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Professor Robert Ruben

Editor-in-Chief, *International Journal of Pediatric Otorhinolaryngology*

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20 May 2014

Dear Prof. Ruben,

We wish to submit a manuscript entitled "Aided cortical response, speech intelligibility, consonant perception and functional performance of young children using conventional amplification or nonlinear frequency compression" to be considered for review by the *International Journal of Pediatric Otorhinolaryngology (*IJPORL*)*.

This paper provides evidence to clinicians on the effectiveness of nonlinear frequency compression processing (NLFC) with young hearing impaired children. The study used both subjective and objective evaluations to determine the effect of NLFC processing on speech detection, speech intelligibility, consonant perception and real-life performance of young children. The possible factors influencing the effect of NLFC on children's performance was also explored. IJPORL has published many articles related to hearing aid usage in the pediatric population. We believe the findings will be of interest to the readers of your journal.

We wish to confirm that there are no known conflicts of interest associated with this publication.

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We hope you find our manuscript suitable for publication and look forward to hearing from you.

Yours sincerely,

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*Title Page

Aided cortical response, speech intelligibility, consonant perception and functional performance of young children using conventional amplification or nonlinear frequency compression

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ABSTRACT

Objective: The aim of this study was to compare conventional processing with nonlinear frequency compression (NLFC) in hearing aids for young children with bilateral hearing loss.

Methods: Sixty-four children aged between 2 and 7 years with bilateral hearing aids were recruited. Evaluations of cortical responses, speech intelligibility rating, consonant perception and functional performance were completed with the children wearing their personal hearing aids with conventional processing. The children were then refitted with new hearing aids with NLFC processing. Following a 6 week familiarization period, they were evaluated again while using their hearing aids with NLFC activated.

Results: The mean speech intelligibility rating and the number of cortical responses present for /s/ were significantly higher when children were using NLFC processing than conventional processing in their hearing aids ($p < 0.05$). Parents judged the children's functional real life performance with the NLFC hearing aids to be similar or better than that with the children's own hearing aids in both quiet and noisy situations. The mean percent consonant score was higher with NLFC processing compared to conventional processing, but the difference did not reach the 5% significance level ($p = 0.056$). An overall figure of merit (FOM) was calculated by averaging the standardized difference scores between processing schemes for all measures. Regression analysis revealed that, on average, greater advantage for NLFC processing was associated with poorer hearing at 4 kHz.

Conclusions: Compared to conventional processing, the use of NLFC was, on average, effective in increasing audibility of /s/ as measured by cortical evaluations, and higher ratings on speech intelligibility and functional performance in real life by parents. On average, greater benefits from NLFC processing was associated with poorer hearing at 4 kHz.

1. Introduction

Audibility of sounds across all speech frequencies is critical in developing speech, language and auditory skills in hearing-impaired children. High-frequency speech sounds play a critical role in denoting plurality, possession, third person singular tense and contractions in English language [1-3]. Previous studies show that extending the audible bandwidth to 8 kHz can improve speech perception of the /s/ sound for adults and children [4]. It can also improve speech understanding in noisy listening environments [5, 6].

Many children with hearing loss have difficulty in hearing high-frequency sounds. Research has shown that speech sounds, such as /f/ /v/ /θ/ /ð/ /s/ /z/ /ʃ/ /ʒ / /tʃ/ /ʤ /, are among the most frequently misperceived and mispronounced phonemes, and are the last to be acquired by children with hearing loss [7]. The benefits of high-frequency amplification may be limited due to listener-related factors, such as loudness discomfort and the severity of hearing loss in these frequencies, as well as device-related factors, such as limited bandwidth, acoustic feedback and inadequate gain in the high frequencies [8]. To overcome this limitation, frequency lowering schemes were developed and implemented in hearing aids (for reviews on the range of schemes [9-11]). One of the schemes is nonlinear frequency compression (NLFC), introduced by Phonak Ltd in 2008. This technology maps a wide frequency range in the input signal into a narrow frequency range in the output. Two programmable parameters, cut-off frequency and compression ratio, define how frequency compression is applied to the input signal. The energy that is above a particular cut-off frequency is compressed and shifted to lower frequency region. Sounds below the cut-off frequency are not affected by NLFC processing, thereby preserving a natural sound quality [9, 12].

Recent studies on the effect of NLFC for children show differing results with some studies showing benefit of NLFC technology for some individuals but not others (for a summary, see [8, 10, 11]). Glista et al [12] compared performance with NLFC and conventional processing for 11 school-aged children with moderately severe to profound sloping high-frequency hearing loss. They reported that 7 out of 11 children had significant improvement on plural recognition and high-frequency consonant recognition in quiet. However, one child showed significantly poorer performance on sound detection when the NLFC processing was activated. The study by Wolfe et al. [13] showed a significant improvement on plural recognition in quiet with NLFC enabled in all 15 school-aged children with mild to moderately severe hearing loss after 6 weeks of familiarisation, but no difference in sentence perception in noise between NLFC enabled and disabled conditions. Despite better identification of /asa/ and /ada/ when NLFC was activated, no significant improvement was observed for identification of /afa/, /aka/, /asha/ or /ata/. The children were reassessed after using NLFC technology for 6 months. The same finding for identification of nonsense syllables was reported. When compared to data obtained at the 6-week assessment, speech recognition thresholds in quiet and in noise were improved. As there was no control condition, it is not clear whether the reported improvement after 6 months of usage was due to effects of practice, maturation or familiarization with the new frequency compression device [14, 15]. A recent study by Hillock-Dunn et al. [16] evaluated speech perception performance in 17 school-aged children with mild to profound hearing loss. The results indicated no significant differences were observed in consonant identification in quiet and spondee identification in competing background noise with and without NLFC activated. Some studies [12, 16, 17] suggest the variability in subjective outcomes may be related to factors such as age group, degree and configuration of hearing loss, the total duration of NLFC use, overall intellectual ability, children's language level, and type of outcome measure. Alexander [10] also emphasized the importance of electroacoustical verification and validation methods that may influence individual outcomes in speech recognition.

The previous studies on school-aged children indicated that the use of NLFC technology led to increased audibility of /s/ for some children. This may be expected to influence acquisition of speech and language by children with hearing loss. Ching et al. [18] conducted a randomized controlled trial to directly investigate the effect of NLFC processing on language development of children at 3 years of age. A range of standardized measures, including receptive language, expressive language, vocabulary, speech production, and functional performance were administered. Receptive vocabulary was significantly better with conventional processing than with NLFC, but expressive language based on parent report was better with NLFC. The scores for multiple measures were combined to form a global language score. Using this as a dependent variable, and a range of demographic characteristics including age of fitting as predictors, regression analysis revealed no significant difference in global language development of children who used NLFC processing in their hearing aids compared to those who were using conventional amplification after allowing for the effects of gender, severity of hearing loss, and maternal education.

The present study extends previous work on young children by using objective measures of cortical auditory evoked potentials (CAEP) to assess the effect of NLFC processing. The CAEP represents summed neural activity in the auditory cortex in response to sounds [19], and has been used previously for evaluation of the effectiveness of hearing aids for infants and young children [20, 21]. The cortical responses can be reliably evoked by speech stimuli at supra-threshold levels in infants with normal hearing [22] and in hearing-impaired infants when hearing aids were fitted with appropriate prescriptive targets [19]. The validity of this method has also been reported in young children, indicating a significant relationship between the presence of cortical responses and speech perception scores for children with auditory neuropathy on the one hand [23], or functional measures of real-world listening behavior [24] on the other. These results suggest that detection of CAEPs to speech stimuli may be a valid measure of aided functional performance in young children.

The aims of this study were to (1) determine the effect of NLFC processing on audibility of high-frequency speech sounds for young children with different degrees of hearing loss; (2) evaluate the effects of NLFC on children's speech intelligibility, consonant perception and real-life performance; and (3) explore the possible factors influencing effect of NLFC on children's performance.

2. Materials and methods

2.1. Participants

The participants were recruited from amongst the 450 children enrolled in the Longitudinal Outcomes of Children with Hearing Impairment (LOCHI) study [25]. Sixty four hearing-impaired children (38 boys, 26 girls), aged from 2.3 to 7.6 years old (mean age of 4.3 ± 1.5 yr), participated in this trial of NLFC which commenced in 2009. All the participants had bilateral sensorineural hearing loss and were fitted with hearing aids in both ears. Mean age at first-fitting of hearing aids was 10 ± 10 months. None of the children had previous experience with NLFC technology. Their average air conduction hearing threshold across four frequencies (4FA) of 0.5, 1, 2, and 4 kHz was 60 ± 16 dB HL in the better ear. Table 1 shows the averaged hearing thresholds in better ear across subjects at each frequency from 250 to 8000 Hz. The low frequency average hearing loss (LFAHL) measured at 0.25, 0.5 and 1 kHz was 50 ± 17 dB HL and the high frequency average hearing loss (HFAHL) measured at 2, 3 and 4 kHz was 67 ± 17 dB HL. Among these 64 subjects, 8 children were diagnosed with auditory neuropathy spectrum disorder, and another 10 children (24%) were reported to have additional disabilities. Table 2 illustrates the specific types of disabilities, age at assessment, gender and better ear 4FA HL information for each of these 18 children.

<Tables 1 and 2>

2.2. Procedure

Written informed parental/legal guardian consent was obtained prior to subject enrolment in this research project. The study was approved by Institutional Research Ethics board.

The children were fitted with Phonak Naída V SP or UP behind-the-ear hearing aids. The Naída V is a 16 channel hearing aid with wide dynamic range compression and nonlinear frequency compression capabilities. The SP model has a maximum power output of 137 dB SPL and a peak gain of 75 dB; the UP model has a maximum power output of 139 dB SPL with a peak gain of 82 dB. All hearing aids were fitted according to the Australian Hearing national paediatric amplification protocol [26] by using individually measured or age-appropriate real-ear-to-coupler differences (RECD) to derive prescriptive targets. As per the randomized control trial of hearing aids prescriptions in the LOCHI study [27], 31 children were fitted with hearing aids according to the NAL-NL1 prescription and 34 children were fitted with the DSL v.5 prescription. The hearing aids were adjusted in a HA2-2cc coupler to match prescription targets at low, medium and high input levels (50, 65 and 80 dB SPL) and maximum power output targets (SSPL 90 dB SPL) as closely as possible. The NLFC function was enabled for the new Naída hearing aids with frequency compression and cut-off frequencies selected according to the default settings in the Phonak fitting software (iPFG version 2.4).

Children were requested to attend two sessions over a period of 6 weeks. In the pre-fitting session, children were evaluated while wearing their own conventional hearing aids. They were then refitted with the new Naída hearing aids with NLFC enabled. After a familiarization period of 6 weeks, the evaluation was administered again. On completion of all evaluations, participants and their families had the choice to either keep the new hearing aids or to continue wearing their own conventional hearing aids. The outcome measurements included objective recording of cortical responses as well as evaluations of speech intelligibility, consonant perception and functional performance of children with the NLFC function activated and compared to the children's own conventional hearing aids.

2.3. Evaluation measures

2.3.1. Speech intelligibility rating

The speech intelligibility rating (SIR) was designed to provide a general outcome measure of speech production in a variety of communicative contexts in real-life situations [28, 29]. The SIR is a 7-point scale describing various degrees of speech intelligibility ranging from unintelligible speech to speech that is intelligible to listeners with little or no effort [30]. Each child was rated by the parents and by a researcher. The parents were asked to think about how well another person could understand the child's speech in a casual communication situation and provide a rating. The researcher also provided an independent rating.

2.3.2. Functional performance in real life

The Parent's Evaluation of Aural/Oral Performance in Children (PEACH) was used to evaluate children's device(s) usage, performance in quiet, performance in noise, and environmental awareness in real-world environments [31]. A comparison PEACH scale was used for rating in the post-fitting session. Parents were asked to observe their child's aural/oral behaviors based on real-life experiences over a period of 6 weeks, and scored each question on a 5-point scale, based on the comparison of the new NLFC settings with previous conventional hearing aids settings. The scale includes the following descriptive increments: much worse (-2), a bit worse (-1), same (0), a bit better (1), and much better (2). The examiner noted down all of the specific examples provided by the parents.

2.3.3. Speech perception of consonants

The Vowel-Consonant-Vowel (VCV) test [32, 33] was used to evaluate consonant perception. The speech test material comprised nonsense syllables produced by a male speaker with a general Australian accent. Each test list includes 24 VCV nonsense syllables, where the vowel was /i/ presented in the initial and final positions. The consonant was one of 24 English consonants /p/ /b/ /t/ /d/ /k/ /g/ /m/ /n/ /ŋ/ /f/ /v/ /θ/ /ð/ /s/ /z/ /ʃ/ /ʒ/ /h/ /tʃ/ /ʤ/ /l/ /r/ /j/ /w/. Two lists were used for each assessment, giving a total of 48 stimuli. The test list and the presentation order of the stimuli within each list were randomized.

The VCV test was administered in a sound treated room (background noise level was < 47 dB A). The stimuli were presented from a free field loudspeaker under computer controlled software. The stimuli were presented at 65 dB SPL at 0 degree azimuth at a distance of 1 m. Children listened with their own conventional hearing aids or with the new NLFC hearing aids, and were required to repeat back the syllables in response to each stimulus. The responses were recorded audio-visually, and were double scored by an experienced speech pathologist.

2.3.4. Aided cortical auditory evoked potential measurement

Cortical responses were recorded by using the ACA module of HEARLab™ system (Frye Electronics) in a sound treated room. The test stimuli /g/, /t/, and /s/ were used because these speech sounds have spectral emphasis in the mid-, high-, and very high frequency regions respectively (Fig. 1), and thus have the potential to give information about the perception of speech sounds in different frequency regions.

<Fig. 1>

Stimuli were presented from a loudspeaker positioned at 0° azimuth at a distance of 1 m in front of the child. The inter-stimulus interval was 1125 ms, and stimuli were presented with alternating onset polarity. The electrodes were positioned at Vertex (Cz, active), mastoid (M1, reference), and forehead (Fz, ground). Electrode impedance was checked to achieve impedance less than 5 kohms between active and ground, and between reference and ground. During acquisition of data, statistical analysis for determining the detection of the responses was performed online. The presence or absence of the cortical response was automatically analyzed and indicated by the HEARLab™ software with a system-generated significance level (*p*-value). A CAEP response was judged to be present if the *p*-value was < 0.05.

During cortical testing, the child was awake and seated in a chair, distracted by quiet and age-appropriate toys, or muted video programs. Stimuli were initially presented at 65 dB SPL with subsequent presentations either at 75 dB SPL or 55 dB SPL, depending on whether a response was present at 65 dB SPL. Where possible, each stimulus at each intensity level was presented until 150 epochs were accepted to complete a full set of testing. The cortical responses were measured with conventional hearing aids and the new Naída hearing aids with NLFC activated.

2.4. Statistical analysis

The primary outcome measures were summarized by using descriptive statistics. To compare the scores between the two hearing aid processing, nonparametric Wilcoxon test or paired *t* test were used, depending on the type of measured variable. Chi-square test was used to compare the differences in percentage correct consonant score between the two processing conditions; and the differences on detection rates on aided CAEP measurements in the two processing conditions. Multiple linear regression analysis was performed to investigate the relationship between a range of predictor variables and performance scores. Statistical calculations were performed using SPSS for Windows version 16 software. Two-sided P-values <0.05 were considered to indicate statistical significance in all tests.

3. Results

Table 3 shows the gains achieved in the hearing aids relative to prescriptive targets. Gain deviations were calculated in terms of root mean square in dB, averaged across octave frequencies between 0.25 and 4 kHz. Averaged gain deviations from prescribed targets across subjects shows that achieved gains in the hearing aids matched targets within 4.5 dB at low frequencies, and within 6.3 dB at high frequencies. A summary table of mean test scores for the NLFC and the conventional processing on each evaluation measure is shown in Table 4.

<Tables 3 and 4>

3.1. Speech intelligibility rating

Speech intelligibility ratings from both processing conditions are shown in Table 4. The nonparametric Wilcoxon statistical analyses indicated that the average SIR rating given by both parents and researchers demonstrated a higher degree of satisfaction with the NLFC than conventional processing in hearing aids (for parents: z = -2.3, p < .05; for researchers: z = -3.12, p < .05). This means children's speech was more easily understood when NLFC processing was used, compared to when they used their own conventional hearing aids. Analysis of variance using SIR ratings as dependent variables, rater (parent and researcher) and processing (NLFC vs conventional processing) as within-subject variables, and additional disability (presence or absence) as a between-subject variable revealed that the main effect of processing was significant (F(1,29) = 6.72, p = 0.02), and the main effect of rater was not significant (F(1,29) = 0.27, p = 0.61). The effect of additional disability was not significant (p = 0.5). There was no significant interaction between processing and rater (p = 0.79).

3.2. Functional performance in real life

Comparative ratings were available for 60 children including 17 children with additional disabilities. On average, there was no significant difference between children with or without additional disabilities (p > 0.05). Therefore, the ratings were combined across all subjects to conduct further analysis. Parents' ratings of children's device usage and loudness discomfort were not significantly different between the two processing schemes (p > 0.05). The averaged preference ratings across all subjects for each of 11 specific situations are shown in Fig. 2. All data points were on or above the zero line, indicating that, on average, parents judged the children's functional real life performance with the NLFC processing to be similar or better than that with conventional processing in both quiet and noisy situations.

A trend, shown in Fig. 2, was for the preference ratings in quiet and for environmental sounds to be better than the ratings in noise. The overall comparison rating showed a significantly better rating for the Quiet subscale compared to the Noise subscale (t = 2.19, p = 0.03). This indicates the NLFC may improve real-life functional performance to a greater degree in quiet situations, as parents observed.

Some comments from individual parent reports indicated benefits included that the children were more engaged, sat longer, followed stories, recognized and responded better to sounds, recognized people's voices better and generally, were able to produce sounds better and more clearly.

<Fig. 2>

3.3. Speech perception of consonants

Twenty-one out of 64 children were able to complete VCV testing with both conventional and NLFC hearing aids. However, only 15 of them had the full 24 responses recorded in at least one test list with both processing schemes. None of these children had additional disabilities. The percent scores were arcsine transformed to normalize variance before statistical analysis [33]. The mean percent score was improved from 54.2% (range: 22.9 to 79.2%; SD = 14.0) for own conventional processing to 61.1% (range: 31.3 to 77.1%; SD = 13.3) for NLFC processing, although the difference did not reach the 5% significance level (t = -2.1, p = 0.056).

Group consonant confusion matrices for the two processing schemes obtained by these 15 subjects are constructed in Table 5(a) and (b), respectively. Three out of 30 lists were excluded from confusion analysis because missing responses were found in one of the two test lists. The number in each cell is the frequency that each stimulus-response pair was obtained. The number of correct responses is shown in the cell along the main diagonal of the matrix. The number in the cells located off the diagonal is the frequency that the specific stimulus-response pair was incorrect. The difference in correct scores between NLFC and conventional processing did not reach the 5% significance level for any of the 24 consonants (p > 0.05), although the improvement for identification /s/ almost reached the 5% significance level when NLFC was activated ($\chi^2(1, N = 54) = 5.0$, p = 0.054). The lack of a significant improvement is likely due to high variance among participants and small sample size.

<Table 5(a) and (b)>

The confusion matrices were further analyzed using information transmission analysis [34]. This method calculates the percentage of information transmitted relative to the amount sent in the stimuli, so that the relative amount of information received for different phonetic features can be quantified. In this study, the 24 consonants were grouped according to five features: voicing (voiced versus voiceless), place (bilabial versus dental versus alveolar versus post-alveolar versus palatal versus back), manner of articulation (plosive versus fricative versus affricate versus nasals versus glide), sibilance (sibilant and non-sibilant) and nasality (nasal and non-nasal). Information transmission analyses were performed to investigate the mean information transmitted for conventional and NLFC processing according to five features (Fig.3). The analysis revealed an increased transmission of sibilance information with the use of NLFC, but this did not reach the 5% significance level ($t = -2.1$, $p = 0.056$).

<Fig. 3 >

3.4. CAEP recordings

Fig. 4 shows the number of cortical responses present for /g/, /t/ and /s/ sounds presented at 55 and 65 dB SPL, respectively. At the 55 dB SPL presentation level, the detection rate for /s/ increased from 34% (13 out of 38 subjects) to 72% (28 out of 39 subjects) when amplification was changed from conventional processing to frequency compression ($\chi^2(1, N = 77) = 10.92$, $p < 0.01$). At the 65 dB SPL presentation level, the effect of a change in amplification processing on the detection rate for /s/ was also significant ($\chi^2(1, N = 78) = 7.34$, $p < 0.01$). In contrast, there were no significant differences in detection rates for /g/ and /t/ sounds between NLFC and conventional processing at presentation levels of 55 and 65 dB SPL respectively ($p > 0.05$).

<Fig. 4>

Analysis of variance using cortical response detection rates as dependent variables, presentation level (55 dB SPL vs 65 dB SPL) and processing (NLFC vs conventional processing) as within-subject variables, and prescription used for fitting as a between-subject variable revealed that the effect of NLFC processing was significant ($F(1,35) = 13.2$, $p = 0.001$). Additionally, the effect of presentation level was also significant ($F(1,35) = 37.1$, $p < 0.001$). The effect of prescription was not significant ($p = 0.74$). There was significant interaction between presentation level and processing ($p = 0.007$). Post-hoc analysis indicates that the effect of processing was significant at 55 dB SPL presentation level ($p < 0.001$). At 65 dB SPL, the effect of processing did not reach the 5% significance level ($p = 0.07$).

3.5. Factors influencing the effect of NLFC

To characterize the difference in children's performance with conventional and NLFC processing, an overall figure of merit (FOM) was calculated by averaging the standardized difference scores between the two hearing aids processing for SIR intelligibility judgments by parents and researchers, percentage correct of consonant perception in quiet, comparative ratings for PEACH scores in quiet and noise subscale, and the total number of cortical responses present for /g/, /t/, and /s/ sounds at 55 and 65 dB presentation levels. Prior to averaging, the dispersion of all quantities to be averaged was equalized by dividing all values by the standard deviation of the respective measure across subjects. Multi-linear forward stepwise regression was performed with the FOM as a dependent variable on data from all 64 children. The three independent variables were hearing threshold at 2 kHz and 4 kHz, and high frequency slope from 1 to 4 kHz in the better ear. Analyses of the total data revealed that children with worse hearing loss at 4 kHz were more likely to benefit from the NLFC processing (Beta = 0.34, $p = 0.006$) (Fig. 5).

<Fig. 5 >

4. Discussion

This study compares children's performance when aided with conventional processing compared to NLFC processing. The outcomes of speech intelligibility ratings, cortical responses, consonant perception, and real-life functional performance were evaluated. The present findings revealed an overall improvement in performance when children were fitted with NLFC processing rather than with conventional processing (Table 4).

4.1. Speech intelligibility rating and functional performance in real life

Comparing children's performance with conventional or NLFC processing showed that mean speech intelligibility and overall functional performance with the NLFC processing were better than that with the conventional processing in real life situations. In addition, as parents observed, NLFC processing may improve real-life functional performance to a greater degree in quiet than in noise situations ($p < 0.05$). The performance with phone usage was found to have the least improvement after 6 weeks of usage with NLFC aids. This may be because conventional telephone systems pass frequencies from 400 to about 3500 kHz, which makes it difficult to understand unfamiliar words containing certain high frequency phonemes with any processing in hearing aids. In this instance, the difference in the child's ability to hear and to discriminate speech sounds over the phone may not be apparent between the two hearing aid's processing schemes. It should be noted that the evaluations were not blinded to the processing used in hearing aids. For this reason, the benefits observed by parents might have been biased by their preference for the new hearing aids.

4.2. Speech perception of consonants

The mean percent consonant score improved from 54.2% to 61.1% (p = 0.056) when amplification was changed from conventional processing to frequency compression. As shown in Fig. 3, information about voicing was equally well transmitted by the two processing schemes. NLFC is unlikely to affect the lowest five harmonics of the voice fundamental frequency, which carry most of the information about voicing. In line with expectations that increased access to high-frequency sounds through NLFC may improve perception of high-frequency consonants [7], the observed perception score of /s/ improved from 63% correct with conventional processing to 89% correct with NLFC processing, which is consistent with findings reported in previous studies [12, 13]. But this difference between the two processing schemes did not reach the 5% level in this present study (p = 0.054). In addition, it was found that participants using NLFC made more place errors for /θ/ and /ð/ sounds (i.e. substituted /θ/ by /f/, and substituted /ð/ by /v/), which were not observed when they were using conventional processing.

4.3. Aided CAEP measurement

The present findings from objective measures of aided CAEP to speech stimuli suggest that children fitted with both processing schemes demonstrate good audibility of sounds presented at 65 dB SPL. On average, there was an increase in number of cortical responses elicited by speech sounds presented at 55 dB SPL levels when children were wearing NLFC processing. Consistent with findings in previous studies, the improvement was associated with the detection of the /s/ sound [12, 14, 35, 36]. There were no instances in which cortical responses were present with conventional processing but not with NLFC processing.

The absence of cortical responses for some children may be related to inadequate sensation levels of amplified sounds, especially for those with steeply sloping loss, because the sensitivity of CAEP detection decreases with sensation level [19]. Missing CAEP responses to sounds that are detected behaviourally have been reported for unaided children [19]. It is, therefore, unlikely that the lack of responses for some children in the present study could be solely attributable to the influence of hearing aid processing [37]. The absence of a cortical response does not suggest that the sound has not been detected by a child. What is certain, though, is that the presence of a cortical response indicates that the sound has been detected. The findings in the present study suggest that the cortical measurements can be used as an objective means to evaluate the effectiveness of amplification for sound detection. This method complements subjective evaluations of auditory behavior for infants and young children who are not able to provide feedback on sound quality or reliable behavioral responses on efficacy of amplification.

4.4. Factors influencing the effect of NLFC

One of the main objectives of the present study was to determine what audiometric characteristics are associated with greater benefits from NLFC processing. Examination of predictors for the overall merit of use with NLFC suggests that, on average, children who have worse hearing loss at 4 kHz have better outcomes with NLFC processing. This finding is consistent with the report from Glista et al. [12], which found that participants with a greater amount of high frequency hearing loss derived greater NLFC benefits on plural recognition and detection tasks. In addition, because NLFC processing causes the signal leaking back to the microphone to occur at a different frequency from the original input, the phase shift between the two sounds would reduce the amplitude build-up thereby lessening the occurrence of feedback. This indirect advantage of NLFC over conventional processing potentially allows greater stable gain to be achieved in hearing aids before feedback oscillation occurs [18, 38]. As feedback occurs frequently when hearing aids are fitted to small and growing ear canals, this benefit may increase audibility that would be useful for some children with severe hearing loss at high frequencies.

4.5. Limitations

This study evaluated the effect of NLFC on young children fitted with Phonak Naída SP or UP hearing aids. The findings cannot be generalized to other frequency-lowering schemes available in commercial hearing aids. In addition, the current study compares the children’s performances with NLFC and conventional processing within a 6 week acclimatization period, future investigation will need to control for the effects of practice, maturation or familiarization. The way in which parameters for NLFC can be optimized for individuals also requires further investigation.

5. Conclusion

The strengths of the present study include then use of both subjective and objective evaluations to evaluate benefit of NLFC processing for young children; and its analysis on the relationship between the overall performance (FOM) and the degree of hearing loss. The present findings in young children suggest that, compared to conventional processing, the use of NLFC was, on average, effective at increasing detection of /s/, as measured by CAEP evaluations, and overall functional performance in real life of children. Ratings of speech intelligibility were also significantly better with NLFC than with conventional processing. The observed benefit from NLFC processing may be attributed to the increased audibility of additional high frequency energy and reduced feedback oscillation. On average, an advantage for NLFC processing was associated with poorer hearing at 4 kHz.

6. Acknowledgements

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Conflict of interest statement

The authors report no conflict of interest.

Figure Captions

Fig.1. The power spectra for speech sound stimuli /g/, /t/, and /s/ with overall levels normalized to 65 dB SPL.

Fig.2. Averaged preference ratings of PEACH questionnaires for 60 children (including additional disabilities). Vertical bars denote 0.95 confidence intervals.

Fig.3. Mean relative information transmitted for voice, place, manner, sibilance, and nasality. The filled circles represent mean percent information transmitted for conventional aids. The open squares represent the NLFC aids. The vertical bars show 95% confidence intervals.

Fig.4. Detection rate of cortical responses for /g/, /t/ and /s/ sounds presented at 55 and 65 dB SPL, respectively.

Fig.5. Hearing threshold at 4 kHz in the better ear in relation to the overall figure of merit.

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Table 1

Averaged hearing thresholds (mean) and standardized deviation (SD) in better ear across subjects at frequencies from 250 to 8000 Hz.

	Frequency (Hz)							
	250	500	1000	2000	3000	4000	6000	8000
Mean	41.3	49.7	57.9	65.1	66.6	68.8	69.0	69.1
SD	18.1	18.3	16.9	17.6	17.8	18.9	19.1	19.3
Range	[5,85]	[15,95]	[25,105]	[30,120]	[35,120]	[40,120]	[40,120]	[40,120]

Table(s)

Table 2

Demographic information of individuals who have additional disabilities (*n* = 18).

Subject No.	Gender	Age (years)	4FA HL in better ear	Types of additional disabilities
NL1	Female	4.2	68	Only 1 kidney function, already had full kidney failure
NL8	Male	2.4	75	ANSD (Bilateral)
NL11	Female	2.8	59	ANSD (Bilateral)
NL13	Male	3.5	70	ANSD (Bilateral)
NL14	Male	3.3	70	Dev Dis and CP
NL17	Male	5.8	48	Dev Dis, CP, and Oromotor dyspraxia
NL18	Male	3.5	65	ANSD (Bilateral)
NL19	Male	3.5	61	ANSD (Bilateral) , Dev Dis, CP, Vision, and Cranio facial Abnormality
NL20	Male	2.3	50	ANSD (Bilateral), Dev Dis and ASD
NL26	Male	2.7	56	ANSD (Bilateral), Vision impairment and Sticklers Syndrome
NL28	Male	2.8	39	Vision impairment
NL40	Male	3.5	79	LVAS
NL60	Female	3.9	100	ANSD (Unilateral)
NL62	Male	6.8	34	cardiac malformation (repaired)
NL63	Female	5.8	58	Vision impairment and Proximal Symphalangism
NL64	Female	3.8	40	CP, Vision impairment, and Genetic Syndrome-unsure
NL65	Female	3.1	41	CP
NL67	Male	3.6	65	Dev Dis, CP, Vision impairment, brain damage to left side)

* Abbreviations: ANSD, Auditory Neuropathy Spectrum Disorder; LVAS, Large Vestibular Aqueduct Syndrome; Dev Dis, Developmental Disorder; CP, cerebral palsy; ASD, Autism Spectrum

Table 3

Deviation of hearing aid gains from prescribed targets.

	50dB input level		65dB input level		80dB input level	
	LF	HF	LF	HF	LF	HF
NLFC processing_NL1	2.8	2.4	2.0	2.2	2.0	3.5
NLFC processing_DSL	2.1	4.1	2.0	4.8	3.5	6.2
Conventional processing_NL1	3.4	3.4	2.5	2.8	2.3	3.1
Conventional processing_DSL	3.9	4.7	2.6	4.5	4.4	4.3

* Abbreviations: LF, Low frequencies from 0.25 to 1 kHz; HF, High frequencies from 2 to and 4 kHz; NL1, NAL_NL1 prescription; DSL, DSL v5 prescription.

Table(s)

Table 4

Comparison of test scores (Mean) and standardized deviation (SD) using NLFC and conventional processing in hearing aids.

Evaluation	Scale	No. of available subjects	Conventional processing	NLFC processing	Difference *p* value
SIR-parent	[1-7]	31	2.87 (1.1)	2.45 (0.85)	< 0.05
SIR-researcher	[1-7]	31	2.90 (1.1)	2.45 (0.93)	< 0.05
Correct score of consonant score	%	15	54.2 (14.0)	61.1 (13.3)	0.056
Number of detection of CAEP- 55dB SPL input level	[0-3]	38	1.95 (1.0)	2.6 (0.7)	< 0.05
Number of detection of CAEP- 65dB SPL input level	[0-3]	38	2.69 (0.6)	2.95 (0.32)	< 0.05
Comparative PEACH-Quiet	[-2, 2]	60	0.89 (0.64)		
Comparative PEACH-Noise	[-2, 2]	60	0.77 (0.63)		

*SIR provided by parent and researcher is depicted by 7-point scale. Consonant score is represented by the percentage correct in %. The number of detected CAEP responses to three speech stimuli ranges from 0 to 3. The comparative PEACH score is represented by 5-point scale.

Table 5(a)

Confusion matrix for conventional processing (*n* = 15).

	p	b	t	d	k	g	m	n	ŋ	f	v	θ	ð	s	z	ʃ	ʒ	h	tʃ	ʤ	l	r	y	w
p	22	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
b	0	20	0	5	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t	1	0	23	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
d	0	1	0	22	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0
k	0	0	2	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
g	2	0	1	8	1	12	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0
m	0	0	0	2	0	0	21	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
n	0	2	0	3	0	0	14	6	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
ŋ	1	0	0	1	0	1	11	4	2	1	1	0	0	0	1	0	0	0	0	0	3	0	0	1
f	2	0	0	3	0	0	0	0	0	17	0	1	0	4	0	0	0	0	0	0	0	0	0	0
v	2	4	0	2	0	0	1	0	0	0	16	0	1	0	0	0	0	0	0	0	0	0	0	1
θ	0	4	1	3	0	0	0	0	0	3	2	6	0	7	0	0	0	1	0	0	0	0	0	0
ð	0	1	2	2	0	0	0	0	0	2	3	0	9	2	0	0	0	1	0	0	0	0	1	4
s	0	0	3	1	0	1	0	0	0	0	0	2	0	17	0	1	0	2	0	0	0	0	0	0
z	0	2	0	4	0	0	0	0	0	0	0	2	1	3	12	2	0	1	0	0	0	0	0	0
ʃ	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	21	0	1	0	0	0	0	0	0
ʒ	0	0	0	2	0	0	0	0	0	1	1	0	0	1	1	11	6	3	0	1	0	0	0	0
h	2	3	0	1	0	0	2	0	0	3	1	2	1	4	0	1	0	7	0	0	0	0	0	0
tʃ	0	0	3	0	2	0	0	0	0	0	0	1	0	0	0	3	0	0	18	0	0	0	0	0
ʤ	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	19	0	0	0	0
l	0	3	0	1	0	0	2	5	0	0	3	0	0	0	0	0	0	0	0	0	12	0	0	1
r	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	14	0	10
j	0	1	0	5	1	2	0	0	0	1	2	1	1	1	1	1	0	0	0	1	0	0	7	2
w	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	22

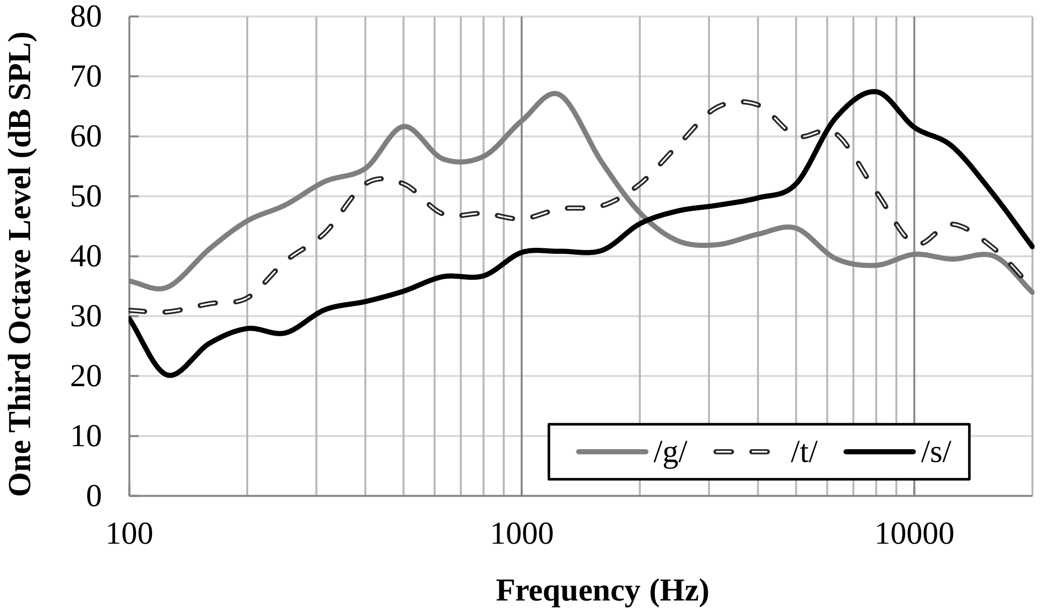
Table 5(b)

Confusion matrix for NLFC processing (*n* = 15).

	p	b	t	d	k	g	m	n	ŋ	f	v	θ	ð	s	z	ʃ	ʒ	h	tʃ	ʤ	l	r	y	w
p	20	0	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0
b	0	22	0	1	0	0	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	0
t	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d	0	1	0	25	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
k	0	0	3	0	23	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
g	4	0	3	8	0	9	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
m	0	0	0	0	0	0	25	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
n	0	0	0	1	0	0	9	10	0	0	4	0	1	0	0	0	0	0	0	0	0	0	0	2
ŋ	0	0	1	1	0	1	14	1	2	0	1	0	0	0	0	0	0	1	0	0	2	0	0	3
f	1	2	0	1	0	0	0	0	0	18	0	1	0	4	0	0	0	0	0	0	0	0	0	0
v	0	2	0	0	0	0	0	0	0	0	21	0	1	0	1	0	0	1	0	0	0	0	0	1
θ	1	2	0	3	0	0	0	0	0	7	2	7	0	3	0	0	0	2	0	0	0	0	0	0
ð	0	2	0	3	0	0	0	0	0	1	8	1	7	2	1	0	1	0	0	0	0	0	0	1
s	0	0	0	1	0	0	0	0	0	0	0	0	0	24	1	1	0	0	0	0	0	0	0	0
z	0	0	2	5	0	0	0	0	0	0	3	0	0	4	11	1	0	1	0	0	0	0	0	0
ʃ	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	22	0	0	2	0	0	0	0	0
ʒ	0	0	2	3	0	0	0	0	0	0	0	0	0	2	0	9	9	2	0	0	0	0	0	0
h	0	0	0	2	0	0	0	0	0	12	0	0	1	2	0	0	0	9	0	0	0	0	1	0
tʃ	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	3	0	0	19	2	0	0	0	0
ʤ	0	0	4	2	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	18	0	0	0	0
l	0	2	0	1	0	0	3	2	0	0	5	0	1	0	0	0	0	0	0	0	10	0	0	3
r	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	14	1	8
j	0	0	0	5	0	3	0	0	0	0	3	0	1	2	1	0	1	1	0	0	0	0	9	1
w	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26

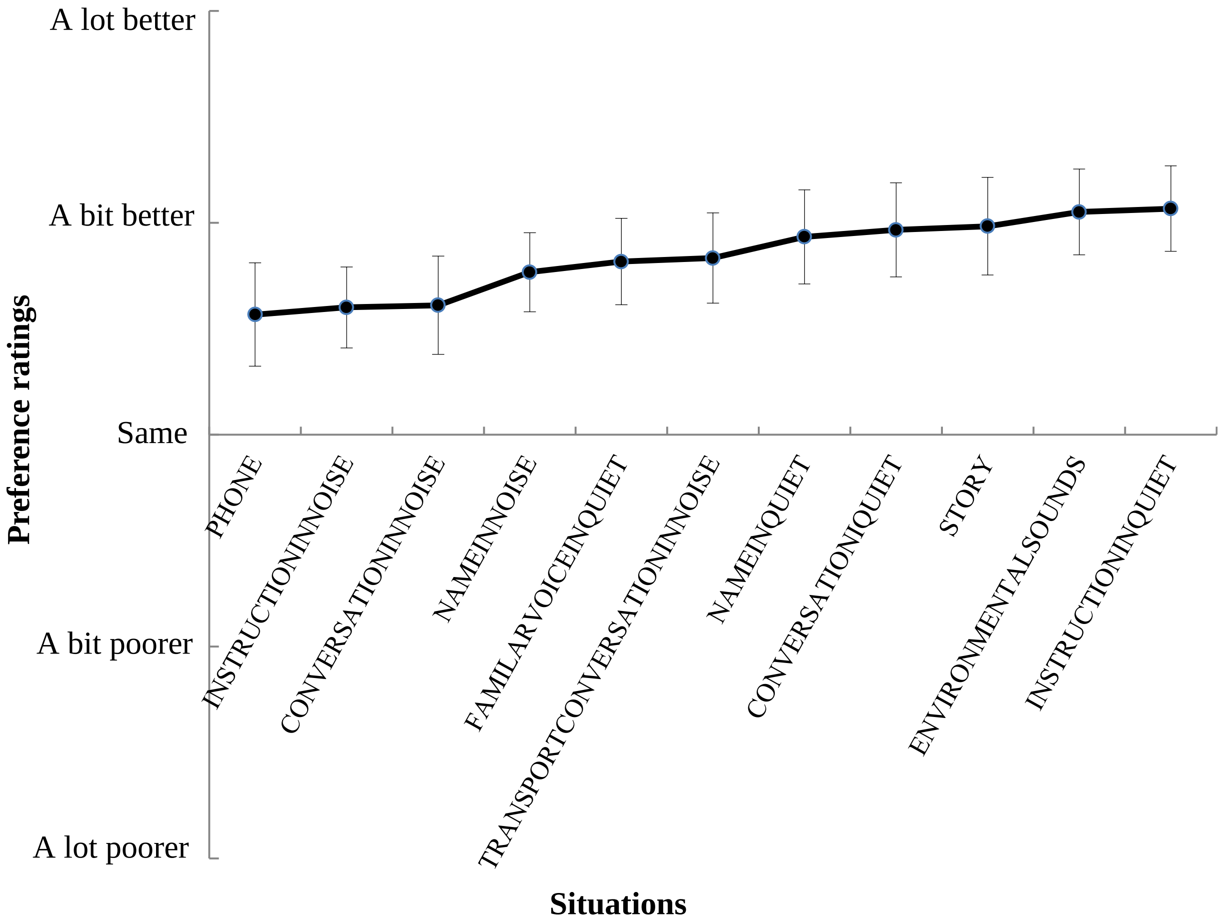
Figure(s)

Fig.1.



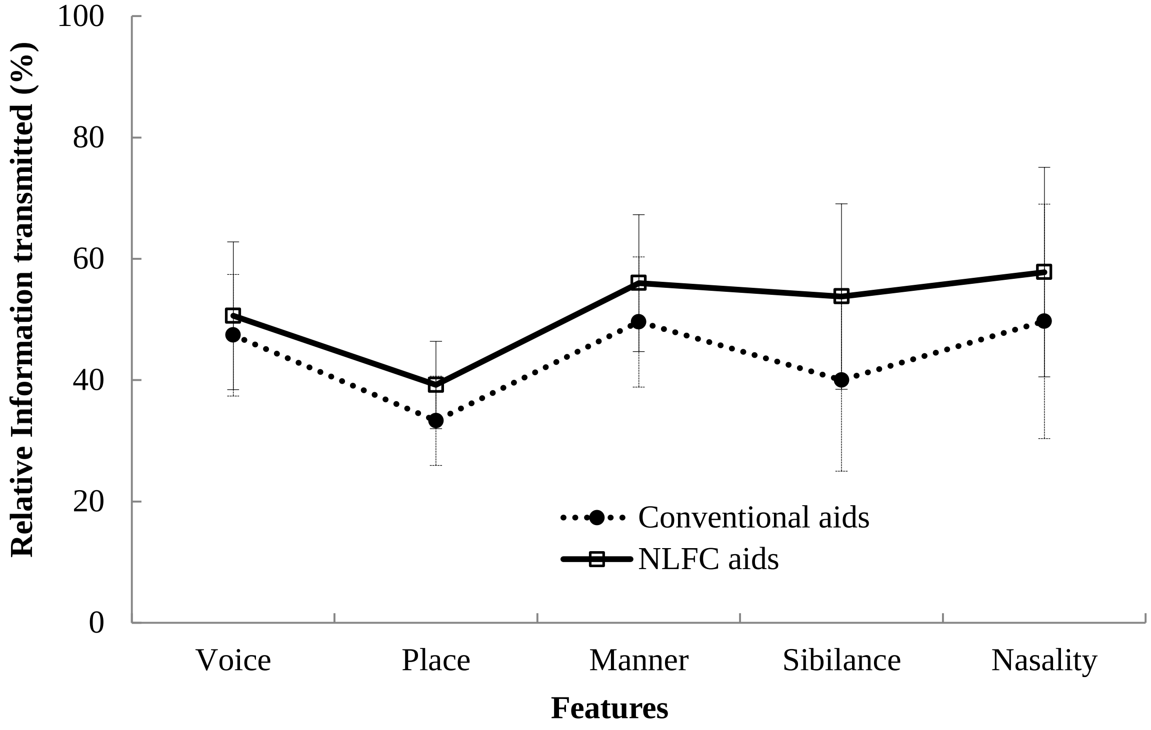
Figure(s)

Fig.2.



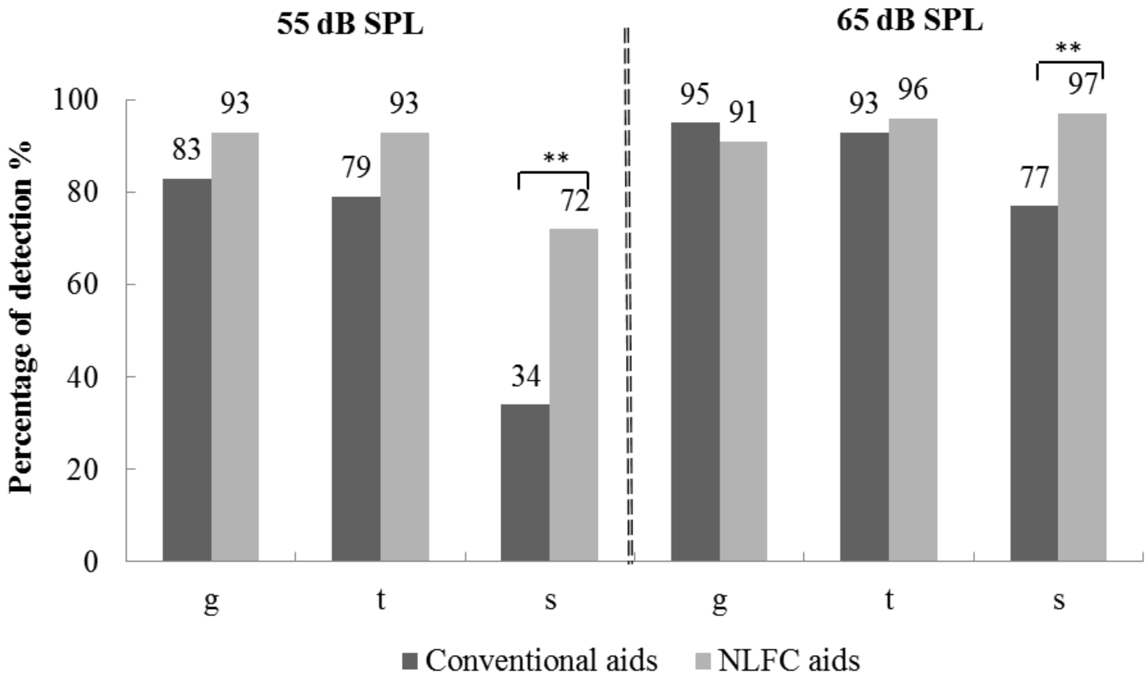
Figure(s)

Fig.3.



Figure(s)

Fig.4.



Figure(s)

Fig.5.