

Study suggests that non-linear frequency compression helps children with moderate loss

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Although children with mild to moderately severe hearing loss typically receive considerable benefit from hearing aids, they frequently have difficulty with certain aspects of speech recognition and production. For instance, Stelmachowicz et al. demonstrated that children with mild to moderately severe hearing loss experience significantly greater difficulty perceiving the phonemes /s/ and /z/ while wearing their personal hearing aids than do children with normal hearing.¹ The authors related these findings to the limited bandwidth of contemporary behind-the-ear (BTE) hearing aids and the necessity of adequate audibility through at least 8000 Hz for discrimination of /s/ and /z/.

Providing sufficient amplification for high-frequency phonemes is critical for the development of language and speech production. The phoneme /s/ is one of the most frequently occurring phonemes in the English language. It distinguishes plural from singular words (cats vs. cat), indicates possession (e.g., the cat's bowl), denotes third-person present tense (e.g., he bites), and is present in many common contractions (e.g., it's).

Inability to hear these cues may result in syntactic and semantic errors during language development and difficulty producing or articulating affricates and fricatives, such as /s/.²⁻⁴

In an attempt to improve high-frequency amplification, manufacturers have developed hearing aids with active acoustic feedback cancellation and bandwidths that extend past 4000 Hz. However, clinicians continue to report difficulty providing adequate audibility through 6000 Hz and beyond because the transmission line of BTE hearing aids results in substantial attenuation of gain above 4000 Hz.⁵ Furthermore, young children often have small external ears that cannot accommodate the large sound bores necessary for a horn effect to enhance high frequencies. In fact, children often require a narrow sound bore, which produces a reverse horn effect leading to additional reduction of high-frequency gain.

Considering these limitations, manufacturers have invested resources in developing a frequency-lowering technology designed to shift high-frequency sounds to a lower frequency range where sufficient audibility is more

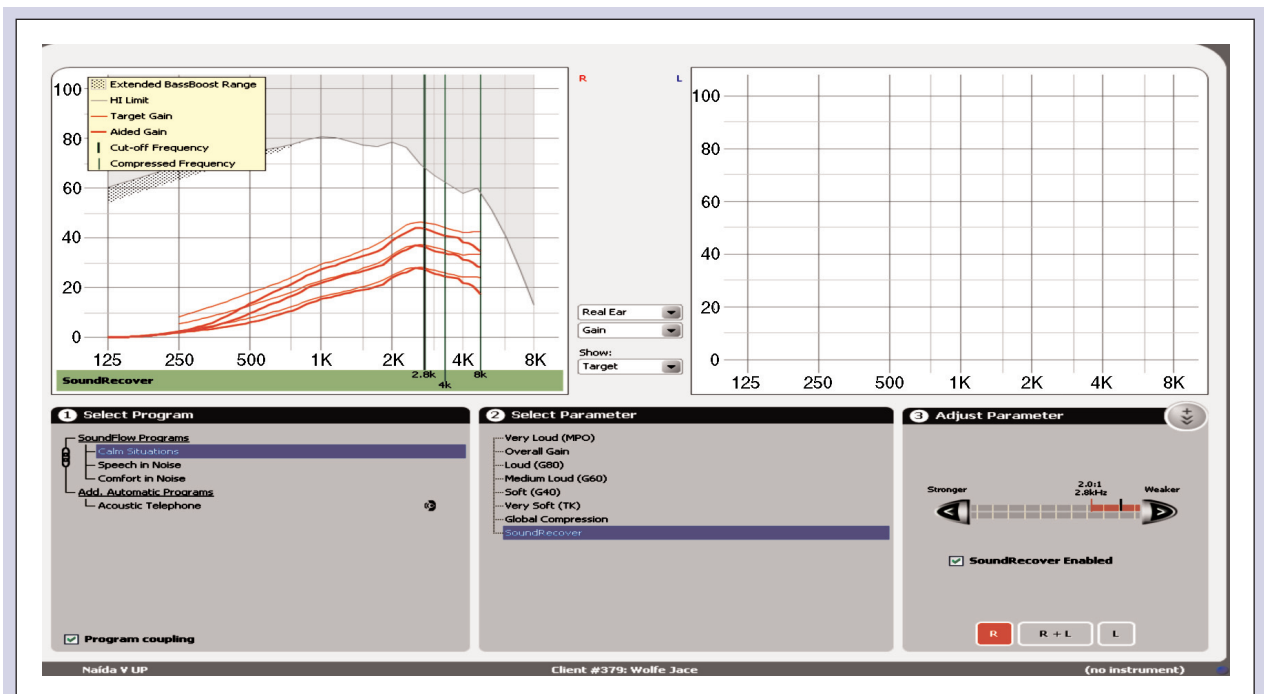


Figure 1. Example of NLFC implemented in the SoundRecover algorithm of the Phonak Nios micro-hearing aid. The cut-off frequency is set to 2800 Hz and the compression ratio is 2:1. Inputs between 2800 and 8000 are compressed by a factor of one-half, e.g., an 8000-Hz input signal will be shifted to 5400 Hz (e.g., $0.5 \times [8000-2800] = 2600$; $8000-2600 = 5400$ Hz).

Table 1. Frequency-specific audiometric inclusion criteria.

Frequency (Hz)	250	500	1000	2000	3000	4000	5000	6000	8000
Range (dB HL)	10-65	10-65	20-65	25-75	30-75	45-75	50+	50+	50+

likely. Few reports have been published on the benefits and limitations of this technology for children with mild to moderately severe hearing loss. This paper describes our early experiences with a group of children fitted with the Phonak Nios micro-hearing aid featuring non-linear frequency compression (NLFC).

NLFC is designed to lower frequencies within a range designated by the clinician. The primary objective is to restore audibility for high-frequency inputs through approximately 8000 Hz. The clinician may adjust the cut-off frequency and the compression ratio. Any acoustic input that exceeds the cut-off frequency is compressed according to the compression ratio. In the example illustrated in Figure 1, the cut-off frequency is set at 2800 Hz with a compression ratio of 2:1. Therefore, all inputs between 2800 and 8000 Hz are compressed toward 2800 Hz by a factor of one-half. Inputs with frequencies below the cut-off frequency are not compressed.

STUDY METHODS

Participants and inclusion criteria

We are currently evaluating the benefits and limitations of non-linear frequency compression for 16 children with mild to moderately severe sensorineural hearing loss through 4000 Hz (see Table 1). The children, all English speakers ranging in age from 5 to 13 years, wear digital hearing aids full-time and have not previously used non-linear frequency compression. Their expressive and receptive language aptitudes are within 1 year of their chronological age, and all of them completed an auditory-verbal therapy program. At the time of writing, we had conducted baseline measures and fitted the instruments bilaterally on 12 children.

Baseline measures

Baseline audiologic testing was conducted while the children used their own bilateral

digital hearing aids. This assessment was performed in the binaural condition and included:

- ❖ aided thresholds for 4000-, 6000-, and 8000-Hz warble tones, as well as the phonemes /sh/ and /s/
- ❖ speech-in-noise thresholds with the Bamford-Kowal-Bench Speech-in-Noise (BKB-SIN) test⁶
- ❖ percent correct plurals recognition with the University of Western Ontario (UWO) Plural Test⁷
- ❖ thresholds for nonsense syllables with the Phonak Logatome Test.

This paper reports the results of baseline comparisons using the UWO Plural Test. This is an open-set, speech-recognition task developed by Susan Scollie and colleagues specifically for evaluating hearing aids with frequency-lowering technology. The test contains 15 separate monosyllabic and bisyllabic words in both the singular and plural form.

Correct identification of the plural of each word requires the child to have access

to acoustic energy in the range of 4000 to 8000 Hz. Two lists were presented for a total of 60 words in each condition (i.e., with the children's own aids and with the study aids with non-linear frequency compression enabled).

Hearing aid fitting

The fitting of the test hearing aid for the 12 children included probe-microphone measures and the Frequency Lowering Verification test with the Audioscan Verifit. They were fitted first with the frequency compression disabled to the DSL i/o v5.0 prescriptive targets for 55-, 65-, and 75-dB-SPL input signals with the objective of matching the targets from 250 through 6000 Hz within +/-2 dB (see Figure 2). For some children, the desired match to the prescriptive target was not achieved at 6000 Hz even when the hearing aid was set to maximum gain.

Next, we used the Frequency Lowering Verification test of the Audioscan Verifit to ensure audibility for inputs out to 6300 Hz. This test is designed to demonstrate the restoration of audibility of high-frequency sounds that a hearing aid has shifted to lower frequencies. The standard speech signal used for the Speech Mapping fitting platform was low-pass filtered with a cut-off frequency of 1000 Hz, except for a 1/3-octave

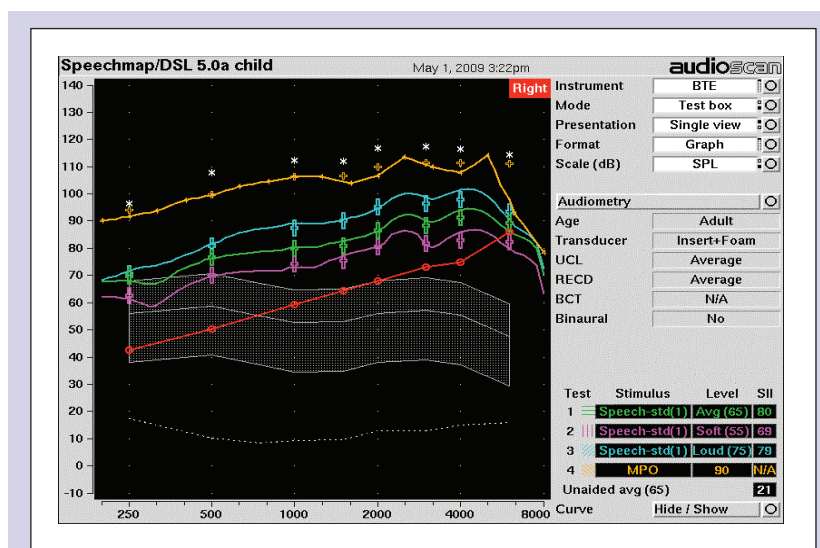


Figure 2. Real-ear aided output in SPL for the "standard speech" signal at 55 (pink line), 65 (green line), and 75 (blue line) dB SPL in the Audioscan Verifit Speechmap fitting platform. Unaided thresholds (red line) and real-ear saturation response for a 90-dB-SPL swept pure-tone (orange line) are also shown.

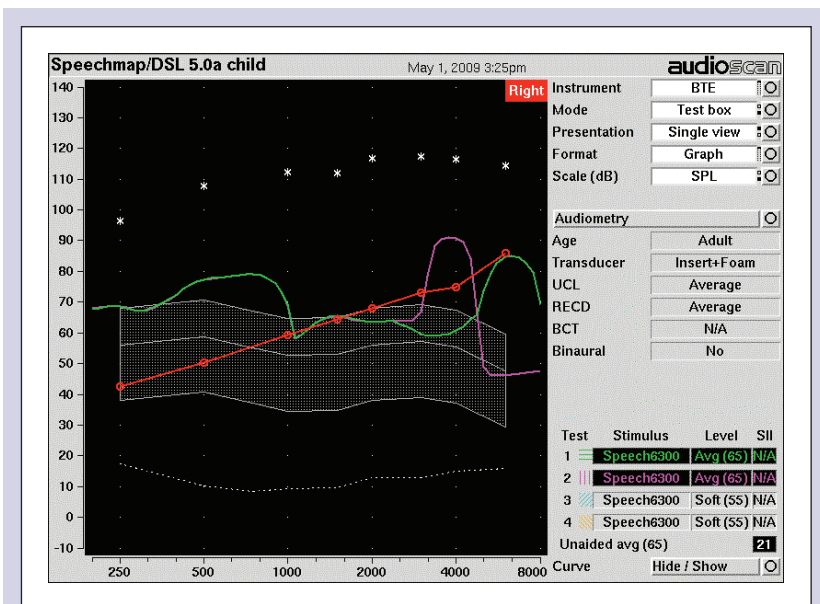


Figure 3. Real-ear aided output for the Frequency Lowering verification test in the Audioscan Verifit fitting system. The red line indicates unaided thresholds, the green line indicates aided output from Phonak Nios micro-hearing aid with NLFC disabled, and the purple line indicates aided output from the test aid with NLFC enabled.

band centered around either 4000, 5000, or 6300 Hz. To reflect the degree of audibility for high-frequency signals, the aided output for this signal (presented at 65 dB SPL for this study) is measured with NLFC disabled and enabled. As seen in Figure 3, this test is intended to show improvement in the audibility of high-frequency speech components upon activation of non-linear frequency compression.

The unaided thresholds (red line) in the example in Figure 3 reveal that average conversational speech will be inaudible in the high-frequency region. Even with the hearing aid on (green line), these high-frequency components will be inaudible. However, when the NLFC is enabled (purple line), substantial improvements in the audibility of high-frequency speech components are expected. The example in Figure 3 illustrates that NLFC has the potential to provide adequate audibility of speech inputs up to 6300 Hz.

In addition to electroacoustic verification, we used informal testing to verify that the children could identify /sh/ and /s/ when spoken at an average conversational speech level from 12 feet away. Finally, we elicited verbal feedback from the subjects to determine the non-linear frequency starting

parameters that yielded acceptable sound quality. In the rare cases in which a child complained of unsatisfactory sound quality, the compression was reduced until sound quality was satisfactory.

Experimental design

We used a switching-replications design for the experiment. After fitting the 12 subjects bilaterally with the test hearing aids, we assigned all of them

randomly to one of two groups. In the first group, six subjects were given a hearing aid program with NLFC enabled. In the second group, the six subjects were given a hearing aid program with the compression disabled. These groups will switch to the other setting later in the experiment.

Approximately 15 minutes after being fitted, the six children who had the frequency compression enabled were given the TWO Plural Test. This provided initial insight into the benefits of NLFC by comparing the children's performance with it to their performance on baseline measures with their own digital hearing aids. The audiograms for these children appear in Figure 4.

RESULTS

Initial findings from the children fitted with this type of compression yielded positive results according to subjective comments, average recognition of plural words, and individual subject evaluation. Subjective comments revealed that none of the 12 children fitted with the Nios instruments objected to the non-linear frequency compression. In fact, many reported better speech understanding.

Positive subjective reports were corroborated by the UWO Plural Test scores for the first six children, who used the NLFC feature. On this test, the children achieved a score of 67.7% correct (SD: 13.9) with their own hearing aids. In contrast, the

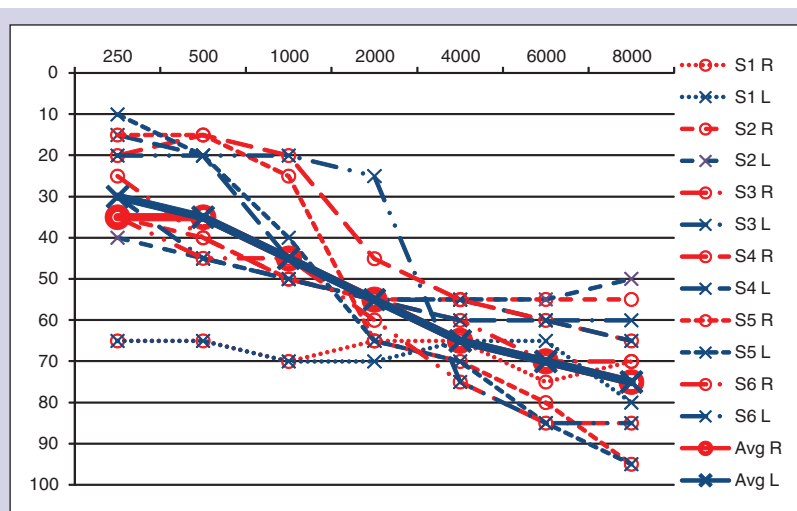


Figure 4. Unaided air-conduction thresholds for the six children fitted with Nios hearing aids with NLFC enabled at the beginning of the study. Heavy lines denote mean thresholds for this group.

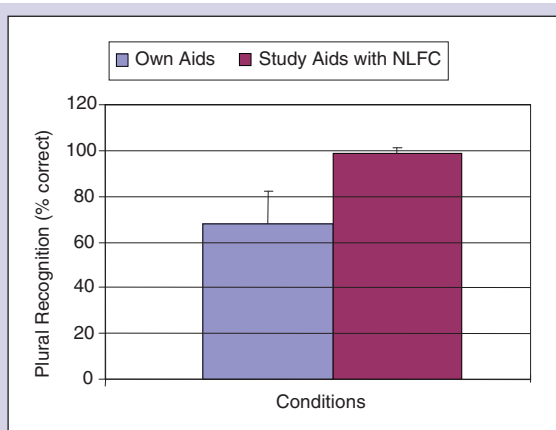


Figure 5. Mean speech-recognition scores for the University of Western Ontario Plural Test. NLFC = non-linear frequency compression. Bars denote one standard deviation from mean.

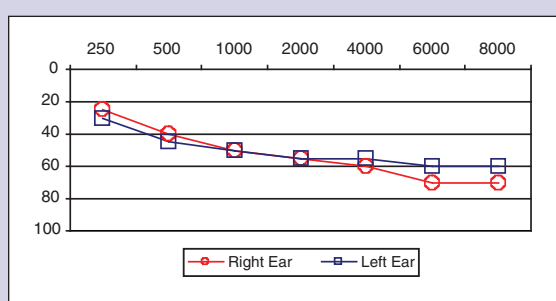


Figure 6. Unaided audiometric thresholds for Subject 3.

children scored 98.6% correct (SD: 0.02) after using the test hearing aids with NLFC enabled for approximately 15 minutes. A paired *t*-test indicated the difference in average performance between the children's own aids and the test devices with NLFC enabled was statistically significant ($p=0.002$).

An examination of performance with NLFC shows clear benefits for individual subjects. For example, Subject 3 is a 12-year-old boy with a mild to moderately severe sensorineural hearing loss (Figure 5). Both his receptive and expressive language exceed what is typical for children of his age with normal-hearing

of the new hearing aids, and reported that his mother's speech sounded "more crisp." He immediately exhibited a preference for the NLFC over traditional amplification. He also liked the small size.

CONCLUSIONS

The preliminary findings of this study suggest that non-linear frequency compression has the potential to substantially improve acquisition and identification of high-frequency speech signals and environmental sounds compared to conventional high-end digital amplification. This type of full-time access to inputs across the entire speech range is critical for

sensitivity. He has been a successful user of high-end digital hearing aids for several years. Although he has excelled in academic and social settings, he still exhibited some difficulty with his hearing and speech at the time of the study. Specifically, he had a lateralized production of the phoneme /s/ (i.e., sounds like /sh/), and he had difficulty understanding soft speech.

The results of our initial assessments are shown in Table 2. After his hearing aid fitting, Subject 3's aided thresholds improved substantially for high-frequency test stimuli. He also did considerably better on the UWO Plural Test with the study aids than with his own aids. Subject 3 was very pleased with the sound quality

developing age-appropriate speech, language, and auditory skills. It is possible that using NLFC can enable young children to overcome many of the deficits that have been found in children with mild to moderate hearing loss.

In the future, we will compare performance with the study aid between the NLFC enabled and disabled conditions and we will seek to identify parameters that influence the benefit children with moderate hearing loss receive from NLFC. For now, we conclude that NLFC should be considered as an option for children with mild to moderately severe hearing loss.

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Table 2. Aided outcomes for Subject 3.

	Aided Threshold: 4000 Hz Warble Tone	Aided Threshold: 6000 Hz Warble Tone	Aided Threshold: 8000 Hz Warble Tone	UWO Plural Test
Own digital hearing aids	24 dB HL	38 dB HL	52 dB HL	65% Correct
Phonak Nios: Frequency Compression Enabled	20 dB HL	15 dB HL	25 dB HL	100% Correct