Nonlinear Frequency Compression for Children with Moderate Hearing Loss

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Introduction

The provision of optimal audibility for high-frequency speech sounds such as /s/, /f/ and /t/ can be difficult when fitting conventional digital amplification for children with high-frequency hearing loss. This difficulty is attributed to the limits in the available gain, before feedback, in the high frequencies (Dillon 2001), as well as to the significant roll-off in the frequency response beyond 4000 Hz for most high-gain hearing aids. Furthermore, in the event that a hearing aid can provide sufficient high-frequency audibility, a child who has a severe to profound hearing loss in the high frequencies may have limited ability to process this information because of impaired spectral processing and/or cochlear dead regions (Malicka, Munro and Baker 2010).

Background Studies

Recently published studies have shown that nonlinear frequency compression (NFC) significantly improves the detection of high-frequency sounds and the recognition of high-frequency phonemes for persons with severe to profound high-frequency hearing loss (Bohnert et al. in this volume; Simpson, Hersbach and McDermott 2005; Glista et al. 2009; Glista et al. in this volume). This evidence, along with the limits in achievable high-frequency audibility with conventional amplification has led some clinicians to consider frequency lowering a viable option for all children with severe to profound high-frequency hearing loss.

Over the past decade, several published reports have suggested that children with moderate degrees of hearing loss also have difficulty with the detection of high-frequency sounds, as well as with the identification and production of high-frequency phonemes such as /s/. Stelmachowicz and colleagues (Stelmachowicz, Pittman, Hoover and Lewis 2001) evaluated the effect of the upper end of the frequency bandwidth of amplified speech on phoneme recognition for children with moderate high-frequency hearing loss. These researchers showed that children with moderate degrees of hearing loss exhibited greater difficulties with the recognition of high-frequency speech sounds compared to adults with hearing loss and children with normal hearing. Also, children with moderate degrees of hearing loss required a bandwidth extending to 9000 Hz for optimal performance. This latter finding is troubling, considering that the bandwidth of contemporary hearing aids typically does not extend much beyond 6000 Hz when worn on the ear.

Additional research conducted at the Boystown National Research Hospital has shown that children with moderate hearing loss typically experience developmental delay and decrements with their own speech production (Moeller et al. 2007). Specifically, infants with moderate hearing loss exhibited delays in the onset of canonical babbling when compared to infants with normal hearing. Also, infants with moderate hearing loss possessed a smaller inventory of consonants than their normal hearing peers. In particular, infants with hearing loss showed deficits in their ability to produce affricates and fricatives such as the phoneme /s/. These findings are not entirely surprising given the aforementioned

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work of Stelmachowicz and colleagues (2001), which indicated children with moderate hearing loss will not have consistent access to and audibility of high-frequency phonemes with the use of conventional hearing aids.

Furthermore, research has shown that insufficient access to high-frequency speech sounds may hinder a child's ability to develop language. Pittman (2008, also summarized in this volume) measured children's ability to learn novel words as a function of the bandwidth employed while the words were presented. Pittman found that novel word learning was impaired when the bandwidth of the presentation was limited at 4000 Hz. Optimal performance was achieved when the bandwidth of the presented words extended to 9000 Hz.

Study Objectives

Given the review above, the primary objective of this study was to evaluate the potential benefit and limitations of NFC for children with moderate hearing loss. Specifically, the goals of the study were to evaluate the effects of NFC on the detection of high-frequency sounds, on speech recognition in quiet in noise, and on speech production. This paper summarizes the design of the study and discusses results for two children who participated in the study. The mean results of all the children who participated in the study will be briefly discussed but have also been presented in detail in prior publications (Wolfe et al. 2010, 2011).

Study Method

Subjects

Eighteen school-age children participated in this study. The study inclusion criteria were as follows:

- Moderate sensorineural hearing loss (no poorer than 70 dB HL at 4000 Hz in the better ear)
- Five to 13 years of age
- Full-time hearing aid wearers with no previous experience with frequency lowering technology
- English as a primary language
- Auditory-oral communicators with expressive and receptive language aptitude within one year of chronological age as determined by a formal speech and language assessment administered by a certified auditory-verbal therapist.
- Children with conductive hearing loss or auditory neuropathy spectrum disorder were excluded from participation.

Hearing Aid Fitting

Each of the study participants was fitted with Phonak Nios V® micro-sized behind-the-ear hearing aids, which possess NFC. These hearing aids were coupled to custom earmolds that were acoustically customized to meet the child's hearing needs. To maximize high-frequency output, the children's earmolds typically included a 3 mm horn tube with a sound bore that was as large as the child's external ear canal would accommodate. This coupling was selected to optimize the delivery of high-frequency signals. For school-age children with moderate hearing loss, a 3 mm horn tube can typically be accommodated by the size of the child's external ear canal. Since the 3mm horn will provide a boost for high-frequency sounds, it is typically a more appropriate choice than standard size 13 tubing with a 1.9 mm internal diameter.

The earmolds were vented if low-frequency thresholds were in the normal to mild hearing loss range. The clinician selected the largest vent diameter that would also allow for sufficient high-frequency gain to meet mid and high-frequency prescriptive targets. For children, we place high priority upon providing adequate audibility throughout the speech frequencies. However, we also consider venting for children with normal to near normal low-frequency hearing, as the inclusion of a vent will likely improve localization and speech recognition in noise for these children (see Johnstone in this volume).

Air conduction thresholds were measured at half-octave frequencies from 250 to 8000 Hz using conventional audiometry under insert earphones. Real-ear probe microphone measurements were conducted using the Audioscan Verifit® hearing aid analyzer in order to evaluate the output of the hearing aids relative to the Desired Sensation Level v5.0 (DSL 5.0; Scollie et al. 2005) prescriptive target for children. Prior to conducting the probe microphone measurements, the real-ear-to-coupler difference (RECD), which is the difference in dB between the SPL measured in the real-ear versus a 2 cc coupler, was measured for both ears of each child. This step was completed to allow for the determination of exact, frequency-specific thresholds in dB SPL at the child's eardrum. This hearing aid fitting procedure follows the steps outlined in the DSL Method (Bagatto et al. 2005).

Next, probe microphone measurements were completed, and the output of the child's hearing aids were matched within ±3 dB to the DSL 5.0 prescriptive targets for the Audioscan Verifit® standard speech signal presented at 55, 65, and 75 dB SPL. Also, the output of the hearing aid was measured to an 85 dB SPL swept pure tone to ensure that the maximum output did not exceed recommended levels. Figure 1 provides an example of a typical real-ear probe microphone measurements obtained within this study. The reader should note that this figure is for illustrative purposes only and was not obtained from an actual participant. The figure shows a simulated real-ear probe microphone result for a moderate hearing loss, but during this study, actual real-ear probe microphone measurements were completed with each child.

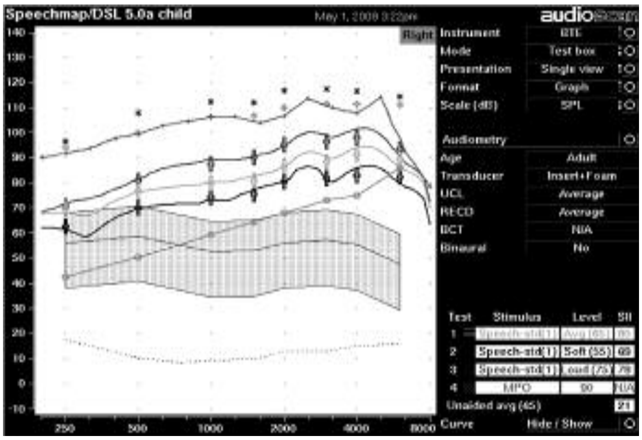

Figure 1. Simulated real-ear probe microphone measurement results illustrating a typical fitting prior to the activation non-linear frequency compression (NFC) for a child with moderate hearing loss.

Probe microphone measures were completed with NFC disabled in the hearing aid in order to ensure that the output of the hearing aids was optimized without frequency compression. Conducting probe microphone measurements with NFC disabled allows the clinician to determine the frequency range over which audibility may be inadequate, which in turn allows for the determination of what frequency range must be compressed to allow for sufficient audibility.

Once the examiner was satisfied that the frequency response of the aid had been optimized without NFC, a second real-ear probe microphone measurement was completed to verify the settings of NFC. The Audioscan Verifit® possesses a specialized signal referred to here as the frequency lowering verification stimulus (FLVS). The FLVS uses the standard speech signal for conventional probe microphone measurements, but the signal is low-pass filtered (30 dB of attenuation) above 1000 Hz except for a 1/3-octave-wide segment centered at either 4000, 5000, or 6300 Hz (see also Glista and Scollie 2009). The 6300 Hz FLVS was presented at 55 and 65 dB SPL to evaluate the output of the hearing aid with NFC disabled. Then, NFC was enabled, and the same signals were presented again. Figure 2 provides an example of a typical outcome for this test. As seen in this example, the 6300 Hz FLVS is inaudible without NFC but is clearly audible once NFC is enabled. Again, the reader should note that Figure 2 is provided for illustrative purposes only and was not obtained from an actual participant.

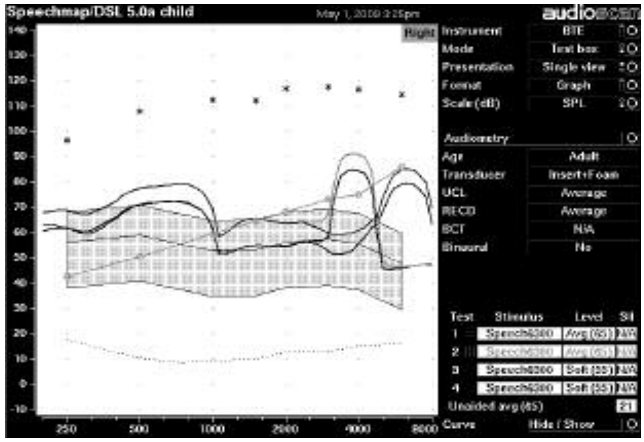

Figure 2. Simulated real-ear probe microphone measurement result showing typical fitting outcomes while using the Audioscan Verifit frequency lowering verification stimulus to verify the fitting of non-linear frequency compression (NFC).

For this study, NFC was initially activated at the fitting software default settings. If sufficient audibility was provided for the FLVS, then the default fitting parameters for NFC were kept. However, if sufficient audibility was not provided for the FLVS at software default settings, then the examiner increased the strength of the NFC settings until audibility was achieved. For five of the subjects, the strength of NFC was increased to improve the audibility of the FLVS.

Furthermore, the examiner ensured that the child could detect and identify the phonemes /sh/ and /s/ when spoken at an average conversational level from 15 feet away. Also, the examiner performed an informal listening check of the hearing aids to determine whether the use of NFC resulted in any deleterious effects (i.e., the phoneme /s/ was perceived as /sh/, or the sound quality was unacceptable). Additionally, the examiner queried the child about the sound quality of running speech to determine whether it was acceptable. There were no cases in which the strength of NFC had to be decreased because of phoneme confusion or poor sound quality.

Study Design

The children were randomly placed into two groups. One group used the hearing aids for a six-week period with NFC enabled, while the other group used the hearing aids for six weeks with NFC disabled. At the end of the six-week interval, speech recognition, speech production, and aided thresholds were measured. Then NFC was enabled for the group of subjects who did not use it for the first six weeks and disabled for the group that did initially use NFC. Both groups used the aids for an additional six weeks, and the test battery was administered again. This repeated measures, counter-balanced design allowed for the removal of an order effect as a variable that may have impacted performance in the two conditions (NFC on versus NFC off). After the two six-week intervals, the subjects used the hearing aids for six consecutive months with NFC enabled to determine whether a period of adjustment or acclimatization was required for optimal performance with NFC. At the end of the 6-month interval, the outcome measures battery was re-administered. The subjects and their families were naive as to what technology was used throughout the study.

Outcome Measures

Speech recognition in quiet and in noise, aided thresholds, speech production, and subjective benefit were evaluated within this study. The following measurements were made after each six-week interval and again after the six-month interval.

Aided Threshold Assessment

Aided thresholds were determined for warble tones at 4000, 6000, and 8000 Hz. Also, aided thresholds were measured for the phonemes /sh/ and /s/. These phonemes were spoken by a female talker and recorded at the University of Western Ontario. Conversion factors obtained from the University of Western Ontario were used to convert the thresholds to dB HL.

Speech Recognition in Quiet

Speech recognition in quiet was assessed with two different measures. The University of Western Ontario (UWO) Plural test (Glista et al. 2009) is an open-set monosyllabic word recognition test featuring 15 different words that are familiar to preschool-aged school children (e.g., cat, skunk, book, etc.). The words are presented in the singular and plural form (/s/ in the final position), and the test is scored on the basis of the number of words the child correctly identifies (in percent correct). As such, the child must identify the word itself and also the presence of the /s/ in the final position of the plural words. The words are spoken by a female talker, and the primary energy for the /s/ is around 9000 Hz. This test was based on previous research showing a similar test to be sensitive to the effects of bandwidth in hearing aids (Scollie, personal communication; Stelmachowicz, Pittman, Hoover and Lewis 2002).

For this study, the UWO Plural Test was presented in recorded format from a loudspeaker located one-meter directly in front of the child. Each word was randomly presented two different times in both the singular and plural form for a total of 60 words presented in each condition. The child orally repeated the target words, and the examiner scored whether the child correctly perceived the words.

The Phonak Logatome test (Boretzki et al. in this volume) was also used to evaluate speech recognition in quiet. This test is a computer-controlled, adaptive assessment of a subject's ability to identify vowel-consonant-vowel (VCV) nonsense syllables. Specifically, the speech recognition threshold (dB SPL) was obtained for seven tokens (ada, afa, aka, ata, asha, asa with peak energy at 9000 Hz, and asa with peak energy at 6000 Hz) presented from a loudspeaker located one meter directly in front of the subject. The tokens were displayed on a computer monitor located directly below the loud-

Figure 3. Display screen for the Phonak Logatome Test.

speaker (see Figure 3), and the subject selected (via a computer mouse) the perceived token. The presentation level of the tokens was adaptively varied by the computer on the basis of whether the child correctly identified the stimulus, and the threshold (in dB SPL) was determined.

Speech Recognition in Noise

The Bamford-Kowal-Bench Speech-In-Noise (BKB-SIN) test was used to evaluate speech recognition in noise (Bench, Kowal and Bamford 1979). Specifically, the signal-to-noise ratio required for 50% correct sentence recognition was determined by administering two list pairs from the BKB-SIN test. The test sentences, which were administered in compact disc recorded format according to the procedures described in the test manual, were presented from a loudspeaker located one meter directly in front of the subject (Etymotic Research 2005).

Assessment of Speech Production

The following measures of speech production were completed immediately prior to the initiation of the study and after the children had used NFC for six consecutive months.

Picture Labeling

Speech production for words in isolation was evaluated via a picture labeling task. In short, a certified auditory-verbal therapist (AVT) placed a picture card in front of the child, and the child verbally labeled the picture (e.g., stop sign, whistle, sock, etc.). The AVT transcribed the child's responses and scored (in percent correct) the production of high-frequency phonemes (/s/, /sh/ and /f/). A total score was obtained for these phonemes along with scores for the production in the initial, medial, and final position.

Sentence Production

Speech production for words spoken within the context of a sentence was assessed by asking the child to read sentences that possessed words containing high-frequency phonemes. Again, the AVT transcribed the child's responses and scored (in percent correct) the production of high-frequency phonemes (/s/, /sh/ and /f/). A total score was obtained for these phonemes along with scores for the production in the initial, medial, and final position.

Goldman-Fristoe Test of Articulation

Speech production was formally assessed with the Goldman-Fristoe Test of Articulation, which is a standardized test of articulation with normative values obtained for children with normal hearing. The test was administered according to the procedures described in the test manual (Goldman and Fristoe 1972), and a standard score was calculated for each child.

Subjective Assessment

Abbreviated Profile of Hearing Aid Benefit

The Abbreviated Profile of Hearing Aid Benefit (APHAB; Cox and Alexander 1995) was administered prior to the study and after each six-week interval. Three APHAB forms, one for each test interval, were provided to each subject. The forms were independently completed by the child with assistance from a parent at baseline and at the testing appointment following each six-week interval. The unaided portion of the form was not completed, and comparisons were made between responses across the three conditions (e.g., baseline versus NFC off versus NFC on). The subjects were allowed to review their responses for previously completed questionnaires while completing the form at each six-week interval. Also, two auxiliary items were included at the end of the APHAB list. One of these items stated, "I can hear /s/ better when listening to others talk." The other item stated, "My speech sounds 'slushy'."

Case Studies

Subject 1

Subject 1 was 12 years-old at the initiation of the study. At 18 months of age, he was diagnosed with a moderate, sensorineural hearing loss of unknown etiology for both ears (see Figure 4 for most recent audiometric results). He was fitted with hearing aids shortly after his diagnosis and began auditory-verbal therapy at that time. Prior to the study he was using high-end digital hearing aids with a reported bandwidth extending to 6900 Hz. He is a graduate of the Hearts for Hearing auditory-verbal therapy program, and he has earned excellent grades in mainstream classrooms throughout his academic career. His case was selected for profile in this article because his outcomes on speech recognition, aided threshold and speech production assessments were typical of what was observed for the group as a whole.

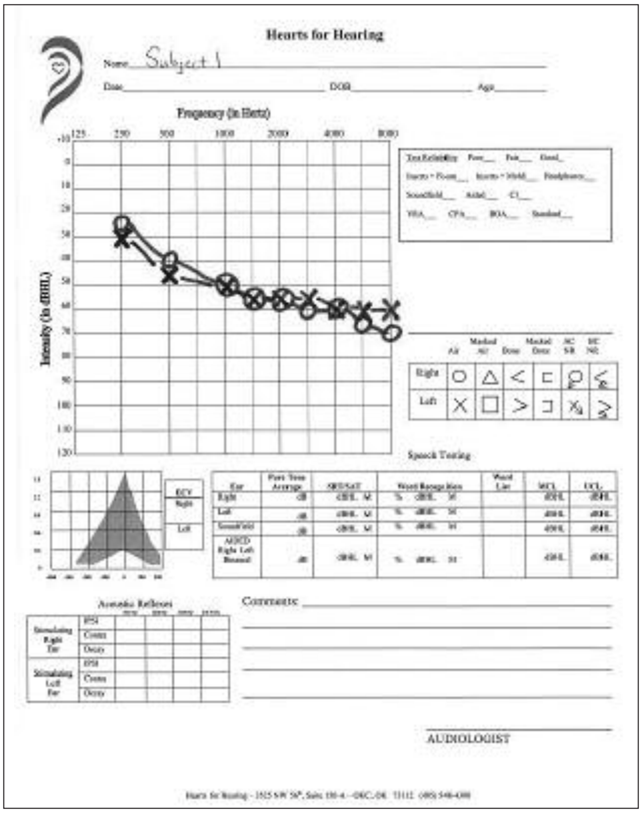

Figure 4. Audiometric results for Subject 1

This subject's outcomes obtained in this study are provided in Tables 1, 2, 3 and 4. As shown, his access to high-frequency signals improved significantly with the study aids with NFC enabled when compared to his old hearing aids and the study aids with NFC disabled. Of particular note, his detection threshold for the phoneme /s/ improved by 17 dB with NFC on compared to NFC off.

	4000 Hz	6000 Hz	8000 Hz	/sh/	/s/
Previous Hearing Aids	24 dB	38 dB	52 dB	25 dB	37 dB
Phonak Nios V NFC Disabled	24 dB	22 dB	39 dB	24 dB	39 dB
Phonak Nios V NFC Enabled (Six Weeks)	20 dB	15 dB	25 dB	21 dB	22 dB
Phonak Nios V NFC Enabled (Six Months)	20 dB	15 dB	22 dB	22 dB	22 dB

Table 1. Aided thresholds (dB HL) obtained from Subject 1.

The improved access to high-frequency sounds resulted in a considerable improvement in speech recognition in quiet (Table 2). His performance on the UWO Plural test improved by 22 percentage points with use of NFC relative to the NFC off condition, and he reached ceiling performance on this test with NFC enabled. Additionally, improvements in speech recognition in quiet were observed on the Phonak Logatome test after six

	UWO Plural (% correct)	Phonak Logatome Test (dB SPL)			BKB-SIN (dB SNR)
		/asa/	/asha/	/ata/	
Phonak Nios V NFC Disabled	78%	43 dB	39 dB	37 dB	2.5 dB
Phonak Nios V NFC Enabled (Six Weeks)	100%	42 dB	38 dB	33 dB	-1 dB
Phonak Nios V NFC Enabled (Six Months)	100%	38 dB	30 dB	29 dB	-1.5 dB

Table 2. Speech recognition results obtained from Subject 1. Speech recognition results for these tests were incomplete with the child's own hearing aids.

	Picture Labeling (Total % Correct)	Sentence Production (Total % Correct)	Goldman-Fristoe Test of Articulation (Standard Score)
Baseline	83%	70.5%	93
NFC – Six Months	100%	98%	101

Table 3. Speech production outcomes for Subject 1

	Ease of Communication	Background Noise	Reverberant Environments	Aversiveness
NFC Disabled (Six Weeks)	8.3%	25%	16.7%	20.8%
NFC Enabled (Six Weeks)	8.3%	25%	16.7%	20.8%

Table 4. Results on the Abbreviated Profile of Hearing Aid Benefit for Subject 1. These scores indicate the percentage of time in which the subject experienced difficulty in a particular type of situation.

months of NFC use compared to the NFC-disabled condition. Additionally, NFC also provided a significant improvement in the signal-to-noise ratio required for 50% intelligibility on the BKB-SIN test.

Furthermore, subject 1 experienced a substantial improvement in his own speech production, which manifested in increases in his scores on every test administered after six months of NFC use compared to his articulation prior to the start of the study. Interestingly, although he expressed a strong preference for the study aids over his previous set of hearing aids, his scores on the APHAB did not change significantly.

Subject 2

Subject 2 was 7 years-old at the initiation of the study. He was diagnosed with a moderate sensorineural hearing loss for both ears (see Figure 5 for most recent audiometric results) and is one of three siblings in his family with hearing loss. He was fitted with hearing aids prior to 2 months of age and began auditory-verbal therapy at that time. Prior to the study he was using high-end digital hearing aids with a reported bandwidth extending to 7100 Hz. Like subject 1, he is a graduate of the Hearts for Hearing Auditory-verbal therapy program, and he has excelled in a typical classroom placement throughout his academic career. His case was selected for profile in this article because he is an example of a child who achieved ceiling performance without NFC on many of the audiometric measures, but nonetheless preferred to use NFC in real word settings.

	4000 Hz	6000 Hz	8000 Hz	/sh/	/s/
Previous Hearing Aids	24 dB	21 dB	38 dB	22 dB	37 dB
Phonak Nios V NFC Disabled	17 dB	14 dB	22 dB	24 dB	35 dB
Phonak Nios V NFC Enabled (Six Weeks)	17 dB	10 dB	22 dB	18 dB	25 dB
Phonak Nios V NFC Enabled (Six Months)	21 dB	12 dB	15 dB	19 dB	25 dB

Table 5. Aided thresholds (dB HL) obtained from Subject 2.

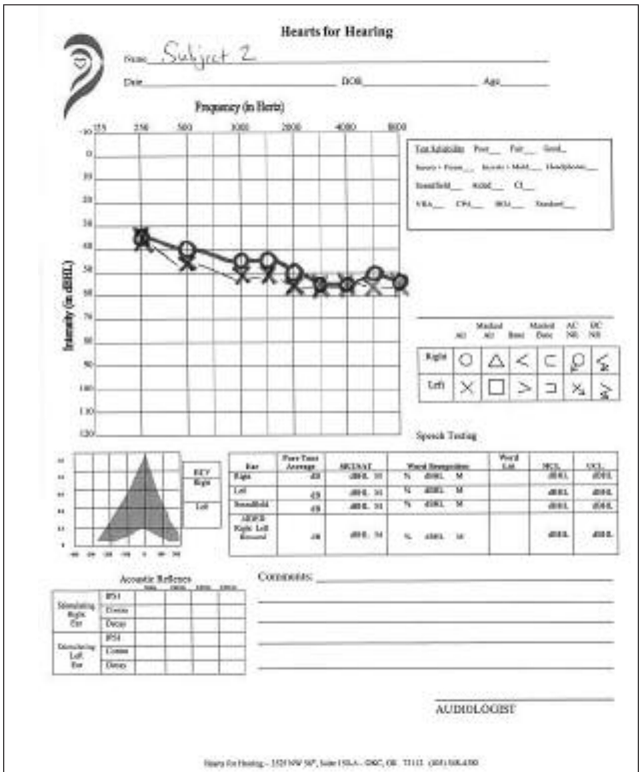

Figure 5. Audiometric results for Subject 2

	UWO Plural (% correct)	Phonak Logatome Test (dB SPL)			BKB-SIN (dB SNR)
		/asa/	/asha/	/ata/	
Phonak Nios V NFC Disabled	100%	53 dB	39 dB	40 dB	3.0 dB
Phonak Nios V NFC Enabled (Six Weeks)	100%	38 dB	35 dB	40 dB	1.5 dB
Phonak Nios V NFC Enabled (Six Months)	100%	35 dB	34 dB	38 dB	1.5 dB

Table 6. Speech recognition results obtained from subject 2. Speech recognition results for these tests were incomplete with the child's own hearing aids.

	Picture Labeling (Total % Correct)	Sentence Production (Total % Correct)	Goldman-Fristoe Test of Articulation (Standard Score)
Baseline	100%	100%	98
NFC – Six Months	100%	100%	108

Table 7. Speech production outcomes for Subject 2

	Ease of Communication	Background Noise	Reverberant Environments	Aversiveness
NFC Disabled (Six Weeks)	25%	33.3%	33.3%	29.1%
NFC Enabled (Six Weeks)	0%	8.3%	4.2%	29.1%

Table 8. Results on the Abbreviated Profile of Hearing Aid Benefit for Subject 2. These scores indicate the percentage of time in which the subject experienced difficulty in a particular type of situation.

Subject 2's objective outcomes obtained in this study are provided in Tables 5, 6, 7 and 8. As shown, subject 2's aided thresholds were fairly similar between the NFC enabled and disabled conditions. His detection threshold for the phoneme /s/ did improve by 10 dB with NFC on compared to NFC off.

Consistent with the slight improvement observed in aided threshold detection, subject 2 only exhibited a slight improvement on speech recognition testing. His performance on the UWO Plural test reached ceiling levels both with NFC disabled and enabled, a fact that demonstrates the need for sensitive measures to assess the benefits of frequency lowering technology for children with moderate hearing loss. Additionally, speech recognition in quiet was similar for many tokens on the Phonak Logatome test, but subject 2 did possess a lower threshold for the /asa/ token with NFC enabled compared to the NFC disabled condition. Also, speech recognition in noise with NFC enabled was at least as good as performance in noise with NFC disabled.

Furthermore, subject 2 approached ceiling on most measures of speech production. However, he did show a trend toward better articulation with NFC as measured on the Goldman-Fristoe Test of Articulation. Of note was the fact that although he did not demonstrate large performance advantages with NFC on many of the objective measures, he did report a large subjective preference for NFC. His APHAB responses (see Table 8 which shows the percentage of time the subject encounters difficulty in a particular type of situation) suggest better subjective performance with NFC in real world use, and he also reported that he felt he could hear the phoneme /s/ better during the six-week interval in which he used NFC. Furthermore, he and his mother expressed a strong preference for the six-week interval in which he used NFC over the interval without NFC. These subjective findings may be considered evidence in favor of NFC given the fact that the subject and his family were blinded to the technology used in the study.

Summary

Nonlinear frequency compression generally provides significant improvement in aided sound detection, speech recognition in quiet and in noise, speech production, and subjective benefit for children with moderate high-frequency hearing loss (see Wolfe et al. 2010 for group results). Children with moderate hearing loss should typically achieve excellent levels of performance in the aforementioned areas with the use of NFC.

Considering the results of previous studies showing similar improvements with NFC for children with severe to profound hearing loss, NFC can be considered as a viable option for improving audibility of high-frequency sounds for children with moderate to profound high-frequency hearing loss.

Verification of NFC performance and benefit is important. The prudent clinician will use probe microphone measures to optimally set the output of the hearing aids without NFC and then use modified probe microphone measures to optimize the fitting of NFC. Assessment of the detection of high-frequency sounds, speech recognition in quiet and in noise, speech production, and subjective benefit is critical to demonstrate that the child is achieving excellent performance with NFC. New measures, such as the Audioscan Verifit® frequency lowering verification stimulus, may be helpful in fitting and verifying hearing aids with nonlinear frequency compression.

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