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THE EFFECT OF NONLINEAR FREQUENCY COMPRESSION AND LINEAR FREQUENCY TRANSPOSITION ON SPEECH PERCEPTION IN SCHOOL-AGED CHILDREN

By

Kelly L. Helm, B.S.

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Approved by:
Nancy McManus, Au.D, Capstone Project Advisor
Regina Saunders, M.S., Second Reader

Abstract: The primary objective of this study is to determine whether nonlinear frequency compression and linear transposition algorithms provide speech perception benefit in school-aged children.

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ABBREVIATIONS

NFC	Nonlinear frequency compression
LFT	Linear frequency transposition
HINT	Hearing in Noise Test
CNC	Consonant-Nucleus Consonant
SNHL	Sensorineural Hearing Loss
HF	High frequency
NH	Normal Hearing
HI	Hearing Impaired
BTE	Behind-the-Ear
DSP	Digital Signal Processing
IHC	Inner Hair Cells
DI	Dynamic Integrator
ISP	Integrated Signal Processing
NFC	Nonlinear Frequency Compression
AE	Audibility Extender
WDRC	Wide Dynamic Range Compression

INTRODUCTION

"Blindness separates people from things; deafness separates people from people (Helen Keller)." This quote truly encapsulates the incredible loss an individual with a hearing impairment can experience. The inability to communicate can have a profound impact on an individual, regardless of his or her age or stage in life. It can be especially debilitating in children. "Approximately 1 to 3 per 1,000 newborns in the well-baby nursery population, and approximately 2 to 4 per 1,000 infants in the neonatal intensive care unit population have been shown to have significant bilateral hearing loss (DeMichele, 2008);" making hearing loss one of the most common congenital anomalies.

Hearing deficits in children can interfere with normal speech and language development, education, and social interaction. Hearing deficits can also have negative psychological and emotional effects. Early detection of hearing loss, however, can considerably reduce these negative consequences. Research suggests that there is significant improvement in expressive and receptive language development, as well as in the vocabulary, reading, and educational progress of children identified with hearing loss when they receive intervention by 6 months of age (Yoshinaga-Itano, Sedey, Coulter, & Mehl, 1998). As a result, universal newborn hearing screening programs have been implemented across the country. Currently 43 states have newborn hearing legislation, with 28 of these laws mandating hearing screenings for all infants. These programs aim to identify all infants with hearing loss as early as possible to ensure appropriate remediation including audiological, educational and medical intervention (EHDI, 2006).

For optimal auditory stimulation, acoustic amplification should be implemented immediately following diagnosis. One of the greatest challenges audiologists face when working

with the pediatric population, is providing access to all the sounds necessary for speech production, speech perception, and language development. This is especially difficult when hearing loss is present in the high frequency region. Providing access to high frequency speech information with conventional acoustic amplification has not always successful, due to inadequate gain, limited bandwidth, and acoustic feedback. Although there have been numerous attempts to address this issue through frequency lowering techniques, most were unpopular because of the poor sound quality they produced. A discussion of these strategies will follow in the literature review section of this paper.

A child's inability to hear high frequency sounds often compromises his or her speech understanding, appreciation of music, environmental sounds (Kuk et al., 2006), and may negatively affect a child's ability to reproduce high frequency phonemes. In addition, delays in phonological and morphological development are common in children with high frequency impairment. The spectral energy for many consonants is primarily located in the high frequency region (Widex, 2010). Phonemes such as /s/, /ʃ/, /t/, /z/, /f/ are therefore difficult to discriminate when hearing loss is present in that region. Although these sounds are softer in intensity, their contribution toward understanding speech is critical.

Stelmachowicz et al. (2004) examined the importance of high frequency audibility in speech and language development of children with hearing loss. Phonological development was evaluated in three groups of children: 1) normal hearing (NH) children, 2) hearing-impaired (HI) children identified with hearing loss prior to 12 months of age (early identified), and 3) HI children identified with hearing loss after 12 months of age, during the first 4 years of life (late identified). In terms of speech recognition, this study concluded that HI children were more negatively affected than their NH peers because they received less high frequency speech

information. HI children also showed delays in the acquisition of all phonemes compared to their NH peers. In infants with hearing loss, the greatest delays occurred for fricatives, consistent with limited hearing-aid bandwidth (Stelmachowicz, Pittman, Hoover, Lewis, & Moeller, 2004). The bandwidth of most conventional hearing aids is inadequate at accurately representing high frequency sounds, particularly for female and child speakers.

Limited access to high frequency acoustic cues and speech information may also interfere with a child's ability to categorize sounds into their morphological contexts (Auriemmo, Kuk, & Stenger, 2008). In the English language high frequency phonemes (/s/, /ʃ/, and /t/) play a critical role in denoting plurals (dog vs. dogs), possessions (Kelly vs. Kelly's), third person singular tense (he vs. she) and contractions (can vs. can't) (Widex, 2010; Auriemmo et al., 2008). "In addition, distinguishing between similar sounding words (sip – tip – ship, and but – bus – bust) can also be impaired when hearing loss is present in the high frequency region" (Widex, 2010). Confusion of a single phoneme for another can change the word entirely (fun vs. sun).

Compounding issues of speech comprehension, high frequency hearing impairment also adversely affects hearing environmental sounds including, alarms, doorbells, telephone ring tones, chirping birds, and music. Audibility of high frequency sounds contributes to enhancing the overall sound quality of music, and allows children to enjoy the sounds of nature. More importantly, a child's safety is dependent upon his or her ability to hear an alarm or warning signal (Stelmachowicz et al., 2004).

As evidenced by the many examples provided above, high frequency speech information is extremely important for speech comprehension, detection of environmental sounds, and safety. Unfortunately, this frequency region is difficult to amplify sufficiently using conventional hearing aids. Hearing aids are not able to provide adequate gain to high frequencies for four

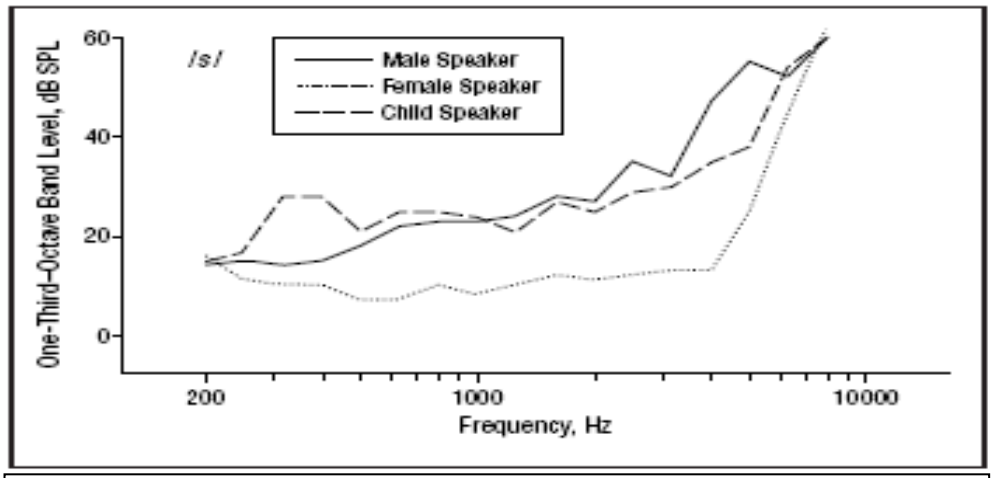
primary reasons: 1) "dead" regions of the cochlea 2) insufficient gain/output, 3) limited bandwidth, and 4) acoustic feedback before the desired gain can be reached (Kuk, Keenan, Korhonen, & Lau, 2009).

Hearing aids are not able to combat a "dead region," defined as a region in the cochlea where there is a complete loss of function or depletion of inner hair cells (IHC) and/or auditory neurons" (Moore, 2001). When a dead region is present at a particular frequency, basilar membrane vibrations in that frequency region are not transduced. This prevents the creation of action potentials in the auditory nerve necessary to interpret the signal in the cerebral cortex (Moore, 2004). Dead regions cannot be determined accurately from thresholds on an audiogram, however a dead region is likely to exist when a threshold is 70 dB or greater at a given frequency. Furthermore, when a dead region exists at the signal frequency, an individual may perceive the signal as distorted or "noise-like" (Moore, 2004). Therefore, acoustic stimulation of "dead regions" may not improve performance. Amplification of a distorted signal may negatively affect the sound quality and further degrade speech understanding (Ching, Dillon, & Bryne, 1998; Turner & Cummings, 1999; Moore, 2004).

In addition to dead regions in the cochlea, hearing aids are not able to amplify high frequency information sufficiently due to inadequate gain, attributable to "low maximum power output, limited bandwidth, or the presence of acoustic feedback before the desired gain is reached" (Kuk et al., 2009). A hearing loss may be so severe that the maximum output of the amplification device may not be able to reach a level at which benefit can be perceived. In addition, hearing aids are restricted in the fitting ranges they can accommodate. Originally, engineers designed amplification devices to target the frequencies where the majority of speech sounds occur; thus, the targeted frequency range was 500 Hz to 4,000 Hz. Above 4,000 Hz, the

frequency response of most hearing aids drops off significantly. Thus, limited bandwidth of hearing aids is another factor contributing to this issue.

Evidence in the literature suggests that there are significant differences between children and adults in the bandwidth required for accurate fricative recognition (Stelmachowicz et al., 2001, 2002, 2004). In these studies, children required greater high frequency bandwidth than adults to achieve similar speech recognition scores for the phoneme /s/. This suggests that children require broader bandwidth for optimal access to high frequency fricative information. Stelmachowicz and colleagues (2004) measured the spectral energy of /s/ spoken by a male, female, and child (Graph 1). As illustrated by the graph below, the spectral energy of /s/ is confined to the high frequency range with a peak at 8,000 Hz or higher (Stelmachowicz et al., 2004).



Graph 1. Relative levels of spectral energy in one-third octave-bands for the utterance /s/, displayed as a function of frequency for male, female, and child speakers (Stelmachowicz, et al., 2004).

Thus, the upper limit of gain hearing instruments are capable of providing may be well below the peak frequencies of certain high frequency phonemes (Stelmachowicz et al., 2004). Furthermore, when a hearing aid is programmed to amplify sounds beyond its fitting range, or

when high levels of gain are applied, feedback is a common consequence. Depending upon the amplitude of the feedback signal, the output signal of the receiver may sound distorted and the sound quality of the signal may be degraded. Whistling may also be audible. Even with sophisticated feedback cancellation systems, the only solution for eliminating feedback is often by decreasing high frequency gain.

Expansion of the signal bandwidth in hearing devices would be an appropriate resolution; however, "technical problems and increased acoustic feedback have precluded the development of wider-bandwidth devices, particularly in behind-the-ear (BTE) hearing aids" (Stelmachowicz et al., 2004). BTE hearing aids, which are typically the most appropriate style of hearing aids for infants and young children, are problematic because of the resonance associated with the tubing (Stelmachowicz et al., 2004).

LITERATURE REVIEW

In the past, hearing aid manufacturers have attempted to achieve high frequency audibility using a number of different frequency lowering techniques. The basic premise of frequency lowering techniques was to shift unaidable high frequency acoustic information into lower aidable frequency regions. "Thus, lower-frequency hair cells would encode the higher frequency information" (Kuk et al., 2009). These techniques consisted of slow-playback, time-compressed slow-playback, frequency modification with amplitude modulation, vocoding, zero-crossing rate division, frequency shifting, and most recently, proportional frequency compression (Kuk et al., 2006). For a detailed review of these methods and research studies evaluating their effects, readers are encouraged to consult Braida et al., (1979).

While these techniques were effective in frequency lowering, leading to better aided thresholds, their acceptance was limited because other aspects of speech, such as harmonic

relationships, spectral transitions, and segmental-temporal characteristics were altered, as well. This resulted in unnatural sounding speech, distorted gross temporal and rhythmic patterns, and extended durations of speech signals (Kuk et al., 2006; Braida et al., 1979). Many individuals reported that the transposed sounds were unnatural, hollow, and more difficult to understand. In order to reduce the effects of unnatural sounding speech, the lowered speech signal must possess the same characteristics as the original signal. "In addition, the lowered speech signal should retain the same extra-linguistic (prosodic) cues, such as pitch, tempo, and loudness" (Kuk et al., 2006).

The limitations of past approaches prompted the development of linear frequency transposition and nonlinear frequency compression. These algorithms both aim to improve audibility of high frequency speech sounds where traditional amplification alone is not sufficient. Their signal-processing schemes for achieving audibility, however, are significantly different.

LINEAR FREQUENCY TRANSPOSITION

The Audibility Extender (AE), a form of frequency lowering using linear frequency transposition (LFT), first appeared in the Inteo series of Widex hearing aids. LFT identifies, filters, and shifts unaidable high-frequency information into a lower frequency region. AE includes Integrated Signal Processing (ISP), which integrates the hearing loss of the user, the environment, and the intermediate processing of each algorithm within the device into the Dynamic Integrator (DI). "In turn, the DI coordinates all the activities and dispatches the appropriate commands to each algorithm so that the processed sounds would be as natural as possible with little or no artifacts" (Kuk et al., 2006).

Based on the degree and slope of the user's hearing loss, the DI determines a "start frequency" at which transposition begins. The frequency region located one octave above the start frequency, known as the "source octave," is the target for transposition (Figure 1a). Frequencies above the start frequency are inaccessible due to possible dead regions of the cochlea or inadequate gain of amplification devices.

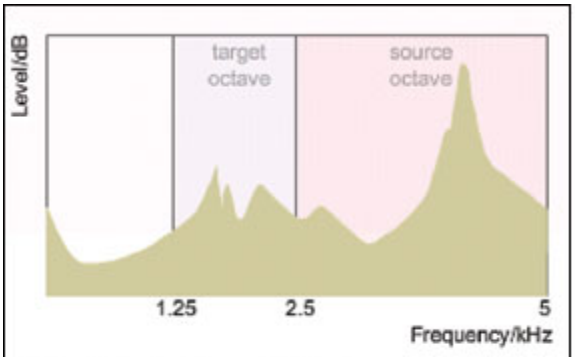


FIGURE 1a. The DI specifies the frequency region to be transposed (source octave) and where it should be transposed to (target octave). The start frequency is 2,500 Hz in this example.

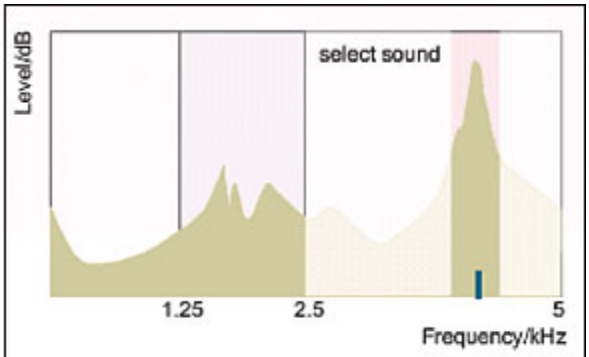


FIGURE 1b. The AE identifies the frequency at 4,000 Hz in the source octave region to have the highest peak.

The most prominent spectral peak of the original signal located within the source octave, is identified and selected for transposition (Figure 1b and 1c). The AE allows frequencies up to two octaves above the start frequency to be lowered linearly, to one octave immediately below the start frequency (Korhonen & Kuk, 2008). By transposing the signal linearly, the harmonic relationship and temporal structure of the transposed and the original signal are preserved. As the peak frequency changes, the transposed frequency also changes, meaning that at any given moment, "the absolute amount of frequency lowering is directly related to the location of the dominant peak in the source octave" (Korhonen & Kuk, 2008). In addition, frequencies around the spectral peak in the source octave are transposed linearly (Figure 1d).

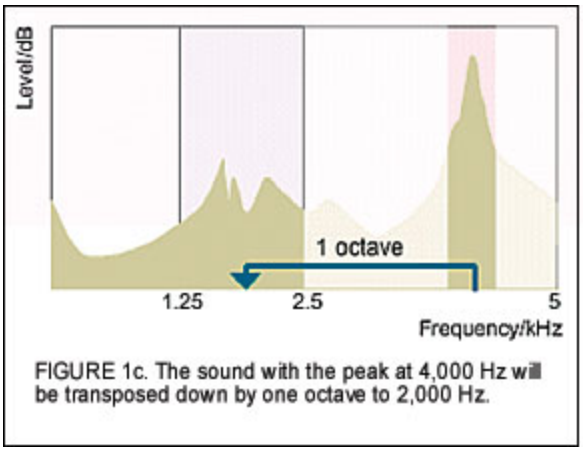


FIGURE 1c. The sound with the peak at 4,000 Hz will be transposed down by one octave to 2,000 Hz.

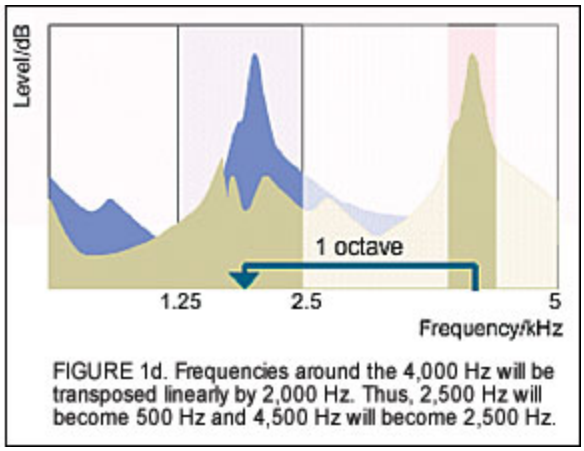


FIGURE 1d. Frequencies around the 4,000 Hz will be transposed linearly by 2,000 Hz. Thus, 2,500 Hz will become 500 Hz and 4,500 Hz will become 2,500 Hz.

High frequency sounds located above the "start frequency " are continuously transposed regardless of their voicing characteristics. Thus, this algorithm is equally effective on periodic and aperiodic sounds, including music and environmental sounds, such as birds chirping. Sounds below the start frequency are amplified without modification. "To limit the masking effect from the transposed signal and any potential artifacts, frequencies that are outside the one octave bandwidth are filtered out" (Figure 1e) (Kuk et al., 2006). The transposed signal is then amplified and mixed with the original signal at the final output (Figure 1f). This method aims to limit potential masking effects, discontinuities of the output signal, and artifact, while preserving the naturalness of the output signal delivered to the user (Kuk et al., 2009; Korhonen & Kuk, 2008).

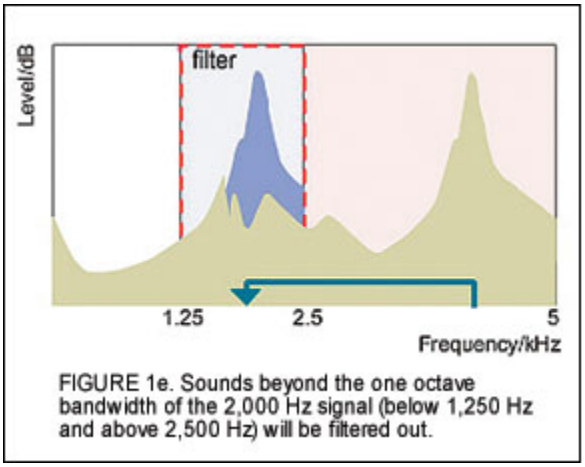


FIGURE 1e. Sounds beyond the one octave bandwidth of the 2,000 Hz signal (below 1,250 Hz and above 2,500 Hz) will be filtered out.

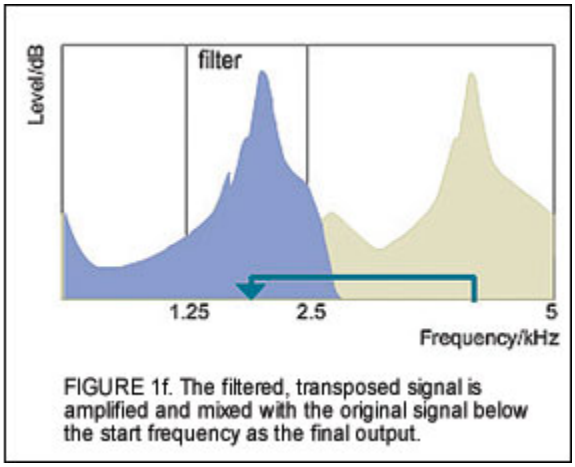


FIGURE 1f. The filtered, transposed signal is amplified and mixed with the original signal below the start frequency as the final output.

In LFT, an optimum start frequency is critical. The more aggressive (or lower) the start frequency is, the higher the frequency compression ratio will be. The result is a more unnatural sound. A more conservative approach (i.e., a higher start frequency) will minimize the disturbance on the original signal and avoid any potential interaction between the original signal and the processed signal. Conversely, if the approach is too conservative and the start frequency is too high, unaidable high frequencies may remain inaudible. To ensure an optimum start frequency, audiologists may manually adjust the start frequency and gain adjustments of the transposed signal.

In summary, when using LFT, only the frequencies above the start frequency – where hearing is most severely impaired – are lowered, as opposed to the full range of frequencies. Importantly, the AE lowers frequencies linearly, preserving transition cues, temporal structure, and the harmonic relationship between the original and the transposed signals. Thus, the original source signal is easily recognizable at a lower frequency. This method thereby preserves the original signal in the lower frequencies, while providing audibility in the high frequencies (Kuk et al., 2009).

Studies Evaluating LFT

Auriemmo et al. (2009) studied the effectiveness of LFT on phoneme recognition and fricative articulation in school-aged children. Ten children between 6 and 13 years of age who had severe-to-profound hearing loss at and above 3,000 Hz particpated in this study. Researchers used the NST test to evaluate performance of phoneme recognition and fricative articulation, for /s/ and /z/. Participants were tested using three different processing schemes: 1) the participants' digital hearing aids 2) Widex Inteo hearing aids with LFT (AE program), and 3) Widex Inteo hearing aids without LFT (master program). The results of this study revealed

significant improvement in consonant and vowel identification for children using the AE program compared to the their performance using digital hearing aids. However, a similar improvement was also recognized when comparing performance using the master program. Therefore, it is likely that the improvement realized between the conditions can be attributed to the quality of the Inteo heairng aids, rather than from the benefit of LFT. The benefit of LFT alone was minimal when compared to the master program.

The literature presents conflicting data regarding whether LFT provides speech perception benefit in the presence of background noise. High frequency speech information is difficult to detect, especially when competing noise is present. Presumably, using LFT would improve speech perception in a noisy environment because LFT provides access to high frequency acoustic cues. Nevertheless, it is important to consider that using LFT could introduce high frequency noise that may not have been audible to a HI person. Consequently, the introduction of high frequency noise could potentially mask the low-to-mid frequencies, resulting in poorer speech recognition in noise with LFT than without LFT (Kuk et al., 2009). The available research on this issue is, unfortunately, conflicting and limited.

Gengel and Foust (1975) conducted a study evaluating speech recognition using sentence material at various SNRs: + 30, +15, and 0 dB. Similar to the study conducted by Auriemmo et al., scores were obtained using two different devices: 1) the subjects conventional amplification and 2) amplification with LFT. The results of this study showed no decrement in performance between the devices. Contrary to the findings of Gengel and Foust, McDermotta and Knight (2001) conducted a study examining recognition of monosyllabic words, medial consonants, and understanding of speech sentences in competing noise. The results of this study revealed that recognition of monosyllabic words and medial consonants did not differ significantly, however

the subjects' understanding of sentences in competing noise was significantly poorer with the ImpaCt (a frequency lowering hearing device) than with the subjects' own aids (McDermott & Knight, 2001).

Another area of research examines LFT's effect when dead regions exist. In 2007, Robinson and colleagues evaluated the use of a transposition algorithm in listeners suspected of having dead regions along the basilar membrane. Recruits for this study were seven subjects with suspected high-frequency dead regions. The researchers tested consonant identification in quiet, using vowel-consonant-vowel (VCV) stimuli. In addition, they evaluated discrimination between /s/ and /z/ using word pairs. The results indicated significant improvement in VCV-testing for two subjects. Even though not every subject benefited equally from the algorithm, all subjects demonstrated an improved perception of the affricatives. In fact, five subjects showed a statistically significant improvement and, even more importantly, no subjects exemplified degradation in performance. Thus, this study suggests that transposition can improve consonant identification in individuals with dead regions (Robinson, Baer, & Moore, 2007).

NONLINEAR FREQUENCY COMPRESSION

Another approach to accessing high frequency speech information, Sound Recover, uses nonlinear frequency compression (NFC), which compresses and shifts inaudible high frequencies into a lower frequency region. SoundRecover was introduced in a number of Phonak hearing aids, including: Audeo, Exelia Art, Naida, and Nios. Similar to LFT, only the frequencies above a specified level are targeted for compression. Frequencies below the cut-off are amplified without modification, thereby preserving a natural sound quality. This approach aims to

minimize artifact, improve speech understanding, and enhance environmental sounds such as birds chirping, alarm clocks, etc.

Automatically configured by Phonak's proprietary software, iPFG, the frequency compression prescription of SoundRecover is determined based on the patient's audiometric thresholds and the prescriptive formula chosen by the fitter. For pediatrics, the DSL v5 formula is most commonly used. The high frequency pure tone average (2,000 Hz, 3,000 Hz and 4,000 Hz) is then calculated, and used to predict the initial "cut-off frequency" and compression ratio values. Input frequencies up to a defined knee-point, called the "cut-off frequency," do not undergo any frequency compression. Speech signals at or below this kneepoint are audible to the user and may be amplified conventionally. All speech signals above the cut-off are shifted to a lower frequency, determined by the compression ratio applied. "For example, if the cut-off parameter is set to 2 kHz, and the ratio is 2:1, each octave range of input frequencies above 2 kHz will be compressed into a half-octave range. Thus an input frequency range of 2-4 kHz, which is one octave wide, will become 2-2.8 kHz or half an octave wide" (McDermott, 2010).

In general, the more severe the hearing loss, the stronger the frequency compression setting will be. Frequencies above the cut-off frequency (i.e., formant 3 in Figure 2a) are selected by the software and compressed into an adjacent area that has less cochlear damage (Figure 2b).

FIGURE 2 a. Formant peaks are represented by numbers 1, 2, and 3 in this figure. As a consequence of high frequency hearing loss, formant 3 is inaudible to the listener.

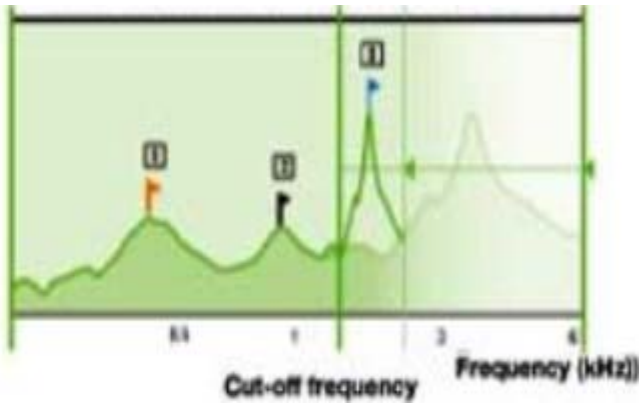


FIGURE 2 b. The frequency range above the cut-off frequency (i.e. the 3rd formant) is selected and compressed into an adjacent area that has less cochlear damage.

The frequency compressed output signals do not overlap or interfere with frequencies below the cut-off. Therefore, artifact is minimized and a clear sound quality maintained.

In summary, NFC provides access to high frequency information, while preserving the natural sound quality of the original signal. The software only compresses frequencies above the cut-off frequency, while amplifying frequencies below the defined kneepoint without modification. Similar to LFT, the cut-off frequency and compression ratios are easy to modify to optimize fitting benefits and user preference.

Studies Evaluating NFC

Several studies have evaluated the benefits of NFC in populations with varying degrees of hearing loss. For instance, Glista et al. (2000) tested this algorithm in children and adults with sloping, high frequency hearing loss. These researchers examined speech sound detection and speech recognition abilities using “multiple outcome measures” including The University of Western Ontario Distinctive Features Differences test (UWO-DFD). The study revealed significant improvement of consonant and plural recognition with NFC enabled; however, they did not observe a significant change in vowel recognition.

Similarly, Boretzki and Kegel (2009) examined the benefits of NFC for subjects with mild to moderate hearing loss. These researchers utilized The Adaptive Test, designed to measure thresholds at which high-frequency consonants are decipherable. The findings of Boretzki and Kegel's study suggest that NFC has the potential to provide substantial improvement in identification of high frequency speech signals and environmental sounds when compared to the subjects' amplification devices. Users participating in this study preferred NFC processing better than their conventional digital hearing aids.

In 2005, Simpson et al. conducted a study to evaluate speech perception in seventeen participants with moderate-to-severe sloping SNHL. Using frequency compression, the researchers programmed a hearing aid to amplify and shift frequencies above 1,600 Hz to a lower frequency range. Researchers then compared participant's recognition of monosyllabic words using compression amplification devices to their recognition using conventional hearing aids. When using frequency compression, eight of the seventeen subjects demonstrated significant improvements in speech recognition scores. Simpson et al. conducted further research evaluating the recognition abilities of seven subjects with moderately-severe to profound, steeply sloping hearing losses in both quiet and noisy conditions. Under quiet conditions, participants' speech perception scores using the frequency compression device were not significantly different from their scores using conventional hearing instruments. Similarly, when testing in noise, only one of the five subjects showed improvement when utilizing compression. Thus, this study concluded that frequency compression provides limited benefit for listeners with steeply sloping hearing losses (Simpson, Hersbach, & McDermott, 2006).

To uncover how hearing loss configuration affects speech perception abilities, Souza and Bishop, in 2000, conducted a study comparing speech recognition in subjects with sloping SNHL

to subjects with a flat SNHL. The researchers aimed to determine whether NFC provided greater improvement in speech recognition in subjects with sloping SNHL, evaluating consonant identification as a function of audibility using wide dynamic range compression (WDRC) amplification and linear amplification. The results of this study revealed similar improvements in recognition for subjects with flat and sloping loss when using linearly amplified speech. However, when using WDRC amplification, subjects with a flat loss showed a greater rate of improvement as audibility increased than that of subjects with sloping loss (Souza & Bishop, 2000). In contrast, a study conducted by Turner and Hurtig (1999), using an identical processing scheme, found that participants with more steeply sloping SNHL showed greater improvement in speech recognition scores than participants with a flat SNHL.

STUDY

As previously discussed, LFT and NFC have been developed in an attempt to overcome the historical limitation of conventional amplification devices providing access to high frequency acoustic information. Presently, there is a large discrepancy among research studies evaluating the efficacy of NLC and LFT. In an effort to distill these incongruent findings and examine whether age is a factor in the efficacy of NFC and LFT, the aim of this study is to evaluate the benefit these algorithms provide in terms of speech perception in school-aged children. Specifically, the primary objectives of this study are to:

1) Evaluate the effectiveness of Phonak's SoundRecover algorithm, and Widex's Audibility Extender algorithm, in providing access to sounds otherwise inaudible for children with high frequency hearing loss. The Consonant/Nucleus/Consonant (CNC) Test served to evaluate speech intelligibility in a quiet environment.

2) Assess speech intelligibility in the presence of noise, as well as, obtain a reception threshold for sentences (RTS), using the Hearing in Noise Test for Children (HINT-C) will be used to evaluate speech intelligibility in the presence of noise.
3) Find signal to noise performance functions at a -4 signal to noise ratio (SNR), -2 SNR, 0 SNR, +2 SNR, and +4 SNR.

This study will compare the performance of the participants with the NFC or LFT algorithm activated to performance with the algorithm deactivated.

It is hypothesized that no significant differences for CNC test scores, RTS (dB), or performance SNR functions will be found. Results will be presented on an individual-level.

This study is relevant for several reasons. First, research evaluating these algorithms in the pediatric population is limited. For developmental purposes, it is imperative that children receive optimal amplification as early as possible. Without evidence-based research, audiologists cannot determine whether they are providing the best available patient care.

Secondly, the available research offers inconsistent results. While some studies demonstrated that frequency lowering and frequency compression algorithms resulted in substantial improvement in speech recognition scores, others showed minimal improvement or degradation in performance. Furthermore, many of these studies compared the users' own hearing aids to LFT or NFC hearing aids, as opposed to comparing performance of the same hearing aids with the algorithm activated and deactivated. While this comparison may seem impressive, it fails to take into account major differences among devices, such as: "bandwidths, number of channels, compression parameters, distortion levels, noise reduction algorithms, directional microphones, etc. A difference in any of these parameters could account for substantial differences in performance" (Kuk et al., 2010).

Lastly, frequency transposition and frequency compression alter the natural spectral content of an input signal. It is possible that this alteration may have a negative effect on the way other phonemes are perceived. Perceptual overlap, for example, is an issue in LFT. Perceptual overlap occurs when different phonemes share the same acoustic information as a result of transposition. "For example, a /ʃ/, that has dominant energy between 2000 and 4000 Hz may be confused with a transposed /s/, which may have the same spectral content after frequency lowering" (Kuk et al., 2009). Increased identification of some phonemes may be offset by the potential decreased identification of others. Thus, the result would be little or no improvement in speech understanding.

METHODS

Study Participants

The Washington University School of Medicine Institutional Review Board and the Human Studies Committee reviewed and approved the research protocol and informed consent used for the present study.

Six participants with audiometric thresholds ranging from normal to profound from 250 Hz to 8,000 Hz were recruited for this study. Four subjects were recruited from St. Louis Special School District, one subject was recruited from St. Louis Children's Hospital, and one subject was recruited through Moog Center for Deaf Education through letters approved by Washington University's Human Research Protection Office (WUHRPO). All participants of this study were experienced hearing aid users. The mean age of subjects was 10.04 years with a range from 6.61 to 13.33 years (SD = 2.53 years). Since all participants were minors, a parent or legal guardian was required to sign the Informed Consent Form, in addition to the Assent Form that each participant signed. These forms were signed and returned at or prior to data collection.

In order to qualify for entrance into this study, each participant was required to: a) have a high frequency SNHL b) wear hearing aids with the NFC or LFT algorithm activated bilaterally, c) and be a native speaker of the English language. Subjects with a major medical problem associated with a cognitive impairment were not included in this study. Individual characteristics of the six participants are reported in Table 1. Hearing thresholds for each of the subjects can be seen in Appendix A.

Table 1. Individual subject characteristics

Subject	Age	Gender	Etiology of HL	Device	Algorithm
1	12.49	F	Unknown	Naida III SP	LFC
2	13.33	M	Premature; Low Birth Weight	Naida V SP	LFC
3	8.93	F	Genetic	Inteo 19	LFT
4	6.61	M	Ototoxic Medication	Nios Micro V	LFC
5	10.30	F	CMV	Inteo 19	LFT
6	8.58	M	PPHN; Respirator	Naida V UP	LFC

Two males and four females participated in this study. The etiologies of their hearing losses include: Cytomegalovirus (CMV), ototoxic medication, prematurity and low birth weight, persistent pulmonary hypertension, and genetic and idiopathic causes. Two subjects wore Widex hearing aids with the Audibility Extender (AE) (LFT), and four subjects wore Phonak hearing aids with SoundRecover (NFC). The parametric data of the subjects using AE can be seen in Table 3, and the parametric data of subjects using SoundRecover can be seen in Table 4.

Table 2. Parametric settings for subjects using SoundRecover.

	Left Ear		Right Ear	
Subject #	Cut-off Frequency (Hz)	Compression Ratio (dB)	Cut-off Frequency (Hz)	Compression Ratio (dB)
1	2.9 kHz	3.5:1	3.2 kHz	3.1:1
2	3.3 kHz	2.5:1	3.3 kHz	2.5:1
4	3.2 kHz	2.4:1	3.2 kHz	2.4:1
6	2.1 kHz	4.0:1	1.8 kHz	4.0:1

Table 3. Parametric settings for subjects using AE.

Subject #	Default SF (Hz)	Expanded LFT	LFT Gain (dB) (Left Ear)	LFT Gain (dB) (Right Ear)
3	2500	No	6	4
5	4000	Yes	0	0

The settings of the devices were not manipulated at any point during data collection, aside from activating and deactivating the LFT or NFC algorithm. Prior to data collection, each of the hearing aids were cleaned using audiowipes and a listening check was performed to verify that the hearing aids were functioning properly. In addition, all zinc air size 13 batteries were checked to ensure that the battery was fully charged and operational prior to testing.

Calibration

Calibration of all recorded speech materials occurred prior to data collection using a Larson-Davis model 831 Sound Level Meter (SLM), which had been previously calibrated using a Larson Davis Model CAL200. To ensure that the overall presentation level was 65 dB (A), a ½" Class 1 free-field pre-polarized microphone, 50 mV/Pa connected to the Larson-Davis model 831 Sound Level Meter was placed at ear level, with the subject absent, one meter from the loudspeaker. The SLM was calibrated using a Larson Davis Model CAL200. A 1,000 Hz tone at

94 dB was presented. The measured output of 1,000 Hz tone at 94 dB was read through the sound level meter to verify that the free field level was -0.12 from the level presented. To verify the appropriate presentation level of the speech stimuli according to ANSI S3.1, a recorded 1,000 Hz calibration tone was used to monitor that the VU meter needle accurately pointed to 0 dB on the audiometer.

Procedure

All testing was conducted in an acoustically treated soundbooth. The subject was placed 1 meter from the soundfield loudspeaker at 0 degrees azimuth. Each subject was instructed to keep his or her head level, and to face the loudspeaker at all times throughout the testing session. Prior to data collection, the subjects were familiarized with the CNC words and HINT-C sentences. They were asked to repeat each word or sentence they heard. If the subjects were uncertain of what they heard, they were instructed to guess.

Consonant/Nucleus/ Consonant (CNC) Test

The Consonant/Nucleus/Consonant Test consists of 10 lists of 50 monosyllabic words with equal phonemic distribution across lists. Each list exhibits approximately the same phonemic distribution as used in the English language. The response can be scored as words correct and/or phonemes correct. For this study, two lists were presented to the subject. The first list was presented at a soft level, 30 dB HL, and the second list was presented at a conversational level, 50 dB HL. Scores were first obtained with the NFC or LFT algorithm active, and then with the algorithm deactivated.

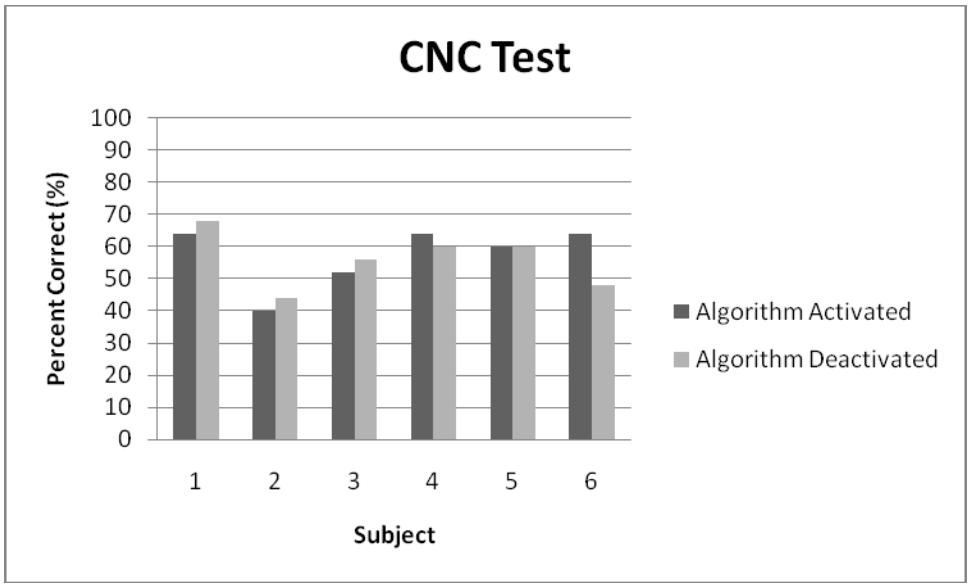
Hearing in Noise Test for Children (HINT-C)

The Hearing in Noise Test for Children (HINT-C) consists of 13 lists of 10 phonetically balanced sentences. The sentences are approximately equal in length (six to eight syllables) and difficulty. Digitally recorded sentences, read by a male speaker, are presented simultaneously

with speech-spectrum noise in order to determine the RTS. The RTS is the level at which the sentences, embedded in background noise, can be repeated correctly 50% of the time. The HINT-C employs an adaptive procedure in which the noise is presented at a fixed level of 65 dB (A), and the presentation level of the sentence is varied depending upon the accuracy of the listener's response. Lastly, SNR performance functions were obtained at -4 SNR, -2 SNR, 0 SNR, +2 SNR, and +4 SNR. HINT-C sentences were utilized as the speech stimulus for this test. These tests provide an accurate estimation of speech recognition abilities in the presence of background noise at various SNRs.

RESULTS

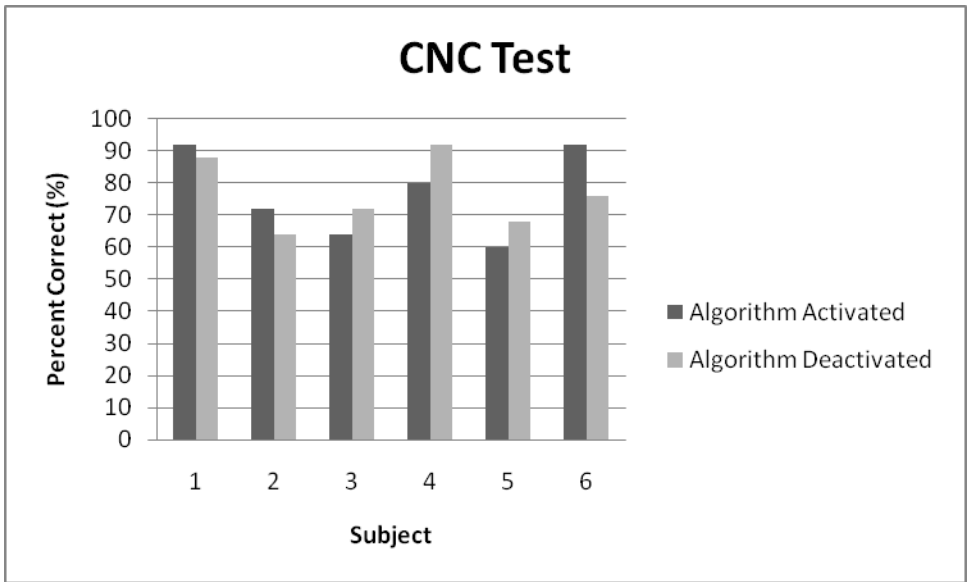
For each test conducted throughout this study, scores were obtained in two conditions: 1) LFT or NFC algorithm activated, and 2) algorithm deactivated. Performance was evaluated on an individual basis using binomial distribution for speech developed by Thornton and Raffin (1978). Thornton and Raffin constructed a Critical Difference Table for Word Recognition Testing. This table delineates the upper and lower limits of the 95% critical range (95% confidence levels) for changes in word recognition scores obtained with monosyllabic word lists (Gelfand, 2009). Using the Consonant-Nucleus-Consonant Test in a quiet soundfield, word lists presented to the subjects at 30 dB HL and 50 dB HL elicited speech intelligibility scores, based on a percentage correct. Graph 2 reports CNC scores for all subjects at 30 dB HL.



Graph 2. CNC scores for all six subjects reported with word lists presented at 30 dB HL. Scores shown for both conditions: 1) algorithm activated, and 2) algorithm deactivated. There were no significant changes displayed between conditions.

A comparison of performance at 30 dB HL revealed no significant improvement between the conditions 1 and 2. Even though these differences were not statistically significant, all subjects, with the exception of Subject 6, performed poorer with the algorithm activated.

Next, speech intelligibility scores were obtained in both conditions using CNC words lists presented at a 50 dB HL. The results indicated that subject performance was significantly better for Subject 6 with the NFC activated at a presentation level of 50 dB HL, as illustrated in Graph 3.



Graph 3. CNC scores for all six subjects with word lists presented at 50 dB. Scores shown for both conditions: 1) algorithm activated, and 2) algorithm deactivated. Subject 6 performed significantly better with NFC.

The HINT-C was then administered to determine the RTS (dB) of each subject. "An RTS (dB) of 0 means the subject required the intensity level of the sentences to be equal to the level of the noise (65 dB) in order to correctly repeat the HINT sentences 50% of the time" (Oeding, 2009). Thus, a negative RTS (dB) indicated that the subject required the sentence presentation level to be higher than the noise level. Table 5 reports the RTS for each subject with the algorithm activated and deactivated.

Table 4. RTS (dB) reported for all subjects.

Subject	Algorithm	Algorithm Activated RTS (dB)	Algorithm Deactivated RTS (dB)	Difference	
1	NFC	-5.57	-2.15	3.35	*
2	NFC	5.57	7.57	2.00	*
3	LFT	1.99	-0.58	1.41	
4	NFC	4.70	4.35	0.35	
5	LFT	7.99	5.99	2.00	*
6	NFC	2.58	3.99	1.05	

Note: "*" Indicates statistical significance as determined by Nilsson et al.'s (1994) confidence interval for two 10-sentence list in noise of +/- 1.5 dB (Oeding, 2009).

Five subjects had an RTS (dB) greater than zero, and one subject had an RTS lower than zero. Thus, the majority of participants required the sentence presentation level to be higher than the noise level. The symbol "*" in the table denotes a statistical significance as determined by Nilsson et al.'s (1994) confidence interval for two 10-sentence HINT lists in noise of +/- 1.5 dB. As seen in the table, performance varied considerably among the subjects. Subject 1 and Subject 2, using NFC, performed significantly better with the algorithm activated. Subject 5, using LFT, performed significantly worse with the algorithm activated. Differences for the other three subjects were not statistically significant.

Performance SNR functions were then performed at -4 SNR, -2 SNR, 0 SNR, +2 SNR, and +4 SNR. Table 6 shows individual performances.

Algorithm Activated

Table 5. Performance on HINT-C at various SNRs.

Subject	-4 SNR	-2 SNR	0 SNR	+2 SNR	+4 SNR
1	84.00% *	87.71% *	98.07% *	96.00%	100.00%
2	5.26%	6.00%	30.00%	41.50%	56.14%
3	49.12%	60.00%	54.00%	88.67%	92.59%
4	21.00%	34.00%	42.00%	67.30%	80.00%
5	22.00%	20.00%	19.23%	54.00%	84.00% *
6	21.05%	26.00%	60.00%	75.00%	80.00%

Algorithm Deactivated

Table 6. Performance on HINT-C at various SNRs.

Subject	-4 SNR	-2 SNR	0 SNR	+2 SNR	+4 SNR
1	60.37%	72.00%	86.67%	90.90%	96.00%
2	0.00%	20.00% *	24.00%	37.73%	58.49%
3	36.00%	62.26%	76.00% *	87.27%	96.07%
4	28.00%	33.96%	46.29%	64.91%	80.39%
5	28.30%	46.00% *	45.28% *	77.19%	60.00%
6	32.00%	39.62%	51.85%	68.42%	74.00%

Again, results varied considerably across participants. Subject 1 performed significantly better at -4 SNR, -2 SNR, and 0 SNR with NFC. On the other hand, Subject 2 performed significantly better without NFC at -2 SNR. Similarly, Subject 3 performed significantly better at 0 SNR, and Subject 5 displayed a significant improvement at -2 SNR and 0 SNR without LFT. There were not significant changes observed with Subject 4 or Subject 6 between conditions across any SNR level. Graphs representing individual performance can be found in Appendix B.

DISCUSSION

The purpose of this study was to determine if NFC and LFT processing provided speech perception benefit relative to the same hearing aid fitting with the algorithm deactivated. This was evaluated across a range of pediatric participants with varying audiometric characteristics. There are material individual differences between subjects that could affect the outcome of studies evaluating the efficacy of NFC and LFT. These differences include: cognitive level, the amount of distortion of the auditory system, degree of hearing loss, subsequent hearing aid use, the extent of cortical reorganization, and auditory training (Kuk et al., 2009). Therefore, the analysis of each subject was conducted on an individual level. The results of this study revealed that performance using NFC and LFT varied considerably across individuals tested.

Specifically, there were no statistically significant differences noted in individual performance with NFC or LFT activated when CNC word lists were presented in a quiet environment at 30 dB HL, compared to performance with the algorithm deactivated. Subject 1 and Subject 2 showed significant improvement when using NFC in the presence of noise. These findings were similar to those of Simpson et al., (2006) who found that participants' speech perception scores using a frequency compression device were not significantly different from their scores using conventional hearing instruments in quiet conditions. Similarly, in Simpson et al.'s study, only one of the five subjects revealed significant improvement when utilizing compression in noise. This finding, thus suggests that NFC and LFT provides limited benefit.

In a quiet condition, Subject 6 demonstrated a significant improvement in speech recognition at 50 dB HL using NFC. Similarly, Subject 1 performed significantly better at various SNRs using NFC. These results are consistent with the findings of Glista et al. (2000)

and Boretzki and Kegel (2009), which revealing significant improvement of high frequency consonants, plural recognition and environmental sounds when NFC was enabled.

Degradation in performance was noted in Subject 3 and Subject 5 using LFT in the presence of noise. This finding coincides with the results of Kuk et al. (2010). These researchers found that while some conditions improved with the use of LFT, others yielded poorer scores. This study also demonstrated the importance of auditory training. There is strong evidence within the literature that suggests that auditory training can significantly improve consonant identification and speech intelligibility in individuals using these algorithms, particularly in LFT. The goal of auditory training is to help a child make fine discriminations among speech sounds in order to gain meaning and clarity.

Limitations

While a great deal of valuable information may be inferred when evaluating individual performance, it is difficult to determine trends and establish statistical significance among groups of children using LFT and NFC, due to the limited number of participants. As in any research, conclusions are more substantially supported when drawn from studies utilizing a greater number of subjects. Furthermore, each participant was only evaluated once due to the time constraints of this project. Individual performance could be considerably affected by a number of contributing factors, including; time of day, testing fatigue, boredom, inattention, etc. Therefore, regular (or repeated) testing over an extended time period, would verify the accuracy of test results. Additionally, recurrent evaluation of speech recognition, using LFT or NFC, would help determine whether benefits were sustained or achieved over time.

Monosyllabic words presented in quiet and sentence tests presented in noise are the evaluation measures most commonly used to determine speech perception performance in

school-aged children. Typically, a male speaker delivers the test stimuli. Since the use of these tests accurately reflects the clinical evaluation of children utilizing these algorithms, CNC word lists and HINT-C sentences, spoken by a male speaker, facilitated the evaluation of speech perception in this study population. As previously discussed, high frequency content varies by gender. Male speakers have a lower fundamental frequency than females, resulting in a spectrum with restricted output in the high frequencies. Thus, female speaker word lists may better demonstrate the efficacy of the processing schemes being evaluated.

Finally, it is difficult to know if the parametric settings for each subject were optimal. Audiometric testing and hearing aid programming related to this study, was performed by the subjects' chosen audiologist. Thus, audiometric testing, hearing aid fitting strategies, and programming lacked uniformity among the hearing aids evaluated in this study.

Clinical Implications

The results of this study suggest that LFT and NFC can potentially improve the audibility of high-frequency consonant sounds and improve speech understanding in both a quiet and noisy environment. Performance varied considerably across subjects, yet the use of LFT and NFC did improve performance for a number of the participants. Therefore, a child with precipitously sloping high-frequency hearing loss, who is unable to gain access to high frequency information through conventional processing, is a candidate for NFC or LFT. Children utilizing these processing schemes require regular monitoring to determine whether they are receiving benefit.

These processing schemes alter the spectral characteristics of the original input signal, resulting in a considerable change in overall sound quality. Thus, an acclimatization period is necessary for children to adapt to this type of processing. Children utilizing LFT or NFC

necessitate enrollment in an auditory training program. Importantly, children who do not receive benefit, or exhibit a decrement in performance, warrant the deactivation of the algorithm.

CONCLUSION

Access to input across the entire speech range is critical for developing age-appropriate speech, language, and auditory skill (Wolf et al., 2009). Yet, successfully providing access to the entire speech range for the hearing impaired pediatric population has not always been possible. Conventional amplification is limited in providing adequate high frequency gain. There have been numerous attempts to address this issue through frequency lowering techniques; although, most were unpopular due to the poor sound quality they produced.

Considering the limitations of these past approaches prompted the development of LFT and NFC. Research evaluating these algorithms is limited and conflicting. Thus, the purpose of this study was to evaluate the benefit these algorithms provide in various listening situations for school-aged children. The results of this study suggest that LFT and NFC can potentially improve the audibility of high-frequency consonant sounds and improve speech understanding in both quiet and noisy environments, in children with precipitously sloping high-frequency hearing loss. When access to high frequency acoustic information is unattainable through conventional processing, one of these two algorithms can make high frequency acoustic information available.

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APPENDICES

Appendix A: Audiometric thresholds for each subject for his or her left and right ear.

Audiometric Thresholds (Left Ear)

	Frequency (Hz)									
	250	**500**	**750**	**1,000**	**1,500**	**2,000**	**3,000**	**4,000**	**6,000**	**8,000**
Subject										
1	35	35	60	60	70	70	95	95	100	120
2	5	5	20	60	60	55	70	80	80	80
3	60	75	80	85	105	100	105	115	115	120
4	5	0	0	5	10	60	55	60	60	70
5	25	20	25	55	70	75	80	75	75	70
6	25	15	10	5	40	70	85	90	80	85

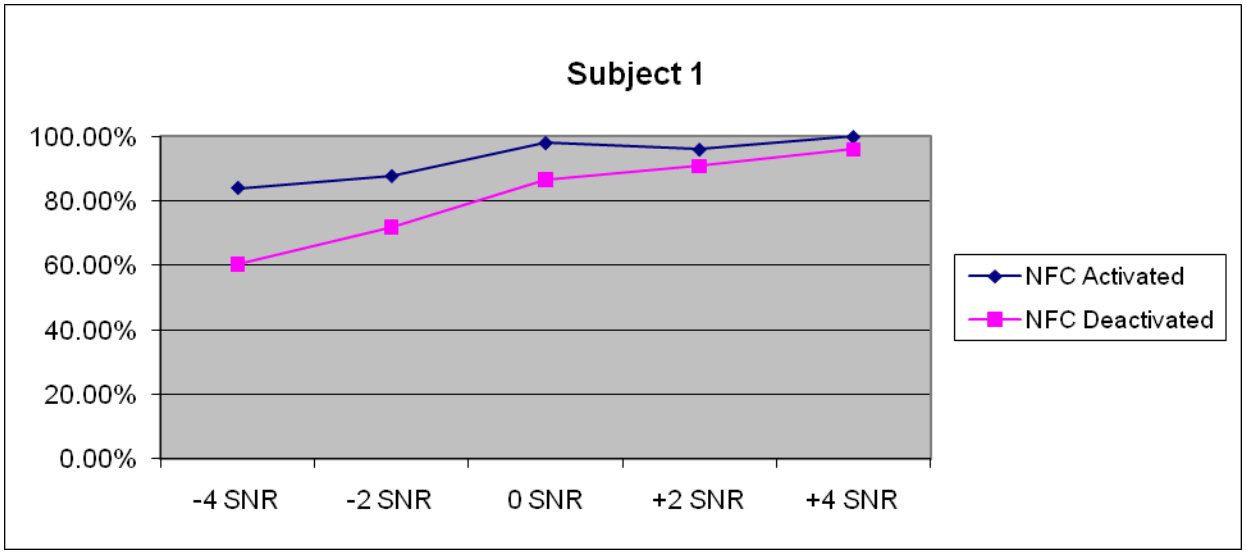
Note: All thresholds are measured in decibels (dB)

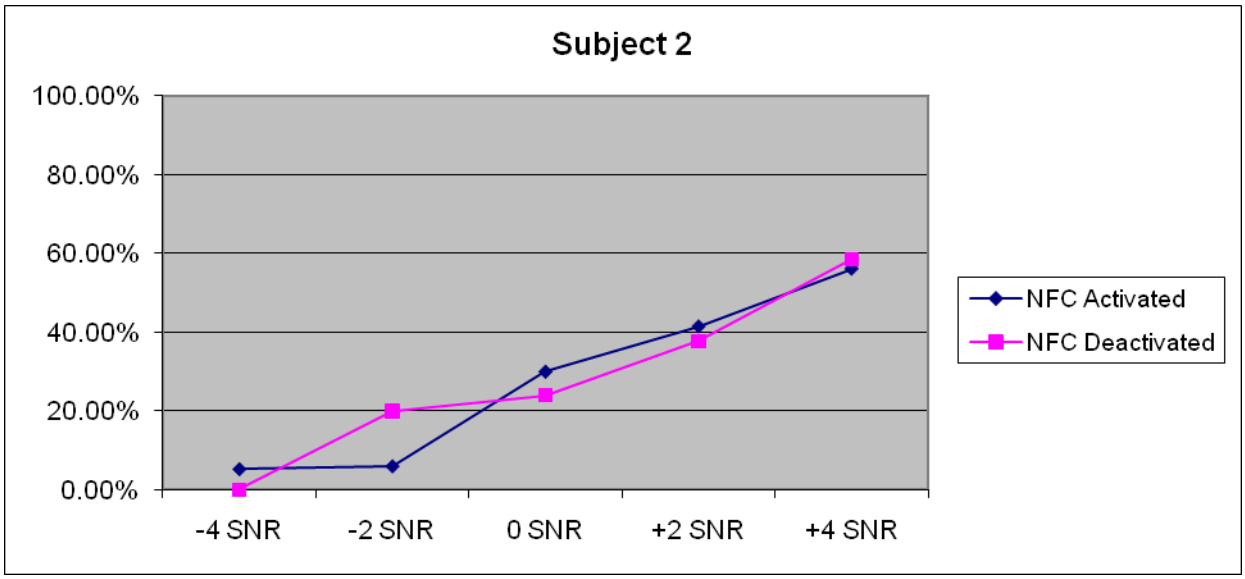
Audiometric Thresholds (Right Ear)

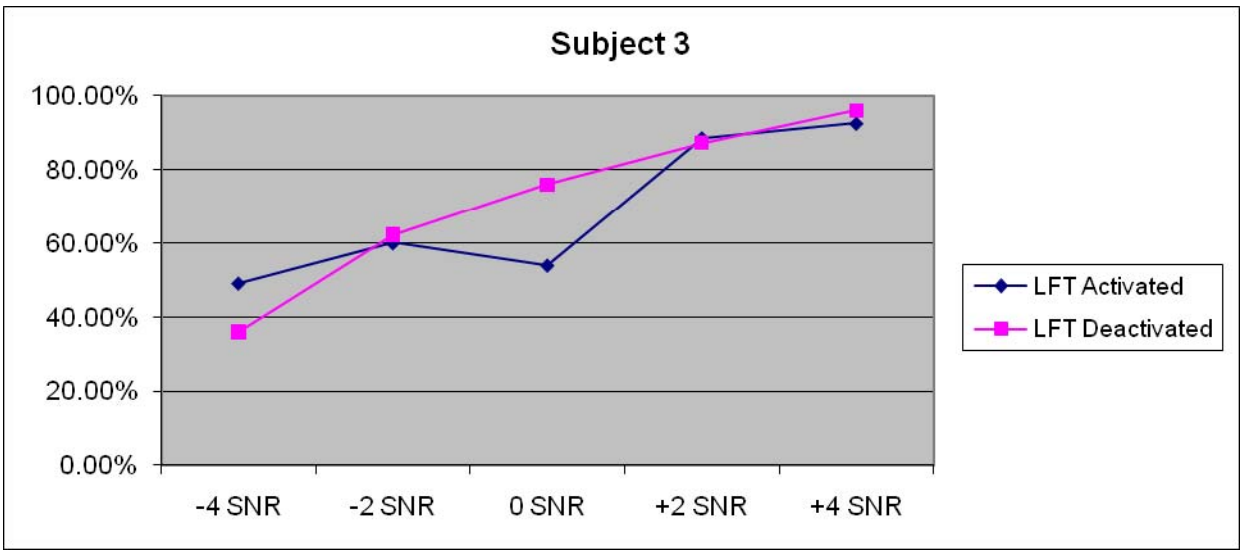
	Frequency (Hz)									
	250	**500**	**750**	**1,000**	**1,500**	**2,000**	**3,000**	**4,000**	**6,000**	**8,000**
Subject										
1	45	50	50	60	80	70	75	70	100	120
2	10	30	60	65	60	55	70	80	85	85
3	45	60	65	70	75	80	90	100	115	120
4	5	0	0	5	10	55	60	60	60	75
5	25	50	70	75	105	105	105	100	95	N/R
6	30	10	10	5	25	70	80	100	85	80

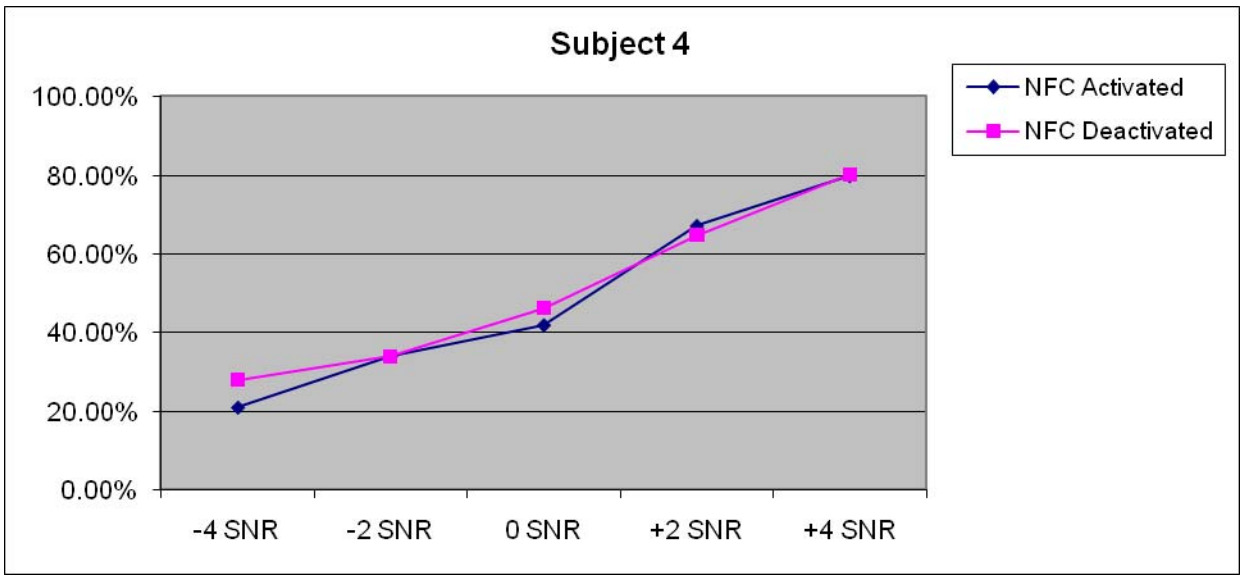
Note: All thresholds are measured in decibels (dB)

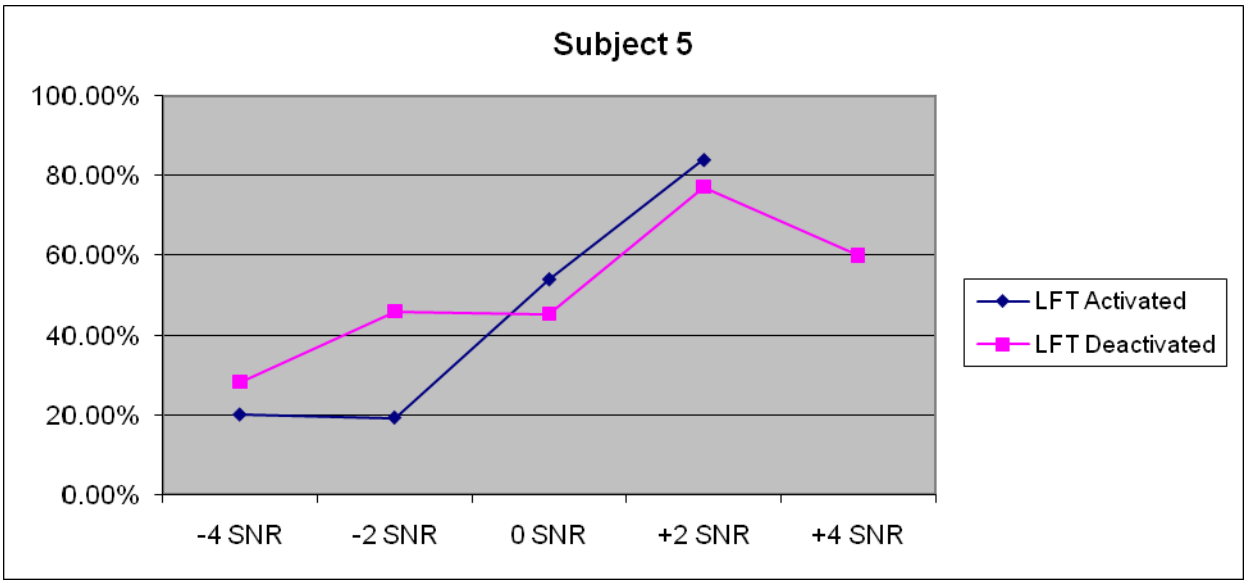
Appendix B: SNR performance functions for all six subjects.

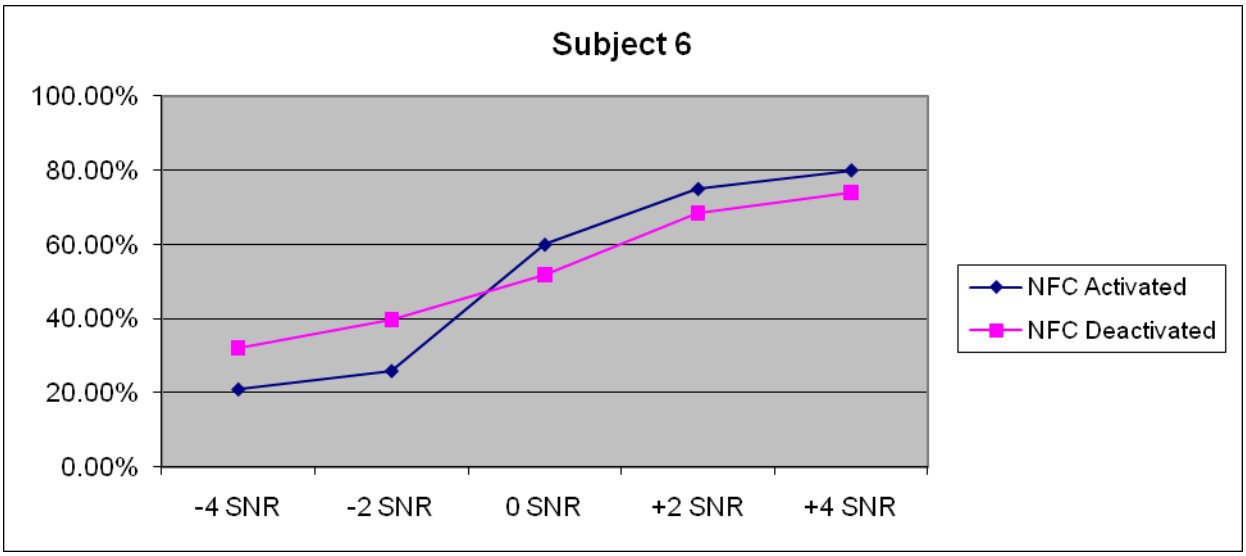





Subject 3
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-4 SNR
-2 SNR
0 SNR
+2 SNR
+4 SNR
LFT Activated
LFT Deactivated


Subject 4
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-4 SNR
-2 SNR
0 SNR
+2 SNR
+4 SNR
NFC Activated
NFC Deactivated


Subject 5
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-4 SNR
-2 SNR
0 SNR
+2 SNR
+4 SNR
LFT Activated
LFT Deactivated


Subject 6
100.00%
80.00%
60.00%
40.00%
20.00%
0.00%
-4 SNR
-2 SNR
0 SNR
+2 SNR
+4 SNR
NFC Activated
NFC Deactivated