Published in final edited form as:

Ear Hear. 2014 ; 35(4): e143–e152. doi:10.1097/AUD.0000000000000030.

Nonlinear Frequency Compression in Hearing Aids: Impact on Speech and Language Development

Ruth Bentler¹, Elizabeth Walker¹, Ryan McCreery², Richard M. Arenas¹, and Patricia Roush³

¹Department of Communication Sciences and Disorders, University of Iowa, Iowa City, Iowa, USA

²Boys Town National Research Hospital, Omaha, Nebraska, USA

³Department of Otolaryngology/Head and Neck Surgery, University of North Carolina-Chapel Hill, Chapel Hill, North Carolina, USA

Abstract

Objectives—The research questions of this study were: (1) Are children using nonlinear frequency compression (NLFC) in their hearing aids getting better access to the speech signal than children using conventional processing schemes? The authors hypothesized that children whose hearing aids provided wider input bandwidth would have more access to the speech signal, as measured by an adaptation of the Speech Intelligibility Index, and (2) are speech and language skills different for children who have been fit with the two different technologies; if so, in what areas? The authors hypothesized that if the children were getting increased access to the speech signal as a result of their NLFC hearing aids (question 1), it would be possible to see improved performance in areas of speech production, morphosyntax, and speech perception compared with the group with conventional processing.

Design—Participants included 66 children with hearing loss recruited as part of a larger multisite National Institutes of Health–funded study, Outcomes for Children with Hearing Loss, designed to explore the developmental outcomes of children with mild to severe hearing loss. For the larger study, data on communication, academic and psychosocial skills were gathered in an accelerated longitudinal design, with entry into the study between 6 months and 7 years of age. Subjects in this report consisted of 3-, 4-, and 5-year-old children recruited at the North Carolina test site. All had at least 6 months of current hearing aid usage with their NLFC or conventional amplification. Demographic characteristics were compared at the three age levels as well as audibility and speech/language outcomes; speech-perception scores were compared for the 5-year-old groups.

Results—Results indicate that the audibility provided did not differ between the technology options. As a result, there was no difference between groups on speech or language outcome

Copyright © 2014 by Lippincott Williams & Wilkins

Address for correspondence: Ruth Bentler, Department of Communication Sciences and Disorders, 250 Hawkins Drive, University of Iowa, Iowa City, IA 52242, USA. Ruth-bentler@uiowa.edu.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and text of this article on the journal's Web site (www.ear-hearing.com).

The authors declare no conflict of interest.

measures at 4 or 5 years of age, and no impact on speech perception (measured at 5 years of age). The difference in Comprehensive Assessment of Spoken Language and mean length of utterance scores for the 3-year-old group favoring the group with conventional amplification may be a consequence of confounding factors such as increased incidence of prematurity in the group using NLFC.

Conclusions—Children fit with NLFC had similar audibility, as measured by a modified Speech Intelligibility Index, compared with a matched group of children using conventional technology. In turn, there were no differences in their speech and language abilities.

Keywords

Audibility; Children; Frequency lowering; Hearing aids; Hearing loss; Nonlinear frequency compression; Speech and language outcomes

INTRODUCTION

Auditory experience is known to play a role in triggering the events that are precursors to typical speech and language development. Early research documents the factors leading to production of well-formed babble, considered to be the first evidence of language emergence (Oller et al. 1998). Infants with normal hearing enter this stage between 7 and 10 months of age (Smith & Oller 1981; Oller & Eilers 1988); in deaf infants, this babble onset is often significantly delayed (Oller & Eilers 1988; Eilers & Oller 1994). A more recent investigation showed that babble also may be delayed in some infants with more moderate hearing loss (Nathani et al. 2007). Moeller et al. (2007) reported that 12 early-identified infants with mild to profound hearing loss entered the canonical babble stage later than 21 age-matched infants with normal hearing. That is, infants with pure-tone averages (PTAs) better than 50 dB HL (ANSI 1996) achieved consistent use of babble earlier than children with losses poorer than 50 dB HL. Fricative/affricates were shown to be slower to develop in babble and early words of infants with hearing loss. The restricted bandwidth of hearing aids was implicated by those authors as a possible cause of this delay. Additional support for the role of auditory experience in babble onset comes from Bass-Ringdahl (2010), who documented a relationship between babble onset, access to speech (i.e., audibility of speech with hearing aid use), and length of hearing aid use in infants with hearing loss.

Aside from these efforts to differentiate infants with normal hearing from those with hearing loss for purposes of understanding the onset of vocalization, few studies have focused on the importance of the audibility of speech on the communication development of children with prelingual mild to moderate hearing loss. Instead, the focus has been on determining how the hearing loss itself impacts the development of speech production, language, and even psychosocial development and academic achievement (e.g., Davis et al. 1986; Sininger et al. 2010). While it is the case that a number of studies support the notion that children with hearing loss can achieve language abilities similar to hearing peers by the time they enter school if *appropriate intervention* is provided by 6 months of age (e.g., Yoshinaga-Itano et al. 1998; Moeller 2000), quantifying the audibility and/or auditory experiences necessary to achieve those milestones has not been studied. Appropriate intervention can encompass early amplification fitting, appropriate speech and language services, and even consistent

access to speech and language modeling. All are integral components of the habilitation process. In this report we will focus on the early amplification fitting with a focus on the audibility of speech provided for by that process.

Technological advances allow for identification of hearing loss soon after birth and the concept of universal newborn hearing screening has been endorsed by the National Institutes of Health (1993), the Joint Committee on Infant Hearing (ASHA 1994) and the American Academy of Pediatrics (AAP 1999). Concomitantly, advances in hearing aid-related technologies and practice guidelines have influenced both the fitting and verification of hearing aids in an effort to ensure that the child has early and optimal access to their acoustic environment. For example, the 2013 Pediatric Amplification Guidelines (AAA 2013) offer evidence-based recommendations for the use of "...independent pediatric-focused and pediatric-validated prescriptive targets ...and fitting methods that take into account the unique developmental and auditory needs of children" (p. 49). Those fitting methods that have specific prescriptive formulae for children include the Desired Sensation Level v. 5.0a (DSL; Scollie et al. 2005) and National Acoustics Laboratories NAL-NL2 (Keidser et al. 2011). Prescriptive approaches developed for children such as these were developed to provide a consistent and systematic fitting outcome that *maximizes the audibility of speech* across a wide range of listening environments, without exceeding levels of loudness discomfort. The same guidelines recommend that pediatric audiologists use probe microphone measurements of hearing aid gain and output to estimate the audibility of speech (Bagatto et al. 2010; King 2010). In all, the importance of establishing and quantifying the child's access to the speech signal has become a primary focus of the pediatric habilitation process.

Hearing aid technologies have also improved the likelihood of the speech signal being optimally delivered to the impaired auditory system. Distortion is no longer a significant factor in hearing aid signal processing (Bentler & Duve 2000). The use of wide-dynamic range compression has provided the opportunity for uniform access to the softest and loudest speech cues (Franck et al. 1999; Yund & Buckles 1995; Souza 2002). The directional microphone has been used to improve the signal-to-noise ratio for school-age children in certain communication settings (Ricketts et al. 2007; Ricketts & Galster 2008). Features such as digital noise reduction have provided some listening comfort without reducing important speech cues for learning (Marcoux et al. 2006; Stelmachowicz et al. 2010; Pittman 2011). Most recently, frequency-lowering schemes have resurfaced as a technical opportunity to increase the usable bandwidth for children and adults with hearing loss. Although this is not a new concept in signal processing for hearing aids, the current digital algorithms provide online access to high-frequency speech cues that might otherwise fall outside the usable bandwidth of the child due to hearing loss configuration or hearing aid band limitations.

The importance of high-frequency bandwidth in the development of speech and language in children has long been studied (e.g., KorteKaas & Stelmachowicz. 2000; Stelmachowicz et al. 2001, 2007). Stelmachowicz and colleagues (2001) have emphasized that energy for important speech information such as fricatives and sibilants is often most prevalent at frequencies above 7000 Hz. When children with hearing loss were asked to identify singular

and plural nouns while listening through hearing aids, they displayed high error rates for plural test items spoken by female talkers, due to the absence of the inflectional morphemes /s/ and /z/ for the female talkers. Pittman & Stelmachowicz (2003) further implicated the negative consequences of limited bandwidth. This group demonstrated that, for children with hearing loss, their own voices perceived through hearing aids contain lower overall energy above 2000 Hz relative to speech originating from the front. Thus, insufficient high-frequency audibility could impact the development of speech-production skills as well.

Frequency lowering in some form has been used in hearing aids for decades. Simpson (2009) provides a thorough compilation of the schemes that have been developed in an attempt to restore audibility for individuals with severe to profound hearing loss in the high frequencies. These schemes include:

- **Vocoding:** Envelopes of high-frequency speech signals are used to modulate the amplitude of pure tones or narrow-bands of noise in the lower frequencies (e.g., Denes 1967; Posen et al. 1993);
- **Slow playback:** Speech segments are recorded and then played back at a lower speed (e.g., Bennett & Byers 1967; MacArdle et al. 2001);
- **Frequency transposition:** Adding high-frequency sound energy to lower frequencies (e.g., Velmans et al. 1973; Kuk et al. 2007);
- **Frequency compression:** Lowering or shifting all frequencies downward. Fixed-frequency compression (a shift of all frequencies by a constant factor) has been modified recently to nonlinear frequency compression (NLFC) wherein lower frequencies are unprocessed while only the higher frequencies are compressed downward depending on the programmed “start frequency” and compression ratio (e.g., Daniloff et al. 1968);
- **Frequency cueing:** High-frequency energy is also represented in the lower-frequency range; that is, high-frequency energy at the input introduces a lower-frequency cue so the listener is alerted to presence of high-frequency speech components such as /s/ or /f/ (e.g., Galster et al. 2012).

Each of these schemes has been scrutinized through laboratory-based efficacy studies, and several are in general use in currently marketed hearing aids. The logic for the concept is obvious: If either the limitations of the auditory system or the limitations of the transducers in hearing aids preclude access to high-frequency speech sounds, the child may not have the necessary input needed for typical development of speech and language with subsequent implications for psychosocial development and educational achievement.

Early work on frequency-lowering schemes (see reviews by Braida et al. 1979 and Simpson 2009) were carried out primarily on adult, postlingual listeners with severe to profound hearing loss, and they were generally unsuccessful in improving speech recognition significantly. However, more recent studies have produced some positive, though mixed, results for speech-perception outcomes for newer implementations of frequency lowering that occur over a more limited frequency range to offset current limitations in hearing aid

bandwidth. For example, most studies of NLFC efficacy have shown improvement for detection of *some* high-frequency tokens (e.g., Wolfe et al. 2010) compared with conventional amplification. Other studies have shown equivocal results for NLFC compared with conventional processing. For example, Glista et al. (2009) compared performance with frequency compression and conventional processing for 11 children, 9 to 13 years of age. They reported that 5 of 11 children showed improvement in detection of /s/ and /z/, 5 of 11 children showed no benefit for /s/ and /z/ detection, and 1 child showed poorer performance with the scheme. Other studies have found no difference in performance using frequency compression for speech recognition in quiet and in noise compared with conventional amplification for adults (Simpson et al. 2006; Nyffeler 2008; O'Brien 2010). Similarly, inconsistent results have been reported when comparing performance using other frequency-lowering technologies with performance using conventional amplification, including frequency transposition (Kuk et al. 2007, 2009; Robinson et al. 2007, 2009) and slow-playback frequency lowering using the AVR Sonovation (Minneapolis, MN) hearing aids (McDermott et al. 1999; McDermott & Knight 2001; Gifford et al. 2007). Overall, emerging evidence of speech-perception studies shows either improvement or stable performance with frequency-lowering strategies, but the influence of these strategies on development of speech and language in children has not been systematically evaluated.

From a (re)habilitative standpoint, the data do not provide clear direction to clinical practice, in part due to the uncertainty of the fitting scheme used across studies, the potential impact of training on outcomes, and the absence of any data relative to the generalization of these results to broader speech and language development and skills. As part of a larger study, Outcomes of Children with Hearing Loss (OCHL), we had an opportunity to look at the effect on speech and language development. In this study 314 children with mild to severe hearing loss are being followed up for up to 3 years to better understand the status of that population (refer to Holte et al. 2012). The study was observational in nature, rather than interventional, allowing us to quantify the children's services, speech and language development, and success with amplification, among many variables. Because a number of the children in the study were using NLFC when they entered the study or changed to NLFC during the course of the study we were able to compare their outcomes with those children who entered the study using conventional signal processing.

Our research questions were:

1. Are children using NLFC in their hearing aids getting better access to the speech signal than children using conventional processing schemes? We hypothesized that children whose hearing aids provided wider input bandwidth would have more access to the speech signal, as measured by an adaptation of the Speech Intelligibility Index (SII; ANSI S3.5-1997, R2007).
2. Are speech and language skills different for children who have been fit with the two different technologies; if so, in what areas? We hypothesized that if the children were getting increased access to the speech signal as a result of their NLFC hearing aids (question 1), we would see improved performance in areas of speech production, morphosyntax, and speech perception compared with the group with conventional processing.

PARTICIPANTS AND METHODS

Participants

Participants included children with hearing loss recruited as part of the OCHL longitudinal study. This National Institutes of Health–funded, multicenter study was designed to explore the developmental outcomes of children with mild to severe hearing loss. Data on communication, academic and psychosocial skills were gathered in an accelerated longitudinal design, with entry into the study between 6 months and 7 years of age. Each child was seen for at least three annual visits and the test protocol was determined to be appropriate for each age level. Three sites were involved: Boys Town National Research Hospital, The University of North Carolina at Chapel Hill, and the University of Iowa. Each site recruited from surrounding areas and states. Children with PTAs between 25 and 75 dB HL and having confirmed bilateral sensorineural, mixed, or permanent conductive hearing loss were included. Children with significant cognitive, visual, or motor impairments were excluded from participation. For all participants, at least one primary caregiver spoke English at home. Children who used manually coded English or American sign language as their primary mode of communication were excluded from the study.

To reduce some of the confounding factors of varying service provision options, all the participants of this report were recruited from the North Carolina database. In that state, the identification and early intervention took place throughout the state; however, the audiology and hearing aid services were typically provided in one setting—University of North Carolina Hospitals Audiology Clinic, where pediatric hearing aid fitting practices are uniform and consistent with best-practice guidelines (AAA 2013). That is, in that clinic, each child's managing audiologist fitted the hearing aids according to DSL v5.0 gain targets for speech and maximum power output (MPO) targets for pure tones using probe microphone measurements (Bagatto et al. 2005; Scollie et al. 2005). The decision about whether or not children received NLFC was made by the child's audiologist at the time of the fitting; therefore, children could not be randomly assigned to NLFC and conventional processing groups for the study.

The NLFC settings were established and verified using an approach developed at the University of Western Ontario (Glista & Scollie 2009). With this method, compression settings were selected to optimize audibility of mid- and high-frequency sounds while maintaining distinctiveness between adjacent bands of spectral energy. Manufacturer default NLFC settings (i.e., compression ratio and threshold kneepoint) were adjusted as needed based on electroacoustic analyses using filtered speech bands. The strength of compression was increased to make the speech bands, and consequently the phonemes with dominant spectral energy within those bands, more audible. Additional fine tuning was performed if indicated based on patient feedback (e.g., increased difficulty distinguishing /s, ʃ/, or poor sound quality).

Three age levels were analyzed: 3-year-olds (n = 14 NLFC, n = 18 conventional processing), 4-year-olds (n = 16 NLFC, n = 19 conventional processing) and 5-year-olds (n = 19 NLFC, n = 21 conventional processing). Due to the design of the study, several of the participants appear in more than one age grouping. In all, there are 66 unique subjects (each appearing

only within 1 age grouping); 4 children with frequency compression and 4 children with conventional processing appear in all three groups. That overlap factor was determined to be insignificant to the purpose of this analysis. Only children who had been using the same processing scheme for more than 6 months immediately before the time of evaluation were included in the analysis to minimize the possibility that inexperience with a specific processing approach might have resulted in differences between groups. Some of the children wore conventional processing before being fit with NLFC hearing aids; that is 2 out of 14 of the 3-year-olds had some experience with a conventional technology before their use of NLFC, as did 7 out of 16 of the 4-year-olds and 14 out of 19 of the 5-year-olds. Average thresholds are shown in Figure 1 (A–C) for each age group.

Hearing Aid Measures

As part of the larger study protocol, one pediatric audiologist at the test site completed electroacoustic hearing aid measurements in a clinical test room. Hearing aid quality control measurements included measures of total harmonic distortion, frequency range, and output sound pressure level at 90 dB (OSPL90) obtained in a 2-cm³ coupler following ANSI S3.22 (2003). After electroacoustic assessment, the audiologist conducted probe microphone measures to quantify the real ear to coupler difference (RECD), if possible, to estimate the current speech audibility for the participant at the time of the visit. When the RECD could not be measured due to limited cooperation or subject noise, an age-related average RECD was used to estimate the acoustic characteristics of the child's occluded ear. Hearing aid assessment was then completed in the 2-cm³ coupler. Audioscan Verifit software calculated the unaided SII for all the participants using the standard male speech signal (carrot passage) presented at 65 dB sound pressure level (SPL; average speech) and 50 dB SPL (soft speech), following ANSI S3.2-2009. The average root mean square (RMS) error for each fitting was calculated as the difference in dB between the DSL prescriptive target and hearing aid output at 500, 1000, 2000, and 4000 Hz for an average-level (65 dB SPL) speech signal measured during study verification. The RMS error of the fitting compared with DSL prescription for all participants was 3.52 dB. For the conventional processing group, the average RMS error of the fitting was 3.63 dB (SD = 1.96; range = 1.12 to 9). For the NLFC group, the average RMS error of the fitting was 3.45 dB (SD = 2.01; range = 1.0 to 9.1).

For purposes of quantifying the audibility provided by the hearing aid at soft and average-level inputs, a calculation of the SII was also carried out. To generate a measure of audibility that would be comparable between children with NLFC and children with conventional processing, we used a custom calculation based on the ANSI standard calculations for the SII (ANSI S3.5-1997 R2007; Bentler et al. 2011) using the 1/3 octave band-importance function from Table 3 of the standard. Because the 160 Hz 1/3 octave band was not measured by the verification system, each band-importance weight was multiplied by 1.0088 to spread the importance of the 160 Hz 1/3 octave band evenly across the remaining bands. A nonreverberant environment was assumed in the SII calculation. For conventional processing, the sensation level (SL) of each 1/3 octave band was calculated based on the hearing aid output for soft and average levels compared with the audiometric threshold interpolated in that 1/3 octave band. The audibility in each band was multiplied by the corresponding importance weight and the result of the multiplication in all bands was

summed to generate the SII for conventional processing. For NLFC, we developed an algorithm that approximates the weighted audibility provided by NLFC hearing aids, based on the audibility of each 1/3 octave band after lowering. For modified test stimuli in the Audioscan Verifit, the 1/3 octave band levels above 1000 Hz are reduced by 30 dB, except for an isolated 1/3 octave band centered at the frequency used (3100, 4000, 5000, and 6300 Hz). With these reduced band levels, the resulting LTASS produces a distinct “cavity” between 1000 Hz and the selected high-frequency band. We calculated the contribution of the isolated 1/3 octave bands to the audibility in their lowered frequency range. We did so by adjusting the SPL thresholds in those bands to produce the same SL for the amplified standard speech signal as is produced by the band-passed speech stimuli in those same frequencies after they have been lowered. We then applied the band-importance functions from the input and the level distortion correction from the lowered-frequency SL.

Speech and Language Assessment

Standardized tests of speech production and language level were administered in a sound suite by one speech-language pathologist. In addition, the 3-year-old children participated in a 15-min language sample in which there was interaction between the child, a parent, and an OCHL examiner. The first 5 min consisted of interactions between the parent and child only. The next 10 min of the interaction incorporated the examiner into the play between the parent and the child. The context for the play interaction included playing with Play-doh and kitchen toys. Parents were instructed to play naturally with their child while also encouraging them to talk. Parents were also asked to refrain from using too many yes/no questions. A research assistant transcribed and coded language samples following Systematic Analysis of Language Transcripts conventions (Miller & Iglesias 2010). Mean length of utterance in words (MLUw) was computed based on the Systematic Analysis of Language Transcripts.

Most of the testing was accomplished in 1 day, although some participants were rescheduled for completion on a subsequent day. The test protocols for each age level included:

Test Protocol, 3 Years of Age

Goldman-Fristoe Test of Articulation-2 (Goldman & Fristoe 2000) is a standardized measure of speech production. The child is directed to look at a picture and name it.

Vineland Adaptive Behavior Scales-II (Sparrow et al. 2005) is a parent-report questionnaire. It examines adaptive behavior, including receptive and expressive language, writing, and fine and gross motor skills.

Comprehensive Assessment of Spoken Language (CASL 3–4; Carrow-Woolfolk 1999) is a standardized measure of global language development. Subtests are designed to evaluate receptive and expressive language in areas of lexical/semantic, syntactic, supralinguistic, and pragmatic development. The 3–4 battery includes: Pragmatic Judgment, Syntax Construction, and Basic Concepts.

Test Protocol, 4 Years of Age

Vineland Adaptive Behavior Scales-II was also administered in the 4-year-old protocol.

Test of Preschool Early Literacy (Lonigan et al. 2007) is a standardized measure of early literacy, specifically phonological processing and print knowledge. Phonological processing refers to the child's ability to manipulate and recall phonological properties of words. Print knowledge refers to the child's familiarity with letters, their names, etc.

CASL 3–4 was also administered in the 4-year-old protocol.

Wechsler Preschool and Primary Scales of Intelligence-III (Wechsler 2002) is an intelligence test that includes two verbal subscales (Vocabulary and Similarities) and nonverbal subscales (Matrix Reasoning and Block Design).

Test Protocol, 5 Years of Age

Goldman-Fristoe Test of Articulation-2 was also administered in the 5-year-old protocol.

Peabody Picture Vocabulary Test-4 (Dunn & Dunn 2007) is a standardized measure of receptive vocabulary. The examiner shows the child a series of pages. Each page shows four pictures. The examiner says a word that describes one of the pictures on the page, and the child attempts to identify the correct picture.

Test of Preschool Early Literacy was also administered in the 5-year-old protocol (print knowledge section only).

Clinical Evaluation of Language Fundamentals–4 Word Structure is a subtest of the Clinical Evaluation of Language Fundamentals–4 (Semel et al. 2003), which assesses morphological development using picture stimuli.

Preschool Language Assessment Instrument–2 (Blank et al. 2003) is a standardized measure of expressive and receptive discourse. The child is asked a series of questions in which the degree of perceptual saliency in the items varies. The measure assesses the ability of the child to cope with the demands of classroom instruction.

Speech-Perception Assessment

Tests for the perception of speech were carried out at the 5-year-old and older visits using the Phonetically Balanced Kindergarten list (Haskins 1949). The Phonetically Balanced Kindergarten list test is an open-set speech-perception measure. The child was seated in a clinic test booth and asked to listen to a recorded list of words presented at 65 dBA at 0-degree azimuth from a loudspeaker. These scores were obtained with the hearing aid(s) worn as fitted. The test is scored as percent correct of 50 words.

RESULTS

Demographic Characteristics

Tables 1 and 2 show demographic information gathered from participants. All the participants were recruited by the University of North Carolina study site where 93% of the site's study sample resides in the state. Because most of these children received their audiology services from pediatric audiologists at the University of North Carolina Hospitals' Audiology Clinic, the actual service provision was determined to be similar across participants. In Table 1, the age at testing, age of intervention, age of loss confirmation, months of hearing aid use, and (where applicable) months of NLFC use are listed. There were no significant differences among the groups on any of the factors. Table 2 shows the comparison of other variables that are considered possible moderators or mediators of outcomes in the larger study. At each visit, parents were asked to report the time the child wore the hearing aids (week and weekend). In addition, for a subset of participants for whom this measure was available, data-logging information was retrieved from each of their hearing aids at the study visit. Mother's educational level was coded (see Appendix A) according to the level attained at the time of the study. Family income was coded (see Appendix B) according to the total household income at the time of the study. Except for parent report of hearing aid use time for the 4-year-old group, none of the factors were significantly different for the two groups at any age level. Parents reported higher daily hearing aid use for children with NLFC processing than children with conventional processing [$t(32) = 2.4, p = 0.02$].

The hearing levels of the two groups are shown in Figure 1A–C. Thresholds were not different across frequency or across age (refer to Table 3 for PTA for each age group).

Audibility Characteristics

Audibility estimates of an average-level speech passage (65 dB SPL) and soft-level speech passage (50 dB SPL) with amplification were calculated for each participant by using the SII. Audibility was also estimated for an average-level speech signal but in the unaided condition. Those average values for the better ear are shown on Table 3 for each age group and indicate no significant difference in audibility for participants with frequency-compression amplification and those with conventional processing at any age group for any of the conditions of measure.

Speech and Language Characteristics

The speech and language tests and their outcomes are shown in Table 3 for the three age groups. t tests were used to test for significance. The p values in bold font indicate those tests for which the mean differences were found to be significantly different.

For the 3-year-old group, two measures indicated different outcomes between groups. The CASL Composite showed mean standard scores of 81.7 (NLFC) and 95.5 (conventional), indicating that the children with conventional processing had significantly higher scores [$t(28) = -2.5, p = 0.02$] than children with NLFC. The MLUw analysis showed mean

MLUw of 1.80 (NLFC) and 2.49 (conventional), indicating that children with conventional processing produced longer utterances than children with NLFC [$t(23) = -2.17, p = 0.04$].

For the test batteries for 4- and 5-year-olds, there were no significant differences in any of the test outcomes.

DISCUSSION

The purpose of this investigation was to determine whether the use of NLFC resulted in better audibility when fit to children with mild to severe hearing loss, consequently generalizing to better speech and language abilities. The study cohorts were three groups of children participating in a larger multisite study of OCHL. Participants from only one site were included; 67% of the subjects in the larger study who were fitted with NLFC came from that site. By comparing these children to the participants using hearing aids without NLFC from the same study site (referred to as conventional processing here), factors such as fitting approach and early intervention services would be more similar than across the other two study sites. In addition, 93% of the study subjects at that site were followed by the same clinic for fitting and follow-up care, making that factor less confounding. Other factors such as degree and configuration of hearing loss, age of diagnosis, age of intervention and hearing aid fitting, and amount of daily hearing aid use were also not significant across the groups at the different age levels.

Several of the children provided data for more than one age group. It was decided at the outset that only children with a 6-month or more experience with amplification and at least 6 months of experience with NLFC processing would be included in this analysis to account for some acclimatization period. Because this subject pool represents every child seen at the study site in the three age categories, there was no subject bias incurred by eliminating participants with certain audiometric or demographic characteristics that might have altered the results.

The results reported here show no NLFC impact on aided audibility or outcomes for the 4- or 5-year-old children; results of *t*-tests on outcomes measured at 3 years of age indicated that scores on the CASL composite measure and MLUw were significantly higher for children with conventional processing compared with the scores for children using NLFC. The CASL composite is derived from standardized, norm-referenced measures that test the lexical/semantic, syntactic, and pragmatic language domains. MLU is an index of language productivity in a child's spontaneous utterances, and was obtained in the present sample via a language sample involving the child, parent, and examiner. There is some overlap in the language constructs that the two measures are assessing; however, both standardized language scores and MLU are unique parts of a full clinical assessment (Rice et al. 2010). Standardized testing provides norm-reference values from which an individual's performance can be compared, while MLU derived from a language sample provides additional ecological validity to the assessment protocol (Hewitt et al. 2005). The differences seen on these two measures at the 3-year testing session may be related to some other differences in the group. For example, there was a higher number of premature births reported in the NLFC group (14) compared with the comparison/conventional group (5).

Although such an explanation might account for developmental language differences at that age, other measures of speech production (Goldman-Fristoe Test of Articulation) and parent report of receptive and expressive language, writing, and fine and gross motor skills (Vineland) did not suggest any difference among the groups.

The present study estimated audibility for NLFC using an adaptation of the SII that accounts for the changes in location for frequency bands above the start frequency. In the larger study, audibility has been shown to be a significant predictor of speech and language outcomes (Tomblin Reference Note 1), but because the two groups did not differ on average in the amount of aided audibility that was provided by their fittings, the expectation that these outcomes would be different seemed unlikely. A related study compared speech recognition for conventional processing and NLFC for the same listeners and quantified the audibility differences between the two processing schemes using the same method applied here (McCreery et al. 2013). In that study, when NLFC was individually optimized to improve audibility for listeners with mild to moderate high-frequency losses, the increase in audibility and corresponding improvements in perception were consistent, but relatively small (5 to 10%). It should be noted that study used normal-hearing adults and the processed stimuli assumed more severe and sloping audiograms (on average). The small improvement in audibility and speech recognition achieved by those investigators is consistent with the amount of speech information contained in frequencies above 4 kHz and predictions of the SII (ANSI 1997). The present study did not allow for the within-subject comparison of audibility estimates with NLFC turned off and on, but even with the optimization of the compression parameters as was reported in the investigation by McCreery et al., the improvement in perception may have been minimal due to the typically flatter configuration of hearing loss found in the present study. Because there was no difference in the audibility afforded the children across the groups, the expectation of differences in speech and language outcomes was negated.

It has been suggested that one predictor of success with the frequency-lowering techniques is the slope of the hearing loss (Glista 2009); that is, for children with sloping audiometric configurations, a frequency-lowering scheme may provide better access to important speech cues. Although configuration characteristics of this larger database and the predictive value of configuration for speech and language outcomes are subjects of another article, we did determine which of the subjects had a sloping configuration of hearing loss. When we considered sloping loss to be defined as 40 at 1000 Hz and 60 at 4000, there was a total of three subjects—one at 3 years and 4 years and two at 5 years. However, each was fitted with the conventional amplification.

It should be noted, however, that the average audiograms of the two groups of subjects were similar. That is, the frequency-lowering technology did not appear to be fit differentially due to differences in thresholds or slope of hearing loss. In fact, the most common audiometric configuration in this study is a flat one. From the estimations of the audibility differences (SII) across the two groups, it is apparent that the difference across the two groups at each age was minimal. From that observation, differences in outcomes would not be expected.

The results of this study may appear to contradict a number of other published reports of pediatric use of NLFC (e.g., Glista et al. 2009; Wolfe et al. 2010, 2011). The previous studies used within-subject comparisons focused on speech-perception performance rather than a more generalized impact of the processing scheme on speech production and language outcomes. Glista et al. (2009) found improvement for /s/ and /z/ perception in 5 of their 11 participants (6 to 17 years of age) while 5 of the 11 showed no improvement and 1 subject showed poorer performance with the lowering technology. Wolfe et al. (2010) carefully fit the technology so that the 15 children could perceive and distinguish the /s/ and /z/ phonemes. The outcome measures that showed support of the technology used in that investigation included tokens /asa/ and /ada/; the same investigators showed no evidence to support use of the lowering techniques for tokens /afa/, /aka/, /asha/, or /ata/ in quiet or for sentence recognition in noise. At the 6-month follow-up (Wolfe et al. 2011), 13 of the 15 participants showed improvement on the University of Western Ontario (UWO) Plural Test (Glista & Scollie 2012), but no benefit or change in benefit for sentence recognition in noise or for tokens /aka/, /asha/, or /ata/. Because the UWO Plural Test is intended for measuring detection of high-frequency consonant sounds, rather than perception of open-set words or sentences, it could be more sensitive to changes in high-frequency audibility that are due to signal-processing strategies such as this. However, it remains unclear whether those perceptual changes would generalize to other measures of speech and language; we would have expected to see evidence of that in the present data. Because the previous studies did not report the change in audibility afforded by the NLFC processing scheme, it was not possible to confirm that the improved performance for the high-frequency token was indeed a result of improved audibility.

Signal-processing options such as NLFC have been introduced to expand the potential for communication success for adults and children with measurable hearing loss. Due to the potentially limiting bandwidth of current transducers, providing a scheme that provides access to frequencies above 6000 Hz has been encouraged by previous research (e.g., Stelmachowicz et al. 2001, 2007). As a result, this and similar schemes are now the default setting in many hearing aids and require disengagement by the managing audiologist. Verification measures can be used to ascertain that engagement (or not) provides optimal access to the high-frequency components of the signal. These data highlight the fact that if the audibility provided is not improved by the signal-processing scheme, there can be no concomitant improvement on speech, language, and hearing outcomes. Further research is needed to determine the likelihood of improving those critical areas of development with alternative fitting and processing schemes. Because the present study compared a group of children fit with NLFC with an independent group of children with conventional processing, the degree to which NLFC extended the hearing aid bandwidth for children in that group cannot be determined. A comparison of NLFC and conventional processing for the same subjects would be needed to determine the extent to which bandwidth was extended for each individual; this is a limitation of the present data set. While it is possible that the decision to use the NLFC was made for reasons other than to increase audibility (parent request, technology upgrade, informal observation of benefit, etc.), those factors are unknown. Instead, this observational study revealed that children fit with NLFC presented with similar audiometric profiles as those who were fit with a conventional processing scheme. The use

of the frequency-lowering scheme did not enhance their access to the speech signal, as measured by the modified SII. In turn, there were no differences in their speech and language abilities.

CONCLUSIONS

In this study, communication outcomes from a sample of children with mild to severe hearing loss, fitted with frequency-compression hearing aids, were compared with a comparable group wearing appropriately fit technology but without the frequency-lowering processing scheme. Results indicate that the audibility provided did not differ between the technology options. As a result, there was no difference among groups on speech or language outcome measures at 4 or 5 years of age, and no impact on speech perception (measured at 5 years of age). The difference in CASL and MLU scores for the 3-year-old group favoring the group with conventional amplification may be a consequence of confounding factors such as increased incidence of prematurity in the group using NLFC.

ACKNOWLEDGMENT

This study was made possible by grant number R01DC009560 from the National Institute of Deafness and Other Communication Disorders (NIDCD). Its contents are solely the responsibility of the authors and do not necessarily represent official views of the NIDCD or the National Institutes of Health.

REFERENCES

- AAA. American Academy of Audiology Pediatric Amplification Protocol. Reston, VA: American Academy of Audiology; 2013.
- ANSI. ANSI S3.5-1997 American National Standard Methods for the Calculation of the Speech Intelligibility Index-R2007. New York, NY: American National Standards Institute; 1997.
- ANSI. ANSI S3.22-2003 Specification of Hearing Aid Characteristics. New York, NY: American National Standards Institute; 2003.
- ASHA. Joint Committee on Infant Hearing: 1994 Position Statement. ASHA. 1994; 36:38–41.
- Bagatto M, Scollie SD, Hyde M, et al. Protocol for the provision of amplification within the Ontario infant hearing program. *Int J Audiol*. 2010; 49(Suppl 1):S70–S79. [PubMed: 20109090]
- Bass-Ringdahl SM. The relationship of audibility and the development of canonical babbling in young children with hearing impairment. *J Deaf Stud Deaf Educ*. 2010; 15:287–310. [PubMed: 20457674]
- Bennett DS, Byers VW. Increased intelligibility in the hypacusis by slow-play frequency transposition. *J Auditory Res*. 1967; 7:107–118.
- Bentler RA, Duve MR. Comparison of hearing aids over the 20th century. *Ear Hear*. 2000; 21:625–639. [PubMed: 11132788]
- Bentler, RA.; Cole, W.; Wu, YH. Driving and audibility index for frequency lowered hearing aids. Poster at Annual Meeting of the American Auditory Society; March 9–12, 2011; Scottsdale, Arizona. 2011.
- Blank, M.; Rose, SA.; Berlin, LJ. Preschool Language Assessment Instrument—2. Austin, TX: Pro-Ed; 2003.
- Braida, LD.; Durlach, NI.; Lippmann, RP., et al. Hearing Aids: A Review of Past Research on Linear Amplification, Amplitude Compression, and Frequency Lowering. Rockville, MD: ASLHA; 1979.
- Carrow-Woolfolk, E. Comprehensive Assessment of Spoken Language (CASL). Circle Pines, MN: American Guidance Service; 1999.
- Daniloff RG, Shriner TH, Zemlin WR. Intelligibility of vowels altered in duration and frequency. *J Acoust Soc Am*. 1968; 44:700–707. [PubMed: 5679936]

- Davis JM, Elfenbein J, Schum R, et al. Effects of mild and moderate hearing impairments on language, educational, and psychosocial behavior of children. *J Speech Hear Disord.* 1986; 51:53–62. [PubMed: 3945060]
- Denes, PB. *On the Motor Theory of Speech Perception.* Cambridge, MA: MIT Press; 1967.
- Dunn, LM.; Dunn, LM. *Peabody Picture Vocabulary Test.* 4th ed.. Circle Pines, MN: American Guidance Service; 2007.
- Eilers RE, Oller DK. Infant vocalizations and the early diagnosis of severe hearing impairment. *J Pediatr.* 1994; 124:199–203. [PubMed: 8301422]
- Franck BAM, van Kreveld-Bos CSGM, Dreschler W. Evaluation of spectral compression in hearing aids, combined with phonemic compression. *J Acoust Soc Am.* 1999; 106:1452–1464. [PubMed: 10489703]
- Galster JA, Valentine S, Dundas A. Spectral iQ: Audibility improving access to high-frequency sounds. *AudiologyOnline.* 2012 Feb 20. 2012. Retrieved from <http://www.audiologyonline.com/articles/spectral-iq-audibly-improving-access-778>.
- Gifford RH, Dorman MF, Spahr AJ, et al. Effect of digital frequency compression (DFC) on speech recognition in candidates for combined electric and acoustic stimulation (EAS). *J Speech Lang Hear Res.* 2007; 50:1194–1202. [PubMed: 17905905]
- Glista D, Scollie S. Development and evaluation of an English language measure of detection of word-final plurality markers: The University of Western Ontario Plurals Test. *Am J Audiol.* 2012; 21:76–81. [PubMed: 22411713]
- Glista D, Scollie S, Bagatto M, et al. Evaluation of nonlinear frequency compression: Clinical outcomes. *Int J Audiol.* 2009; 48:632–644. [PubMed: 19504379]
- Goldman, R.; Fristoe, M. *Goldman Fristoe Test of Articulation 2.* Minneapolis, MN: Pearson Assessments; 2000.
- Haskins, J. *Kindergarten Phonetically Balanced Word List (PBK).* St. Louis, MO: Auditec; 1949.
- Hewitt LE, Hammer CS, Yont KM, et al. Language sampling for kindergarten children with and without SLI: Mean length of utterance, IPSYN, and NDW. *J Commun Disord.* 2005; 38:197–213. [PubMed: 15748724]
- Holte L, Walker E, Oleson J, et al. Factors influencing follow-up to newborn hearing screening for infants who are hard of hearing. *Am J Audiol.* 2012; 21:163–174. [PubMed: 22585937]
- Keidser G, Dillon H, Flax M, et al. The NAL-NL2 prescription procedure. *Audiol Res.* 2011; 1:e24, 88–90.
- King AM. The national protocol for pediatric amplification in Australia. *Int J Audiol.* 2010; 49:S64–S69. [PubMed: 19919326]
- Kortekaas RW, Stelmachowicz PG. Bandwidth effects on children's perception of the inflectional morpheme /s/: Acoustical measurements, auditory detection, and clarity rating. *J Speech Lang Hear Res.* 2000; 43:645–660. [PubMed: 10877435]
- Kuk F, Keenan D, Korhonen P, et al. Efficacy of linear frequency transposition on consonant identification in quiet and in noise. *J Am Acad Audiol.* 2009; 20:465–479. [PubMed: 19764167]
- Kuk F, Keenan D, Peeters H, et al. Critical factors in ensuring efficacy of frequency transposition I: Individualizing the start frequency. *Hear Rev.* 2007; 14:60–67.
- Lonigan, CJ.; Wagner, R.; Torgesen, J. *Test of Preschool Early Literacy.* Austin, TX: Pro-Ed; 2007.
- MacArdle BM, West C, Bradley J, et al. A study of the application of a frequency transposition hearing system in children. *Br J Audiol.* 2001; 35:17–29. [PubMed: 11314907]
- Marcoux AM, Yathiraj A, Côté I, et al. The effect of a hearing aid noise reduction algorithm on the acquisition of novel speech contrasts. *Int J Audiol.* 2006; 45:707–714. [PubMed: 17132559]
- McCreery RW, Alexander J, Brennan MA, Hoover B, Kopun J, Stelmachowicz. *The Influence of Audibility on Speech Recognition With Nonlinear Frequency Compression for Children and Adults With Hearing Loss.* *Ear Hear.* (in press).
- McDermott HJ, Dorkos VP, Dean MR, et al. Improvements in speech perception with use of the AVR TranSonic frequency-transposing hearing aid. *J Speech Lang Hear Res.* 1999; 42:1323–1335. [PubMed: 10599615]

- McDermott HJ, Knight MR. Preliminary results with the AVR ImpaCt frequency-transposing hearing aid. *J Am Acad Audiol*. 2001; 12:121–127. [PubMed: 11316049]
- Miller, JF.; Iglesias, A. Systematic Analysis of Language Transcripts (SALT), English & Spanish (Version 10) [Computer software]. Madison, WI: University of Wisconsin—Madison, Waisman Center, Language Analysis Laboratory; 2010.
- Moeller MP. Early intervention and language development in children who are deaf and hard of hearing. *Pediatrics*. 2000; 106:E43. [PubMed: 10969127]
- Moeller MP, Hoover B, Putman C, et al. Vocalizations of infants with hearing loss compared with infants with normal hearing: Part I—Phonetic development. *Ear Hear*. 2007; 28:605–627. [PubMed: 17804976]
- Nathani S, Oller DK, Neal AR. On the robustness of vocal development: An examination of infants with moderate-to-severe hearing loss and additional risk factors. *J Speech Lang Hear Res*. 2007; 50:1425–1444. [PubMed: 18055766]
- National Institutes of Health. NIH Consensus Statement: Early identification of hearing impairment in infants and young children. 1993; 11:1–24.
- Nyffeler M. Study finds that non-linear frequency compression boosts speech intelligibility. *Hear J*. 2008; 61:22–26.
- O'Brien A, Yeend I, Hartley L, et al. Evaluation of frequency compression and high-frequency directionality. *Hear J*. 2010; 63:32–37.
- Oller DK, Eilers RE. The role of audition in infant babbling. *Child Dev*. 1988; 59:441–449. [PubMed: 3359864]
- Oller DK, Eilers RE, Neal AR, et al. Late onset canonical babbling: A possible early marker of abnormal development. *Am J Ment Retard*. 1998; 103:249–263. [PubMed: 9833656]
- Pittman A. Children's performance in complex listening conditions: Effects of hearing loss and digital noise reduction. *J Speech Lang Hear Res*. 2011; 54:1224–1239. [PubMed: 21330646]
- Pittman AL, Stelmachowicz PG. Hearing loss in children and adults: Audiometric configuration, asymmetry, and progression. *Ear Hear*. 2003; 24:198–205. [PubMed: 12799541]
- Posen MP, Reed CM, Braida LD. Intelligibility of frequency-lowered speech produced by a channel vocoder. *J Rehabil Res Dev*. 1993; 30:26–38. [PubMed: 8263827]
- Rice ML, Smolik F, Perpich D, et al. Mean length of utterance levels in 6-month intervals for children 3 to 9 years with and without language impairments. *J Speech Lang Hear Res*. 2010; 53:333–349. [PubMed: 20360460]
- Ricketts TA, Galster J. Head angle and elevation in classroom environments: Implications for amplification. *J Speech Lang Hear Res*. 2008; 51:516–525. [PubMed: 18367693]
- Ricketts T, Galster J, Tharpe AM. Directional benefit in simulated classroom environments. *Am J Audiol*. 2007; 16:130–144. [PubMed: 18056881]
- Robinson JD, Baer T, Moore BC. Using transposition to improve consonant discrimination and detection for listeners with severe high-frequency hearing loss. *Int J Audiol*. 2007; 46:293–308. [PubMed: 17530514]
- Robinson JD, Stainsby TH, Baer T, et al. Evaluation of a frequency transposition algorithm using wearable hearing aids. *Int J Audiol*. 2009; 48:384–393. [PubMed: 19382018]
- Scollie S, Seewald R, Cornelisse L, et al. The Desired Sensation Level multistage input/output algorithm. *Trends Amplif*. 2005; 9:159–197. [PubMed: 16424945]
- Semel, E.; Wiig, E.; Secord, WA. Clinical Evaluation of Language Fundamentals 4 (CELF-4). San Antonio, TX: The Psychological Corporation; 2003.
- Simpson A. Frequency-lowering devices for managing high-frequency hearing loss: A review. *Trends Amplif*. 2009; 13:87–106. [PubMed: 19447764]
- Simpson A, Hersbach AA, McDermott HJ. Frequency-compression outcomes in listeners with steeply sloping audiograms. *Int J Audiol*. 2006; 45:619–629. [PubMed: 17118905]
- Sininger YS, Grimes A, Christensen E. Auditory development in early amplified children: Factors influencing auditory-based communication outcomes in children with hearing loss. *Ear Hear*. 2010; 31:166–185. [PubMed: 20081537]

- Smith BL, Oller DK. A comparative study of pre-meaningful vocalizations produced by normally developing and Down's syndrome infants. *J Speech Hear Disord.* 1981; 46:46–51. [PubMed: 6451768]
- Souza PE. Effects of compression on speech acoustics, intelligibility, and sound quality. *Trends Amplif.* 2002; 6:131–165. [PubMed: 25425919]
- Sparrow, S.; Cicchetti, D.; Balla, D. Vineland-II: Vineland Adaptive Behavior Scales: Survey Forms Manual. 2nd ed.. Circle Pines, MN: American Guidance Services; 2005.
- Stelmachowicz PG, Lewis DE, Choi S, et al. Effect of stimulus bandwidth on auditory skills in normal-hearing and hearing-impaired children. *Ear Hear.* 2007; 28:483–494. [PubMed: 17609611]
- Stelmachowicz PG, Lewis DE, Hoover BM, et al. Effects of digital noise reduction on speech perception for children with hearing loss. *Ear Hear.* 2010; 31:345–355. [PubMed: 20081536]
- Stelmachowicz PG, Pittman AL, Hoover BM, et al. Effect of stimulus bandwidth on the perception of /s/ in normal-and hearing- impaired children and adults. *J Acoust Soc Am.* 2001; 110:2183–2190. [PubMed: 11681394]
- Velmans M, Marcuson M. The acceptability of spectrum- preserving and spectrum-destroying transposition to severely hearing-impaired listeners. *Br J Audiol.* 1983; 17:17–26. [PubMed: 6860819]
- Wechsler, D. Wechsler Preschool and Primary Scales of Intelligence—Third Edition. San Antonio, TX: The Psychological Corporation; 2002.
- Wolfe J, John A, Schafer E, et al. Evaluation of nonlinear frequency compression for school-age children with moderate to moderately severe hearing loss. *J Am Acad Audiol.* 2010; 21:618–628. [PubMed: 21376003]
- Wolfe J, John A, Schafer E, et al. Long-term effects of non- linear frequency compression for children with moderate hearing loss. *Int J Audiol.* 2011; 50:396–404. [PubMed: 21599615]
- Yoshinaga-Itano C, Sedey AL, Coulter DK, et al. Language of early- and later-identified children with hearing loss. *Pediatrics.* 1998; 102:1161–1171. [PubMed: 9794949]
- Yund EW, Buckles KM. Multichannel compression hearing aids: Effect of number of channels on speech discrimination in noise. *J Acoust Soc Am.* 1995; 97:1206–1223. [PubMed: 7876443]

REFERENCE NOTES

1. Tomblin JB, Oleson J, Ambrose SE, et al. The influence of hearing aids on the speech and language development of children with hearing loss. *JAMA Otolaryngol Head Neck Surg.* (in press).

APPENDIX A

Ordinal values assigned to mother's educational level:

- 1 = Completed elementary school
- 2 = Completed junior high
- 3 = Received General Education Diploma (high school equivalence)
- 4 = Completed high school
- 5 = Completed 1 or more years of technical/vocational school
- 6 = Completed technical/vocational school
- 7 = Completed 1 or more years of university/college
- 8 = Bachelor's degree
- 9 = Completed 1 or more years of graduate school

10 = Master's degree; Course work completed for PhD, but no dissertation; Law degree without bar; Medical degree without internship completed; PhD; Law degree with bar; Medical degree with internship completed

APPENDIX B

Ordinal values assigned to annual salary increments:

Income of \$0 to 20K = 1

20K to 40K = 2

40K to 60K = 3

60K to 80K = 4

80K to 100K = 5

100k to too much = 6

Fig. 1.

A. Mean audiometric thresholds and ranges for 3-year-old participants, shown with 1 SD. B. Mean audiometric thresholds and ranges for 4-year-old participants, shown with 1 SD. C. Mean audiometric thresholds and ranges for 5-year-old participants, shown with 1 SD.

TABLE 1

Comparison of the two groups for age of hearing loss confirmation, age at intervention, months using hearing aids, and months that the children using frequency-compression hearing aids were using that processing scheme

	NLFC		Conventional		<i>p</i> Value
	n	Mean	n	Mean	
3-year-olds					
Age at test (mos)	14	37	18	38	0.36
Age began intervention	12	7	16	9	0.39
Age loss confirmed	14	6	17	5	0.48
Months using aids	14	28	18	31	0.26
Months using compressed	14	26	—	—	—
4-year-olds					
Age at test (mos)	16	50	19	50	1.0
Age began intervention	15	10	18	14	0.27
Age loss confirmed	16	9	19	14	0.18
Months using aids	16	39	19	36	0.44
Months using compressed	16	24	—	—	—
5-year-olds					
Age at test (mos)	19	60	21	62	0.08
Age began intervention	17	10	19	16	0.12
Age loss confirmed	19	11	20	13	0.79
Months using aids	19	47	21	45	0.57
Months using compressed	19	21	—	—	—

There were no significant differences between groups in terms of ages at service provision.

TABLE 2

Comparison of reported use, data-logged use, mother's educational level, and income for two groups at 3, 4, and 5 years of age

	3-Year-Olds			4-Year-Olds			5-Year-Olds		
	n	Mean	(SD)	n	Mean	(SD)	n	Mean	(SD)
Reported use time (hr per day)									
NLFC	14	10.9	(3.0)	15	12.9	(2.5)	19	12.7	(1.4)
Conventional	18	10.9	(2.9)	19	10.8	(2.6)	21	12.1	(3.1)
Data logging (right) (hr per day)									
NLFC	9	7.4	(3.4)	9	8.2	(3.9)	11	10.3	(1.8)
Conventional	6	7.9	(2.6)	4	9.9	(1.0)	4	11.3	(1.9)
Data logging (Left) (hr per day)									
NLFC	6	6.4	(3.6)	9	7.7	(4.1)	11	10.4	(2.3)
Conventional	6	7.6	(2.5)	4	10.1	(0.7)	4	10.8	(2.5)
Mother education									
NLFC	12	7.2	(2.3)	14	8.4	(1.5)	18	8.3	(2.3)
Conventional	17	7.2	(2.1)	18	7.9	(1.5)	21	7.9	(1.4)
Family income									
NLFC	10	4.0	(1.5)	13	4.6	(1.5)	19	4.3	(1.6)
Conventional	17	3.9	(1.9)	16	4.13	(2.0)	18	3.8	(1.9)

Refer to Appendixes A and B for nominal coding of mother education and family income.

NLFC, nonlinear frequency compression.

TABLE 3

Outcomes from 3-, 4-, and 5-year protocols, with *p* values

	NLFC		Conventional		<i>p</i> Value
	<i>n</i>	Mean	<i>n</i>	Mean	
3-year-olds					
GFTA (standard score)	13	87.8	17	99.4	0.06
Vineland Behavior Comp	13	95.6	17	97.1	0.77
CASL Comp	12	81.7	18	95.5	0.02
Better ear PTA	14	56.4	18	51.2	0.30
Better ear SII (Unaided, 65)	14	0.18	18	0.23	0.50
Better ear SII (65)	13	0.70	18	0.77	0.18
Better ear SII (50)	12	0.53	18	0.58	0.49
MLU Words	8	1.80	17	2.49	0.04
4-year-olds					
Vineland Behavior Comp	16	92.38	18	95.39	0.50
TOPEL PHONO (standard score)	14	93.79	15	91.67	0.78
TOPEL Print Knowledge (standard score)	15	111.67	18	105.50	0.31
CASL Comp	15	104.00	19	102.16	0.80
WPPSI Block (standard score)	15	10.73	16	9.81	0.49
WPPSI Mat Reason (standard score)	12	12.08	15	10.53	0.26
WPPSI Vocab (standard score)	12	8.17	15	8.13	0.98
Better ear PTA	16	52.39	19	47.89	0.36
Better ear SII (unaided, 65)	16	0.21	18	0.31	0.26
Better ear SII (65)	6	0.77	18	0.78	0.76
Better ear SII (50)	6	0.56	18	0.62	0.48
5-year-olds					
GFTA (standard score)	17	96.77	20	94.95	0.76
PPVT (standard score)	17	105.53	21	100.33	0.38
TOPEL Print Knowledge (standard score)	19	107.90	21	105.67	0.58
CELF (standard score)	13	10.08	19	8.21	0.20
PLAI discourse analysis	14	110.29	21	106.43	0.59

	NLFC		Conventional		p Value
	n	Mean	n	Mean	
PBK score	17	82.82	21	78.57	0.36
Better ear PTA	19	50.24	21	51.6	0.75
Better ear SII (unaided, 65)	18	0.26	21	20.27	0.85
Better ear SII (65)	16	0.77	20	0.75	0.70
Better ear SII (50)	15	0.59	20	0.56	0.69

Bold font indicates significance. See text for description of tests.

CASL, Comprehensive Assessment of Spoken Language; CELF, Clinical Evaluation of Language Fundamentals; GFTA, Goldman-Fristoe Test of Articulation; NLFC, nonlinear frequency compression; PBK, Phonetically Balanced Kindergarten; PHONO, Phonological Awareness; PLAI, Preschool Language Assessment Instrument; PTA, pure-tone average; SII, Speech Intelligibility Index; TOPEL, Test of Preschool Early Literacy; WPPSI, Wechsler Preschool and Primary Scales of Intelligence.