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A randomised controlled trial of nonlinear frequency compression versus conventional processing in hearing aids: speech and language of children at 3 years of age

Teresa YC Ching^{1,2}, Julia Day^{1,2}, Vicky Zhang^{1,2}, Harvey Dillon^{1,2}, Patricia Van Buynder^{1,2}, Mark Seeto^{1,2}, Sanna Hou^{1,2}, Vivienne Marnane^{1,2}, Jessica Thomson^{1,2}, Laura Street^{1,2}, Angela Wong^{1,2}, Lauren Burns^{1,2}, and Christopher Flynn^{1,3}

¹National Acoustic Laboratories, Australia

²The HEARing CRC, Australia

³Australian Hearing, Australia

Abstract

Objective—To determine the effect of nonlinear frequency compression (NLFC) on children's development of speech and language at 3 years of age.

Design—A randomised controlled trial was conducted as part of the population-based Longitudinal study on Outcomes of Children with Hearing Impairment (LOCHI). Participants were randomly assigned to fitting with NLFC (Phonak Naida V SP or UP) or with conventional processing in hearing aids, prescribed by using either the NAL or the DSL formula. Standardized tests of speech production, receptive and expressive language were administered, and parent ratings were collected. All assessments were double-blinded.

study sample—Participants were 44 of the 450 children in the LOCHI cohort.

Results—Compared to children using conventional processing, receptive and expressive language was higher but receptive vocabulary and consonant articulation scores were lower for children who use NLFC. There was increased substitution of affricates by fricatives for children using NLFC, compared to children using conventional amplification. After allowing for the effect of multiple demographic variables, the difference in global language scores between groups was not significant (effect: 0.8 [confidence interval: -6.7, 8.3]).

Conclusions—There is insufficient evidence to support a difference in language ability between children using NLFC and those using conventional amplification.

Keywords

Nonlinear frequency compression; hearing aids; children; randomised controlled trial; language; speech production; functional performance; CDI; DEAP; PEACH; PLS-4; PPVT

Children with hearing loss rely on amplified signals to acquire speech and language, as well as to learn about their environment. As speech and environmental sounds contain, and are

Address for correspondence: Teresa YC Ching, National Acoustic Laboratories, Level 4, Australian Hearing Hub, 16 University Avenue, Macquarie University, NSW 2109, Australia, Teresa.Ching@nal.gov.au.

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sometimes dominated by, high-frequency components, it is important to detect and identify such sounds. Limited access to high-frequency sounds has a negative impact on children's identification of /s/ and /z/ (Stelmachowicz, Lewis, Choi & Hoover, 2007). This hampers their abilities to acquire grammatical markers of number and person (Kortekaas & Stelmachowicz, 2000; Moeller et al, 2010) in the English language and poses difficulties for them to acquire production of high-frequency fricative sounds (Moeller, 2007).

There is some evidence to indicate that audibility of speech energy up to 8 kHz is important for perception of the fricative /s/ produced by female and child speakers (Stelmachowicz et al, 2001). As the spectrum level of speech falls progressively with increasing frequency above about 500 Hz, a large amount of gain will be required to restore audibility of some high-frequency sounds for people with mild to moderate high-frequency hearing loss. For this reason, it may be impractical to restore full audibility of speech in the frequency band around 10 kHz for many people with hearing loss (Moore et al, 2008). In order to help hearing-aid users to gain access to information about the high-frequency components of speech, hearing aid manufacturers have developed sound-processing schemes to shift or compress high-frequency sounds into a lower frequency range. Several of these schemes are now widely available in commercial hearing aids (for reviews on the range of schemes and laboratory-based efficacy: see Simpson, 2009; Alexander, 2013). In a non-linear frequency-compression (NLFC) scheme, an entire range above a certain start frequency (or cut-off frequency) is compressed in frequency by a specific amount (frequency-compression ratio), and shifted to an adjacent lower-frequency region. Frequencies below the cut-off frequency are unaffected by NLFC processing. For example, when a cut-off frequency of 2 kHz is selected, speech energy within the 2 to 10 kHz range may be compressed and presented in the 2 to 5 kHz range; the energy below 2 kHz is left unchanged. The input-output function is entirely determined by selection of the two parameters. Signal components processed by NLFC do not overlap in frequency with any other components present at the same time. Together with components below the cut-off frequency, signals that have been compressed in frequency are amplified and additionally processed as usual. This scheme would be expected to increase audibility of some high-frequency components of speech, but also distort other sounds (McDermott, 2011). Given that reduced hearing sensitivity is often accompanied by decreased frequency resolution, a listener may be able to hear the amplified sounds but may not be sufficiently able to resolve the shape of the compressed spectrum.

The published literature on NLFC processing for children (for a summary see Ching, 2012) indicates that this processing can improve audibility of /s/ for some listeners, but there is a lack of consistency across studies (Alexander, 2013). Glista et al (2009) compared performance with NLFC and conventional processing for children aged 9 to 13 years using hearing aids fitted according to the DSL m[i/o] prescription (Desired Sensation Level multistage input/output algorithm, Scollie et al, 2005). They reported that out of 11 children tested for detection of /s/ and /z/ used for marking plurality in words (UWO Plural test, Glista & Scollie, 2012), 5 showed improvement in detection, 5 showed no benefit, and one child showed poorer performance with NLFC. Wolfe et al (2010) evaluated 15 children (ages 6–12 years) with mild to moderately severe hearing loss who were fitted with hearing aids according to the DSL m[i/o] prescription. Use of NLFC resulted in significantly better detection of plural markers (UWO Plural Test), and increased identification of nonsense tokens /asa/ and /ada/, compared to conventional processing. There was however no significant difference for identification of /afa/, /aka/, /asha/, /ata/ in quiet, or sentence perception in noise. After familiarisation for 6 months, 13 of the 15 children showed increased identification of /s/ and /z/ with NLFC compared to conventional processing when tested using the UWO Plural test. The remaining 2 children performed at ceiling with conventional processing. However, no benefit or change in benefit for sentence recognition in noise or for identification of tokens /afa/, /aka/, /asha/ or /ata/ presented in quiet with

NLFC relative to conventional processing was evident (Wolfe et al, 2011). In a similar vein, Bohnert (2009) reported no significant benefits for word perception in 6- to 15-year olds with moderate to profound hearing loss when they compared NLFC with conventional processing implemented in the same hearing aids fitted according to the DSL (Desired Sensation Level) prescription. These studies revealed considerably different perceptual effects for children using the same frequency lowering scheme, even for similar audiometric configurations, and for hearing aids fitted in accordance with the same prescription and fitting procedure.

As the published studies that examined NLFC for children used the DSL prescriptive formulae to verify the gain and maximum output of the hearing aid, these findings cannot be generalised to other prescriptive approaches for hearing-aid fitting. The National Acoustics Laboratories (NAL) prescription, which is also widely used for pediatric amplification, provides target gain-frequency responses that vary from the DSL prescription for the same audiometric characteristics (Ching et al, this issue). These differences in audibility that relate to the choice of prescriptive formula may affect the extent to which frequency lowering increases audibility and its relative effectiveness for children.

There is a lack of high-quality evidence on the effect of frequency lowering for school-age children (see systematic review by McCreery et al, 2012); there is no information on effectiveness of the processing for younger children. This poses a major challenge to clinical management of children with hearing loss. Although the use of NLFC can increase audibility of /s/ under specific conditions for some listeners, the concomitant effect of processing on reducing spectral cues for perception of or discrimination between sounds is not well understood. Whereas an increase in audibility may be expected to affect speech perception, thereby influencing speech and language acquisition, there is as yet no research that directly examines the effect of using NLFC on language development and speech production of young children.

The present study aimed to investigate whether language and speech development of young children would be affected by frequency lowering implemented as NLFC in hearing aids. Considering the variability in current literature, we hypothesised that there would be no difference in language and speech outcomes at 3 years of age between children using amplification with NLFC and children using conventional processing.

Method

Design of the study

This was a randomised controlled trial. We randomly assigned children to be fitted with hearing aids that provided either NLFC or conventional processing (CP), and conducted blinded assessments of their speech and language outcomes at the chronological age of 3;0 to 3;6 years.

Participants

The participants were 44 children from amongst the 450 children enrolled in the Longitudinal Outcomes of Children with Hearing Impairment (LOCHI) study (Ching et al, 2013). The study prospectively followed a population-based cohort of children whose hearing loss was detected via either universal newborn hearing screening programs or standard care, who first received intervention before 3 years of age. Enrollment to the LOCHI study was completed in 2007. Children who enrolled prior to initial amplification were randomly assigned to being fitted with either the NAL prescription for non-linear hearing aids version 1 (NAL-NL1) or the DSL prescription version 4 (DSL v4) (Ching et al, this issue). Those who enrolled after initial amplification were fitted with hearing aids using

the NAL prescription, in accordance with standard practice of Australian Hearing (AH), the government-funded national hearing-service provider for all children with hearing loss in Australia.

The present trial on NLFC commenced in 2009 when hearing aids with NLFC became available in Australia. LOCHI children with bilateral sensorineural hearing loss fitted with hearing aids in both ears were invited to participate. To be eligible, they must have had audiometric thresholds of ≤ 30 dB HL at 1 kHz, in accordance with the manufacturer specified fitting range for the devices to be used for fitting. Children were not eligible if they had reverse slope audiograms, known additional disabilities, or were not using spoken English for communication. All eligible families were invited to give informed consent for participation. The consented participants were randomly assigned to either re-fitting with Phonak Naida V SP or UP hearing aids with NLFC activated, or to continue using their personal hearing aids that had wide-dynamic range-compression capabilities with conventional processing.

Written informed consent for participation was provided by parents or guardians of child participants. The study was approved by the institutional ethics review board. Parents of 110 children gave consent for participation in this randomised controlled trial. This report focuses on findings from 44 children who enrolled in the trial before they turned 3 years of age. Of these, 25 were refitted with Phonak Naida V (model SP or UP as appropriate to their hearing loss). As the children were previously randomly assigned to fitting with either the NAL (NAL-NL1) or DSL (DSL v4) prescription for initial fitting, this was maintained in the refitting. Consequently, the NLFC group comprised 12 children fitted with the NAL formula and 13 children fitted with the DSL formula. The CP group comprised 12 children fitted with the NAL formula and 7 children with the DSL formula. Table 1 summarises the demographic characteristics and hearing aid experience of the children.

Hearing-aid fitting of children

All children enrolled in the study were fitted with hearing aids according to the AH national paediatric amplification protocol (King, 2010) by the AH network audiologists. Hearing aid fitting involved the use of individually measured or age-appropriate real-ear-to-coupler differences (RECD) to derive custom prescriptive targets. Hearing aids were measured in an HA2-2cc coupler to verify that targets were matched to within 5 dB at 4 of the 5 octave frequencies between 0.25 and 4 kHz.

Manufacturer default NLFC settings (i.e. frequency-compression ratio and cut-off frequency) were adjusted as needed, based on aided cortical evoked potential measurements in response to /t/, /g/, and /s/ presented at 65 dB and 55 dB SPL in the sound field (Zhang et al, 2012). Additional fine-tuning was performed for two children based on parent or teacher feedback (e.g. increased difficulty distinguishing between /s/ and /ʃ/; degraded speech production; poor sound quality). Figure 1 shows the cut-off frequency and frequency-compression ratio in relation to cut-off frequency used in children's hearing aids.

Participant-related measures: predictor variables

To control for baseline characteristics that potentially influence outcomes, we collected information about a range of characteristics that have been reported in the literature to be associated with child outcomes. The predictor variables included age at first-fitting of hearing aids, prescription used for fitting (NAL or DSL), severity of hearing loss, gender, birth-weight, maternal education, family socio-economic status, and communication mode used at home and in early education during the first 3 years of life.

Information about demographic characteristics was solicited from parents or primary caregivers using purpose-designed questionnaires. Family socio-economic status was determined on the basis of the location of the family residence according to the Australian census-based Index of Relative Socioeconomic Advantage and Disadvantage (IRSAD), one of the four indexes that make up the Socio Economic Index for Areas (Australian Bureau of Statistics, 2008). The IRSAD defines relative socioeconomic advantage and disadvantage in terms of “people’s access to material and social resources, and their ability to participate in society” (ABS, 2008, p.6). In this paper, the IRSAD was specified in terms of deciles, with a lower index associated with greater relative disadvantage. Maternal education was specified in terms of a 3-point scale: less than or equal to 12 years of school attendance, diploma or certificate, and university qualification. Data relating to audiological management of children were collected from the clinical files and national client database held at AH.

Outcome measures

Outcome measures included both direct assessments of children and questionnaire-based reports from parents or caregivers. Formal assessments included the Preschool Language Scale version 4 (PLS-4; Zimmerman et al, 2002) for assessing expressive and receptive language; the Peabody Picture Vocabulary Test version 4 (PPVT-4; Dunn & Dunn, 2007) for assessing receptive vocabulary; and the Articulation and Phonology subtest of the Diagnostic Evaluation of Articulation and Phonology test (DEAP; Dodd et al, 2002) for assessing speech production. The PLS-4 incorporates interactive play, picture pointing, and verbal elicitation activities targeting children’s knowledge of English semantics, morphology, and syntax. Children’s performance was scored in terms of Auditory Comprehension and Expressive Communication. The PPVT-4 is based on a four-alternative, forced-choice, picture-selection format. Children were required to respond to each verbal stimulus by pointing at one of the pictures, giving an overall score of receptive vocabulary. In the DEAP phonology subtest, 50 single-word utterances are elicited using pictures, verbal cues, and/or imitation. The target words cover all English consonants in syllable-initial (except /ŋ/ and /ʒ/) and syllable-final positions (except /ʒ/, /t/, /w/, /j/, /h/), and all vowels and diphthongs (except /æ/). Children’s speech output was scored in terms of percent consonants correct (PCC) and percent vowels correct (PVC); errors in production were analysed in terms of confusions and phonological processes. For all measures, published normative data were used to derive z scores.

Written report tools included checklists from the Child Development Inventory (CDI; Ireton, 2005) for soliciting information on expressive and receptive language as well as social and motor skills development. The Language Comprehension, Expressive Language, Social, Self-help, Gross motor, and Fine motor subscales were used. Raw scores were converted into developmental ages using published normative data, and quotients were calculated by dividing the child’s developmental age by their chronological age, expressed as a percentage. Parents were also requested to complete the Parents Evaluation of Aural/oral functional performance of CHildren (PEACH), which is a measure of children’s functional communicative performance in real-world situations (Ching & Hill, 2007). The group mean score and standard deviation in children with normal hearing were used to derive z scores for the participants. The PEACH also provided a measure of usage of hearing device and listening comfort in daily lives, as reported by parents.

Procedure

A team of speech pathologists administered tests directly to children in their homes or early education centres after they turned 3 years of age. All children had at least 6 months of experience with the devices they were using at the time of evaluation. The researchers who collected outcomes data were blinded to the hearing aid prescription used for fitting, the use

of NLFC or conventional processing, the screening status, and severity of hearing loss of children. Direct assessments were video- and audio-recorded. Randomly selected samples constituting at least 10 percent of the total were subjected to a second, independent scoring. The inter-rater reliability was 97 percent. Written checklists and questionnaires were sent to parents prior to direct evaluation of children, and were collected either at or soon after the assessments.

Data analyses

The primary outcome measures were summarised in terms of means and standard deviations. Means were compared using independent sample t-tests with unequal variance. Effect sizes between the two samples for continuous scales were calculated by subtracting the mean of the CP group from the mean of the NLFC group and dividing the result by the pooled standard deviation (Cohen, 1977).

The production data from children were transcribed according to the International Phonetic Alphabet system, and the transcriptions were entered into the CASALA software (CASALA, 2007) for calculating proportion of correct vowel and consonant scores, for determining phonological processes from speech errors, and for constructing confusion matrices. These matrices were analysed further to calculate how much information about selected articulatory features was conveyed (Miller & Nicely, 1955). The features examined were voicing, place of articulation, manner of articulation, sibilance, and nasality.

In the LOCHI study, factor analysis was first used to form composite scores from a collection of 9 measures: PLS-4 Auditory comprehension score; PLS-4 Expressive Communication score; PPVT-4 receptive vocabulary score; DEAP consonant correct score; DEAP vowel correct score; CDI Language Comprehension score; CDI Expressive Language score; CDI Social score; and PEACH score. The multiple imputation method (Rubin, 1987) was applied to handle missing values in predictor and outcomes variables. The global language score was a linear combination of multiple test measures, weighted by the coefficients obtained using factor analysis. The scores were scaled so that children with normal hearing would have a mean value of 100 and a standard deviation of 15. Using this global language score as the dependent variable, multiple regression analysis was conducted in the main LOCHI study to examine the effect of a range of predictor variables on outcomes. The variables included gender, presence or absence of additional disability, presence or absence of auditory neuropathy, communication mode in early education, communication mode at home, language used at home, maternal education, prescription, age at first-fitting of hearing aids, birth weight, four-frequency-average hearing loss, and socio-economic status.

The present investigation used the residuals from the main regression model as dependent variables to determine whether children fitted with NLFC perform significantly differently from those using CP in hearing aids.

The analysis was performed using Statistica (version 10.0.1011) and R (version 3.0.0). We used two-tailed tests and set statistical significance at $p < 0.05$.

Results

Outcomes of children

Evaluations were completed between 36 and 42 months of age (median: 37.2; interquartile: 36 to 38). Table 2 shows mean test scores for the NLFC group and the CP group on standardised assessment measures. On average, the estimated effect size of NLFC processing was in the negative direction for receptive vocabulary ($p = 0.04$) and speech

production ($p > 0.05$), but in the positive direction for the CDI fine motor ($p = 0.03$), CDI Language comprehension ($p = 0.03$), and receptive and expressive language measured using PLS-4, CDI of social, self-help and gross motor subscales, and PEACH ($p > 0.05$). Parents reported in the PEACH questionnaire that children used hearing aids for more than 90% of their waking hours (interquartile range: 75 to 100), on average. This applied to both groups of children.

Separate analyses of variance using individual test scores as the dependent variable, processing (NLFC vs CP) and prescription (NAL vs DSL) as between-group variables revealed that the main effect of processing was not significant for any of the measures ($p > 0.05$). The interaction between processing and prescription was not significant for any of the measures ($p > 0.05$).

The results of speech production were further analysed to determine how much information about phonetic-articulatory features was conveyed by each group. As shown in Figure 2, information about voicing and nasality was similar between groups, but a slightly higher proportion of information about place of articulation, manner of articulation, and sibilance was transmitted in the production of the CP group compared to the NLFC group. The difference between scores of the two groups was significant for place ($t = -3.13$, $p = 0.004$) and manner of articulation ($t = -2.48$, $p = 0.02$), but not for voicing, nasality, or sibilance ($p > 0.05$).

This raises the question of the extent to which frequency lowering was effective at providing additional information about high-frequency features of the speech spectrum to support acquisition. Perception of such information would be expected to affect the production of /f/, /v/, /θ/, /ð/, /s/, /z/, /ʃ/, /ʒ/, /tʃ/, /dʒ/, and /h/ more than others, because these consonants are distinguished particularly by acoustic cues in the high frequencies. To investigate this issue further, the scores for correct production were extracted from the confusion matrices for each group. Figure 3 shows the mean correct production scores for all consonants. On average, the difference in correct scores between groups was significant for /tʃ/ ($t = -3.45$, $p = 0.002$) and /dʒ/ ($t = -2.77$, $p = 0.01$), but none of the differences for other consonants reached significance level ($p > 0.05$).

In the main LOCHI study, a regression model investigating predictors for global language scores of the complete cohort at 3 years of age showed that gender, severity of hearing loss, and maternal education, among others, were significant predictors of 3-year outcomes at the 5% level (Ching et al, 2013). Of the 44 children in this sub-study, 41 had outcomes measured on at least two measures to form a global language score (24 in the NLFC and 17 in the CP group). Analysis of the effect of processing on the global language score revealed that the use of NLFC relative to CP was associated with an effect size of 0.8 (95% confidence interval: -6.7, 8.3), $p = 0.83$. Figure 4 shows the predicted values and 95% confidence intervals for the mean global language scores of the two groups of children. In this plot, the mean scores were adjusted to remove the effects of the other predictor variables.

Discussion

This study investigated the effect of nonlinear frequency compression on language and speech development of children with hearing loss at 3 years of age. The present study extended findings from previous studies by using a randomised controlled trial with blinded assessments. We evaluated language and speech development of young children using standardized measures rather than specifically designed tests of detection of high-frequency consonants, and estimated the effect of processing after controlling for a range of variables

that are known to affect children's outcomes (Ching et al, 2013). Our findings do not provide any evidence that NLFC improves language development and speech production relative to conventional amplification for children with audiometric characteristics like those in this study. These audiometric characteristics fit within manufacturer-specified fitting range for NLFC in hearing aids. Individual test measures revealed that children who used NLFC obtained lower mean scores for receptive vocabulary and consonant articulation, but higher language scores and parental ratings than children who used conventional amplification. However, none of these between-group differences reached the 5% significance level.

Given the significance of high-frequency audibility for the development of phonological (Moeller et al, 2007) and morpho-syntactic skills (Moeller et al, 2010) as well as novel word learning (Pittman, 2008), the use of NLFC has been proposed for enhancing speech and language skills. The present findings do not lend support to this view. On average, receptive vocabulary was better for children using conventional processing than for those using NLFC in their hearing aids, with a medium effect size of -0.45 ($p = 0.04$). Consonant production was better for children using conventional processing compared to those using NLFC, with an effect size of -0.43 , although this did not reach significance level ($p = 0.27$). On the other hand, mean expressive language scores based on parent reports (CDI) showed that NLFC was superior to CP (effect size = 0.29 ; $p = 0.03$), and mean scores based on the PLS-4 were higher for NLFC than for CP (effect size = 0.03 for auditory comprehension; 0.307 for expressive communication) but these latter differences did not reach significance level ($p > 0.05$). Because multiple factors are known to affect speech and language development, we have quantified the effect of NLFC on global language scores after allowing for the effects of a range of predictors known through multiple regression analysis to affect language outcomes. Although the overall effect size associated with the use of NLFC on global language is positive, it is only 0.8 points. The evidence is insufficient to reject the null hypothesis that there is no difference in language scores between children with NLFC and children with CP. With a confidence interval of ± 7.5 points, the true mean effect of using NLFC lies within the range of -6.7 points to $+8.3$ points. Given the wide range of performance, we could not rule out the possibility that a larger sample size may reveal clinically significant differences, in either direction, between the device types.

The present trial also allowed an examination of the potential interaction of prescription choice with processing in hearing aids, by design of the LOCHI study. It is possible that the effect of NLFC may be greater for children fitted with DSL than those with NAL because the former prescribes higher gain than the latter for the same audiogram. Conversely, the effect of NLFC could be less with the NAL prescription if the prescription did not provide gain sufficient to enable frequency lowered speech cues to be audible. Nonetheless, the present results indicated neither a significant main effect of processing nor an interaction with prescription on any of the test measures. These findings add to previous studies on the effect of NLFC that have been exclusively based on fittings using the DSL prescription (Glista et al, 2009; Wolfe et al, 2010; 2012).

With regard to speech production, overall vowel scores were comparable to those of normal-hearing children, with correct scores close to 90% for both groups of children with hearing aids. As the lowest cut-off frequency of NLFC processing is 1.5 kHz, the first formant for all vowels and the second formant for most vowels and most talkers would be expected to be largely outside the range of frequency compression (Harrington et al, 1997; Hillenbrand et al, 1995). The overall consonant production scores were one standard deviation below the normative mean. Feature analysis of confusion errors revealed that voicing and nasality were equally well transmitted for both groups of children. Because NLFC processing is unlikely

to affect the lowest five harmonics of the voice fundamental frequency, which carry most of the information about voicing and nasality, this finding is as expected.

In line with expectations that increased access to high-frequency sounds through NLFC may improve articulation of high-frequency consonants (Moeller et al, 2007), the observed production scores for /s/ and /z/ were slightly, but not significantly, higher for the NLFC group (28% correct for /s/; 33% correct for /z/) than for the CP group (26% and 31% respectively). However, the use of NLFC was not associated with an increase in correct production of other high-frequency consonants, compared to the use of CP (see Figure 3). Correct production of affricates /tʃ/ and /dʒ/ occurred significantly more often, on average, for children using CP (68% and 63% respectively) than for those using NLFC (24% and 33% respectively). Errors in production of /tʃ/ involved stopping (i.e. substituted by /t/) for both groups (16% of errors for the CP group and 33% for the NLFC group), but children using NLFC also made many more frication errors (i.e. substituted /tʃ/ by /ʃ/) – a phonological process that was not commonly observed for children using conventional processing in hearing aids or children with normal hearing.

The substitution of an affricate /tʃ/ by a fricative /ʃ/ suggests that the acoustic cues relating to the silence gap, the release burst and/or the transition that distinguish between the two sounds (e.g. Dorman et al, 1979; Dorman et al, 1980; Kluender & Walsh, 1992) may have been reduced by the processing. This was investigated by performing spectrographic analysis of the sounds before and after hearing aid processing. Figure 5 shows the spectrogram of the original sound /tʃi/ in the top panel, followed by the spectrograms depicting the output of a Phonak Naida V UP hearing aid programmed for a steeply sloping hearing loss to match NAL prescriptive targets in the bottom panels. The bottom two panels depict spectrograms of the hearing aid output after activation of NLFC, revealing that the silent interval corresponding to articulatory closure and the burst corresponding to articulatory release of the closure were much reduced in saliency. As the bandwidth of the hearing aid output of about 6 kHz was reduced to about 4.5 kHz or 2.5 kHz when NLFC was activated at two different parameter settings (see Figure 5 legend), the transition cues corresponding to articulatory movements associated with the /tʃ/-/ʃ/ distinctions were further reduced.

Implications for audiological management

The present study revealed no significant difference in overall language outcomes between children who used NLFC and children who used conventional processing in hearing aids. As NLFC deliberately alters the spectra of sounds resulting in some form of acoustic distortion, the present evidence supports the recommendation of the American Academy of Audiology Guidelines on Pediatric Amplification (AAA, 2013) that “frequency lowering should not be prescribed unless electroacoustic verification revealed that high-frequency speech audibility cannot be restored through conventional means”, and that “fitting of the technology should be accompanied by behavioural validation”. If the goal of using the technology is to provide access to high-frequency consonants which would otherwise not be audible, the use of a broadband test signal with a notch and narrow peak in its spectrum can be used to verify whether the lowering achieves audibility of speech in the region of the spectral peak for the audiogram to be aided (Glista & Scollie, 2012). Furthermore, the effectiveness of frequency lowering for detection of high-frequency sounds for children who are too young to provide reliable behavioural responses can be evaluated by objective measures of aided cortical evoked potential responses to high-frequency sounds presented at low input level (Zhang et al, 2012) and subjective measures based on parent-report outcomes (in preparation).

An incidental advantage of frequency lowering is that it allows greater stable gain to be achieved before feedback oscillation occurs. Whenever the real-ear-aided gain of a hearing

aid exceeds the attenuation of the signal as it leaks from the ear canal, out past the earmould, to the hearing aid microphone, feedback oscillation is likely (Dillon, 2012). Because frequency lowering 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 benefit of permanently-engaged frequency lowering increases audibility that would be useful for some children, as feedback occurs frequently when hearing aids are fitted to small and growing ear canals for which earmoulds may not consistently provide a good seal. Nonetheless, other options of feedback cancellation should be considered before resorting to engaging frequency lowering algorithms solely for this purpose given that frequency lowering is a form of distortion of the acoustic signal.

Limitations

The current findings apply only to children at 3 years of age, and cannot be generalised to other age groups. The longitudinal design of the LOCHI study means that the participants will be evaluated at an older age (5 years) to investigate the impact of NLFC on speech and language development, including speech perception which could not be reliably measured at 3 years. As a proportion of children participating in the trial enrolled after their 3-year evaluation, future follow-up of the cohort at 5 years will have an increased sample size. This will increase the statistical power of the study to investigate the effect of NLFC on outcomes. Cognitive ability will be assessed at 5 years, allowing its effect on language acquisition to be taken into account when quantifying the effect of NLFC on children's speech and language development. Additionally, accounting for cognitive ability will likely reduce the wide confidence interval of the effect size found in the present study.

This study evaluated the effect of NLFC on young children fitted with Phonak Naida SP or UP hearing aids. The findings cannot be generalised to other frequency lowering schemes available in commercial hearing aids. The relative efficacy of different schemes remains to be investigated.

Summary and Conclusion

The strengths of the present study include its random assignment of NLFC or conventional processing to a population-based cohort, its prospective measurement of language and speech production at 3 years of age, its use of blinded assessments, and its allowance for multiple predictors in determining the effect of NLFC on language outcomes. There is currently insufficient evidence to reject the hypothesis that there is no difference in speech and language development between children who use NLFC and children who use conventional amplification.

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Phonak Ltd. provided the Naida V SP and UP hearing aids used in this study.

Abbreviations

4FA	four-frequency average, across 0.5, 1, 2, and 4 kHz
CASALA	Computer Assisted Speech and Language Assessment software
CDI	Child Development Inventory
CP	conventional processing
DEAP	Diagnostic Evaluation of Articulation and Phonology
DSL	Desired Sensation Level
DSL v4	Desired Sensation Level prescription, version 4
DSL m[i/o]	Desired Sensation Level multi-stage input/output algorithm, also known as DSL v5
IRSAD	Index for Relative Socioeconomic Advantage and Disadvantage
kHz	kilo Hertz
LOCHI	Longitudinal Outcomes of Children with Hearing Impairment study
NAL	National Acoustic Laboratories
NAL-NL1	National Acoustic Laboratories' prescription for non-linear hearing aids, version 1
NLFC	Nonlinear Frequency Compression
PCC	Percent consonants correct
PEACH	Parents' Evaluation of Aural/oral performance of CHildren
PLS-4	Preschool Language Scale, 4 th Ed
PPVT	Peabody Picture Vocabulary Test
PVC	Percent vowels correct
RECD	real-ear-to-coupler differences
UWO	University of Western Ontario

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Figure 1. Frequency-compression ratio in relation to cut-off frequency used in hearing aids. The size of markers is proportional to the number of superimposed points.

Figure 2.

Results of information transmission analysis of the consonant confusion data based on speech production errors of children who used nonlinear frequency compression (NLFC) and those who used conventional processing (CP) in hearing aids. The features examined were voicing, place of articulation, manner of articulation, sibilance and nasality.

Figure 3.

Percent correct production of each of the consonants indicated in the horizontal axis. The labels for the consonants /ŋ/, /θ/, /ð/, /ʃ/, /tʃ/, and /dʒ/ were represented by 'ng', 'th', 'dh', 'sh', 'ch', and 'dg' respectively. The data shown are mean correct production scores (%) for children using nonlinear frequency compression (NLFC, filled symbols) and children using conventional processing (CP, open symbols). Vertical bars denote 0.95 confidence intervals.

Figure 4. Mean global language factor scores (filled circles) and 95% confidence intervals (vertical bars) for children using conventional processing (CP) and those using nonlinear frequency compression (NLFC) in hearing aids.

Figure 5.

Spectrograms of /itfi/ measured by a microphone mounted on the right ear of KEMAR. The top two panels show spectrograms of the original sound followed by the output of a Naida V UP hearing aid with NLFC de-activated over the frequency range from 0 to 8 kHz. The bottom two panels show spectrograms of the outputs of the same hearing aid with NLFC activated over the frequency range from 0 to 5 kHz, first with cut-off frequency at 2.4 kHz and a compression ratio of 1.7:1 and then with cut-off frequency set at 1.5 kHz and a compression ratio of 4:1.

Table 1

Demographic characteristics of participants using nonlinear frequency compression (NLFC) and those using conventional processing (CP) in hearing aids.

Characteristics		NLFC (n=25)	CP (n=19)
Gender (Male)	No.	14	6
Age at first fitting (months)	Mean (SD)	4.9 (4.4)	4.3 (3.2)
Birthweight (gms)	Mean (SD)	2892 (1225)	2848 (826)
Hearing loss (dB HL)	Better ear 4FA (SD)	61.6 (17.7)	59.7 (17.2)
Maternal education	School	3	8
	Diploma or certificate	7	4
	University	15	7
Months using hearing aids	Mean (SD)	33.0 (4.2)	33.0 (2.7)
Months using frequency compression	Mean (SD)	7.7 (1.8)	-
Socio-economic status (IRSAD Decile)	Mean (SD)	7.3 (2.5)	7.8 (2.5)

Comparison of test scores obtained by children using nonlinear frequency compression (NLFC) and children using conventional processing (CP) in hearing aids. Means, standard deviation (SD), effect size (NLFC relative to conventional processing), and *p* value for test of significance between groups are shown. The test scores included Preschool Language Scale - Auditory Comprehension (PLS-AC), Preschool Language Scale - Expressive Communication (PLS-EC), Peabody Picture Vocabulary Test of Receptive Vocabulary (PPVT), Diagnostic Evaluation of Articulation and Phonology - Consonant correct score (DEAP_C), Diagnostic Evaluation of Articulation and Phonology - Vowel correct score (DEAP_V), Child Development Inventory Social Scale Quotient (CSQ), Child Development Inventory Self-Help Scale Quotient (CSHQ), Child Development Inventory Gross Motor Scale Quotient (CGMQ), Child Development Inventory Fine Motor Scale Quotient (CFMQ), Child Development Inventory Expressive Language Scale Quotient (CELQ), Child Development Inventory Language Comprehension Scale Quotient (CLCQ), and Parents' Evaluation of Aural/oral performance of Children (PEACH). Asterisks depict significance at 0.05 probability level.

Table 2

	NLFC			CP			Effect size		<i>p</i>
	<i>n</i>	mean	SD	<i>n</i>	mean	SD	Cohen's <i>d</i>		
PLS-AC	23	82.0	24.1	15	81.2	23.5	0.034		0.95
PLS-EC	23	88.5	16.5	15	82.9	19.9	0.307		0.42
PPVT	18	87.9	19.2	9	94.3	9.3	-0.427		0.04*
DEAP_C	18	5.7	2.0	10	6.6	2.2	-0.442		0.68
DEAP_V	18	6.8	2.3	10	6.8	1.5	-0.011		0.17
CSQ	18	94.5	33.5	15	99.6	45.5	-0.126		0.23
CSHQ	18	99.3	28.9	15	87.5	40.9	0.336		0.17
CGMQ	18	99.0	40.3	15	82.5	32.5	0.450		0.42
CFMQ	18	102.6	21.2	15	99.9	37.7	0.089		0.03*
CELQ	18	81.8	14.6	15	75.5	25.9	0.298		0.03*
CLCQ	18	78.1	18.9	15	72.4	27.3	0.241		0.15
PEACH	19	75.8	16.9	13	69.1	26.1	0.309		0.09