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# Effect of adaptive frequency lowering on phoneme identification and sound quality of music in hearing-impaired listeners

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Effect of Adaptive Frequency Lowering on Phoneme Identification and Sound  
Quality of Music in Hearing-impaired Listeners

Kaitlyn A. Sabri

A dissertation submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

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## **Abstract**

The most common type and configuration of hearing loss seen in clinics is high frequency sensorineural hearing loss. High-frequency hearing losses can lead to difficulties understanding speech in noise. Traditional amplification can aid in audibility of high-frequency information; however, its success is limited due to acoustic feedback, output limitations of the hearing aids, and loudness discomfort (Bohnert, Nyffeler, & Keilmann, 2010, Turner & Cummings, 1999). Cochlear dead regions further hinder the success of traditional hearing aids, as speech recognition may not improve with increased audibility (Turner & Cummings, 1999). Frequency-lowering algorithms, developed by four major hearing aid manufacturers, attempt to provide improved audibility and speech understanding. Several studies have assessed the success of this technology; however mixed results have been found. The current study's purpose is to examine the effects of adaptive frequency lowering on phoneme identification and sound quality of music. Seven subjects with high frequency hearing loss were fit with Starkey Xino RITE hearing aids and were tested in two conditions (adaptive frequency lowering on and adaptive frequency lowering off). The Nonsense Syllable Test, Speech Perception In Noise test, and sound quality of music forced choice protocol were used to compare the two algorithms. The results of this study revealed no significant differences between traditional amplification and adaptive frequency lowering algorithm for identification of nonsense syllables, speech perception in noise, and preference of sound quality of music.

## **Chapter 1**

### **Introduction**

The most common type and configuration of hearing loss in adults is high-frequency sensorineural hearing loss. According to ANSI, 25% of audible speech signals required for identification of oral language are represented by speech information at or above 3,000 Hz (ANSI S3.5-1997). Many patients with high-frequency hearing loss complain of poor clarity of speech and difficulty with speech understanding when in background noise. Success of traditional amplification is limited in this population due to acoustic feedback, output limitations of the hearing aids at high frequencies, and loudness discomfort (Bohnert, et al., 2010; Turner & Cummings, 1999). The success of traditional amplification is further confounded by cochlear dead regions, areas within the cochlea with extensive damage to the inner and outer hair cells (Moore, 2001; 2004). Hearing losses that have a great impact on audibility and understanding are those caused by cochlear dead regions (Moore, 2004). When dead regions are present, traditional amplification from hearing aids help to make sounds audible, but may not improve speech recognition (Turner & Cummings, 1999). Hearing aid manufacturers incorporated frequency lowering as an attempt to improve audibility for individuals who have cochlear dead regions. These technologies are implemented through frequency compression, frequency transposition, and adaptive frequency lowering in digital hearing aids. The term frequency-lowering will be used in this paper to include all types of frequency lowering algorithms. Currently there are five major manufacturers offering frequency lowering technology in their hearing aids – Widex (frequency transposition,

commercial name- Audibility Extender), Phonak (frequency compression, commercial name- SoundRecover), Starkey (adaptive frequency lowering, commercial name- Spectral iQ), ReSound (frequency compression, commercial name – Sound Shaper), and Siemens (frequency compression, commercial name – FCo). Despite the proliferation of frequency lowering technology in hearing aids, current literature points to mixed results in patient benefits. The current study's purpose is to examine the effects of adaptive frequency lowering on phoneme identification and sound quality of music. Specifically, the frequency lowering algorithm offered by Starkey Hearing Technology (Spectral iQ) will be tested on listeners with high frequency hearing loss.

## **Chapter II**

### **Review of Literature**

#### **High-frequency hearing loss**

Severe high-frequency hearing loss is typically associated with cochlear dead regions, or areas within the cochlea where significant damage to the inner and outer hair cells can be found (Moore, 2001). The cause of the dead regions, although variable, result in a malfunction in the transduction of basilar-membrane movement at the frequency regions for which they are located (Moore, 2004). The total loss of inner hair cells in certain regions of the cochlea has also been described as ‘holes in hearing’ (Shannon, Galvin, & Baskent, 2002). Cochlear dead regions were first studied in the early 1900s, and were further investigated by Schuknecht and colleagues in the 1990s. Schuknecht and Gacek, 1993 identified that detection thresholds for pure tones are relatively unaffected until the hair cell loss exceeds 80-90%. The spread of excitation across the basilar membrane allows for the detection of a sound in an adjacent region where the hair cells are intact (Cox, Johnson, & Alexander, 2012; Halpin, 2002). Conversely, sound discrimination, and most importantly speech discrimination, can be unfavorably affected when the inner hair cell loss surpasses 50% (Moore, 1996, 2004).

Cochlear dead regions are defined by the extent of damage that is encompassed across the basilar membrane (Moore, 2001, 2004). Typically, these locations respond best to a certain frequency known as the characteristic frequency. The basilar membrane of a hearing-impaired listener differs from that of a normal hearing listener due to the shifting of characteristic frequencies across the membrane when damage occurs. Because

of this, cochlear dead regions are commonly referred to the characteristic frequency that is directly adjacent to the region that is damaged (Moore, 2001).

Threshold testing using puretone audiometry results in misleading test outcomes when cochlear dead regions are present (Halpin, 2002; Moore, 2004). As previously mentioned, detection of thresholds at any frequency using pure tones is not affected unless there is 80-90% neural loss at that frequency region (Moore, 2004). With an increase in stimulus intensity, adjacent regions of the basilar membrane are able to respond to the test tone. This response can be seen even though the test frequency falls within a cochlear dead region (Halpin 2002; Moore, 2004).

To identify cochlear dead regions, several masking tests have been developed. Two widely used tests for diagnosing cochlear dead regions include: 1. Psychophysical Tuning Curves and 2. The Threshold Equalizing Noise Test (TEN). Psychophysical Tuning Curves aid in the ability to identify cochlear dead regions. This is done by presenting a tone at a fixed frequency and intensity level and introducing a narrow band noise or sinusoid masker (Moore, 2001). The frequency for which the masker is most effective is the closest to the characteristic frequency. Cochlear dead regions present with the tip of the tuning curve being far away from the signal frequency (Moore, 2001). Although psychophysical tuning curves are considered the gold standard for identifying cochlear dead regions, this test is time consuming and challenging, and therefore not practical for clinical use (Cox, Alexander, & Johnson, 2011). Another test for cochlear dead regions, the TEN test, identifies cochlear dead regions through masking of adjacent frequencies (Moore, Huss, Vickers, Glasberg, & Alcantara, 2000). A cochlear dead region is identified by a shift of 10 dB or greater than what is expected for a normal

hearing ear (Cox et al., 2011). If no shift in threshold is identified with masking, no cochlear dead region can be identified. In comparison to the psychophysical tuning curves, the TEN test is more clinically useful: less demanding and time consuming. However, inconsistent results on the reliability and validity of the TEN test have been found (Cox et al., 2011).

Using the TEN(HL) test, Cox and colleagues measured the prevalence of cochlear dead regions in adults with moderate to severe hearing loss. They tested 170 adults for cochlear dead regions between 500-4000 Hz, and found that 31% of the subjects in this study had cochlear dead regions at one or more frequencies in at least one ear (Cox et al., 2011). The majority of dead regions were found to be present at frequencies above 1.5 kHz (Cox et al., 2011). In comparison to other studies, the prevalence of cochlear dead regions has been variable. Preminger et al., (2005) reported 29% as compared to Vinay and Moore (2007) with 57% (as cited in Cox et al., 2011). Although a large range in the prevalence of cochlear dead regions has been identified, the majority of studies agree that as the hearing loss increases so does the incidence of cochlear dead regions.

### **Effects of high frequency hearing loss on speech perception**

The effects of cochlear dead regions on speech perception have been described in many research articles. The articles dramatically vary in their conclusions of the effect of high frequency hearing loss on speech perception and sound quality. Early studies found that listeners with moderate-to-severe high-frequency hearing losses receive less benefit from amplification (Amos & Humes, 2007; Moore, 2004; Hogan & Turner, 1998). There is also evidence of poorer performance with amplification in the high frequencies, said to

be the result of cochlear dead regions (Galster, Valentine, Dundas, & Fitz, 2011; Haastrup, 2014; Moore, 2004; McDermott, 2008; Nyffeler, 2010; Robinson, Baer, & Moore 2007). Conversely, more recent articles suggest that amplification to provide audibility is beneficial for both individuals with and without cochlear dead regions suggesting that traditional amplification is advantageous (Cox et al., 2011; Simpson, McDermott, & Dowell, 2005; Turner et al., 2002).

Turner and Cummings (1999) investigated the benefit and limitations of providing high frequency information to individuals with high frequency hearing loss. The investigators found that by providing audible information, speech recognition did not reach 100% as it does for normal-hearing individuals. Furthermore, audiogram results suggest that by providing audible speech information to individuals with hearing losses exceeding the breaking point, 55 dB HL at 3000 Hz and above, little to no improvement in recognition scores were observed (Turner & Cummings, 1999). In contrast, individuals with flat severe-to-profound losses have not shown a similar pattern in speech recognition. In fact, individuals with flat severe-to-profound losses were found to have improved speech reception scores when audible information was presented. Turner and Cummings identified that individuals with moderate to severe high frequency hearing loss do not fully benefit from providing audible speech information and traditional amplification algorithms are not suitable for this type and configuration of hearing loss (Turner & Cummings, 1999).

Hogan and Turner investigated the benefit of audible high frequency speech information for hearing-impaired listeners (Hogan & Turner, 1998). An investigation using a new measure of efficiency and the Articulation Index was used. Hogan and

Turner defined efficiency as how well hearing-impaired listeners use information that is within specific frequency regions (Hogan & Turner, 1998). Results from this study showed that as the amount of hearing loss increased past 55 dB HL at a given frequency, the efficiency to that frequency lessened. Consistent with the Turner and Cummings' findings, audibility alone does not explain the poorer speech recognition scores for listeners with moderate-to-severe high frequency hearing loss (Hogan & Turner, 1998). Hearing thresholds greater than 60 dB HL suggest both outer and inner hair cell losses, which cause poor clarity of speech and may in turn, decrease speech recognition (Hogan & Turner, 1998). Additionally, high frequency amplification for those with a high frequency hearing loss can negatively impact speech reception scores when the loss surpasses 55 dB HL. Hogan and Turner propose that amplification for individuals with high frequency hearing losses greater than 55 dB HL should be cautiously considered as amplification may cause decreased performance (Hogan and Turner, 1998)

Ching, Dillon, and Byrne discussed speech recognition of hearing impaired listeners in their 1998 publication. This article investigated the relationship between speech recognition and audibility through two different experiments. The first, an assessment using the Speech Intelligibility Index (SII), was used to assess speech scores in normal-hearing listeners, quantify the deficits hearing-impaired listeners experience with speech, and modify the SII to decrease inconsistencies in speech scores of the hearing-impaired between observed and predicted values (Ching et al., 1998). The second experiment was used to evaluate the SII, with and without the modifications, for predicting speech performance (Ching et al., 1998). Both experiments used the same subjects and found that audibility cannot entirely explain the speech recognition in

individuals with hearing loss. This is particularly true for individuals with high frequency sensorineural hearing losses, and therefore amplification may achieve only small to no sensation levels at this frequency region (Ching et al., 1998).

In contrast to the previously reviewed studies, which state that audible high frequency information may not give benefit and could be detrimental to speech reception, the following studies provide evidence of benefit of audible high frequency information for individuals with cochlear dead regions. These studies were conducted more recently, and provide contrasting evidence to the studies previously discussed in this literature review.

Cox and colleagues, previously mentioned for their work with identifying the prevalence of cochlear dead regions, also studied the effect of cochlear dead regions on the individual's ability to use high frequency cues that occur in speech (Cox et al., 2011). 170 subjects were tested using high-frequency emphasis and low-pass filtered Quick Speech in Noise test stimuli. The results suggest that although individuals with dead regions benefit less from high-frequency information than individuals without dead regions, audible high frequency information is beneficial for both groups (Cox et al., 2011). They also found no evidence to reduce amplification in the presence of cochlear dead regions to avoid reduction of speech recognition (Cox et al., 2011).

Simpson, McDermott, and Dowell conducted a study, which suggests improvement of speech understanding with increased bandwidth (Simpson et al., 2005). Simpson et al. (2005), proposed that studies which report reduced speech understanding may not be providing audible information and therefore inaccurately conclude that less high frequency gain will result in better speech understanding. In this study 10 hearing-

impaired subjects with moderate-to-severe high frequency hearing loss were tested for cochlear dead regions using the TEN test (Simpson et al., 2005). The TEN test revealed only one subject with widespread cochlear dead regions, while the others presented with dead regions above 3 kHz. All subjects were evaluated using consonant identification tests with varying low-pass filter conditions and were found to have improved significantly with the bandwidth of the signal increased (Simpson et al., 2005). In all, this study suggests that with audible information, subjects with high frequency hearing loss will benefit from this information (Simpson et al., 2005)

The benefit of providing audible speech information to individuals with high-frequency hearing loss has been largely studied in quiet environments. In contrast, Turner and Henry evaluated the benefits of audible speech information to individuals with hearing loss when in the presence of background noise (Turner & Henry, 2002). This study presented speech stimuli, which was low pass filtered using varying cut off frequencies, in the presence of multitalker babble. As the cut-off frequency increased, improved recognition scores were found regardless of the severity of hearing loss, as long as the information was audible. This study suggests that with more audible high frequency information, subjects perform better at speech recognition even in the presence of background noise (Turner & Hogan, 2002).

In summary, the benefits of audible high frequency information to hearing aid users have been debated for many years. Research has both supported and opposed the hypothesis that audible high frequency information is beneficial for hearing aid users with significant high frequency sensorineural hearing loss. Regardless of the contradictory research findings, hearing aid companies have continued to move forward

in addressing difficulties that arise when fitting hearing instruments to an individual with severe high frequency hearing loss.

### **The hearing aid solution**

From an amplification standpoint, individuals with high frequency hearing loss can be difficult to fit. Amplification for this population is limited due to acoustic feedback, output limitations of the hearing aids, loudness discomfort, and decreased speech recognition even with audibility (Bohnert, et al., 2010, Turner and Cummings, 1999). To resolve many of the aforementioned issues, linear frequency transposition (LFT) or frequency compression (FC) algorithms in hearing aids can be implemented.

Linear frequency transposition is one solution to significant high frequency hearing loss. It is the process of moving high frequency information from an unaidable region and superimposing it onto a lower frequency region where the hearing aid user can effectively utilize the sound (Dillon, 2001). The lower frequencies, below a certain cutoff frequency, are free of compression and the distance between harmonics that are transposed remain intact (Widex, 2013). Frequency transposition has both positive and negative characteristics. One potential problem with linear frequency transposition is that both natural energy and transposed energy fall within the same frequency region (Dillon, 2001). This can create perceptual confusion as both the natural and transposed information being presented to the user in the same fashion. Frequency transposition also has its benefits. Frequency transposition can be successful for its users with moderate to severe high frequency hearing losses because clarity of speech is improved (Dillon, 2001). Currently, Widex is the only major hearing aid manufacturer using a linear

frequency transposition algorithm. Widex markets their frequency transposition algorithm as “Audibility Extender”. Widex suggests that it provides high frequency information, without distortion because it maintains the harmonic spacing, keeping the signal as close to its original sound (Widex, 2013). Several manufacturer sponsored studies have reported the benefits of linear frequency transposition in Widex hearing aids that include improved speech understanding and better sound quality (Auriemmo et al., 2009; Korhonen & Kuk, 2008; Kuk Keenan, Korhonen, & Lau, 2009; Lau, Kuk, Keenan, Schumacher, 2004). However, there are no independent studies confirming the findings of the manufacturer’s reports.

Kuk et al., (2009) evaluated the efficacy of linear frequency transposition on consonant identification in quiet and in noise. Eight adult subjects with severe-to-profound high-frequency hearing loss were recruited and fit with Widex m4-m hearing aids binaurally. The subjects performance using the aids were evaluated using the ORCA nonsense syllable test in 4 conditions, conventional amplification, transposition at initial fit, transposition at one month post-fit, and transposition at 2 months post fit. The results of this study revealed significant improvements in fricative identification over time. The authors of this study stressed the importance of suitable candidacy and appropriate training.

Frequency compression is another solution for severe high frequency hearing loss. Frequency compression is the process of taking a normal frequency region above a certain cut off frequency and compressing it into a lower region without overlapping output information (Dillon, 2012). High frequency regions receive more compression, while lower frequency regions, closer to the cut off, receive less compression (Galster,

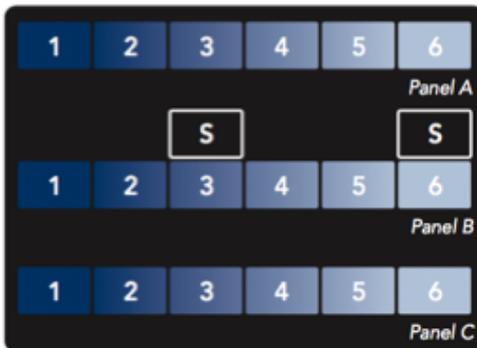
Valentine, Dundas, & Fitz, 2011). This process eliminates natural and modified energy from being in the same frequency region, thus creating less distortion. There are several types of frequency compression, providing different advantages and disadvantages. Linear frequency compression, power frequency compression, and non-linear frequency compression have all been implemented in hearing aids. Linear frequency compression creates the output of the hearing aids as a portion of the input frequency (Dillon, 2012). Power frequency compression involves raising the output equalizing the input and then raising it to a certain power. Lastly, non-linear frequency compression, the most common type of frequency compression, results in the high frequencies having different amounts of compression applied above a certain cut off frequency (Dillon, 2012). This results in a reduced dynamic range, where the frequency information above the cut off frequency is compressed (Alexander, 2013). Non-linear frequency compression is the method of frequency lowering used in Phonak and more recently in GN ReSound and Siemens hearing aids. Phonak's proprietary algorithm for frequency compression is called "SoundRecover". This algorithm has two potential areas for modification: cut-off frequency and frequency-compression ratio. GN ReSound's algorithm, "Sound Shaper" has been released more recently. It has a similar algorithm; however its manufacturer stresses the importance of simplicity of the algorithm allowing less manipulation of the compression ratio and cut off frequencies. Siemens' adaptive frequency lowering is commercially marketed as frequency compression (FCo). As of this writing there is no technical information available on how this technology is different from other available frequency lowering algorithms. Several manufacturer-sponsored and field studies have reported the benefits of frequency compression in Phonak hearing aids that include

improved speech understanding with and without background noise, better sound quality, and improved music perception (Leifholz, Margolf-Hackl, Kreikemeier, & Kiessling, 2013; McDermott, 2008; Nyffeler, 2010; Parsa, Scollie, Glista, & Seelisch, 2013; Uys, 2013).

Phonak's SoundRecover has been evaluated in several field studies. One of which investigated the possibility of improved speech understanding in noise when utilizing SoundRecover (Nyffeler, 2010). The Oldenburger Statzest (OLSA), a test of adaptive speech in noise, was used for this study. The results of the frequency compression algorithm were compared to that of conventional amplification for 11 subjects. This study identified improvement in the majority of its participants (7 out of 11), however statistical significance was not reached (Nyffeler, 2010). Sound quality of SoundRecover was also found to have improved over two and four months of use. The majority of subjects reported preference for SoundRecover in the sound quality of fricatives in quiet when compared to conventional amplification (Nyffeler, M., 2010).

Lastly, adaptive Spectral (frequency) lowering is a third approach to address high frequency hearing losses. Adaptive frequency lowering is utilized by Starkey and is marketed as Spectral iQ. According to Starkey the prescription of Spectral iQ is intended for use with subjects who have severe-to-profound high-frequency hearing losses. Starkey outlined the candidacy criteria as follows: "1. All thresholds below 1000 Hz must be 55 dB HL or below. 2. High-frequency hearing loss slope must be greater than or equal to 25 dB HL per octave. 3. A single threshold between 1000 Hz and 3000 Hz must be 55 dB HL or worse. 4. All thresholds between 4000 Hz and 8000 Hz must be 55 dB HL or worse" (Galster, 2012).

Adaptive frequency lowering is a technique which utilizes frequency lowering only when high frequency information is detected by the hearing aid (Galster, J., Valentine, S., Dundas, A., Fitz, K. (2011). This technique is technically described as Spectral Envelope Warping (SEW) (Galster, 2012). The algorithm monitors the acoustic input for high-frequency spectral peaks that are responsible for identification of high-frequency speech sounds. Once the high frequency spectral peaks are identified, they are characterized by their spectral shape and then recreated in the lower frequency region. The lowered information, which maintains the original spectral shape, is prescribed by Starkey's Inspire programming software. There are two Spectral iQ controls that allow for adjustment of bandwidth and gain. In addition to lowering the high frequency signals to a lower frequency region, the high frequencies are also amplified in their normal frequency region maintaining the bandwidth. This allows the high frequency information to be audible both in its original frequency region and in a lowered region. According to Starkey, by maintaining the bandwidth, the hearing aids provide a relatively undistorted signal as compared to other frequency lowering methods. Additionally, Spectral iQ allows for maintained harmonic relationships through frequency transposition. Due to the adaptive nature of this algorithm, introduction of unwanted high frequency noise is eliminated when Spectral iQ is not activated. Figure 1 depicts Starkey's Spectral iQ.



**Figure 1:** Spectral iQ. Panel A depicts traditional amplification from a hearing aid utilizing 6 channels. Panel B: shows Spectral iQ activated and transposing the /s/ phoneme. Panel C represents the hearing aid reverting back to traditional amplification when no high frequency stimulus is detected (Galster et al., 2011)

The effect of Starkey's Spectral iQ have been described in several white papers published by researched funded through the Starkey corporation. One particular study evaluated the effect of Spectral iQ on performance of the S-test (Galster et al., 2011). This test requires the subject to identify the presence or absence of the word-final consonant /s/. Researchers found 16 out of the 18 participants demonstrated improvement. This suggests that participants benefited from Spectral iQ and demonstrated improvements in high frequency speech detection (Galster et al., 2011).

## Conclusion

In summary, frequency-lowering algorithms deliver high frequency speech energy to a lower, more audible, region for listeners. The literature is mixed in its conclusions on the benefits that frequency-lowering algorithms provide to its listeners. The

manufactures' purpose of these algorithms is to make high-frequency speech sounds accessible to patients with significant high frequency hearing loss.

The current study's purpose is to evaluate the effectiveness of these algorithms through evaluation of performance in phoneme identification and speech in noise. Additionally, preference of sound quality of music will be examined to determine each patient's preference for this algorithm. This dissertation will explore the following hypotheses:

1. With adaptive frequency lowering, there will be a significant increase in correct phoneme identification compared to when frequency lowering is turned off.
2. The overall percentage correct and percentage of high context sentences when listening to sentences in noise will be similar for both conditions: frequency lowering on and frequency lowering off.
3. The percentage correct for low context sentences in noise will be significantly improved with adaptive frequency lowering on as compared to off.
4. Subjects will prefer the sound quality of music when frequency lowering is turned on.

## **Chapter III**

### **Materials and Methods**

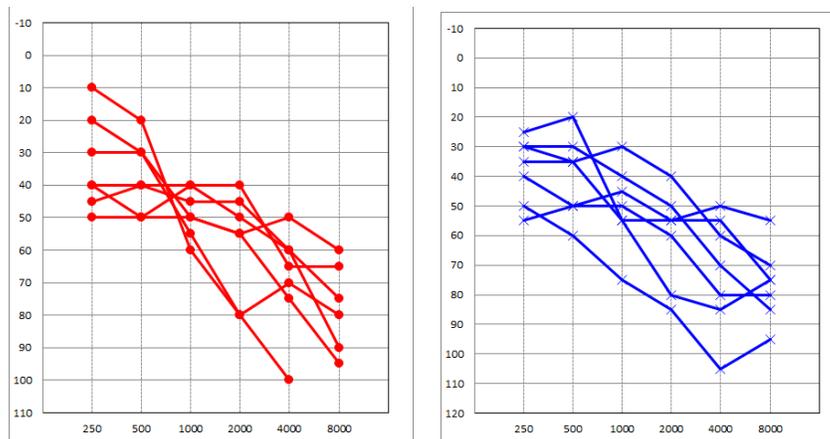
#### **Subjects**

A total of seven individuals participated in this study. All participants remained in one group with a mean age of 67 years (SD=20.3). The participants were recruited through flyers posted at private audiology practices and using word of mouth in the Harrisonburg, VA area. For inclusion into the study the participant must be an adult, 18 years of age or older, be fluent in English, have a high frequency sensorineural hearing loss of >55 dB HL beyond 2,000 Hz, and currently wear hearing aids binaurally. Figure 2 displays the subjects' audiograms. Additionally, all participants had no known cognitive or neurological deficits, which would impact attention levels. All subjects completed this study with no known experience using the frequency compression algorithm. The participants were offered one box of hearing aid batteries for their participation in the study.

#### **Inclusion criteria screening:**

Immediately prior to the study, all participants completed the Mini-Mental State Exam (MMSE) to verify normal cognitive function based on an MMSE score of 23 or greater (maximum score is 30). The participants underwent a hearing screening consisting of otoscopy, tympanometry, and pure tone testing using the octave frequencies 250 to 8000 Hz for both air conduction and bone conduction. A GSI 33 tympanometer using a 226 Hz probe tone was used to verify normal middle ear status for each

participant. Additionally, a GSI 61 audiometer and ER-3 insert earphones were used to complete the puretone testing using the Hughson Westlake method. Participants with high frequency hearing loss greater than 55 dB HL beyond 2000 Hz and no present middle ear pathology were considered eligible for the purpose of the study.

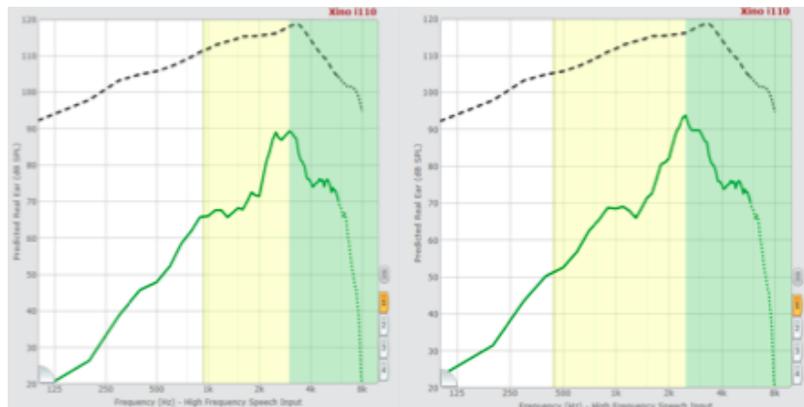


**Figure: 2:** Hearing threshold in dB HL (re: ANSI 1996) for individual subjects for right (red) and left (blue) ears.

### Hearing instruments

The hearing instruments used in this study were two Starkey Xino i110 RIC 312 hearing aids. Using the Starkey fitting software the hearing aids were programmed with all advanced features turned off, with the exception of the PureWave Feedback Eliminator set to adaptive to reduce feedback. The instruments were fit using Starkey's proprietary algorithm and were verified for appropriate amplification and frequency lowering through the Audioscan RM500 SL. Amplification was assessed using a pink noise stimulus at 65 dB SPL. Output measurements were considered acceptable when within 10 dB SPL within Starkey's algorithm estimated gain. To assess frequency lowering, white noise was presented in the sound field through a Tannoy System 600

loud speaker at 65 dB SPL. The effect of frequency lowering on the output could be confirmed on the speech map using the Audioscan RM500 SL in live voice mode. Figure 3 demonstrates the Starkey software-simulated output of a hearing aid when frequency lowering is turned on and when turned off.

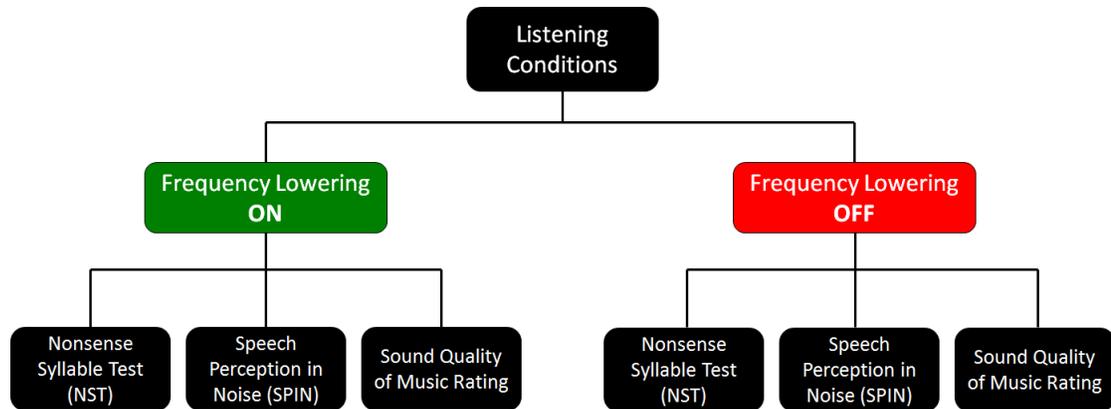


**Figure 3:** Starkey programming software: Predicted real ear measures (dB SPL) represented by the solid green line as a function of frequency (Hz). Right panel: Spectral iQ on, Left panel: Spectral iQ off.

### Study design

The participants were required to complete three listening tasks in two conditions: frequency lowering turned on and frequency lowering turned off. The participants' tasks included the CUNY Nonsense Syllable Test (Levitt & Resnick, 1978), the Speech Perception in Noise Test (Kalikow, Stevens, & Elliott, 1977), and finally music samples. The stimuli for all three tasks were presented through Tannoy System 600 sound field speaker. Signal recording, manipulation and streaming were accomplished via commercially available sound editing software (Sound Forge). All testing was conducted in an IAC double walled sound treated booth (2 meters x 2 meters) located in the Hearing

Aid Research Laboratory at James Madison University. Figure 4 displays a flow-chart to illustrate the six trials that were conducted for each subject. Of note, NST and SPIN tests were counterbalanced. Additionally, the on and off conditions were also counterbalanced.



**Figure 4:** Research design: six test conditions for each subject.

**CUNY Nonsense Syllable Test:** The CUNY Nonsense Syllable Test (NST) was chosen to assess speech understanding in multiple conditions due to its sensitivity to changes in hearing aid parameters. The NST contains no contextual information offering minimal learning and practice effects (Levitt, & Resnick, 1978). The test contains a closed set of responses, and the phoneme errors can be analyzed and compared between and within conditions. The CUNY Nonsense Syllable Test contains seven subsets. Each subset is comprised of 7 to 9 nonsense syllables in the CV or VC configuration. Three vowels, /i,a,u/, that occur in distant points on the vowel triangle were used throughout the test. Additionally, the consonants that occur either before or after the vowels are those that may cause the most difficulty for the potential hearing aid wearer. The consonants that

were weighted more heavily include those that contain high frequency information such as fricatives and voiceless plosives. Figure 5 demonstrates the test items in the Nonsense Syllable Test. Each column contains nonsense syllables that make up a subtest with each subtest differing in: the vowel context, the class and the position of the constants (Levitt, & Resnick, 1978). Appendix A contains the NST test form used in this study.

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
af	uθ	ij	ab	fa	la	na
aʃ	up	if	aθ	ta	ba	va
at	us	it	ad	pa	da	ma
ak	uk	ik	am	ha	ga	za
as	ut	is	az	θa	ra	ga
ap	uf	iθ	ag	tʃa	ja	ba
aθ	uj	ip	an	sa	dʒa	θa
			aŋ	ʃa	wa	da
			av	ka		

**Figure 5:** Test items making up the NST. Each column shows the nonsense syllables used in each subtest of the NST (Levitt, & Resnick, 1978).

The test was administered at 65 dB SPL (speech), +15 dB SPL SNR (multitalker babble), using the Tannoy System 600 sound field speaker at a 0 degree azimuth. For each test item a male speaker used the carrier phrase “you will mark \_\_\_\_\_ please”. The subjects had 7-9 options listed on the answer form, with one being the correct response. The subjects were instructed to circle the nonsense syllable for which they heard. One practice sample was used to familiarize the subjects to the task. Brief pauses were provided between each presentation.

The Nonsense Syllable Test was scored based on total phonemes correct with sixty-two phonemes presented in each condition: frequency lowering on and frequency lowering off. The nonsense syllables were also scored based on individual phonemes. A confusion matrix was created with the subjects' responses on the y-axis and the stimuli on the x-axis. The percentage correct was calculated for each column/row.

***Speech Perception in Noise Test:*** The Speech Perception in Noise test (SPIN) was also chosen to assess the effects of adaptive frequency lowering on speech perception in noise (Kalikow, Stevens, & Elliott, 1977). The test is composed of 50 pre-recorded sentences presented at 60 dB SPL with + 15 dB SNR (multi-talker babble). The scored test items are the final word of each sentence; test items are common, monosyllabic nouns. One half of the sentences are considered “high-predictability sentences” such that the listener is provided with contextual information throughout the sentence (e.g. “The watchdog gave a warning GROWL”). The other half of the sentences is considered “low-predictability sentences”. These sentences provide little to no contextual information about the final word (e.g. “I had not thought about the GROWL.”) (Kalikow, Stevens, & Elliott, 1977). The test was scored three ways: total percent correct, percent correct of low context sentences, and percent correct of high context sentences.

***Musical sound quality:*** To assess preference of sound quality between frequency lowering and traditional amplification, five musical selections were presented to each

subject at 65 db SPL from the Tannoy System 600 sound field speaker at 0 degrees azimuth. The musical selections included: Mozart's Symphony No. 41, Handel's Music for the Royal Fireworks; Minuet II, and Bach's Cello Concertos Minuet in G-Major and Cello Suite III in C major. The genre of the music was classical, as it appealed to most listeners. Additionally, the musical selections contained a variety of instruments representing low to high pitches. The subjects listened to each musical selection twice, once with traditional amplification and once using Spectral iQ. Each subject was asked to compare the overall sound quality of each selection and indicate which they prefer: musical selection 1 or 2.

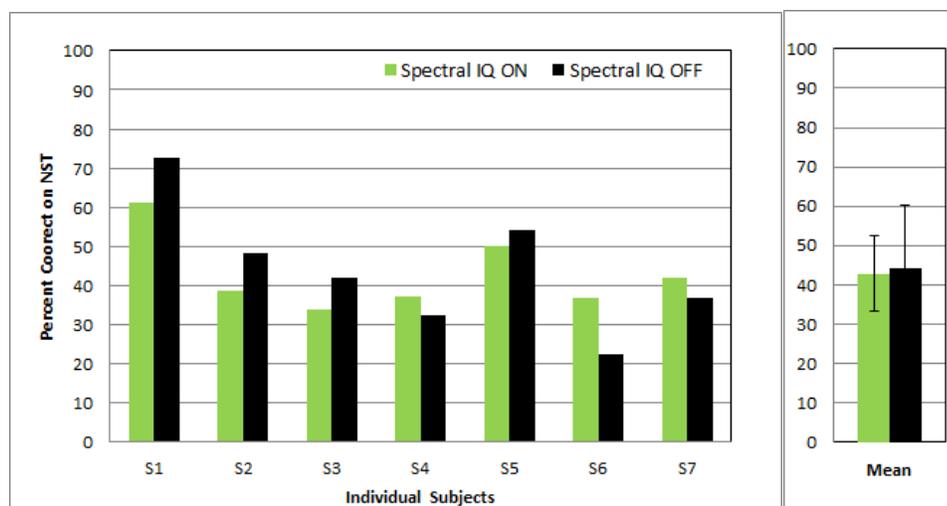
## **Chapter IV**

### **Results**

Seven subjects with high frequency sensorineural hearing loss were fit with Starkey Xino receiver in the ear hearing aids based on Starkey's proprietary fitting algorithm. Two conditions, frequency lowering on and frequency lowering off, were evaluated using the Nonsense Syllable Test, the Speech Perception In Noise Test, and overall sound quality preference when listening to music. The tests were scored and analyzed based on individual and mean data.

#### **Effect of Spectral iQ on NST performance**

The effect of Spectral iQ on Nonsense Syllable Test performance was evaluated in two conditions, frequency lowering on and frequency lowering off. The percent correct from vowel consonant and consonant vowel pairs were combined for all analyses. Both conditions were completed using identical methods. It was hypothesized that subjects would perform better in the frequency lowering enabled condition due to improved access to high frequency information. Figure 6 shows the NST results, both individual and mean data for all 7 subjects. Percent correct scores are shown for each subject for both the Spectral iQ on (light bars) and Spectral iQ off (dark bars) conditions.



**Figure 6:** Nonsense Syllable total percent correct scores for individual subjects and mean data for two test conditions, Spectral iQ on (light green) and Spectral iQ off (black). Error bars in the mean data represent  $\pm 1$  SD.

Individual NST scores with Spectral iQ ranged from 33.9% to 61.3% in the 7 subjects. The mean score for Spectral iQ engaged was 42.9% (SD= 9.6) and disabled was 44.1% (SD=16.3). The effect of Spectral iQ on nonsense syllable identification was evaluated by paired t-test, which revealed no significant difference between Spectral iQ on and off conditions for nonsense syllables [ $t(6) = -0.34$ ,  $p=0.74$ ].

Although no significant group differences were found, it was of interest to study the effect of the Spectral iQ algorithm on individual phonemes, particularly, consonants with high frequency spectral energy (e.g. /s/, /sh/, /f/, /th/). The target stimulus and the subjects' responses were arranged in a confusion matrix. The individual confusion matrices of the seven subjects were consolidated into one matrix- resulting in a total of two matrices: Spectral iQ on and Spectral iQ off. Figure 7 shows the combined confusion matrix of each phoneme stimulus (y-axis) and the subjects' response phoneme (x-axis).

The matrices depict the percentage of correct identifications and incorrect identifications. Correctly identified phonemes are arranged diagonally and are highlighted. Incorrectly identified phonemes are those that deviate from the diagonal line. The numerical values represent the percentage of phonemes identified.

## Subject Response

Stimulus Presented

	p	t	k	f	θ	s	ʃ	tʃ	b	d	g	v	ð	z	ʒ	dʒ	m	n	ŋ	l	r	w	h	y	
p	11	29	18	7	11	4	11																	11	
t	29	29	11	11	11	4	7																		
k	20	11	29	11	9	3	6																		11
f	20	9	11	23	17	3	9						9												
θ	14	11	4	11	14	14	7				11	4		4					7						
s	2	2	2	5	14	24	50																		
ʃ	4		7			4	75	7					4												
tʃ								86					14												
b					5				48		14	5	14							10	5				
d									11	50	14		4	14					4			4			
g									5	38	48		5						5						
v									7	29	14	36						7	7						
ð				14			7	14		7			43	7					7						
z										29				57					14						
ʒ															0										
dʒ										14						71									14
m									7			7					71	14							
n										5	5						10	76	5						
ŋ					14					14				14				29	29						
l																				71		29			
r																					86	14			
w																				14		86			
h	14		29	14		14							14										14		
y																						7		93	

Panel A: Spectral iQ on

## Subject Response

	p	t	k	f	θ	s	ʃ	tʃ	b	d	g	v	ð	z	ʒ	dʒ	m	n	ŋ	l	r	w	h	y
p	18	29	7	14		7	14						4											7
t	29	29	7	18	18																			
k	20	17	34	11	6	3	3																	6
f	17	20	3	14	14	3	6						14											9
θ	29	21	7	11	18		4		4		7													
s	7	10	7	7	12	43	10						5											
ʃ	4	4		7	7	4	71	4																
tʃ								100					0											
b									48	10	24	5	5	5			5							
d									7	57	25	4	4			4								
g									0	29	57							5	10					
v									36	29	14	0	7	7					7					
ð	21								7	21		7	43											
z										7	7		7	50				7	7	14				
ʒ															0									
dʒ											14						71				14			
m										14								57	21	7				
n										10	5							14	67	5				
ŋ											14		14						14	57				
l																					71		29	
r																						86	14	
w																					29		57	14
h			14				14						14										57	
y																					7	7		86

Panel B: Spectral iQ off

**Figure 7:** Consonant Confusion Matrix for Spectral iQ ON (Panel A) and OFF (Panel B) The x-axis represents the subject's response; the Y-axis represents the recorded stimulus. All numerical values represent percent correct. Cells highlighted in red indicate a decrease in performance compared to the other panel.

Results revealed phoneme misidentifications for both conditions. The Spectral iQ on condition revealed that phonemes /s/, /h/, and /ŋg/ were consistently misidentified. In contrast, phonemes /v/ and /m/ were consistently misidentified when Spectral iQ was disengaged. Overall, no significant differences were found between conditions, however,

noteworthy misidentifications were made in both conditions. Further consideration of these misidentifications will be examined in the discussion section.

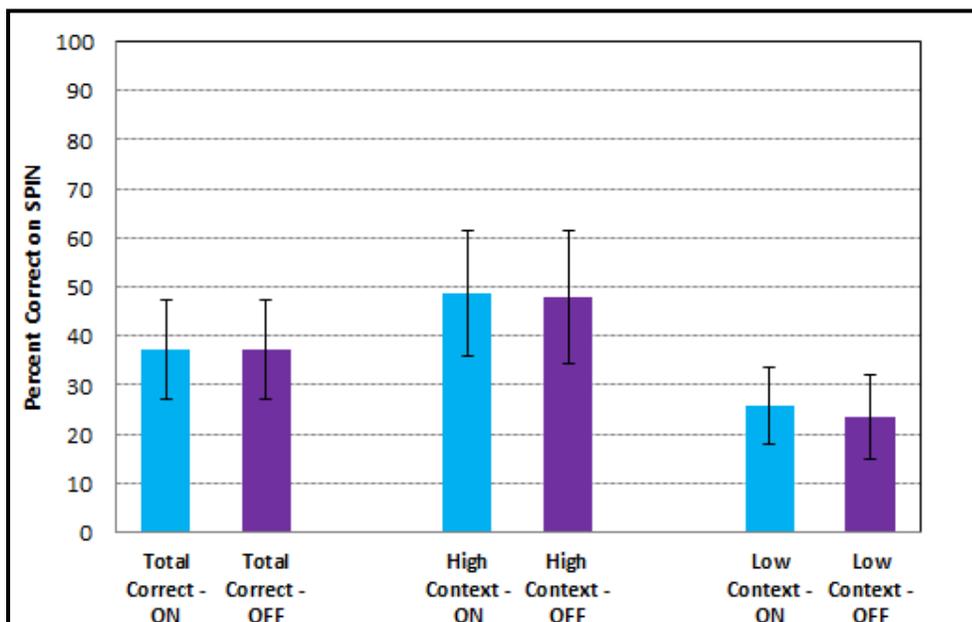
### **Effect of Spectral iQ on performance of speech perception in noise**

The effect of Spectral iQ on performance of speech perception in noise was evaluated using the SPIN test. The SPIN test, a list of 50 sentences with 25 high context sentences and 25 low context sentences were presented to each subject in both conditions. It was hypothesized that subjects would perform equally across Spectral iQ conditions when presented with high context sentences. Differences in performance would be identified when presented with low context sentences yielding better performance when utilizing Spectral iQ due to access of high frequency information. Individual and mean scores for the SPIN test in both conditions are listed in Table 1. Figure 8 shows percent correct on the Speech Perception In Noise Test for both the on and off conditions when evaluated based on high context sentences, low context sentences, and total correct.

Effect of the Spectral iQ on speech perception in noise performance was analyzed by a t-test. Mean SPIN scores were found to be essentially identical between conditions Spectral iQ<sub>on</sub> (mean=37.1%, SD=26.6), Spectral iQ<sub>off</sub> (mean= 31.6%, SD=28.8). Overall, results indicate that there were no significant differences between frequency lowering on and off for the SPIN sentences [ $t(6) = 0.854, p=0.42$ ].

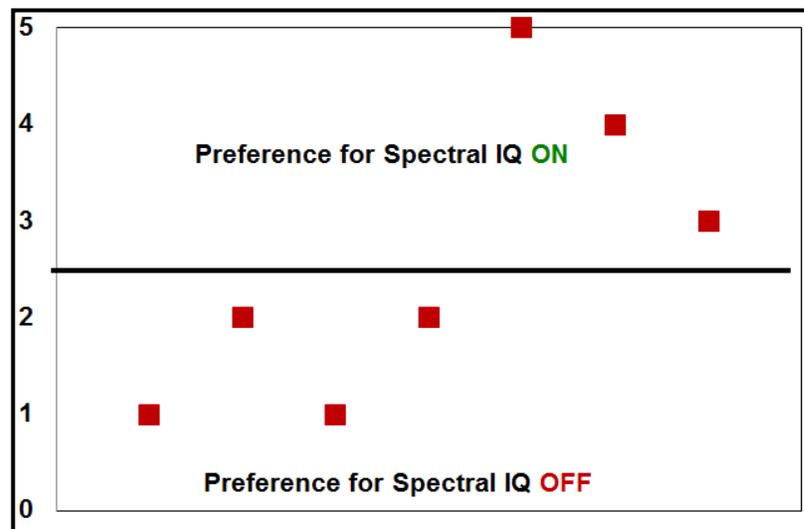
**Table 1:** Individual and Mean SPIN data in percent correct.

Subject ID	Spectral iQ On			Spectra iQ Off		
	Total % Correct	High Context % Correct	Low Context % Correct	Total % Correct	High Context % Correct	Low Context % Correct
1	70	84	56	74	84	64
2	10	16	4	4	4	4
3	28	36	20	36	48	24
4	14	24	4	14	24	4
5	66	84	48	25	72	24
6	14	12	16	2	12	4
7	58	84	32	66	92	40
Mean	<b>37.14</b>	<b>48.6</b>	<b>25.7</b>	<b>31.5</b>	<b>48</b>	<b>23</b>
SE	10.04	12.84	7.75	10.9	13.46	8.52

**Figure 8:** SPIN scores for Spectral iQ on and off for high context sentences, low context sentences, and total sentences. Error bars indicate  $\pm 1$  SE.

### Effect of Spectral iQ on sound quality of music

The sound quality of music was evaluated based on overall preference to either condition, Spectral iQ on or off. Overall preference was formulated through binary calculation with preference for Spectral iQ<sub>on</sub> receiving a 1 for each selection and preference for Spectral iQ<sub>off</sub> receiving a 0. A total was calculated for overall preference for sound quality of music. Figure 9 is a scale from 0 to 5 indicating preference of overall sound quality for Spectral iQ<sub>on</sub> or Spectral iQ<sub>off</sub> for each subject. A score of 0 represents a strong preference for the Spectral iQ<sub>off</sub>, and a score of 5 represents a strong preference for Spectral iQ<sub>on</sub>. Each square denotes a subject. Overall, tremendous individual variation in preference for sound quality of music with Spectral iQ was identified. No common trends were observed for the preference of overall sound quality of music.



**Figure 9:** Overall preference for sound quality of music. Each data point represents one listener. Higher values indicate stronger preference for Spectral iQ on. The horizontal line represents no preference for Spectral iQ on or off.

## **Chapter V**

### **Discussion**

Based on these seven subjects, the Spectral iQ algorithm tested did not result in overall improvement of speech scores or identification of phonemes when presented in the presence of noise. Furthermore, there was tremendous individual difference in preference for sound quality of music with Spectral iQ. The data based on the limited sample size did not support the benefits of the adaptive frequency lowering algorithm for hearing aid users.

#### **Nonsense Syllable Identification with Spectral iQ**

Spectral iQ did not improve nonsense syllable identification in the seven subjects. Through further analysis, differences in phoneme identification and errors were found within conditions. Phonemes, /s/, /h/, and /ng/, were misidentified more often in the on condition as compared to /v/ and /m/ in the off condition. When looking further into the consonant confusions specifically for the on condition, it can be concluded that /s/ was identified as /sh/ 50% of the time in the on condition. The phoneme /s/ has more acoustical energy in the high frequencies (4 kHz and beyond), while the phoneme /sh/ has more acoustical energy in the mid frequencies (2.5 kHz and beyond). We hypothesize that this misidentification of /s/ as /sh/ is likely due to the lowering of high frequency information through Spectral iQ. According to Scollie et al., 2009, excessively aggressive frequency lowering techniques can cause consonant confusion due to distortion of cues helpful for differentiating between phonemes (as cited in Simpson, 2009). Unfortunately, this trend was not true of the /h/ and /ng/ phonemes that were also

misidentified in the on condition. Frequency lowering can result in distorted sound quality as the incoming sound through such an algorithm may be perceived as lisps.

### **Speech Perception in Noise Test**

Speech Perception In Noise Tests also resulted in no significance between groups. We hypothesized that there would be no difference between groups with high context sentences due to the ample contextual information provided. We did, however, believe that a difference between high and low context sentences would be found. With little to no contextual information, the errors between groups would increase as high frequency information would be limited in the Spectral iQ off condition. Conversely, groups performed equally across conditions, likely due to redundancy of frequency information within the individual words that were assessed.

### **Sound quality of music**

Preference for sound quality of music with Spectral iQ varied tremendously between subjects. No trend in the data was identified, with two subjects strongly preferring the sound quality of Spectral iQ, three subjects who expressed no preference, and two subjects with strong preference for conventional amplification. With a small sample size ( $n=7$ ), a significant finding for sound quality preference is unlikely. This study revealed no trend in the data, likely due to the small sample size. A larger sample size may give insight into this population's preference for Spectral iQ when listening to music.

Through review of the literature, several studies evaluated the preference for sound quality of frequency lowering algorithms. These studies utilized different frequency lowering algorithms. Each study compared the sound quality of the lowering algorithm to conventional amplification.

According to a field study conducted by Phonak, the sound quality of SoundRecover was compared to the sound quality of conventional amplification through a questionnaire containing 5 categories of satisfaction (Nyffeler, 2010). This study found that subjects reported improved sound quality of SoundRecover following 2 and 4 months of use. The majority of subjects reported preference for SoundRecover in the sound quality of fricatives in quiet when compared to conventional amplification (Nyffeler, 2010).

An independent study completed by Simpson, Hersbach, and Mcdermott, 2006, evaluated the sound quality of frequency compression using Phonak Supero 412 hearing aids. Subjects with steeply sloping audiograms were asked to complete the Abbreviated Profile of Hearing Aid Benefit (Cox & Alexander, 1995) for both traditional amplification and frequency compressed amplification. The results of this study revealed largely higher scores for four of the six subjects for the conventional algorithm over the frequency-compression algorithm (Simpson et al., 2006)

### **Limitations of the current study**

Sample size: Due to the limited resources and hearing-impaired population available in the Harrisonburg, VA area, this study's sample size was small, with only seven subjects. Subjects who participated in this study may not have fit the ideal

candidacy criteria for frequency lowering algorithms (sharply sloping high frequency hearing loss).

Degree of hearing loss: Additional factors were unaccounted in this study, which may have contributed to insignificance. According to Glista et al., 2009, age group and degree and configuration of the hearing loss were related to the benefit received when utilizing nonlinear frequency compression (NFC) (Glista et al., 2009). Glista described the magnitude of the high frequency hearing loss and its correlation to the benefit of speech sound detection tasks. In the current study, seven subjects demonstrated high frequency hearing loss; however, the magnitude of the high frequency hearing loss varied. With few subjects demonstrating a steeply sloping high frequency hearing loss, the likelihood of identifying benefit and the degree of benefit from the frequency lowering is reduced according to Glista and colleagues.

According to Starkey's Spectral iQ candidacy criteria, none of subjects who participated in this study were truly candidates for a fitting with Spectral iQ (Glista, ND). The majority of the subjects met the first criteria of having audiologic thresholds at or better than 55 dB HL below 1000 Hz. The majority of the subjects did have a high frequency hearing loss slope greater than or equal to 25 dB HL per octave. Only half the subjects had a single threshold between 1 and 3 kHz at 55 dB HL or worse. Lastly, all but 1 subject had thresholds worse than 55 dB HL between 4000 and 8000 Hz. Unfortunately, due to limited access to subjects, the results of this study could have been affected by the improper fitting of Spectral iQ.

### **Acclimatization to frequency lowering**

Acclimatization has been studied for many years and has been known to aid in the performance of those who are fit with frequency lowering hearing aids. Several studies evaluated auditory training and found that this training allows the subject to better adjust to the difference in sound quality of a frequency-lowered signal. Additionally, the subject is trained to utilize the lowered, and now audible high frequency information.

According to several studies Biondi & Bondi, 1973, Ling, 1968, and Oeken, 1963 frequency lowering algorithms in addition to training allow for improved intelligibility of speech (as cited in Simpson, 2009). However, McDermott and Dean, 2000, explained that the effect of training using frequency-transposed speech had no significance on performance following 10 weeks of training. With contradictory evidence on auditory training using frequency lowering, the lack of significance in this study should not be attributed to auditory training at this time.

### **Differences in proprietary algorithms**

Lastly, frequency-lowering algorithms used by hearing aid manufacturers are proprietary. Educated guesses and backward engineering allow us a glimpse into this technology we are evaluating and utilizing in the clinic daily. When comparing the results of frequency lowering strategies from different manufacturers a variety of results can be identified. Starkey's proprietary algorithm utilizes frequency lowering and more specifically adaptive frequency lowering. With this algorithm, the bandwidth is maintained and the application of the frequency lowering is transient. In contrast, frequency compression strategies used by Phonak and GN ReSound compress the high

frequency information and therefore reduce the bandwidth of the signal for all inputs. When comparing a traditionally amplified signal to the aforementioned lowering strategies, one can accept the differences in frequency compression are greater than frequency lowering. According to Plyler and Fleck, and Turner and Henry, audibility can significantly improve speech understanding for those with sloping high frequency sensorineural hearing losses (Plyler & Fleck, 2006; Turner & Henry, 2002). Starkey's algorithm maintains the frequency bandwidth, and this might explain why the data did not reveal a significant difference between groups in the current study.

## **Conclusions**

Based on our seven subjects, Spectral iQ is neither a benefit nor a detriment to the hearing aid wearer. Subjects had no adverse reactions to the programming algorithm. In fact, two of our of seven subjects strongly preferred and three subjects were neutral in preference for the sound quality of music when using Spectral iQ.

From a clinical perspective, based on results of this study and other reported findings, it is recommended that frequency lowering algorithms be available as an option for individual patients. Based on the current findings it is anticipated that most patients may not benefit from frequency lowering, some individuals might find the sound quality more acceptable than conventional amplification algorithms.

## Appendix I

**CUNY Nonsense Syllable Test (NST)**

Instructions:

You are about to hear several nonsense syllables (e.g. OT, OOF) from the loud speaker directly in front of you. Each syllable will be spoken by a male talker embedded in a sentence (e.g. you will mark OT please). Your task is to identify the syllable spoken by the talker and circle the one you thought you heard. It is alright to guess. Once you have completed the answer for the first sentence, I will play the next sentence. You can take a break between sentences if you need one.

**Test 1M****Page 1**

1. OTT    OTH    OSH    OFF    OPP    OSS    OKK

2. OTT    OTH    OSH    OFF    OPP    OSS    OKK

3. OTT    OTH    OSH    OFF    OPP    OSS    OKK

4. OTT    OTH    OSH    OFF    OPP    OSS    OKK

5. OTT    OTH    OSH    OFF    OPP    OSS    OKK

6. OTT    OTH    OSH    OFF    OPP    OSS    OKK

**7. OTT    OTH    OSH    OFF    OPP    OSS    OKK**

**8. OTT    OTH    OSH    OFF    OPP    OSS    OKK**

**Page 2:**

**1. OOS OOT OOSH OOF OOK OOP OOTH**

**2. OOS OOT OOSH OOF OOK OOP OOTH**

**3. OOS OOT OOSH OOF OOK OOP OOTH**

**4. OOS OOT OOSH OOF OOK OOP OOTH**

**5. OOS OOT OOSH OOF OOK OOP OOTH**

**6. OOS OOT OOSH OOF OOK OOP OOTH**

**7. OOS OOT OOSH OOF OOK OOP OOTH**

**8. OOS OOT OOSH OOF OOK OOP OOTH**

**Page 3:**

**1. EEF EESH EET EEK EES EEP EETH**

**2. EEF EESH EET EEK EES EEP EETH**

**3. EEF EESH EET EEK EES EEP EETH**

**4. EEF EESH EET EEK EES EEP EETH**

**5. EEF EESH EET EEK EES EEP EETH**

**6. EEF EESH EET EEK EES EEP EETH**

**7. EEF EESH EET EEK EES EEP EETH**

**8. EEF EESH EET EEK EES EEP EETH**

**Page 4:**

**1. OB ON OD OG OM OZ OTH ONG OV**

**2. OB ON OD OG OM OZ OTH ONG OV**

**3. OB ON OD OG OM OZ OTH ONG OV**

**4. OB ON OD OG OM OZ OTH ONG OV**

**5. OB ON OD OG OM OZ OTH ONG OV**

**6. OB ON OD OG OM OZ OTH ONG OV**

**7. OB ON OD OG OM OZ OTH ONG OV**

**8. OB ON OD OG OM OZ OTH ONG OV**

**9. OB ON OD OG OM OZ OTH ONG OV**

**10. OB ON OD OG OM OZ OTH ONG OV**

**Page 5:**

1. FA SA CHA PA TA SHA KA THA HA

2. FA SA CHA PA TA SHA KA THA HA

3. FA SA CHA PA TA SHA KA THA HA

4. FA SA CHA PA TA SHA KA THA HA

5. FA SA CHA PA TA SHA KA THA HA

6. FA SA CHA PA TA SHA KA THA HA

7. FA SA CHA PA TA SHA KA THA HA

8. FA SA CHA PA TA SHA KA THA HA

9. FA SA CHA PA TA SHA KA THA HA

10. FA SA CHA PA TA SHA KA THA HA

**Page 6:**

**1. DA      BA      WA      RA      LA      YA      GA      JA**

**2. DA      BA      WA      RA      LA      YA      GA      JA**

**3. DA      BA      WA      RA      LA      YA      GA      JA**

**4. DA      BA      WA      RA      LA      YA      GA      JA**

**5. DA      BA      WA      RA      LA      YA      GA      JA**

**6. DA      BA      WA      RA      LA      YA      GA      JA**

**7. DA      BA      WA      RA      LA      YA      GA      JA**

**8. DA      BA      WA      RA      LA      YA      GA      JA**

**9. DA      BA      WA      RA      LA      YA      GA      JA**

**Page 7:**

**1. BA DA VA ZA GA NA THA MA**

**2. BA DA VA ZA GA NA THA MA**

**3. BA DA VA ZA GA NA THA MA**

**4. BA DA VA ZA GA NA THA MA**

**5. BA DA VA ZA GA NA THA MA**

**6. BA DA VA ZA GA NA THA MA**

**7. BA DA VA ZA GA NA THA MA**

**8. BA DA VA ZA GA NA THA MA**

**9. BA DA VA ZA GA NA THA MA**

## Appendix II

**Sound quality of music**

**Directions:** This portion of the study is looking at the sound quality of the hearing aids using 5 different musical selections. Each 15-second music clip will be played twice. After the second presentation of each music selection, circle either 1 (for the first presentation) or 2 (for the second presentation) to indicate your preference of **OVERALL** sound quality.

Music selection 1:

**1**

**2**

Music selection 2:

**1**

**2**

Music selection 3:

**1**

**2**

Music selection 4:

**1**

**2**

Music selection 5:

**1**

**2**

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