

**FREQUENCY LOWERING IN THE PEDIATRIC POPULATION: OUTCOMES  
AND CONSIDERATIONS FOR FITTING**

Capstone

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By

Lauren Virginia Ross, B.A.

Graduate Program in Audiology

The Ohio State University

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Capstone Committee:

Gail Whitelaw, Ph.D., Advisor

Eric Bielefeld, Ph.D.

Julie Hazelbaker, Ph.D.

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## **ABSTRACT**

Children with hearing loss are at a disadvantage for language learning because they are unable to hear many of the important, yet subtle, cues necessary for speech and language development. Even when using current digital hearing aids, children with hearing loss are often unable to hear speech cues in the high frequency range. Frequency lowering is a processing strategy in which the hearing aid transfers higher frequency inputs to a lower frequency range that can be adequately amplified by the device. Two types of frequency lowering algorithms are currently available for use in children and have been shown to be successful for improving high frequency audibility in children with high frequency hearing loss.

The purpose of this capstone is to describe the use of frequency lowering techniques to improve high frequency audibility for children with hearing loss. Specifically, this capstone will focus on the different types of frequency lowering and recent research outcomes, fitting considerations in the pediatric population, and considerations in acclimatization and auditory training with frequency lowering technology. In addition, a case example is provided to demonstrate candidacy, fitting, and verification concepts in a real world situation.

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**VITA**

September 7, 1989.....Born - Cincinnati, Ohio

March 18, 2012.....BACHELOR OF ARTS  
SPEECH AND HEARING SCIENCE  
MINOR: DISABILITY STUDIES  
The Ohio State University  
Columbus, Ohio

2013.....GRADUATE TEACHING ASSISTANT  
The Ohio State University  
Columbus, Ohio

2014-2015.....LEND TRAINEE  
Nisonger Center  
The Ohio State University  
Wexner Medical Center  
Columbus, Ohio

2015-2016.....AUDIOLOGY EXTERN  
Little Ears Hearing Center  
Louisville, Kentucky

**FIELD OF STUDY**

Major Field: Audiology

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## **CHAPTER 1**

### **INTRODUCTION**

One of the most important amplification goals for children with hearing impairment is to provide access to speech cues that would otherwise be inaudible and, therefore, unavailable for use in the development of speech and language skills (McCreery, Venediktov, Coleman, & Leech, 2012). Since Universal Newborn Hearing Screening (UNHS) has become mandatory in the United States, children with hearing loss are being identified within months of their birth and are provided with interventions, including amplification, at a much younger age than in the past (National Institutes of Health, 1993). Earlier access to speech cues has been shown to greatly improve the speech and language development of children with hearing loss. Studies have shown that children with hearing loss who receive early intervention have the potential to develop speech and language skills similarly to their normal hearing peers (Yoshinaga-Itano, 2003).

Even though appropriately fit hearing aids can improve speech and language outcomes in children with hearing loss, hearing aids are still restricted in the access to speech cues that they are able to provide. Due to the limitations of most hearing aid receivers, many of the current commercially available hearing aids are only able to amplify a limited frequency bandwidth, extending to approximately 5-6 kHz (Beck & Olsen, 2008; Pittman, 2008; Stelmachowicz, Pittman, Hoover, & Lewis, 2001). A study

by Stelmachowicz et al. (2001) showed that certain important speech cues, especially those for fricatives like /s/ and /z/, can occur as high as 9 kHz, especially when spoken by females and children. Because they provide important linguistic cues such as plurality, tense, and possession, access to these phonemes early in life is critical for age appropriate speech and language development (Stelmachowicz et al., 2001).

An audible bandwidth that exceeds 5-6 kHz is necessary for accurate speech perception, especially for children. The study by Stelmachowicz et al. (2001) demonstrated that children with hearing loss required a wider bandwidth for accurate perception of the /s/ phoneme for female and child speakers when compared to adults with similar degrees of hearing loss. Even at their best performance, children with hearing loss performed significantly poorer than adult participants on /s/ recognition tasks. The study suggested that children with hearing loss require additional bandwidth for accurate speech perception as a result of their inexperience with language in conjunction with limited audibility (Stelmachowicz et al., 2001).

Stelmachowicz, Pittman, Hoover, and Lewis (2002) investigated the performance of children with hearing loss on a plural identification task in which the children were given a target word and asked to identify the picture that corresponded with the target word. Each target word was presented in either the singular or plural form and the child was given both the plural and singular target word picture cards for identification. All participants were experienced hearing aid users. The results of the study showed that the children with hearing loss performed significantly poorer on the plural identification task when listening to a female speaker than when listening to a male speaker. These results suggested that the mid frequency cues (2 to 4 kHz), that are important for fricative



perception for male speakers, are accessible for children with hearing loss with the use of amplification, but that accessibility to the higher frequency cues (2 to 8 kHz), that are important for fricative perception for female speakers, may be limited (Stelmachowicz et al., 2002).

Stelmachowicz, Pittman, Hoover, Lewis, and Moeller (2004) suggested that limited high frequency audibility resulting from the limited bandwidth of current hearing aids can negatively affect a child's perception of fricative phonemes, such as /s/ and /z/. As a result of inconsistent audibility for these important phonemes, development of linguistic rules may be delayed in children with hearing loss (Stelmachowicz et al., 2004). Limited high frequency audibility may also affect a child's ability to monitor his or her own speech productions of fricative phonemes, resulting in misarticulations and omissions of these sounds (Stelmachowicz et al., 2004). Limited audibility of fricative phonemes combined with the limited ability to monitor the production of fricative phonemes may be factors in the delay of phonological development evident in children with hearing loss, even when early amplification is implemented.

Moeller et al. (2007) investigated the speech development of children with hearing loss who received early intervention services as compared to the speech development of children with normal hearing. Participants with hearing loss were fit with hearing aids before 12 months of age and had been enrolled in their local public or private early intervention educational programs for children with hearing loss (Moeller et al., 2007). When matched in developmental age to normal hearing peers, children with hearing loss demonstrated similar phonetic inventories at the reduplicated babble stage of speech development. This result was not surprising because at this stage of development,

typically developing children do not frequently produce high frequency fricative phonemes, as development is focused on earlier phonemes, such as vowels, bilabials, alveolars, and velars. At the 50-word stage, the development of nonfricatives was similar between the groups, but the development of fricatives and affricates was significantly delayed for the children with hearing loss (Moeller et al., 2007). The results of this study indicated that early identification and amplification with conventional hearing aids may not be enough to support typical language development in hearing impaired children (Moeller et al., 2007).

Research has suggested that improvements in hearing aid technology may improve the perception and production of fricatives in children who are hearing impaired by providing the child with access to high frequency speech cues (Moeller et al., 2007; Stelmachowicz et al., 2004). Before digital signal processing was available in hearing aids, attempts were made to lower the frequency of the incoming signal to improve audibility for high frequency cues. These attempts included slow-playback techniques and vocoding (see Chapter 2 for details) (Kuk et al., 2006). With the advent of digital hearing aid technology, new strategies for improving high frequency audibility, such as extended bandwidth and frequency lowering, became available in current commercial hearing aids.

Extended bandwidth refers to extending the frequency range that hearing aids are able to amplify. Up until recently, many commercially available hearing aids were only able to amplify up to approximately 5-6 kHz as a result of the large size of the receiver, limitations in signal processing rate, and the acoustics of standard earmold tubing (Beck & Olsen, 2008; Pittman, 2008; Stelmachowicz et al., 2001). Improvements in more

current hearing aids have eliminated some of the issues that limited the frequency output of older hearing aids.

The receiver is, essentially, the speaker for the hearing aid. The receiver produces the amplified sound that travels into the ear canal of the hearing aid user. The use of multiple receivers or changing the receiver size can result in improvements in extended bandwidth for hearing aid outputs (Kuk & Baekgaard, 2009; Peeters, Lau, & Kuk, 2011). Inside the receiver, the diaphragm vibrates at the same frequency of the signal that is being transduced. In order to vibrate fast enough to transduce higher frequency signals, the diaphragm must be smaller and stiffer than the diaphragm used in most commercial hearing aids (Kuk & Baekgaard, 2009). A smaller receiver would allow for the transduction of higher frequency signals, but it is also likely to compromise the quality of lower frequency signals, which require a larger diaphragm. Another solution for creating an extended bandwidth is to use multiple receivers, a smaller receiver for high frequency signals and a larger receiver for low frequency signals (Kuk & Baekgaard, 2009). This technique allows for the transduction of high frequency speech cues without altering the low frequency output of the hearing aid.

Additionally, improvements in signal processing power and faster sampling rates have resulted in extended bandwidths in some current commercial hearing aids (Beck & Olsen, 2008). Previously, hearing aid processing algorithms lacked the power and speed to sample an incoming frequency signal at a high enough rate to avoid distortion in the output signal (Beck & Olsen, 2008). Improvements in signal processing, however, have made sampling out to higher frequencies, such as 8-10 kHz, possible (Beck & Olsen, 2008).

Finally, changes in hearing aid style, such as the receiver-in-the-canal (RIC) style hearing aid, have eliminated the need for traditional earmold tubing which often attenuated high frequency sound (Beck & Olsen, 2008). The RIC style hearing aid replaced the traditional earmold tubing with a wire that extends from the behind-the-ear portion of the hearing aid to the receiver that extends into the ear canal. By eliminating earmold tubing and placing the receiver closer to the eardrum, better high frequency amplification can be achieved (Beck & Olsen, 2008). High frequency amplification is still possible, even with extended bandwidths, with traditional earmold tubing, however, the RIC hearing aid does have an advantage for this type of signal processing (Beck & Olsen, 2008).

Research has shown improvements in speech recognition, loudness perception, and listening in background noise with the use of extended bandwidth hearing aids (Kreisman, Mazevski, Schum, & Sockalingam, 2010; Peeters et al., 2011). Although there is benefit from extending the bandwidth of hearing aid amplification, this benefit appears to be limited to individuals with mild to moderate hearing loss (Kuk & Baekgaard, 2009). As a result, those with greater degrees of hearing loss may not be able to benefit to the same extent as those with mild to moderate hearing loss from extending hearing aid bandwidth.

The decrease in benefit from extended bandwidths noted in those with greater degrees of high frequency hearing loss is likely related to the limitations of the hearing aid, as well as the increased possibility of cochlear dead regions in individuals with more high frequency hearing loss (Kuk & Baekgaard, 2009). As stated previously, extended bandwidths require a much smaller receiver with a diaphragm that is able to vibrate such

that it is able to create outputs as high as 10,000 Hz. Because extended bandwidth requires the use of a smaller receiver, increased limitations in maximum output, especially for high frequency inputs, are noted. Therefore, it is unlikely that the hearing aid is able to provide enough power to make the entire extended bandwidth audible for individuals with greater degrees of hearing loss in the high frequency region (Kuk & Baekgaard, 2009). Additionally, as hearing sensitivity decreases, especially in the higher frequencies, the likelihood of cochlear dead regions increases. As a result, even when the hearing aid is able to provide enough power for high frequency outputs, it is unlikely that the individual would be able to make use of the auditory information due to the damaged state of the cochlea (Kuk & Baekgaard, 2009).

Frequency lowering is a processing strategy in which the hearing aid transfers higher frequency inputs to a lower frequency range that can be adequately amplified by the device. It has been suggested that frequency lowering can be used as an alternative solution to overcome the limitations in high frequency speech outputs in current hearing aids (McCreery et al., 2012).

The focus of this capstone is on the use of frequency lowering techniques in order to improve high frequency audibility for children with high frequency hearing loss. Specifically, this paper aims to address the different types of frequency lowering, recent research outcomes with frequency lowering devices, fitting considerations for professionals with a case example, and auditory acclimatization and training.

## **CHAPTER 2**

### **FREQUENCY LOWERING TECHNIQUES AND OUTCOMES**

Children with hearing loss are at a disadvantage for language learning because they are unable to hear many of the important, yet subtle, cues necessary for speech and language development. Even when using current digital hearing aids, children with hearing loss are often unable to hear speech cues in the high frequency range, cues that are important for understanding plurality, possession, and tense (Stelmachowicz et al., 2002). This lack of audibility can lead to delays in speech production and in language learning for children with hearing loss (Moeller et al., 2007; Stelmachowicz et al., 2004).

The delays in language learning for children with hearing loss, even when provided with amplification and early intervention, are likely the result of the limitations of conventional hearing aids; hearing aids that utilize the manufacturer's standard signal processing settings. Most of the current commercially available hearing aids are unable to amplify important speech cues that fall above approximately 5-6 kHz (Beck & Olsen, 2008; Pittman, 2008; Stelmachowicz et al., 2001). In response to this issue, some hearing aid manufacturers have attempted to extend the frequency bandwidth of their hearing aids. While research has demonstrated benefit for listeners with mild to moderate hearing loss, extended bandwidths seem to have minimal benefit for individuals with greater degrees of hearing loss as a result of the limitations of the smaller receiver required for extended bandwidths and the increased possibility of cochlear dead regions in individuals

with more severe high frequency hearing loss (Kuk & Baekgaard, 2009). As an alternative to extended bandwidth, frequency lowering has been introduced as another solution for improving high frequency audibility.

Frequency lowering is a processing strategy in which the hearing aid transfers higher frequency inputs to a lower frequency range that can be adequately amplified by the device and/or made audible to the listener. Early attempts at frequency lowering included slow-playback techniques and vocoding (Glista et al., 2009; Kuk et al., 2006). Slow-playback devices record the incoming speech signal and then play it back to the listener at a slower rate. By slowing the rate of playback, the signal is lengthened in time and lowered in frequency (Simpson, 2009). Vocoding refers to the process by which the incoming speech signal is divided into frequency bands. Each band is used to modulate a carrier frequency or noise and then each carrier is added together and played back to the listener. By using this process, high frequency bands in the incoming signal can be used to modulate lower frequency carrier tones which are more likely to be audible to the listener (Simpson, 2009).

These techniques were ultimately unsuccessful because, although they lowered the frequency content of the signal, they also altered other characteristics, such as spectral and temporal cues, that degraded the incoming speech signal (Glista et al., 2009; Kuk et al., 2006). As a result, minimal improvements in high frequency speech recognition were noted with these devices. In many cases, the improvements for high frequency signals resulted in poorer performance for low frequency signals (Simpson, 2009).

Following some of the earlier attempts to improve speech recognition with frequency lowering, advancements in digital technology allowed for the advent of more

sophisticated frequency lowering technology (Levitt, 2007). As a result, earlier versions of frequency lowering have become obsolete and have been largely replaced with newer digital technology: linear frequency transposition and nonlinear frequency compression. When utilizing linear frequency transposition, the digital processor in the hearing aid moves the inaudible high frequency sounds to a lower frequency where the hearing aid can provide adequate amplification for audibility (Alexander, 2013; McDermott, 2011; Simpson, 2009). This processing algorithm is favorable because it is able to almost completely preserve the frequency spectrum and, therefore, is able to provide a more natural sound quality (McDermott, 2011; Simpson, 2009). Linear frequency transposition has been criticized, however, for its creation of an overlap between high and low frequency information. This overlap has the potential to create masking of important speech signals and unwanted background noise (Simpson, 2009).

The first linear frequency transposition hearing aid was introduced by AVR Sonovations. The TranSonic FT-40, originally a body worn hearing aid, was soon replaced by the ImpaCt, a behind the ear (BTE) style hearing aid (Glista et al., 2009). The AVR Sonovations ImpaCt utilized a linear frequency transposition scheme in which all frequencies above 2.5 kHz were shifted downward by one octave (McDermott & Knight, 2001). Studies showed mixed results when comparing outcomes using the ImpaCt BTE to conventional hearing aids (McDermott & Knight, 2001; Miller-Hansen, Nelson, Widen, & Simon, 2003). Children with severe hearing loss showed marked improvements in word recognition scores with the ImpaCt BTE when compared to performance with their own hearing aids (Miller-Hansen et al., 2003). Adults with similar degrees of hearing loss, however, demonstrated no significant improvements on



Consonant-Nucleus-Consonant (CNC) word recognition and consonant recognition tasks when using the ImpaCt hearing aid. Additionally, performance in background noise with the ImpaCt was poorer than performance with the participants' personal hearing aids. Masking of speech sounds due to increased noise was cited as a reason for variable results with the ImpaCt BTE (McDermott & Knight, 2001).

As a solution to the problem of unwanted noise and artifact introduced into the frequency lowered signal, Kuk et al. (2006) suggested taking a conservative approach in which only the frequencies necessary for speech understanding, rather than the full range of high frequencies, were lowered. The more conservative frequency lowering scheme developed by Widex, known as Audibility Extender, has since been incorporated into commercial Widex hearing aids. When Audibility Extender, a linear frequency transposition (LFT) scheme, is activated, the hearing aid constantly searches the high frequency source region for a dominant spectral peak. When this peak is determined, the LFT algorithm will transpose the signal to a target region that is located one octave below the source region (Alexander, 2013; Kuk et al., 2006; McDermott, 2010). The high frequency information mixes with any lower frequency information present in the target region and is amplified by the hearing aid (Kuk et al., 2006; McDermott, 2010). To limit any masking effects or artifacts, any frequencies outside of one octave bandwidth from the target frequency are filtered out of the signal. This process removes any unnecessary auditory information that has the potential to create a masking effect when the high frequency signal is transposed to a lower frequency region (Kuk et al., 2006).

To investigate the efficacy of LFT on speech recognition, Kuk, Keenan, Korhonen, & Lau (2009) measured speech recognition outcomes on the Office of

Research in Clinical Amplification (ORCA) Nonsense Syllable Test of adults with severe-profound high frequency hearing loss. Results demonstrated improvements in speech recognition outcomes for high frequency speech sounds in quiet when listening to the LFT processing in the Widex Mind 440 BTE hearing aids (Kuk et al., 2009). Additionally, Auriemma et al. (2009) measured aided high frequency thresholds, speech recognition outcomes, and speech production in school-age children with severe high frequency hearing loss. Results showed significant improvement in high frequency thresholds as well as consonant recognition in quiet when listening to the LFT processing in the Widex Inteo BTE hearing aids (Auriemma et al., 2009). Improvements were also noted on speech production tasks, which included reading from the Dynamic Indicators of Basic Early Literacy Skills (DIBELS) Oral Reading Fluency passages and conversation with the investigators (Auriemma et al., 2009). These data demonstrated that LFT can provide significant benefit for adults and children with high frequency hearing loss.

In contrast to linear frequency transposition, nonlinear frequency compression compresses or reduces the bandwidth of the speech signal, rather than moving high frequency sounds to a lower frequency range. Nonlinear frequency compression applies greater amounts of frequency lowering to the highest frequency signals and applies smaller amounts of frequency lowering to relatively lower input frequencies (Alexander, 2013; McDermott, 2011; Simpson, 2009). As a result, the bandwidth of the speech signal is compressed into the audible bandwidth of the hearing aid user. This processing algorithm is favored because it avoids any overlap between low and high frequency signals, which can result in masking of important speech information and unwanted

background noise. It is also able to largely preserve the frequency spectrum of low and mid frequency inputs (McDermott, 2011; Simpson, 2009). The disadvantage of nonlinear frequency compression is that its nonlinear nature does not allow for preservation of the high frequency speech spectrum. As a result, distortion of the signal, especially as more frequencies are included in the frequency lowering algorithm, is possible (Simpson, 2009).

Simpson, Hersbach, and McDermott (2005) developed a multichannel nonlinear compression frequency lowering algorithm in which only the high frequency inputs were compressed. This algorithm was able to preserve the formant ratios in the low frequencies for a more natural sound quality, however, this system utilized the input from only one of the listeners hearing aids for frequency lowering. The frequency compressed signal was then wirelessly delivered to both hearing aids (Glista et al., 2009; Simpson et al., 2005). An initial study of this experimental algorithm showed improvement in speech recognition for eight of seventeen subjects (Simpson et al., 2005). A subsequent study, however, showed no change in speech recognition with the use of the nonlinear frequency compression algorithm (Simpson, Hersbach, & McDermott, 2006).

Improvements in digital signal processing and an understanding of the importance of verification of frequency lowering systems have led to improvements in nonlinear frequency compression (NFC). Phonak has since introduced an NFC algorithm which they titled SoundRecover. When activated, Phonak's SoundRecover algorithm compresses frequency inputs located above the start frequency into a lower frequency range that may be better amplified by the hearing aid and/or may be audible to the listener. With NFC, the clinician has control over two settings: the start frequency and the

compression ratio (McDermott, 2011). The frequency lowering in NFC is progressive, such that the higher frequencies are compressed to a greater extent than the lower frequencies. In Phonak's current products, NFC will extend to about 10 kHz (Alexander, 2013; McDermott, 2011).

Recent studies investigating the use of NFC have showed promising results. Glista et al. (2009) investigated the speech detection and recognition outcomes of adults and children with sloping moderately-severe to severe high frequency hearing loss using NFC. Results demonstrated improvements in speech detection thresholds as well as in speech recognition scores for high frequency speech sounds. Both children and adults demonstrated benefits from the NFC processing (Glista et al., 2009). Wolfe et al. (2010) demonstrated much improved high frequency thresholds and speech recognition in quiet as measured by the UWO Plurals Test and the Phonak Logatome test in school-age children with moderate to moderately-severe hearing loss when fit with Phonak Nios BTE hearing aids with SoundRecover, or NFC, activated. Additionally, greater improvements in speech recognition in quiet and improvements in speech recognition in noise as measured by the Bamford-Kowal-Bench Speech in Noise test were noted in the same children after a 6 month acclimatization period (Wolfe et al., 2011). These studies indicated that NFC may provide significant benefit to children with hearing loss with a wide range of thresholds, especially after a period of acclimatization (see Chapter 4).

A technical comparison of these frequency lowering algorithms indicated that, over time, outcomes are likely to be similar for each processing algorithm. Measurements of hearing aid outputs produced by a series of notes played on a flute indicated that, despite the distortion from LFT, both algorithms were able to amplify each note while

preserving information about pitch (McDermott, 2011). Because both frequency lowering algorithms alter the frequency response, neither frequency lowering algorithm was able to preserve the natural differences in frequencies across the spectrum. The smaller frequency shift of the NFC algorithm, however, may be less noticeable to listeners when compared to the one octave shift of the LFT algorithm (McDermott, 2011). Although differences in performance with NFC versus LFT may be apparent early, it is possible that experience with the altered frequency response may make performance similar for both algorithms over time (Alexander, 2013).

## **CHAPTER 3**

### **FITTING CONSIDERATIONS FOR CHILDREN**

Currently, both LFT and NFC are available in commercial hearing aids like those from Phonak and Widex. Research has demonstrated the potential for improvements in high frequency speech understanding with both frequency lowering algorithms. Before activating frequency lowering technology, however, several considerations must be taken into account. The following describes considerations in candidacy, fitting, and verification of frequency lowering as they apply to the pediatric population and provides a case example to better demonstrate these concepts.

#### *Candidacy*

A current topic of discussion in the literature is the topic of appropriate candidacy criteria for frequency lowering technology in children. Originally, children with precipitously sloping high frequency hearing loss were thought to potentially benefit the most from frequency lowering due to the limited access to high frequency speech cues in this population. While earlier versions of frequency lowering technology were unsuccessful in this population, recent studies with more current technology have demonstrated benefit for individuals with precipitously sloping hearing loss (Auriemmo, Kuk, Stenger, 2008; Auriemmo et al., 2009; Glista et al., 2009; Simpson et al., 2006). Improvements in performance with newer technology are likely a result of reductions in the amount of distortion added to the frequency lowered signal and the addition of filters,

which remove any unnecessary frequency information to alleviate masking of important speech cues (Kuk et al., 2006). This population has also been found to receive more benefit from frequency lowering than individuals with less high frequency hearing loss and has demonstrated a higher preference for frequency lowering technology over conventional hearing aid processing (Glista et al., 2009).

Although children with precipitously sloping hearing loss have been found to benefit from frequency lowering technology, special considerations must be made when determining candidacy for this processing strategy in this population. With the continuously changing criteria for cochlear implantation, many children with precipitously sloping hearing loss may now be considered candidates for implants (Simpson, 2009). Additionally, audiologists may find that fitting hearing aids with frequency lowering processing for children with steeply sloping audiograms may be more challenging due to an increase in phoneme confusions where the individual is unable to distinguish one phoneme from another or mistakes one phoneme for another, and reports of poorer sound quality for this population (Glista et al., 2009). The audiologist should be prepared to carefully monitor for phoneme confusions with the use of discrimination or identification tasks in children with precipitously sloping hearing loss if he or she is considering the use of frequency lowering for this population (See Verification).

Children with lesser degrees of high frequency hearing loss have also demonstrated benefit from hearing aids that have frequency lowering technology (Glista et al., 2009; McCreery et al., 2014; Wolfe et al., 2010). Wolfe et al. (2010) noted increased audibility of high frequency pure tones and improved speech recognition for children with moderate to moderately-severe high frequency hearing loss. Similarly,

McCreery et al. (2014) found improved speech recognition and increased audibility, as measured by a modified Speech Intelligibility Index (SII), for children with gently sloping (mild to severe) audiograms. These studies suggested that children with at least a moderate high frequency hearing loss could benefit from frequency lowering technology as well.

A final consideration in the discussion of candidacy for frequency lowering processing is the concept of audibility. McCreery et al. (2014) determined that an increase in audibility, as measured by a modified SII, was proportional to the increase in speech perception performance of participants. In other words, children who experienced a larger increase in audibility with the addition of frequency lowering also experienced greater improvements in speech perception. This outcome suggested that a change in audibility plays a key role in the benefit obtained from frequency lowering technology (McCreery et al., 2014).

In contrast, a recent study by Hillock-Dunn, Buss, Duncan, Roush, & Leibold (2014) found no significant difference in performance between the use of frequency lowering technology and the use of conventional amplification. Although there could be many other reasons for these results, including the short acclimatization period used in the study and the effectiveness of the individual frequency lowering settings, the authors concluded that the majority of the participants in the study had audibility for the /s/ phoneme, as verified with a 6300 Hz filtered speech band, with conventional amplification and, therefore, may not have experienced a significant change in audibility with the frequency lowering technology. This could have resulted in the limited benefit noted with the use of frequency lowering (Hillock-Dunn et al., 2014). Similarly, Bentler,



Walker, McCreery, Arenas, and Roush (2014) measured speech and language development and speech perception ability of two groups of children; those who used nonlinear frequency compression and those who did not. The children in the study had similar degrees of hearing loss. The results showed no significant difference in speech and language development or in speech perception, as measured by performance on the Phonetically Balanced Kindergarten (PBK) word lists, between the two groups (Bentler et al., 2014). Again, the authors noted no differences in audibility, as measured by a modified SII, between the two groups (Bentler et al., 2014). This research suggested that an improvement in high frequency audibility with frequency lowering as compared to high frequency audibility with conventional hearing aid processing is a key factor for improving speech perception with the use of frequency lowering and should also be considered as a factor for determining candidacy for frequency lowering technology.

To determine whether or not a child with hearing loss is an appropriate candidate for frequency lowering, the audiologist should consider the following: audibility across the frequency spectrum, the slope of the audiogram, and the frequency at which conventional hearing aid processing is no longer able to provide sufficient audibility. Audibility plays a large role in the successful fitting of frequency lowering technology (Hillock-Dunn et al., 2014; McCreery et al., 2014). In order to see measureable improvements in performance with frequency lowering, it has been suggested that an improvement in audibility is key (Bentler et al., 2014).

Speech mapping at 55, 65, and 75 dB SPL should be completed via real-ear probe microphone or Real-Ear-to-Coupler Difference (RECD) measures to determine if appropriate audibility can be achieved with conventional hearing aid processing.

Audibility is considered to be appropriate when the frequency response curve of the hearing aid for a 65 dB SPL input falls above the child's auditory thresholds, as entered by the audiologist, for each frequency (Alexander, 2014; Glista & Scollie, 2009a; Glista & Scollie, 2009b). *The Clinical Practice Guidelines on Pediatric Amplification* (American Academy of Audiology, 2013) state that a child should not be fit with frequency lowering until the audiologist has verified that audibility of high frequency speech cues cannot be achieved with conventional hearing aid processing. Audiologists should make every attempt to fit a child with conventional processing before adding a frequency lowering algorithm (American Academy of Audiology, 2013). Only if appropriate audibility cannot be achieved with conventional hearing aid processing, should the clinician consider adding frequency lowering.

In addition to considering audibility of the speech signal, audiologists should also consider the degree and configuration of the child's hearing loss. Children with steeply sloping hearing losses often make good candidates for frequency lowering (Auriemma et al., 2008; Auriemma et al., 2009; Glista et al., 2009; Simpson et al., 2006). Some children with this configuration, however, may experience greater improvements in speech perception with the use of a cochlear implant (Simpson, 2009). The audiologist should examine the audiogram and the real-ear probe microphone or RECD measurements to determine the frequency at which conventional hearing aid processing can no longer provide appropriate amplification. If this point falls at 500, 1000, or even 2000 Hz, providing appropriate audibility for speech and language development becomes more challenging as there is less audible bandwidth to utilize with a frequency lowered signal. Additionally, children with this audiometric configuration would likely require extremely

strong frequency lowering settings and are likely to experience unwanted effects of the increase in distortion added to the signal, such as poorer sound quality and increased discomfort of listening, as a result (Alexander, 2013; Alexander, 2014). Therefore a cochlear implant evaluation may be more appropriate for that child than the addition of a frequency lowering algorithm (Simpson, 2009).

***Case Example – Candidacy***

The case example is a 5-year-old female with a sloping moderate to profound high frequency hearing loss. Figure 1 shows the pure tone audiogram from 250-8000 Hz for the right ear. There was no response at 8000 Hz at the limits of the audiometer. A 120 dB HL threshold will be assumed for future figures.

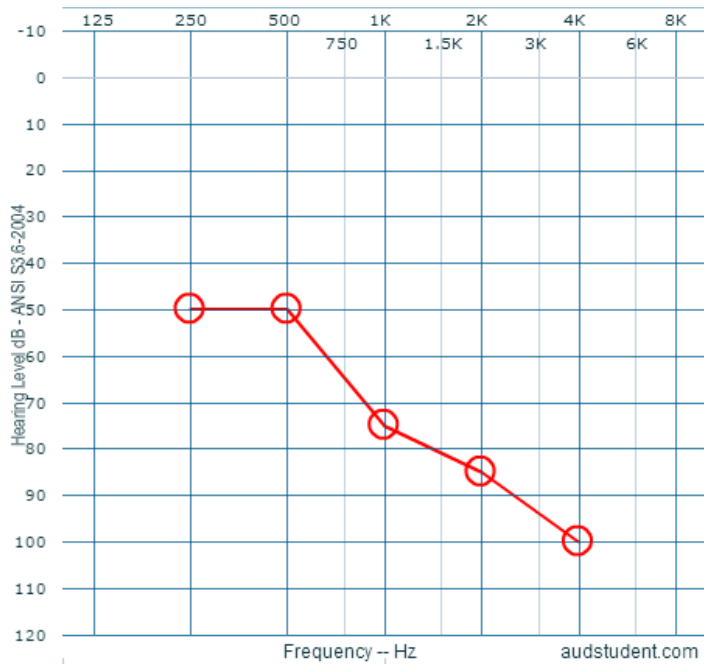


Figure 1. Pure tone hearing thresholds (dB HL) for the 250-8000 Hz range for the right ear.

The audiologist has fit Phonak BTE hearing aids on this child and wants to ensure that the prescribed gain is a good match to DSL v5 pediatric targets. The audiogram is entered into the Audioscan Verifit verification system and speech mapping at 65 dB SPL is completed with measured RECD values in the test box. In Figure 2, the green curve, shows the aided verification results for an average speech level input. In this case, it can be assumed that the audiologist has made every attempt to fit the hearing aid to DSL v5 pediatric targets in the high frequency region.

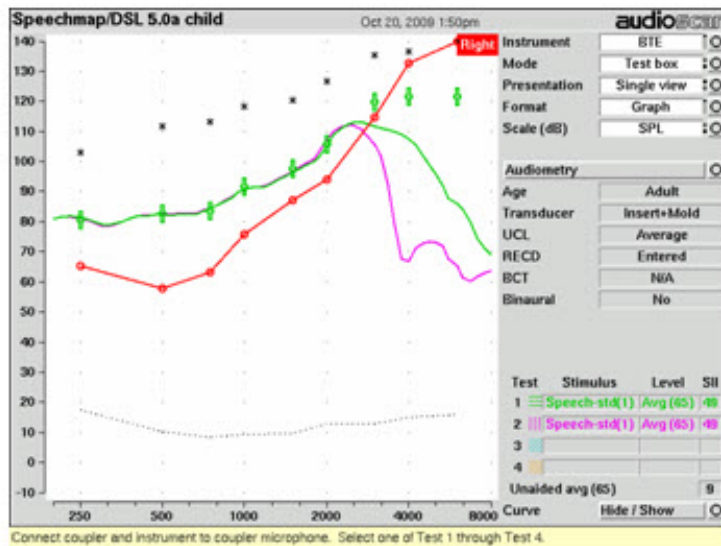


Figure 2. Retrieved from Glista & Scollie, 2009a. The aided verification results for average speech with frequency lowering turned off (green curve) and with frequency lowering turned on (purple curve).

As demonstrated by the green curve in Figure 2, the hearing aids, when matched well to DSL v5 targets, are only able to provide sufficient audibility up to approximately 3000 Hz. This child would be a good candidate for frequency lowering technology

because conventional hearing aid processing is not able to provide her with appropriate high frequency audibility. The hearing aids are able to provide good audibility for low and mid frequency sounds, however, which suggests that this child would not likely be considered a cochlear implant candidate. As a result, the audiologist elects to turn the frequency lowering feature, SoundRecover or NFC, on for this child.

### ***Fitting***

Current commercially available hearing aid software will often provide recommended settings for fitting frequency lowering technology based on the audiometric data provided by the audiologist. It has been suggested, however, that individualized settings, based on the recommendations in the fitting software, may be more appropriate to achieve a desired outcome (Glista, Scollie, & Sulkers, 2012). To achieve optimal benefit, the recommended fitting in the software should be used as a starting point. From there, the clinician must attempt to maximize high frequency audibility while limiting the distortion of low frequency inputs (Alexander, 2013).

Probe microphone measurements may be used to determine the frequency lowering settings that maximize benefit while limiting distortion. To do this, the audiologist should measure the audible bandwidth of the listener without the frequency lowering algorithm activated. Speech mapping at a 65 dB SPL input level should be completed via probe microphone or RECD measurements (Alexander, 2014). The frequency at which the output of the hearing aid no longer exceeds the threshold of the listener should be noted as the maximum audible bandwidth frequency (Alexander, 2014). An optimal fitting is one in which the individual's maximum audible bandwidth is not altered by the use of frequency lowering. In other words, the frequency lowering

technology simply introduces higher frequency sounds into the users existing audible bandwidth (Alexander, 2013; Alexander, 2014). If the audiologist does not attempt to maximize the audible bandwidth of the listener, unnecessary distortion may be added into the signal (Alexander, 2014).

The audiologist should then add frequency lowering at the settings recommended by the hearing aid software. With frequency lowering turned on, the audiologist should re-measure the speech map for a 65 dB SPL input to ensure that the frequency lowered signal does not significantly reduce the maximum audible bandwidth of the listener, as measured with conventional hearing aid processing (Alexander, 2014). Adjustments can be made to the start frequency or compression ratio of the frequency lowered signal to maximize the audible bandwidth. Additional real ear measures or subjective listening tests can also be used to verify and fine tune the frequency lowered signal (see Verification) (Alexander, 2013). In general, the audiologist should aim to use the highest start frequency and lowest compression ratio possible while still achieving maximum audibility. This technique allows the audiologist to avoid adding unnecessary distortion into the signal (Alexander, 2014, American Academy of Audiology, 2013).

The fitting strategy described here is one of many described in the literature. It has yet to be determined which strategy may provide the most benefit to listeners and further research is required on this topic. A common theme among researchers, however, is the use of probe microphone measures, such as speech mapping at multiple input levels, to maximize fitting benefit (Alexander, 2013; Alexander, 2014; Glista & Scollie, 2009a; Glista et al., 2009; Kuk et al., 2010).

### ***Case Example – Fitting***

After turning on the frequency lowering feature in the hearing aids to the recommended software settings, the audiologist re-measures the output of the hearing aid for a 65 dB SPL input. In Figure 2, the purple curve shows the aided verification results for the average speech input with frequency lowering turned on. As determined by the aided verification results with frequency lowering off (green curve), the maximum audible bandwidth for this child is about 3000 Hz. In order to maximize the audible bandwidth with frequency lowering on, the purple curve and the green curve should closely match until about 3000 Hz when the maximum audible bandwidth has been reached. In this example, the purple curve demonstrates a frequency lowering setting that may be slightly stronger than is necessary. In this case, the audiologist might increase the start frequency or lower the compression ratio so that the two curves more closely match and the child's audible bandwidth is not unnecessarily restricted (Alexander, 2014). Following the initial fitting procedure, the audiologist should complete verification measures to ensure that the child is receiving appropriate benefit and to make any fine tuning adjustments.

### ***Verification***

As with the use of any amplification device, especially in children, verification of hearing aid settings should be included in the fitting protocol for frequency lowering devices. Erber's hierarchy of auditory skills suggests that auditory detection, discrimination, and identification must all precede comprehension of auditory stimuli (Smiley, 2004). Therefore, it has been suggested that a complete evaluation of frequency lowering algorithms must include verification of the fitting as well as detection, discrimination, and identification tasks. These tasks should focus on high frequency

information, as the goal of frequency lowering is to improve the perception of high frequency phonemes (Kuk et al., 2010).

Before administering any test of performance, it is important to verify the frequency lowering settings through the use of test-box or real ear measures (Glista & Scollie, 2009b; Kuk et al., 2010). A verification protocol should include typical verification measures, such as speech mapping for soft (55 dB SPL), average (65 dB SPL), and loud (75 dB SPL) speech, to ensure the potential for audibility across the frequency spectrum and to ensure that DSL v5 pediatric targets have been met for those frequencies that fall below the start frequency (Glista & Scollie, 2009a). Maximum power output (MPO) measures should also be included to ensure that the output of the hearing aid does not exceed a level which may be uncomfortable or harmful for the child (Glista & Scollie, 2009a). This measurement is especially important in young children because, in many cases, the child may not be able to report discomfort. Results of MPO measures may be more accurate if measured with frequency lowering turned off because of the narrow MPO frequency filters in the verification system used to measure the output from the hearing aid (Alexander, 2014). Because frequency lowering shifts high frequency inputs downwards, the output frequency where MPO is measured has been shifted outside of the narrow filter. Consequently, MPO measurements made with frequency lowering on are measured as lower than the true output of the hearing aid (Alexander, 2014).

In addition to typical verification measures, frequency lowering settings can be verified with the use of frequency-specific speech bands available in the Audioscan Verifit verification system. Specifically, the 3150-6300 Hz speech bands should be used



at a 65 dB SPL input level to approximate the productions of the high frequency phonemes, /sh/ and /s/. The 6300 Hz band provides a relatively accurate representation of the phoneme /s/ while the 3150-6300 Hz bands can be used to approximate the broader /sh/ phoneme (Glista & Scollie, 2009a; Glista & Scollie, 2009b). These measurements ensure that, specifically, high frequency speech cues have the potential to be audible to the listener. Additionally, frequency-specific speech bands can be used to determine the amount of overlap in the frequency lowered signal for fine tuning purposes (Glista & Scollie, 2009a).

Ideal frequency lowering settings should result in minimal overlap between frequency-specific speech bands when measured on the Verifit system. Due to the nature of this processing strategy, some overlap of frequency bands is expected, but should be kept to a minimum (Glista & Scollie, 2009b). Significant overlap between speech bands may result in phoneme confusions and incorrect productions in children using frequency lowering. Overlap of frequency-specific speech bands may also indicate that the frequency lowering settings may be too “strong” and efforts should be made to increase the start frequency or lower the compression ratio until significant overlap is no longer noted (Glista & Scollie, 2009b).

Similar to the use of frequency-specific speech bands, live voice or recorded productions of the phonemes /sh/ and /s/ may be used for verification of the frequency lowered signal (Glista & Scollie, 2009a). Live voice or recorded phoneme productions offer a more “real world” option for verification of frequency lowered settings. However, they may not be as accurate as the use of frequency-specific speech bands. The use of recorded phonemes, such as Ling-6 sounds, presented via an audiometer or with speakers

into the microphones of the hearing aid, is recommended to improve accuracy and reduce variations in phoneme productions (Glista & Scollie, 2009b). The audiologist can measure hearing aid output with live phoneme productions with the use of the “speech – live” input option on the Audioscan Verifit system. This measurement can be made in a quiet office or a sound booth. The audiologist should attempt to closely match recorded or live voice productions to a normal conversational level of approximately 65 dB SPL. Live voice or recorded phoneme productions should be sustained long enough to record a consistent response within the verification system (Glista & Scollie, 2009a). Again, the audiologist should evaluate the audibility of each phoneme and the amount of overlap between phonemes (Glista & Scollie, 2009b).

Although important, verification of the frequency lowered signal simply allows the clinician to ensure that prescriptive targets for amplification have been met. The *Clinical Practice Guidelines on Pediatric Amplification* state that additional outcome measurements allow the clinician to ensure that the auditory needs of the child are met, especially when introducing additional features, such as frequency lowering, into the processing of the hearing aid (American Academy of Audiology, 2013). Additional outcome measurements may include measures of auditory detection, auditory discrimination, and auditory identification for high frequency speech sounds.

Auditory detection tasks allow the clinician to determine if high frequency sounds have been made audible with the use of frequency lowering. Conventional audiometry, with the use of warble tones or narrowband noise, conducted in the sound field can be useful for measuring changes in audibility. Improvement in high frequency aided thresholds indicates that the frequency lowering algorithm has provided the user with

access to these cues for speech perception (Auriemma et al., 2008; Kuk et al., 2010; Wolfe et al., 2010). It has been suggested, however, that measurements of functional gain may not be accurate assessments of audibility as these measurements can be affected by the signal processing of the hearing aid, movement of the child, developmental level, interest, and attention (American Academy of Audiology, 2013). As a result, the use of actual phonemes may be a more appropriate measure of high frequency audibility, especially for children (American Academy of Audiology, 2013; McCreery et al., 2012). The Ling-6 test includes six phonemes (/ah/, /oo/, /ee/, /s/, /m/, /sh/) that span a broad frequency range and can be used similarly to pure tone stimuli for detection tasks (Scollie et al., 2012; Smiley, 2004). The Ling-6 test has been shown to be a reliable measure of sound field speech detection (Scollie et al., 2012).

In addition to detection tasks, discrimination tasks allow the clinician to determine if the patient is able to discriminate between two different high frequency sounds and can also be helpful for monitoring possible phoneme confusions. Discrimination tasks may be valuable for this purpose. In plural discrimination tasks, patients are asked to indicate whether the singular and plural forms of a word are the same or different (Kuk et al., 2010). The higher frequency phonemes (/s/ and /sh/) from the Ling-6 test may also be utilized for discrimination (Smiley, 2004). If the child is unable to discriminate between two high frequency sounds or confuses one phoneme for another, fine tuning of the frequency lowering settings may be warranted (Glista & Scollie, 2009a).

Many factors must be taken into consideration when choosing an appropriate speech identification measure for verification of frequency lowering technology. Speech tasks should include a good representation of high frequency stimuli, as the goal of

frequency lowering is to maximize high frequency audibility. Speaker characteristics should also be taken into consideration, as male talkers are less likely to provide high frequency speech cues than female talkers (Kuk et al., 2010). For example, a study by Auriemma et al. (2008) utilized two identification tasks: the California Consonant Test (CCT) and the Edgerton-Danhauer nonsense syllable test (NST). The CCT requires identification of a single word out of a set of words that differ by only one phoneme and is especially useful for evaluating frequency lowering algorithms because of its emphasis on high frequency consonants. The CCT, however, was designed for use with adults and therefore a nonsense syllable test, such as the NST, may be more appropriate for young children (Auriemma et al., 2008). A wide range of nonsense syllable tests have been developed and utilized for research in this area and may also be appropriate for clinical evaluations of frequency lowering (Glista et al., 2009; Kuk et al., 2010; McCreery et al., 2012). A plural detection task, such as the University of Western Ontario (UWO) Plurals Test, can also be a viable option for evaluation of performance with frequency lowering technology (Scollie & Glista, 2012). Finally, identification tasks can help the clinician to determine if a child is experiencing any phoneme confusions that may warrant additional fine tuning of the frequency lowering settings.

Although a thorough assessment of the efficacy of frequency lowering is recommended for all patients, it is not realistic to expect that a full verification test battery can be completed with every patient. For example, young children may not be able or willing to complete discrimination or identification tasks or remain still long enough to complete real ear measurements. It is important that frequency lowering settings are verified for each patient to ensure that the technology has been appropriately

fit; this process, however, may differ from patient to patient. The audiologist should, at the very least, complete real ear or test box measures to ensure audibility and comfort of the frequency lowered signal. Otherwise, clinicians should use their best judgment and clinical experience to determine the appropriate verification measures for use with an individual patient.

***Case Example – Verification***

After setting frequency lowering so that the audible bandwidth is maximized, the audiologist completes speech mapping for soft, average, and loud input levels and completes MPO testing to ensure appropriate gain and comfort of listening. Figure 3 shows the aided verification output for the soft (green curve), average (purple curve), and loud (blue curve) speech signals with frequency lowering turned on. MPO (yellow curve), in this example, has been measured with frequency lowering on.

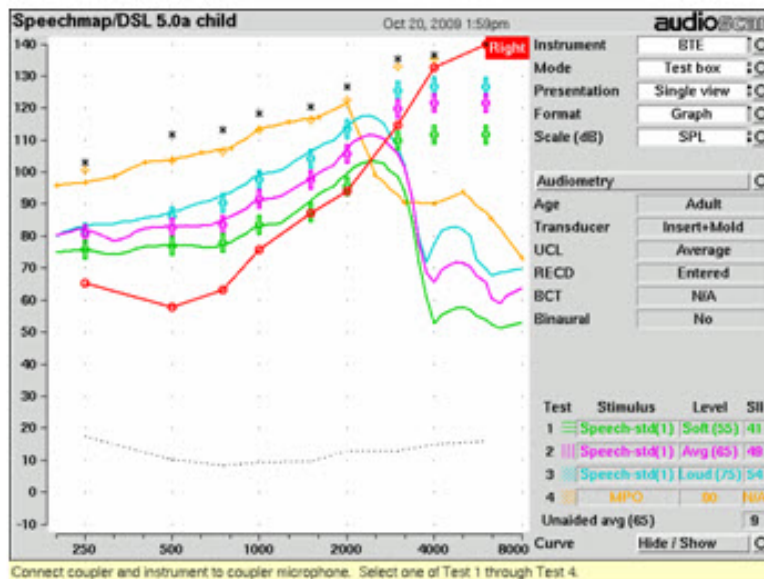


Figure 3. Retrieved from Glista & Scollie, 2009a. The aided verification results for soft, average, and loud speech, and MPO results with frequency lowering turned on.

After demonstrating that DSL v5 pediatric targets have been met for those frequencies which fall below the start frequency of the frequency lowered signal, the audiologist measures the output of the hearing aid using the 4000 Hz and 6300 Hz speech bands at 65 dB SPL to ensure audibility for high frequency speech sounds. Figure 4 shows the aided verification results for the 4000 Hz and 6300 Hz speech bands. Note that the audiometric data in Figure 4 are different, but the concepts presented are the same.

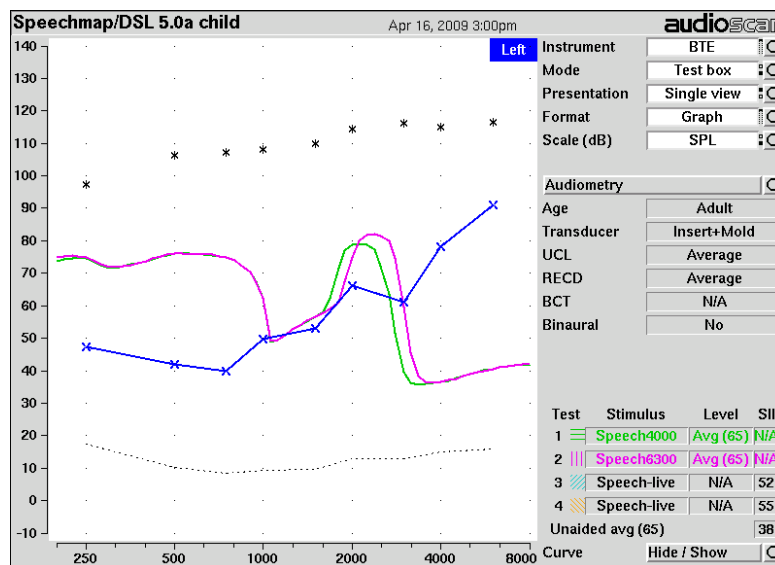


Figure 4. Retrieved from Glista & Scollie, 2009b. The aided verification results for the 4000 Hz (green curve) and 6300 Hz (purple curve) speech bands at 65 dB SPL.

In Figure 4, the 4000 Hz speech band grossly represents the /sh/ phoneme and the 6300 Hz speech band represents the /s/ phoneme. The goal of frequency lowering is for both phonemes to be audible with minimal overlap between the two frequency response curves. In Figure 4, both speech bands are measured to well above the audiometric thresholds, suggesting that both phonemes are audible to the child. However, there is

significant overlap between the 4000 and 6300 Hz speech bands, suggesting that the frequency lowering settings are too strong. This may result in confusions between these two phonemes. The audiologist lowers the frequency compression ratio and re-measures hearing aid output for the 4000 Hz and 6300 Hz speech bands. The results of this measurement are shown in Figure 5.

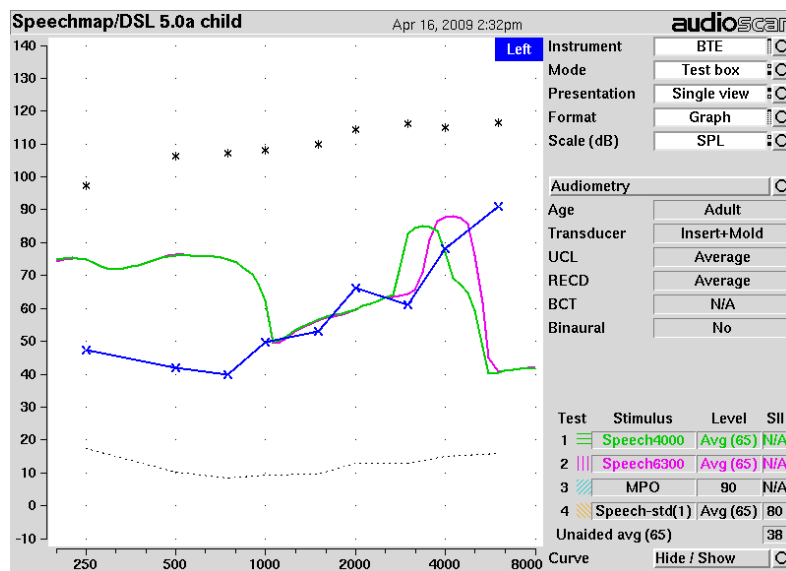


Figure 5. Retrieved from Glista & Scollie, 2009b. The aided verification results for the 4000 Hz (green curve) and 6300 Hz (purple curve) at 65 dB SPL after the frequency compression ratio has been lowered.

The aided verification results in Figure 5 demonstrate that, again, both the /sh/ and /s/ phoneme are likely to be audible to the child. Additionally, the overlap between the two speech bands has been reduced and, therefore, the likelihood of phoneme confusions has also been reduced. To ensure that the information gathered here will translate to a more “real world” environment, the audiologist measures the hearing aid

output for live voice productions of /sh/ and /s/. Figure 6 shows the aided verification results for the live voice /sh/ and /s/ productions.

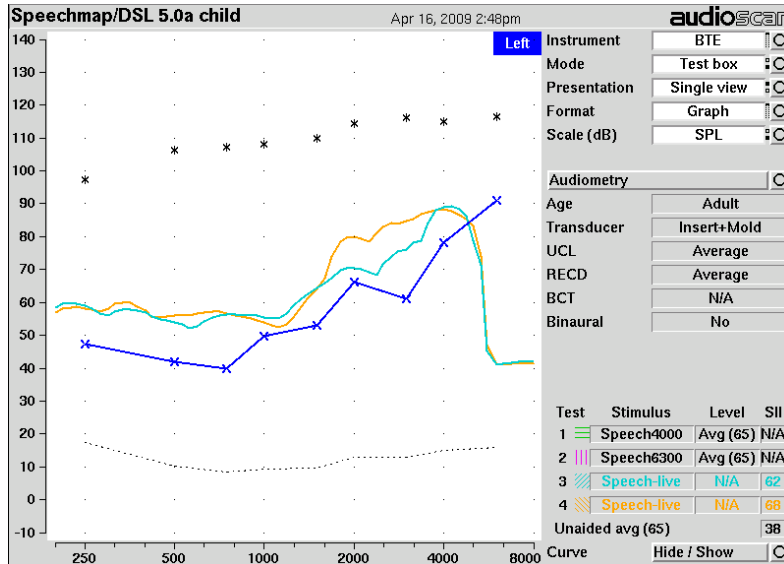


Figure 6. Retrieved from Glista & Scollie, 2009b. The aided verification results for live voice productions of /sh/ (yellow curve) and /s/ (blue curve).

From Figure 6, it is clear that the live voice production of /sh/ has a much broader frequency response than can be measured accurately with the 4000 Hz speech band. This is why the addition of the live voice productions can be helpful to ensure that frequency lowering has been set appropriately. When measuring live voice productions of /sh/ and /s/, each phoneme's frequency response should be clear and distinct from one another. Overlap, especially in the higher frequencies, is expected but should be minimal, as demonstrated in Figure 6.

After completing verification measures on the test box, the audiologist chooses to add additional outcome measures to the test battery to ensure that the child is receiving



the expected benefit from the frequency lowered signal. This child is particularly active and will generally only cooperate for short periods of time. The audiologist chooses to measure detection of the Ling-6 sounds using Conditioned Play Audiometry in the sound booth and to complete the UWO Plurals Test. Both assessments are quick and interactive to help keep the child's attention. The child is able to detect all of the Ling-6 sounds in the 15 to 25 dB HL range and is able to correctly identify 27/30 items on the UWO Plurals Test for a score of 90%. The audiologist has, at this point, verified that the frequency lowering settings are appropriate and that the child is able to use the frequency lowered information appropriately. The audiologist will continue to assess performance with frequency lowering technology at follow-up appointments and make adjustments to gain and frequency lowering settings as necessary.

## CHAPTER 4

### ACCLIMATIZATION AND AUDITORY TRAINING

#### *Acclimatization*

A factor that remains consistent throughout the frequency lowering literature is the importance of the acclimatization period. Acclimatization refers to the process in which a listener gradually adjusts to the frequency lowered auditory signal (Glista et al., 2012). Acclimatization occurs over time, without any specific auditory training. As the listener adjusts to the altered signal, it is expected that listening performance will improve.

Research has shown that measureable benefits from the use of frequency lowering technology may not always be apparent at the time of the fitting (Auriemmo et al., 2009; Hillock-Dunn et al., 2014; Wolfe et al., 2010). With increased listening experience, the majority of participants will demonstrate improvements in performance. Studies have noted measureable benefits in as little as three weeks from the time of the fitting (Auriemmo et al., 2009; Glista et al., 2009). This is not to say, however, that improvement in performance does not continue beyond this point. Research has also demonstrated continued improvements in performance with acclimatization periods extending as long as six months (Wolfe et al., 2011). As a result, it is important to recognize that certain individuals may require additional time, beyond the six week time frame typically found in the literature, with a frequency lowered signal to demonstrate

benefit (Glista et al., 2009; Wolfe et al., 2010; Auriemmo et al., 2008; Auriemmo et al., 2009).

When addressing acclimatization in the pediatric population, one must consider the possibility that improvements in performance over time may be influenced by auditory development (Glista et al., 2012). In an attempt to factor out the effects of development on acclimatization, Glista et al. (2012) measured outcomes with frequency lowering technology in a small group of adolescents over time. Out of six participants, five demonstrated benefit with frequency lowering technology after an acclimatization period. The time period necessary for significant improvements on speech perception measures varied considerably among participants suggesting that the acclimatization period may be different from patient to patient. Factors contributing to these differences may include performance with conventional hearing aid processing, audiometric configuration, maturation, and brain plasticity (Glista et al., 2012).

Additionally, the authors noted that participants appeared to require less time to achieve benefit for detection tasks, such as detecting the presence of Ling 6 sounds in the soundfield, than for recognition tasks, such as the CCT, which require a higher level of auditory skills (Glista et al., 2012). These findings are consistent with results from previous studies investigating frequency lowering benefit in children (Auriemmo et al., 2009; Wolfe et al., 2011). Again, this research demonstrated that most children will require experience with a frequency lowered signal to achieve significant benefit and that some auditory skills may improve more quickly than others.

### *Auditory Training*

Auditory training has proven to be a successful method for the rehabilitation of children with hearing loss who have been fit with conventional amplification (Rochette & Bigand, 2009). Specific auditory training has also been suggested to be useful for improving speech perception outcomes for children with hearing loss who are fit with frequency lowering technology (Auriemmo et al., 2008; Simpson, 2009). In addition to allowing the child to gain experience with the frequency lowered signal, auditory training explicitly teaches the child to use the new auditory signal in an efficient manner (Simpson, 2009). A number of studies have included auditory training and have measured improvements in speech perception abilities with frequency lowering technology (Auriemmo et al., 2008, Auriemmo et al., 2009; Simpson, 2009). What remains unclear, however, is how much of the improvement in speech perception outcomes noted in these studies can be attributed to auditory training alone.

Attempting to address this issue, Kuk and Keenan (2010) investigated the benefits of explicit training for individuals with high frequency hearing loss using conventional hearing aid technology versus frequency lowering technology. Improvements in speech perception, as measured by the ORCA-NST, were only evident for participants after they had completed training with frequency lowering technology (Kuk & Keenan, 2010). These data suggested that explicit auditory training in the absence of improved audibility does not result in improved performance. Therefore, in addition to training, improvements in high frequency audibility, as a result of frequency lowering technology, also contribute to improvements in performance (Kuk & Keenan, 2010). Further research

must also consider whether benefit from auditory training is related to the training itself, or whether experience alone may result in similar outcomes.

Currently, there is little consensus on auditory training approaches for frequency lowering. Very few auditory training programs that focus on strengthening auditory skills with frequency lowering have been described in the literature. A training program that focuses on auditory detection and discrimination of target high frequency phonemes, such as /s/, /sh/, /f/, /ch/, and /z/, as well as production of these phonemes, has been implemented with children using frequency lowering technology (Auriemmo et al., 2008; Auriemmo et al., 2009). It has been suggested that the audiologist or speech language pathologist who provides the training should incorporate target phonemes into games and activities which keep the child motivated and attentive (Auriemmo et al., 2008). Further research, however, is still required to determine the auditory training approaches and materials that may be most appropriate for the rehabilitation of children who use frequency lowering.

Should the audiologist wish to implement an auditory training program, multiple factors must be taken into consideration. These include the design of the training protocol, the training materials, and the frequency of training (Fu & Galvin, 2007). Training protocols typically require the participant to be actively involved in the training process. As a result, most training programs will vary the level of difficulty of the training tasks to help maintain the participants' interest (Fu & Galvin, 2007). Varying the difficulty to support learning is also common among training protocols. Finally, most protocols provide auditory or visual feedback to the participant so that the participant is able to learn from previous mistakes (Fu & Galvin, 2007). Researchers in the field of

frequency lowering have often opted for the use of a bottom-up approach to auditory training protocols (Kuk & Keenan, 2010). The bottom-up approach focuses more on basic auditory skills, such as detection and discrimination, and has been suggested to be a more beneficial approach to auditory training, especially when phoneme identification is the goal, as it would be for a child using frequency lowering (Eisenberg, 1985; Fu, Nogaki & Galvin, 2005; Fu & Galvin, 2007).

Appropriate testing materials should be chosen with patient characteristics in mind. As noted previously, the use of high frequency phonemes, such as /s/, /sh/, /f/, /ch/, and /z/, should be considered when designing an auditory training program for use with frequency lowering (Auriemmo et al., 2008; Auriemmo et al., 2009). It has also been suggested that patients with good speech recognition performance should be trained with more difficult training materials, such as conversational speech in background noise, while patients with poor speech recognition performance may benefit more from simpler test materials, such as clearly articulated phonemic contrasts in quiet (Fu & Galvin, 2007). For optimal benefit, the training materials that are the most effective and will allow for generalization to a variety of listening environments should be included in an auditory training program (Fu & Galvin, 2007).

The frequency of training is highly variable in the literature (Auriemmo et al., 2008; Auriemmo et al., 2009; Kuk & Keenan, 2010). It has been suggested that the amount of training rather than the frequency of training is the most important factor for successful training outcomes (Nogaki, Fu & Galvin, 2007). The audiologist may have more success with auditory training when the frequency of training is decided upon on an individual basis (Nogaki et al., 2007).

## **CHAPTER 5**

### **A PROPOSED RESEARCH PROTOCOL**

To date, much of the research involving frequency lowering has focused on either nonlinear frequency compression (NFC) or linear frequency transposition (LFT). While data demonstrating the potential benefits of NFC and LFT individually are promising, there is currently little peer-reviewed research that directly compares the two frequency lowering algorithms. Further research is required to determine the relative benefit of each frequency lowering algorithm and to determine if children with certain audiometric configurations may benefit more from one frequency lowering algorithm versus the other. Based on the research conducted as a part of this capstone, a number of considerations are proposed to improve clinical practice in applying frequency lowering. First, comparison of the efficacy of both NFC (in Phonak hearing aids) and LFT (in Widex hearing aids) is needed. Specifically, the effectiveness of the two frequency lowering algorithms would be assessed when worn by school-age children with moderate to severe high frequency hearing loss.

In such a study, the independent variable would be the use of LFT versus NFC for frequency lowering. The dependent variable would address performance on outcome measures assessing speech perception in quiet, speech perception in noise, and subjective preference. Participants would be fit with either LFT hearing aids or NFC hearing aids. Hearing aid fit and frequency lowering would be verified through speech mapping for

soft, average, and loud speech and through the use of 3150-6300 Hz speech bands at a 65 dB SPL input level. Speech perception in quiet and in noise, including the ORCA NST (Kuk et al., 2009) and the UWO Plurals Test (Scollie & Glista, 2012) with the frequency lowering feature turned off would be completed by each listener. After testing, the frequency lowering feature would be turned on. After a four week acclimatization period, each listener would return for testing with the frequency lowering feature on. Listeners would then be fit with the second set of hearing aids and test procedures would be repeated. Participants would also complete the Life Inventory for Education-Revised (LIFE-R) questionnaire on listening difficulty in the classroom (Anderson, Smaldino, & Spangler, 2011). This protocol would be able to demonstrate if frequency lowering improved speech recognition and if one frequency lowering algorithm may result in greater improvements than the other. Improvements in speech recognition would support that children who benefitted from frequency lowering would experience greater ease of listening, particularly in less than optimal listening environments, and a reduction in the stresses associated with childhood hearing loss.

The proposed protocol would provide an additional evidence base for future hearing aid fittings in which the clinician intends to implement frequency lowering. In other words, the clinician may be able to make a more informed decision when selecting a frequency lowering aid and when fitting the aid to the child. Improved fittings would be expected to improve speech recognition and, therefore, speech production in children with high frequency hearing loss.



## **CHAPTER 6**

### **SUMMARY AND FUTURE CONSIDERATIONS**

Children with high frequency hearing loss are at a disadvantage for developing speech and language similar to their normal hearing peers due to the amplification limitations of current commercial hearing aids. Alternative amplification methods include extended bandwidth and frequency lowering. While extended bandwidth may be an appropriate solution for children with mild to moderate degrees of hearing loss, children with greater degrees of loss are more likely to require frequency lowering technology.

Early frequency lowering technology resulted in variable outcomes and soon gave way to the improved technology used in current commercial hearing aids. Linear frequency transposition and nonlinear frequency compression are two strategies available in today's hearing aids. Outcomes with both technologies have demonstrated improvement in the speech perception and production abilities of children with high frequency hearing loss.

When fitting these devices, it is important to consider the characteristics of the individual to determine candidacy and an appropriate fitting strategy. As with any amplification device, verification of the frequency lowered signal is an important component to the fitting process and can help the clinician achieve an optimal fitting. An acclimatization period should be expected following the initial fitting of a frequency

lowering device. This period can vary greatly from patient to patient. Explicit training to improve auditory skills has the potential to additionally increase benefit.

Further research on frequency lowering technology is warranted. As part of the research conducted for this capstone, a research protocol in which the LFT and NFC algorithms are directly compared has been proposed. A comparison of these algorithms in school-age children with moderate to severe high frequency hearing loss would demonstrate if frequency lowering improves speech recognition in a variety of environments and if one of these algorithms results in greater improvements in speech recognition than the other. The proposed protocol would provide an additional evidence base for future hearing aid fittings in which the clinician intends to implement frequency lowering.

In addition to the proposed research protocol described above, further research is needed in the areas of candidacy, fitting, and auditory training as they relate to frequency lowering. Candidacy criteria should be investigated to determine the ideal candidate for frequency lowering technology. Fitting strategies must also be further investigated to determine the optimal fitting procedure for improved audibility. Finally, the concept of auditory training should be explicitly investigated to determine the contribution of training to the overall improvement in speech perception and to determine an appropriate training curriculum for this population of hearing aid users.

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## Appendix A: Outcome Assessments

**Bamford-Kowal-Bench Speech in Noise test** - The BKB-SIN was developed for evaluating speech perception in noise in children and CI users. It was designed to be similar to the QuickSIN with easier target sentences for use with a younger population. The BKB-SIN uses a four talker babble from Auditec. The test is designed to automatically decrease the signal to noise ratio for ease of use and speed. Each list consists of 10 sentences with one sentence at each signal to noise ratio: +21, +18, +15, +12, +9, +6, +3, 0, -3 and -6 dB. Each list pair must be presented together for valid scoring. The BKB-SIN has been normed on children age 5 to age 14 (Bench, Kowal, & Bamford, 1979).

**California Consonant Test** – The CCT is a 100 item multiple choice test in which the listener must choose the target item from a list of 4 items which differ by only 1 phoneme. The CCT has been determined to be especially sensitive for individuals with high frequency hearing loss and has been shown to be a reliable measure of speech perception for individuals with hearing loss. The CCT may also be especially useful for identifying phoneme confusions for programming purposes (Owens & Schubert, 1977).

**Dynamic Indicators of Basic Early Literacy Skills** – The DIBELS measure the development of early literacy skills in children from kindergarten to sixth grade. Subtests areas include phonological awareness, alphabetic principle and phonics, accuracy and fluency, comprehension, and vocabulary and oral language. The DIBELS Oral Reading Fluency passages include multiple reading passages which increase in difficulty to assess performance or progress in reading fluency (Good & Kamiski, 2002).

**Edgerton-Danhauer Nonsense Syllable Test** – The Edgerton-Danhauer NST is an open set nonsense syllable test that consists of 25 nonsense syllable test items. Test syllables are in the CVCV format. The 25 items have been recorded for consistency between presentations (Auriemma et al., 2008).

**Ling 6 Sounds** – The Ling 6 Sound Test includes 6 phonemes (/ah/, /ee/, /oo/, /m/, /sh/, /s/) which span the frequency range of speech. The Ling 6 sounds have been determined to be an accurate and reliable measure of auditory detection in the soundfield and can be used in place of pure tone stimuli to evaluate auditory detection (Scollie et al., 2012; Smiley, 2004). Additional applications include auditory discrimination tasks and auditory identification tasks. The Ling 6 sounds can also be



useful for speech-language pathologists, other therapists, teachers, or parents to complete quick equipment checks for children with hearing aids or cochlear implants or to quickly assess a child's auditory abilities (Smiley, 2004).

**Listening Inventories for Education-Revised questionnaire** - The LIFE-R was developed as a valid and reliable tool for measuring the effectiveness of intervention in a classroom setting. The questionnaire includes 15 questions for the student which reflect the level of difficulty he or she experiences in different social situations in the classroom (Anderson, Smaldino, & Spangler, 2011).

**ORCA Nonsense Syllables Test** - The ORCA NST is a randomized nonsense syllable test with sufficient high frequency information for measuring efficacy of frequency lowering without providing the subject with context clues. Syllables are formed in a CVCVC pattern. Because the items on the test are randomized every time they are presented, the potential for observing a learning effect is minimized. The test includes lists read by both male and female speakers and includes a short list version (32 syllables) and a long list version (115 syllables). Consonants tested include / p, t, k, b, d, g, m, n, ŋ, f, v, θ, ð, s, z, ʒ, ʃ, l, w, wh, dʒ, j, h, ɹ / and vowels tested include / i, ə, æ, ʌ, u/. Testing is controlled on a computer screen and scoring occurs automatically (Kuk et al., 2010).

**Phonak Logatome Test** – The Phonak Logatome test uses nonsense syllables produced by a female speaker to evaluate discrimination between high frequency speech sounds. Nonsense syllables are all of the format /a/-/s/-/a/, with only the middle phoneme differing between stimuli. Phonemes presented include /b/, /f/, /h/, /k/, /l/, /m/, /n/, /r/, /s/, /sh/, /t/, and /w/. The target syllable is presented with the carrier phrase, “My name is...” and the listener chooses the correct answer from a closed set of six syllables (Boretski & Kegel, 2009; Wolfe et al., 2010).

**Speech Intelligibility Index (modified)** – As described by ANSI S3.5-1997, the Speech Intelligibility Index (SII) is a series of measurements that allow for prediction about the intelligibility of speech in various listening conditions such as noise masking, filtering, and reverberation. Calculation of the SII relies on the measurement of two different functions: band importance functions and band audibility functions. Band importance functions represent the relative importance of individual frequency bands for speech intelligibility. Band audibility functions represent the proportion of speech within individual frequency bands that can contribute to speech understanding. The SII is then calculated by taking the product of the band importance and the band audibility for each individual frequency band and summing them across all of the frequency bands. This calculation results in the predicted intelligibility of speech signals presented under the different conditions under which the SII was measured (ANSI S3.5, 1997). The SII calculation was modified by McCreery et al. (2014) such that band audibility functions for high frequency inputs were measured at the frequency to which the signal was lowered rather than at the input frequency.

**University of Western Ontario Plurals Test** – The UWO Plurals Test can be used to measure detection of high frequency speech sounds in the presence of low level background noise. All items in the test are read by a female speaker in both the singular and plural form. Words tested include: Ant, Balloon, Book, Butterfly, Crab, Crayon, Cup, Dog, Fly, Flower, Frog, Pig, Shoe, Skunk and Sock. The test includes 10 lists of 30 randomized items. A low level noise played at a 20 dB signal to noise ratio will play in addition to each list of items (Scollie & Glista, 2012).

## Appendix A: References

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