway. Hearing loss is a complication that has a relatively high prevalence (almost 1 to 2 children in every 1000 births) [2-4] with an obvious negative impact on speech, linguistic, cognitive, and social-emotional skills [5, 6]. When hearing impairment is diagnosed and confirmed, hearing aid fitting is the first essential step to improving hearing and communicational skills in children with impaired hearing [7, 8]. Since speech is the most vital communication signal, the main target for the hearing aid fitting process is audible speech [9].

The auditory system is nonlinear [10] and speech is a complex acoustic stimulus full of temporal and spectral features; therefore, response to simple stimuli (such as pure tones, warble tones, etc.) cannot properly represent the response to speech sounds. Compared to words and sentences, speech phonemes have less acoustic complexity and can be controlled appropriately. In 1976, Daniel Ling designed a test in which the production of several phonemes with the experimenter's live voice was used as a tool to qualitatively assess the hearing status in low, medium, and high-frequency spectrums [11].

The phonemes used in the Ling test were /a/, /u/, /i/, /ʃ/, and /s/. Phoneme /m/ was later added and created in the Ling-6 sound test. The logic behind the Ling-6 sound test is the selection of everyday speech sounds that are within the speech frequency range of 250–8000 Hz. This range is similar to that assessed in conventional audiometry [11]. Audiologists, speech and language pathologists, teachers, and parents have long used the Ling-6 sound test to examine whether hearing aids and/or cochlear implants for hearing-impaired people properly amplify the minimum sounds needed to hear, understand, and learn speech [12]. However, as mentioned earlier, the results are qualitative because of using the live sound, and it is not easy to calibrate the intensity of the live sound. In addition, the results may vary greatly from one experimenter to another. For the first time, the recorded and calibrated versions of the Ling-6 sound test were designed and produced by Scollie et al. and used for audiometry in adults with normal-hearing and hearing loss. The results confirmed good test-retest reliability of these stimuli in both adult groups [13]. Glista et al. achieved similar results in children with normal-hearing and hearing loss using the same version of the Ling-6 sound test [14]. The researchers of both studies argued that, although further research was still needed to use this test in audiometry extensively, the Ling-6 sound test seemed to have a potential value and utility as an evidence-based speech recognition tool [13, 14]. Therefore, it appears that the Line-6 sound test can be used to estimate the amount of amplification to the audible speech. In the process of hearing-aid fitting, there are usually different methods to estimate the amount of amplifications for hearing-impaired individuals.

Fitting methods are applied to estimate the amount of amplification needed for users according to different data, such as hearing thresholds (threshold-based) and loudness (supra threshold-based). Desired sensation level version 5.0 (DSL v5.0) and National Acoustic Laboratories-Nonlinear 2 (NAL-NL2) fitting methods are the most updated and most common fitting methods. DSL v5.0 normalizes the loudness and NAL-NL2 equalizes the loudness [15]. Therefore, these two fitting methods appear to estimate different amounts of amplifications for every section of the frequency range. As of now, different studies have compared different aspects of the two DSL v5.0 and NAL-NLs fitting methods, such as insertion gain, loudness, compression ratio, and the Speech Intelligibility Index (SII), in hearing-impaired children and adults [16-18].

The present study was conducted to investigate whether there is a statistically significant relationship between obtained unaided and aided thresholds using the Ling-6 sound test and the routine stimulus (warble tones) under the standard conditions of audiometric evaluation. If the criterion of the upper limit of speech banana is desirable [19], which will primary estimated amplification provided by DSL v5.0 and NAL-NL2 fitting methods bring the six phonemes-added thresholds of the Ling-6 sound test closer to the upper limit of the speech banana?

Methods

Participants

Eighteen normal-hearing children aged 5–8 years (M=7.17, SD=0.61), including 7 girls and 11 boys, and 15 hearing-impaired children aged 5–8 years (M=6.53, SD=0.99), including 7 girls and 8 boys, participated in the study. This age range was selected because the children can cooperate in behavioral audiometry, and their behavioral response is closer to their actual hearing threshold than younger children.

The inclusion criteria for normal-hearing children included the following: the external ear (lack of impacted earwax, obstruction, or foreign bodies in the ear canal) (using Welch Allyn otoscope, USA) and middle ear functions (type A_n tympanogram with a 226 Hz probe tone and pressure changes of +200 to –400 dapa) (AT235 impedance audiometer, Interacoustics, Denmark) were normal. The hearing thresholds for all participants were 0–15 dB HL across the audiometric frequency range for both ears. Speech and language development (assessed by asking parents based on the speech and language developmental milestones checklist) [20] was normal in these children. It is worth noting that these children had no history of otitis media in the past 3 months, neurological diseases, or head trauma. In addition, they had no history of viral diseases causing hearing damage during pregnancy and after birth, as well as no history of using ototoxic drugs. The inclusion criteria of hearing-impaired children were: the impaired hearing of all 15 children with hearing impairment was diagnosed at birth using a hearing screening program. These children had symmetrical, moderate to severe hearing loss, and the configuration of their hearing loss was flat, sloping, and gradually sloping (Figure 1) External and middle ear functions were normal in these children. They were fitted with a hearing aid within the first 2 years and received a comprehensive hearing rehabilitation program. All children were permanent hearing aid users. According

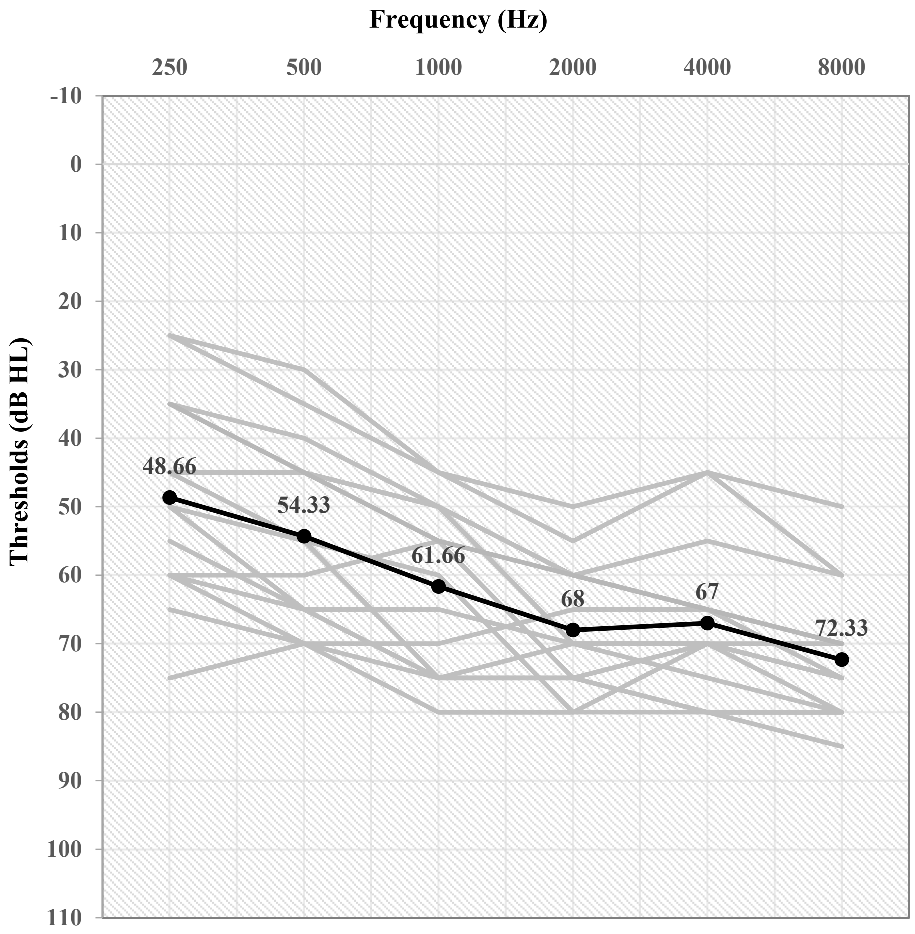

Figure 1. Audiogram of hearing-impaired children (light gray lines). Due to the fact that the hearing loss of the two ears was similar, only the audiogram of the right ear was considered in the figure drawing. The solid black line shows the average hearing loss of the children who participated in this study

to Parents' Evaluation of Aural/oral performance of Children (PEACH) [21], a child is a permanent hearing aid user if (s) they use a hearing aid for more than 8 h per day. Furthermore, these children had no history of neurological diseases or head trauma. The exit criterion for both groups was fatigue and unwillingness to continue the evaluation. The names and information of all participants in the study were not published anywhere and were completely confidential.

Test materials

Speech phonemes /m/, /u/, /a/, /i/, /ʃ/, and /s/ were recorded in a recording studio by a female native speaker at the level of conversational speech intensity (65 dB SPL). The accuracy of this intensity level was monitored using a Sound Level Meter (SLM) on a recording desk. Since the spectral shape of soft speech is very smooth and the spectral shape of loud speech is extremely uneven, we used the shape of the spectrum resulting from average speech (conversational speech). This speech lies between the two extremes of the spectrum (soft and loud) and seems to be the most appropriate average shape for producing all speech stimuli with a human voice. All speech sounds were monophonic in a wave format with a sampling rate of 44 kHz. To observe proper production, the female native speaker was selected from speech and language pathologists with no history of speech or language disorders. After recording test materials, the distance from the speaker's mouth to the microphone was 30 cm at all stages of recording [13, 14]. Based on the opinion of 10 phoneticians and 10 speech and language pathologists, the best sample out of 25 recorded samples for each phoneme was selected to be used in the next stages of the study. This version was saved for calibration on a CD with a pure tone of 1000 Hz and broadband noise. Each stored audio track consisted of four repetitions of the desired sound. The duration of each phoneme was approximately one second (range: 0.89–1.25 s), and the interval between repetitions was 5 seconds [13, 14]. Figure 2 illustrates the distribution of energy in the frequency domain of each phoneme. The selected speech phonemes were also played for 60 children (30 girls) with normal hearing, using an ASUS notebook (UX430U model) and a Tascam TH-05 circumaural headphones at the most comfortable level so that they could recognize the speech phonemes. There were no errors in the recognition of speech phonemes by these children.

Procedure

Conditional play audiometry (PC-based clinical diagnostic Primus, Audiodata, Denmark) was performed using warble tones stimuli to assess normal-hearing children's binaural sound field thresholds within the audiometric frequency range (250–8000 Hz) in an acoustic chamber. The intensity level was increased and decreased in 5-dB steps for searching thresholds. After finding the approximate threshold limits, 1-dB steps were used to find a more accurate threshold. The criterion for determining the threshold was the response to 50% of the provided stimuli. In this assessment, the Primus speaker was positioned at 0-degree azimuth, 1 m from the child's head position.

The Ling-6 sound test was added to the audiometer speech section such that the researcher could present each audio track several times to find the threshold. In addition to the internal calibration performed by the audiometer on the external stimuli, calibration steps of the sound field were performed using a 1000 Hz tone and broadband noise in four steps. These include step 1) a 1000 Hz pure tone was played and a VU audiometer was adjusted to 0 (central position); step 2) an SLM (Nor 140, Norsonic, Norway) was placed in a hypothetical position in the center of the child's head at a distance of 1 m from the speaker at an azimuth of 0°; step 3) the audiometer dial was set to 65 dB HL, and step 4) broadband noise was played, followed by monitoring the intensity level received by the SLM, which had to be 60±2 dB(A) [13]. An audio track was then played randomly, and the threshold was tracked afterwards. Similar to the warble tone evaluation stage, 5-dB steps were used in this stage to increase and decrease the intensity level. After finding the approximate threshold limits, a more accurate threshold was detected using 1-dB steps. The criterion for determining the threshold was to respond to 50% of the provided stimuli. In both stages of assessing the sound field thresholds, the position of the child's head was determined using a marker, and the examiner monitored the correct position of the child's head throughout the assessment period. In addition, the SLM was at the same level as the child's head in the evaluation stage using the Ling-6 sound test, and the accuracy of the intensity level that reached the child's ear was monitored throughout the evaluation.

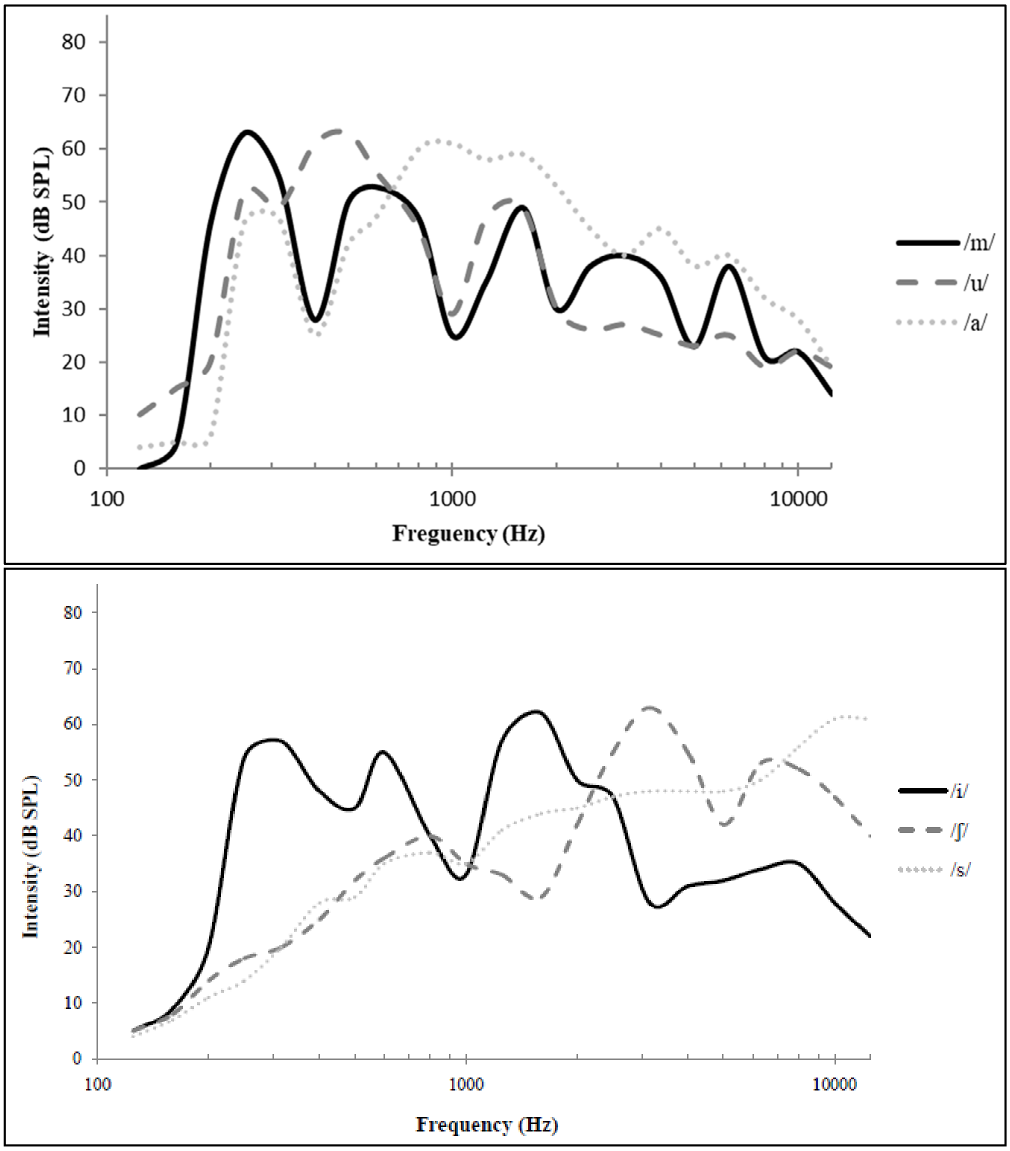

Figure 2. Frequency content diagram of each of the Ling-6 sound test based on one-third of an octave, balanced at an intensity level of 65 dB sound pressure level

The order of the assessment phases was similar in hearing-impaired and normal hearing children. The only difference was that a predetermined pair of hearing aids was fitted on the ears of the hearing-impaired children in all assessment phases. Behind the ear, P4G5 hearing aids (made by Audio Service, Germany) were used for this purpose. This hearing aid has eight channels and can cover specified degrees of hearing loss. These hearing aids were attached to the children's ear molds and positioned on their ears. This hearing aid has multiple dynamic range compression channels. Other fitting considerations during the entire assessment phases included an omnidirectional microphone pattern, deactivation of all adaptive features (such as frequency compression, noise reduction, etc.), activation of feedback cancellation, and use of the hearing aid's first program (calm environment) [13]. Furthermore, the selected hearing aid did not have the option to automatically change the frequency responding curve according to the environment. For each hearing-impaired child, the hearing aids were fitted once with DSL v5.0 and the second time with the NAL-NL2 fitting method. The order of using fitting methods was not fixed and changed randomly. Adaptation with the prescriptive targets was assessed using conventional Real Ear Measurement (REM) procedures (positioning the speaker at 0-degree azimuth 1 m away from the subject) (Primus Real Ear Measurement, Audiodata, Denmark) at three intensity levels of 55, 65, and 75 dB SPL and the stimuli of the international speech test signal. Real-ear aided response was used for assessment, and the accepted amount of difference between amplification and the prescriptive targets was considered ±5 dB for the frequencies of 500, 1000, and 2000 Hz and ±8 dB for the frequencies of 3000 and 4000 Hz [22]. To ensure the conformity of the amount of amplification with the prescriptive targets after the REM, the child entered the aided hearing assessment phase using the warble tone in the audiometric frequencies of 250-8000 Hz and the Ling-6 sound test. The order of the fitting method for hearing-impaired children changed randomly.

Statistical analysis

The data were analyzed using Statistical Package for Social Sciences (SPSS) version 17.0 Non-parametric tests were used due to the non-normal distribution of data and the nature of variables (parents' perception of the explanations about the audiometric results=rank quality). The correlation between thresholds with the two types of stimuli (warble tones and the Ling-6 sound test) was evaluated using the Spearman correlation coefficient. The upper limit of speech banana was selected as a criterion to assess the audibility created by each fitting method for each speech phoneme [19] using the Mann-Whitney U test for this comparison. In addition, the Wilcoxon test was applied to compare the aided thresholds created by these two fitting methods in each speech phoneme. A significance level of 99% (p<0.01) was considered in all statistical analyses.

Results

Relationships between thresholds of warble tones and the Ling-6 sound test in normal-hearing and hearing-impaired children

The results show, there was a significant relationship between the unaided and aided threshold of each phoneme and the warble tone threshold at 250, 500, 1000, 2000, and 4000 Hz (p<0.01), except for the speech phoneme /s/ (Table 1). Unaided and aided threshold speech phoneme /s/ was not significantly correlated with both the unaided and aided warble tone thresholds at 8000 Hz and those at the other frequencies. The positive sign of the coefficients indicated direct correlations, and their values indicated strong and very strong correlations (Figure 3).

Comparison of aided thresholds of the Ling-6 sound test with the upper limit of the speech banana and in two fitting methods

The result of the Mann-Whitney U test showed significant differences between the aided thresholds of each speech phoneme and the upper limit of speech banana in the corresponding frequency in NAL-NL2 and DSL v5.0 fitting methods (Z=–4.99, p≤0.001, Mean Rank DSL v5.0 & NAL-NL2 in all speech phonemes=23.00, the mean rank upper limit of speech banana in all frequencies=8.00) (see Figure 3 for a better understanding).

The results of the Wilcoxon test showed significant differences between the aided thresholds of the DSL v5.0 fitting method and the aided thresholds of the NAL-NL2 fitting method in all speech phonemes (p=0.001). According to Table 2, the aided thresholds of the DSL v5.0 fitting method were not higher than those of the NAL-NL2 fitting method in all speech phonemes. Only in one subject and for /i, /a/, and /u/ speech phonemes, the aided thresholds of the DSL v5.0 fitting method were equal to those of the NAL-NL2 fitting method. The aided thresholds of the DSL v5.0 were lower than those of the NAL-NL2 fitting method in all speech phonemes and all cases, except for one subject in whom the aided thresholds for the /i/, /a/, and /u/ speech phonemes were equal in both fitting methods (see Figure 3 for a better understanding).

Discussion

The present study was conducted to investigate the relationship between unaided and aided thresholds in children with hearing impairment obtained with two types of stimuli (warble tones versus Ling-6 sound test), the line of the aided thresholds obtained from the first fit in DSL v5.0 and NAL-NL2 fitting methods, Ling-6 sound test in the speech banana range. The results are discussed in more detail in the following.

The thresholds of 5-phonems /m/, /u/, /a/, /i/, and /ʃ/ are statistically highly correlated with the biggest energy peak of their corresponding warble tones in normal and hearing-impaired children (and in both two fitting methods). These findings are in accordance with

Table 1. Results of Spearman's rho between warble tones and Ling-6 sound test thresholds in normal-hearing and hearing-impaired children with desired sensation level version 5.0 and national acoustic laboratories-nonlinear 2 fitting method

Variable	Frequency (Hz)		/m/	/u/	/a/	/i/	/ʃ/	/s/
Normal-hearing	250	r_s	0.87	0.76	0.25	0.65	0.48	-0.13
		p	0.000*	0.01*	0.29	0.13	0.23	0.60
Hearing-impaired DSL v 5.0		r_s	0.95	0.85	0.46	0.46	0.46	0.46
		p	0.000*	0.01*	0.09	0.06	0.08	0.25
Hearing-impaired NAL-NL2		r_s	0.95	0.65	0.37	0.50	0.29	0.42
		p	0.000*	0.01*	0.17	0.06	0.24	0.11
Normal-hearing	500	r_s	0.57	0.90	0.32	0.36	0.27	-0.21
		p	0.01*	0.000*	0.19	0.14	0.26	0.39
Hearing-impaired DSL v 5.0		r_s	0.76	0.96	0.36	0.15	0.48	0.34
		p	0.001*	0.000*	0.17	0.58	0.07	0.21
Hearing-impaired NAL-NL2		r_s	0.62	0.98	0.46	0.46	0.21	0.31
		p	0.01 *	0.000*	0.08	0.07	0.43	0.25
Normal-hearing	1000	r_s	0.47	0.48	0.61	0.33	0.10	-0.22
		p	0.07	0.11	0.008*	0.17	0.68	0.39
Hearing-impaired DSL v 5.0		r_s	0.57	0.51	0.92	0.41	0.44	0.41
		p	0.07	0.14	0.000*	0.12	0.36	0.14
Hearing-impaired NAL-NL2		r_s	0.43	0.48	0.94	0.52	0.54	0.43
		p	0.10	0.06	0.000*	0.08	0.31	0.54
Normal-hearing	2000	r_s	0.40	0.45	0.37	0.88	0.62	0.02
		p	0.06	0.13	0.12	0.000*	0.006*	0.92
Hearing-impaired DSL v 5.0		r_s	0.51	0.35	0.57	0.91	0.89	0.37
		p	0.17	0.18	0.09	0.000*	0.000*	0.21
Hearing-impaired NAL-NL2		r_s	0.47	0.38	0.46	0.91	0.88	0.33
		p	0.06	0.15	0.08	0.000*	0.01 *	0.08
Normal-hearing	4000	r_s	0.41	0.43	0.34	0.47	0.90	0.17
		p	0.80	0.06	0.58	0.07	0.000*	0.48
Hearing-impaired DSL v 5.0		r_s	0.46	0.49	0.50	0.47	0.98	0.49
		p	0.21	0.07	0.53	0.09	0.000*	0.06
Hearing-impaired NAL-NL2		r_s	0.33	0.21	0.45	0.67	0.99	0.21
		p	0.22	0.43	0.09	0.07	0.000*	0.17
Normal-hearing	8000	r_s	0.29	0.03	0.16	0.20	0.10	0.36
		p	0.20	0.80	0.51	0.42	0.67	0.14
Hearing-impaired DSL v 5.0		r_s	0.43	0.33	0.47	0.45	0.36	0.49
		p	0.38	0.22	0.09	0.12	0.11	0.10
Hearing-impaired NAL-NL2		r_s	0.38	0.24	0.33	0.34	0.33	0.29
		p	0.15	0.38	0.21	0.25	0.15	0.09

DSL V 50; desired sensation level version 5.0, NAL-NL2; national acoustic laboratories-nonlinear 2
* Correlation is significant at the 0.01 level (2-tailed)

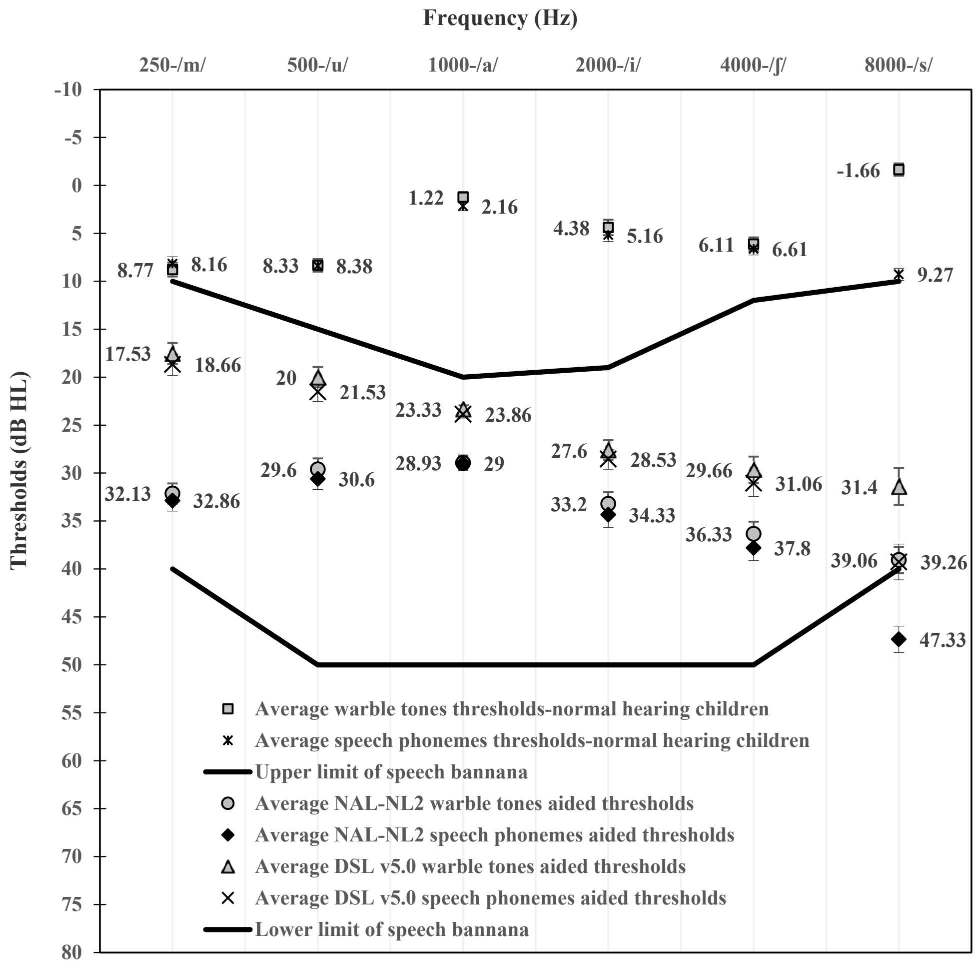

Figure 3. The average unaided and aided thresholds of warble tones and Ling-6 sound test in normal-hearing and hearing-impaired children with desired sensation level version 5.0 and national acoustic laboratories-nonlinear 2 fitting method. The correction factor for converting phoneme thresholds into dB HL for phonemes /m/, /u/, /a/ and /i/ was -5 for /ʃ/, -10 and -15 for /s/. The average aided thresholds of desired sensation level version 5.0 and National acoustic laboratories-nonlinear 2 for each speech phoneme and warble tones are shown in the range of speech banana. The values mentioned in the 6th edition of "hearing in children" book have been used to draw the speech banana range. NAL-NL2; national acoustic laboratories-nonlinear 2, DSL V 50; desired sensation level version 5.0

several studies [23-25]. Regarding the phoneme /s/, its frequency spectrum has lack of remarkable energy peak up to 10 KHz and it has not statistically correlated with 8 kHz threshold in all participated groups. Souza and Iorio [23] and Tenhaaf and Scollie [24] reported that there is a conceivable energy peak at frequencies higher than 10000 Hz for the phoneme /s/. In some cases, high-frequency hearing assessment is helpful for correct decision-making in therapeutic processes and audiological interventions. For instance, consider a child receiving ototoxic drugs. Hearing loss caused by these medicines begins at high frequencies [26,27]. Conventional audiometry assesses the range of 250–8000 Hz. Hearing in this frequency range may not be damaged by consuming these medicines, or hearing damage may appear later in this frequency range. In that case, therapeutic measures, such as reducing the dose or changing the type of medicine, may not be very helpful anymore. Moreover, the absence of a significant relationship between the aided thresholds for the /s/ speech phoneme and the 8000 Hz warble tone in hearing-impaired children cannot be attributed to the position of the /s/ phoneme at the end of the Full-On Gain curve because this pattern can also be observed in normal-hearing children. It appears that the speech-aided audiogram assessment is a simple and accessible method to assess the amount of audibility created by different fitting methods for these six speech phonemes. This study demonstrated that Ling-6 sound test can be applied in audiometry assessment in children as its test-retest reliability is less than 5 dB HL among all participants. Tenhaaf and Scollie [24] and the study by Scollie et al.[13] used Ling-6 sound test for the evaluation of normal-hearing adults. The results showed that the test-retest reliability of these stimuli is clinically acceptable. Furthermore, the results of Glista et al.'s study confirmed the use of Ling-6 sound test in children [14].

In this study, the audible criterion suitable for speech was the upper limit of the speech banana, similar to the speech mapping method [19]. There were significant differences between the aided thresholds for each of these six speech phonemes in both fitting methods and the upper limit of speech banana ($Z=-4.99$, $p\leq 0.001$).Figure 3 demonstrates the average aided thresholds for each phoneme for DSL v5.0 and NAL-NL2 fitting methods in the speech banana range. According to Figure 3, the estimated primary amplification in the DSL v5.0 fitting method could place the average aided thresholds in the banana speech range for all speech phonemes. This was also true for the NAL-NL2 fitting method, except for the /s/ phoneme in which the estimated primary amount of amplification in the NAL-NL2 fitting method did not place its average aided thresholds in the speech banana range. Moreover, significant differences were obtained in aided thresholds for all speech phonemes in both fitting methods ($p=0.001$). Figure 3 also shows that the average aided thresholds for all speech phonemes are lower in the DSL v5.0 fitting method than those in the NAL-NL2 fitting method. Therefore, it can be concluded that the DSL v5.0 estimates a higher amount of amplification for similar degrees of hearing loss in the first fit phase than the NAL-NL2 fitting method. This is consistent with other studies that have compared the loudness and insertion gain provided by these two fitting methods. Studies have shown that loudness and insertion gain estimated in the DSL v5.0 fitting method are higher than the values estimated in the NAL-NL2 fitting method, particularly in the pediatric population [16-18].In this study, the lower aided thresholds for speech phonemes in the DSL v5.0 fitting method than the NAL-NL2 fitting method suggest that the former estimates a higher amount of amplification than the latter for similar degrees of hearing loss. A principle in the NAL-NL2 fitting method is to provide a higher amount of amplification in middle frequencies to increase speech intelligibility, which was also proved in this study. According to Figure 3, the average aided thresholds for the /a/ speech phoneme, which is positioned in the middle-frequency range, is lower than that at the two ends of the spectrum (the average aided thresholds for /m/ and /s/ speech phonemes in the low and high-frequency areas of the spectrum, respectively). The obtained upward curve line proves that a higher amplification is estimated in the middle-frequency areas. On the other hand, it is important to note that although the DSL v5.0 fitting method provides more audibility in the first fit than the NAL-NL2 fitting method, it is likely that the estimated amplification in this fitting method causes over-amplification if the child's unaided thresholds are overestimated wrongly. However, the estimated amount of amplification provided by NAL-NL2 is more cautious, which reduces the probability of over-amplification. Therefore, when the clinician is certain about the child's unaided thresholds, hearing aid fitting using the DSL v5.0 fitting method provides higher audibility for speech phonemes than the NAL-NL2 fitting method. Nonetheless, if there is no certainty about the child's unaided thresholds, it is wise to apply the NAL-NL2 fitting method because of the lower probability of over-amplification and further damage to the remaining hearing ability. Given the findings of this study, it appears that the provided amplification in the first fit does not provide very good audibility for speech phonemes. Thus, it is necessary to improve the amount of amplification for further improvement of audibility. Since hearing-impaired children are unable to provide spoken explanations for the improvement of their hearing aid fitting, the speech-aided audiogram assessment is probably a simple method without the need for advanced equipment and special training to determine the audibility status of speech phonemes after every fitting phase. It seems that the information obtained from this method is also useful in improving hearing aid fitting in the children population.

In the current study, the phoneme thresholds compared with the upper limit of the English speech banana due to the lack of such data in the Persian language. Hence, this is one of the limitations of the study. Another limitation of the study is the binaural evaluation of the participants and for clinical settings, the evaluation must be performed monaurally.

Further studies are required to reduce the ambiguities and limitations of using the Ling-6 sound test in auditory system assessments and may focus on assessment methods for younger children, such as visual reinforcement audiometry, calibrated behavioral observation audiometry, and different tasks (discrimination and recognition). It is, also, suggested that the future studies may consider high-frequency phonemes which are better consistent with the 8 kHz threshold.

Conclusion

According to the results, it seems that the use of the Ling-6 sound test for the assessment of aided thresholds allows the clinician to understand the audibility amount of speech phonemes within the first sessions regardless of the type of fitting method. This is very important for hearing-impaired children because they may be unable to provide spoken expression appropriately. If this important is achieved, it will facilitate and accelerate improving the amount of amplification and adjustment of rehabilitation programs. Therefore, it seems that the most significant benefit of using speech phonemes in such assessments is that the results can be used as an evidence-based tool for speech detection. It should be noted that audiometry with speech phonemes provides complementary data as a test battery along with other methods of hearing aid fitting verification.

Ethical Considerations

Compliance with ethical guidelines

This study was approved by the ethics committee of TUMS under the code of IR.TUMS.FNM.REC.1398.223.

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Authors' contributions

MS: Study design, acquisition of data, interpretation of the results, statistical analysis, and drafting the manuscript; NR: Study design, interpretation of the results, and drafting the manuscript; FF: Interpretation of the results and drafting the manuscript; NR: Interpretation of the results and drafting the manuscript; SJ: Statistical analysis.

Conflict of interest

The authors report no conflict of interest.

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References

1. Moon C. The role of early auditory development in attachment and communication. Clin Perinatol. 2011;38(4):657-69. [DOI:10.1016/j.clp.2011.08.009]
2. Dalzell L, Orlando M, MacDonald M, Berg A, Bradley M, Cacace A, et al. The New York State universal newborn hearing screening demonstration project: ages of hearing loss identification, hearing aid fitting, and enrollment in early intervention. Ear Hear. 2000;21(2):118-30. [DOI:10.1097/00003446-200004000-00006]
3. Kaye CI; Committee on Genetics; Accurso F, La Franchi S, Lane PA, Hope N, et al. Newborn screening fact sheets. Pediatrics. 2006;118(3):e934-63. [DOI:10.1542/peds.2006-1783]
4. Wood SA, Sutton GJ, Davis AC. Performance and characteristics of the Newborn Hearing Screening Programme in England: The first seven years. Int J Audiol. 2015;54(6):353-8. [DOI:10.3109/14992027.2014.989548]
5. Stika CJ, Eisenberg LS, Johnson KC, Henning SC, Colson BG, Ganguly DH, et al. Developmental outcomes of early-identified children who are hard of hearing at 12 to 18 months of age. Early Hum Dev. 2015;91(1):47-55. [DOI:10.1016/j.earlhumdev.2014.11.005]
6. Ching TYC, Leigh G. Considering the impact of Universal Newborn Hearing Screening and early intervention on language outcomes for children with congenital hearing loss. Hear Balance Commun. 2020;18(4):215-24. [DOI:10.1080/21695717.2020.1846923]
7. Yoshinaga-Itano C, Sedey A.Early speech development in children who are deaf or hard of hearing: interrelationships with language and hearing. Volta Review. 1998;100(5):181-211.
8. Newton V.Benefits of an early identification and diagnosis of permanent bilateral hearing loss.Hear Balance Commun. 2013;11(3):91-9. [DOI:10.3109/21695717.2013.820512]
9. Ching TY. Is Early Intervention Effective in Improving Spoken Language Outcomes of Children With Congenital Hearing Loss? Am J Audiol. 2015;24(3):345-8. [DOI:10.1044/2015_AJA-15-0007]
10. Nagarajan SS, Cheung SW, Bedenbaugh P, Beitel RE, Schreiner CE, Merzenich MM. Representation of spectral and temporal envelope of twitter vocalizations in common marmoset primary auditory cortex. J Neurophysiol. 2002;87(4):1723-37. [DOI:10.1152/jn.00632.2001]

11. Ling D. Foundations of Spoken Language for the Hearing-Impaired Child. Alexander Graham Bell Association for the Deaf. 1989.
12. McCreery RW, Walker EA. Hearing aid verification for children.In: McCreery RW, Walker EA, editors. Pediatric amplification: enhancing auditory access. San Diego, CA:Plural Publishing; 2017. p. 77-104.
13. Scollie S, Glista D, Tenhaaf J, Dunn A, Malandrino A, Keene K, et al. Stimuli and normative data for detection of Ling-6 sounds in hearing level. Am J Audiol. 2012;21(2):232-41. [DOI:10.1044/1059-0889(2012/12-0020)]
14. Glista D, Scollie S, Moodie S, Easwar V; Network of Pediatric Audiologists of Canada. The Ling 6(HL) test: typical pediatric performance data and clinical use evaluation. J Am Acad Audiol. 2014;25(10):1008-21. [DOI:10.3766/jaaa.25.10.9]
15. Dillon H. Hearing aids. 2nd ed. New York: Thieme; 2012.
16. Johnson EE, Dillon H. A comparison of gain for adults from generic hearing aid prescriptive methods: impacts on predicted loudness, frequency bandwidth, and speech intelligibility. J Am Acad Audiol. 2011;22(7):441-59. [DOI:10.3766/jaaa.22.7.5]
17. Ching TYC, Zhang VW, Johnson EE, Van Buynder P, Hou S, Burns L, et al. Hearing aid fitting and developmental outcomes of children fit according to either the NAL or DSL prescription: fit-to-target, audibility, speech and language abilities. Int J Audiol. 2018;57(sup2):S41-54. [DOI:10.1080/14992027.2017.1380851]
18. Ching TYC, Johnson EE, Seeto M, Macrae JH. Hearing-aid safety: A comparison of estimated threshold shifts for gains recommended by NAL-NL2 and DSL m[i/o] prescriptions for children. Int J Audiol.2013;(52 Supl 2):S39-45. [DOI:10.3109/14992027.2013.847976]
19. Mueller HG, Ricketts T,Bentler RA.Speech Mapping and Probe Microphone Measurements. San Diego,CA:Plural Publishing; 2017.
20. Nelson HD, Nygren P, Walker M, Panoscha R. Screening for speech and language delay in preschool children: systematic evidence review for the US Preventive Services Task Force. Pediatrics. 2006;117(2):e298-319. [DOI:10.1542/peds.2005-1467]
21. Ching TY, Hill M. The Parents' Evaluation of Aural/Oral Performance of Children (PEACH) scale: normative data. J Am Acad Audiol. 2007;18(3):220-35. [DOI:10.3766/jaaa.18.3.4]
22. Mehta K, Watkin P, Baldwin M, Marriage J, Mahon M, Vickers D. Role of Cortical Auditory Evoked Potentials in Reducing the Age at Hearing Aid Fitting in Children With Hearing Loss Identified by Newborn Hearing Screening. Trends Hear. 2017;21:2331216517744094. [DOI:10.1177/2331216517744094]
23. Souza MRF, Iorio MCM. Speech Intelligibility Index and the Ling 6(HL) test: correlations in pediatric hearing aid users. Codas. 2021;33(6):e20200094. English. [DOI:10.1590/2317-1782/20202020094]
24. Tenhaaf JJ, Scollie SD.Normative threshold levels for a calibrated, computer-assisted version of the ling six-sound test. Can Acoust. 2005;33(3):44-5.
25. McDonnell S.The Ling Sound Test: What is its Relevance in the New Zealand Classroom?. Kairaranga. 2014:15(2):48-55. [DOI:10.54322/kairaranga.v15i2.250]
26. Yoshikawa S, Ikeda K, Kudo T, Kobayashi T. The effects of hypoxia, premature birth, infection, ototoxic drugs, circulatory system and congenital disease on neonatal hearing loss. Auris Nasus Larynx. 2004;31(4):361-8. [DOI:10.1016/j.anl.2004.07.007]
27. Guo J, Chai R, Li H, Sun S. Protection of Hair Cells from Ototoxic Drug-Induced Hearing Loss. Adv Exp Med Biol. 2019;1130:17-36. [DOI:10.1007/978-981-13-6123-4_2]