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The effects of frequency lowering on speech perception in noise with adult hearing aid users

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Abstract

Objective—Frequency lowering (FL) strategies move high frequency sound into a lower frequency range. This study determined if speech perception differences are observed between some of the different frequency lowering strategies that are available.

Design—A cross-sectional, repeated-measures design was used to compare three hearing aids that used wide-dynamic range compression (WDRC) and either non-linear frequency compression (NFC), linear frequency transposition (LFT), or frequency translation (FT). The hearing aids were matched to prescriptive real ear targets for WDRC. The settings for each FL strategy were adjusted to provide audibility for a 6300 Hz filtered speech signal. Sentence recognition in noise, subjective measures of sound quality, and a modified version of the speech intelligibility index (SII) were measured.

Study Sample—Ten adults between the ages of 63 to 82 years with bilateral, high frequency hearing loss.

Results—LFT and FT led to poorer sentence recognition compared to WDRC for most individuals. No difference in sentence recognition occurred with and without NFC. The quality questionnaire and SII showed few differences between conditions.

Conclusion—Under similar fitting and testing conditions of this study, FL techniques may not provide speech understanding benefit in certain background noise situations.

Keywords

frequency lowering; hearing aids; speech perception

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Declaration of Interest

The authors report no declarations of interest.

BACKGROUND

One goal of amplification is to provide audibility across the speech spectrum; however, many individuals with high frequency sensorineural hearing loss (SNHL) are unable to achieve audibility from traditional hearing aid processing. A significant amount of linguistic information is present in the high frequencies and audibility of high frequency speech sounds, particularly consonants, is crucial for optimal recognition of speech in quiet and noise (Wolfe et al., 2011; Stelmachowicz et al., 2007, 2008). Stelmachowicz and colleagues (2007) demonstrated that restricted stimulus bandwidth, such as that in hearing aids, can negatively affect the perception of /s/ and /z/ spoken by female talkers. Audibility of high frequency cues is even more important in background noise, where a wider bandwidth is required to equate performance to that obtained in quiet (Silberer et al., 2015). For more information on the contribution of high frequency information to speech perception, see the introduction of Alexander et al. (2014).

The bandwidth provided by hearing aids has improved over time due to higher sampling rates and receivers with wider bandwidths, some of which now reportedly extend to 10000 Hz (Kreisman et al., 2010; Kuk & Baekgaard, 2009). However, because the level of the speech signal decreases at higher frequencies more gain is required to achieve consistent audibility than at lower frequencies. Higher amounts of gain can lead to distortion and acoustic feedback, which may make extended bandwidth only possible for listeners with milder losses (McCreery et al., 2012). Additionally, individuals with steeply sloping losses are more likely to have high frequency dead regions, and therefore may not benefit from high frequency amplification provided by extended bandwidth hearing aids (Moore, 2004; Ricketts et al., 2008).

Various signal-processing strategies have been designed as an alternative to extended bandwidth with the aim of presenting information from high frequency components of speech at lower frequencies (Simpson et al. 2006). Collectively known as frequency lowering (FL), these algorithms relocate high frequency acoustic information to lower frequency regions. Typically individuals have better hearing in the lower frequency regions, and less gain is required to achieve audibility. At the time of this study, there were three approaches to FL available in commercial hearing aids: nonlinear frequency compression (NFC), linear frequency transposition (LFT), and frequency translation (FT).

Nonlinear frequency compression moves high frequency information to low frequencies by compressing the energy on a log scale above the cut off frequency. There is no overlap between the shifted and un-shifted signal, and frequency information below the cut off frequency remains preserved. A disadvantage of this method is that the harmonic ratios above the cut-off frequency are not preserved (McDermott, 2011), which could negatively affect speech perception. For the most widely used variant of LFT, frequencies up to two octaves above the designated start frequency are lowered linearly to one octave below the start frequency and added to the unprocessed lower frequency signal. An advantage of this method of lowering is that the harmonic relationship of the transposed signal is preserved. However, the overlap of high and low frequency information has the potential to mask useful information (Simpson, 2009). Frequency translation (FT) is similar to the transposition

method of LFT, however FT retains the original signal while simultaneously transposing the high frequency signal. Also referred to as Spectral Envelope Warping (e.g., Alexander, 2013), FT is an adaptive algorithm that only implements FL when a high frequency emphasis input is detected (Galster et al., 2011). For a comprehensive description of these strategies, see Alexander (2013).

Although studies on FL do not always demonstrate improved speech recognition, multiple studies investigating the use of this technology in adult and pediatric populations with hearing impairment have reported significant perceptual benefits compared to conventional amplification (Simpson et al., 2005; Alexander et al., 2008; Auriemma et al., 2009; Kuk et al., 2009; Glista et al., 2009; Wolfe et al., 2010; Gou et al., 2011; Alexander, 2012; McCreery et al., 2012, 2014). Most studies to date compared each FL technology to a condition without FL. While the methodologies have varied, in general studies have shown benefit in quiet and noisy environments with FL activated compared to conventional processing (Simpson et al., 2005, 2006; Auriemma et al., 2009; Galster et al., 2011; Glista et al., 2009; Kuk et al., 2009; Bohnert et al., 2010; Robinson et al., 2007; McCreery et al., 2014; Wolfe et al., 2010; Gou et al., 2011). However, mixed findings among participants in the same study and across studies have complicated the matter of determining how and when to use FL (McCreery, 2012).

Although research has demonstrated the perceptual benefits of each of the three FL techniques relative to conventional amplification, no study to date has compared the three currently available methods on the same population. This information would be useful for clinicians when selecting a frequency lowering technology for a patient. Alexander et al. (2014) compared NFC and LFT using high-frequency loaded fricatives and affricates in speech-shaped noise at 10 dB SNR in listeners with hearing loss. Fricative and affricate identification was poorer with LFT activated compared to deactivated, while identification was the same with NFC activated compared to deactivated. Further analysis using confusion matrices suggest that with LFT activated, /s/ and /z/ were significantly confused with other sounds compared to performance with LFT deactivated. With NFC activated compared to deactivated, no significant patterns of confusions were made. These results would suggest that performance would be better with NFC compared to LFT due to fewer confusions being made with NFC in listeners with hearing loss.

The aim of the present study was to evaluate if differences in speech perception in noise are observed between three different FL strategies (NFC, LFT, FT) and conventional wide dynamic range compression (WDRC) processing. The choice was made to include a WDRC condition because each manufacturer implements WDRC using different time constants and kneepoints. We hypothesized individuals with sloping high frequency sensorineural hearing loss would show improved speech perception in noise with FL active over WDRC processing because of the added audibility of high frequency speech sounds. We further hypothesized that NFC would provide greater benefit than LFT and FT, due to less distortion of the signal with NFC.

METHOD

Participants

Ten adults between the ages 63 to 82 years (5 males, 5 females, mean = 70.9 years) were recruited from the University of Washington Communication Studies Participant Pool. Each participant voluntarily signed a written consent form approved by the UW Institutional Review Board and were offered \$10/hour upon completion of the study. All participants had bilateral downward sloping high frequency SNHL and were current binaural hearing aid users. Table 1 lists participant demographics including age, sex, personal hearing aids, amount of experience with amplification and previous experience with FL. Hearing aid programming was read from the software, when available, to determine if they were currently using FL technology. Four participants had previous experience with NFC and one participant had experience with FT. Participant 7 did not have experience with any FL technology. For the remaining four participants, we were unable to read the programming from their hearing aids and consequently their experience with FL technology was unknown. Unaided pure-tone air conduction thresholds for frequencies 250–8000 Hz and bone conduction thresholds from 250–4000 Hz were obtained in both ears prior to participation in the study. Figure 1 shows average hearing thresholds for each participant.

Hearing Aid Fitting

Each participant was fit binaurally with three commercially available behind-the-ear hearing aids. Each hearing aid used WDRC processing and one of either FL strategy (NFC, LFT, or FT). The hearing aid used for NFC processing was the Phonak Ambra (16 channels, 129 dB SPL maximum output, 60 dB maximum gain), for LFT processing was the Widex Mind 440 (15 channels, 124 dB SPL maximum output, 56 dB maximum gain), and for the FT processing was the Starkey 3 Series i110 (16 channels, 126 dB SPL maximum output, 65 dB maximum gain). The hearing aids were coupled to either comply tips or the participant's own earmolds (participants 2 and 7). Advanced features such as digital noise reduction and automatic program selection were disabled. All instruments were set to have an omnidirectional microphone. Each device was programed to have two manual programs; program 1 = FL off, and program 2 = FL on. Using individual measures of the real-ear-to-coupler difference (RECD), the hearing aids were matched to NAL-NL2 or NAL-NL1 (participants 8, 9 and 10) targets in the WDRC condition using the standard speech signal presented at 65 dB SPL in the Verifit (Audioscan, Dorchester, Ontario). For each ear, the FL strategy was set to provide audibility for the peak of a 6300 Hz filtered speech signal in the Audioscan Verifit with the lowest settings possible, while preserving the maximum audible bandwidth established in the WDRC condition (Glista & Scollie, 2009). Maximum audible bandwidth was defined as the highest frequency at which the aided long-term-average-speech spectrum last crossed threshold to become inaudible.

The fitting procedure resulted in average output levels of each HA without FL activated being within 2 dB of each other from 250–4000 Hz and within 3 dB of each other at 6000 Hz using the standard speech signal in the Audioscan Verifit presented at 65 dB SPL. A repeated-measures ANOVA showed no significant main (hearing aid model, frequency) or interaction effects ($p > .05$). The maximum audible frequency was 4000 Hz on average for

all three hearing aids without FL activated. With frequency lowering activated to settings described in the previous paragraph, a set of four measures were taken using the filtered speech stimuli (3150, 4000, 5000, 6300 Hz) in the Audioscan Verifit. Output frequency was defined as the highest amplitude in the output range from 1500 to 6000 Hz. Averaged across subjects, Figure 2 shows the output frequencies for each device as a function of input frequency peak of the filtered speech stimuli (e.g., 3150, 4000, 5000, 6300 Hz). In the NFC condition, as the input frequency increases, the output frequency also increases, with an output range from approximately 2700 to 4100 Hz. With NFC, all input frequencies were lowered by some amount, ranging from 450 Hz to 2200 Hz. The LFT condition also shows lowering for all input frequencies, but with more lowering for higher frequency inputs than NFC. Output frequencies ranged from 2900 to 3400 Hz on average. The results of LFT processing would be different if input frequencies were presented simultaneously, as the amount of lowering would depend on the dominant frequency in the input. In the FT condition, input frequencies of 3150 and 4000 Hz were not lowered for any individual. In contrast, the 6300 Hz signal was lowered to 3000 Hz for all individuals, which is consistent with previously presented data (Cord et al., 2013). The 5000 Hz input resulted in an average output of 4000 Hz.

Speech Intelligibility Index

Audibility was assessed for each condition using a modified speech intelligibility index (SII) procedure for FL processing (Bentler et al., 2011; Bentler et al., 2014; McCreery et al., 2014). The unmodified SII was calculated by filtering speech into 1/3-octave bands, computing the sensation level of the amplified signal in each band, and then multiplying the sensation level by an importance function for each band. The SII provides a number between zero and one, with zero representing no audibility and one indicating complete audibility of speech. The modified SII differs from the unmodified SII by computing the sensation level based on the frequency region of the relocated signal (with method used for Figure 2), but using the source frequency region for the importance function.

Speech Testing

The signal-to-noise ratio (SNR) required to achieve 50% correct performance (SNR-50) was measured for each condition (FL and WDRC) in three hearing aid models using the American English Matrix Sentence Test in Noise. This test is an American English version of the Oldenburg Sentence Test (Wagner et al., 1999) created by the Center of Competence for Hearing Aid System Technology (HörTech gGmbH, 2014) in Oldenburg, Germany (Kreisman et al., 2013). The test is composed of a 50-word matrix, which includes ten names, verbs, numerals, adjectives and nouns. Each test list consists of twenty sentences spoken by a female talker, with each sentence containing a name, verb, number, adjective, and object selected from the matrix (e.g., “*Nina bought sixty cheap houses*”). The background noise was a steady-state, speech-shaped noise filtered to match the long-term average speech spectrum of the Matrix sentences.

Subjective Sound Quality

Subjective sound quality was assessed for each condition using a questionnaire (Table 2). The questionnaire included five questions that addressed sound quality, which were

answered on a 7-point response scale, and one yes/no question, which asked whether the participant would want to try the device in a real world situation. The questionnaire also included a section for the participant to provide written feedback on the sound quality of the device.

Procedure

Speech perception in noise with each device in both programs was assessed. All testing was conducted in an acoustically treated soundbooth. The sentences and competing noise were presented from a computer routed to a loudspeaker (Tannoy, Di 5DB, North Lanarkshire, Scotland). Participants were seated 1 meter from the loudspeaker at 0° azimuth. They were instructed to remain facing the loudspeaker at all times throughout the testing session and to repeat exactly what they heard. The presentation order of the hearing aids, FL conditions, and the stimulus lists were randomized across participants prior to data collection. Training consisted of one of the WDRC conditions, randomly selected, presented at a fixed SNR of 0 dB. To ensure that the participant could complete the task, participants were required to achieve at least 80% recognition. If 80% could not be achieved, the SNR was increased by 5 dB until they achieved 80% recognition. Then each participant completed a practice trial using the adaptive procedure described later. Each device was tested under two conditions, FL deactivated (NFC-off, FT-off, LFT-off) and FL activated (NFC, FT, LFT), and two lists were presented for each condition. Starting at an SNR of 0 dB and a noise level of 65 dB SPL, the presentation level of the sentences was varied using an adaptive procedure (Brand and Kollmeier, 2002). Within a trial, if 3–5 words were repeated correctly, the speech level was reduced. If less than three words were repeated correctly, the speech level was increased. The test stopped after 20 trials. Thresholds for 50% correct were estimated with a logistic model function and maximum likelihood criterion as described by Brand and Kollmeier (2002). After completing two tests lists for a given condition, participants were given the subjective quality questionnaire to fill out before moving on to the next condition.

ANALYSIS

The results of each condition were compared using a repeated-measures ANOVA with signal processing (WDRC and FL) and hearing aid model (NFC, LFT, FT) as the within-subject factors. Post-hoc analysis was completed using paired t-tests.

RESULTS

Figure 3 displays SNR-50 thresholds for each condition; lower thresholds indicate better performance. The mean SNR-50 thresholds for HA model NFC, LFT, and FT were -5.12 , -5.55 , and -4.94 dB, respectively. A repeated-measures ANOVA showed a significant main effect of hearing aid model, $F(2,18) = 4.716$, $p=.023$. Thresholds for the LFT model were statistically better than thresholds for the NFC model, $F(1,9)=5.760$, $p=.04$, and the FT model, $F(1,9)=7.292$, $p=.024$. Other contrasts were not statistically different. The main effect of processing was also statistically significant, $F(1,9)=14.605$, $p=.004$, with thresholds for WDRC (-5.6 dB) being significantly better than thresholds for FL (-4.8 dB).

The interaction between HA model and signal processing condition was also significant, $F(2,18)=8.740$, $p=.002$. Mean (and standard deviation) SNR-50 values for NFC-off, NFC-on, LFT-off, LFT-on, FT-off, and FT-on were: -5.19 (1.6), -5.06 (1.6), -5.86 (1.3), -5.25 (1.7), -5.70 (1.4), and -4.19 (1.3), respectively. Paired t-tests were conducted between the WDRC and FL condition within each device. Activation of FL did not significantly change scores for the NFC device ($p=.73$), but FL did significantly cause thresholds to increase (i.e. poorer) in the LFT ($p=.03$) and FT ($p=.0001$) devices.

Mean (and standard deviation) SII values for NFC-off, NFC-on, LFT-off, LFT-on, FT-off, and FT-on were: $.65$ (.13), $.65$ (.13), $.65$ (.15), $.66$ (.15), $.66$ (.13), and $.66$ (.14), respectively. No statistically significant differences in SII between conditions were found with the fitting method used in this study. The results of the subjective questionnaire, shown in Table 2, showed very few differences between conditions.

DISCUSSION

This study evaluated speech perception in noise between FL strategies and WDRC processing and determined whether a particular FL strategy led to better perception than other FL strategies. FL did not improve sentence recognition in noise compared to WDRC. However, with LFT and FT activated, significantly poorer thresholds were found than when FL was not activated. Consistent with our hypothesis, FL processing that resulted in overlap of the original and lowered frequencies resulted in the least benefit (i.e. showed a decrement) than FL processing that did not overlap the transposed frequencies (NFC). However, the subjective questionnaire showed no differences between conditions, suggesting listeners did not notice the decline in speech understanding under these conditions.

The use of different fitting methods across studies may have contributed to the contrasting findings across studies. Methods used include manufacturer default settings (e.g., Gou et al., 2011; McCreery et al., 2013), detection of /s/ (e.g., Auriemma et al., 2009), maximizing audibility with the Verifit band-passed speech (e.g., Glista et al., 2009; Wolfe et al., 2010, 2011), SoundRecover fitting assistant (Alexander, 2013; McCreery et al., 2013; McCreery et al., 2014), listener preference (e.g., Bohnert et al., 2010), and edge frequency of dead regions (e.g., Robinson et al., 2007). Few studies have comparatively evaluated each fitting method. Our method was previously found to result in improved speech recognition in quiet and in noise with NFC processing (Wolfe et al., 2010, 2011). It is not clear why we saw degraded speech understanding with LFT and FT processing. Our SII estimates demonstrated that audibility did not change with FL activated, suggesting we could have been too conservative in estimating when the lowered band was audible enough while maintaining the maximum audible frequency. However, in our quest to match the output of the three devices output, settings for a given strategy may have been stronger than recommended by the manufacturers. Consequently, excessive distortion without concurrent improvement in audibility may have occurred. Further research is needed to determine optimal FL settings for each strategy.

Audibility (SII)

The lack of improvement in SII could be explained by multiple factors. In some cases, we were unable to achieve audibility of the lowered signal due to the degree of hearing loss and limitations of the fitting software. It is also possible that we were too conservative in the fitting method we used, erring on the side of not reducing the maximum audible bandwidth. A third possibility is that the SII method underestimated the output achieved in that frequency band due to using a filtered input signal. If the filtered and lowered signal did not fall within a single amplitude-compression channel, a lower dB SPL at the output would occur than if the full spectrum had been used. Furthermore, because FT only lowers when the processing detects spectral peaks the output level of the lowered signal with the Verifit was likely underestimated. Even though SII did not change, speech thresholds in noise were significantly lower for two of the three types of FL processing, suggesting that our method of measuring the SII underestimated audibility of the lowered signals.

Stimuli

The majority of studies have used high frequency weighted stimuli with little contextual information, such as phoneme or plural recognition (Alexander et al., 2014; Auriemma et al., 2009; Glista et al., 2009; Glista et al., 2012; Simpson et al., 2005; Wolfe et al., 2010). Phonemes with high frequency energy, such as affricates and fricatives, can contain frequencies beyond the bandwidth of conventional processing and therefore may potentially be more audible with FL. However, improvements with FL for this type of stimuli may overestimate the magnitude of improvement and generalizability (McCreery et al., 2014). Other studies have evaluated word recognition (Gou et al., 2011; McDermott et al., 2000;) while others have measured sentence recognition (Souza et al., 2013; Bohnert et al., 2010; Wolfe et al., 2010), which has the advantage of assessing the perception of multiple speech sounds within one trial (Hochmuth et al., 2012) and has better real-world validity. The American English Matrix Sentence Test in Noise was chosen to evaluate speech understanding in noise because it was designed to have high sensitivity to audibility changes and reliability, while maintaining real-world generalizability through the use of sentences. Although the Matrix sentences do not emphasize high frequencies and therefore may not be as sensitive to the high frequency emphasis provided by FL strategies, we were able to detect differences between the three FL strategies that were evaluated. However, it is possible that the benefit from FL observed would have been different had we used high-frequency weighted stimuli.

Effects of Noise

Although outcomes in quiet listening conditions have generally been positive with FL (Auriemma et al., 2009; Kuk et al., 2009; Wolfe et al., 2010; Glista et al., 2009; Bohnert et al., 2010), improvement in noise has not consistently been demonstrated (e.g., Wolfe et al., 2010, 2011; McCreery et al., 2014). The most frequently reported difficulty associated with hearing loss is speech understanding in the presence of background noise (Committee on Hearing Bioacoustics and Biomechanics, 1988) and improved understanding of speech in noisy settings is the hearing aid function that is most desired by hearing aid users (Kochkin, 2002; Bridges et al., 2012). Multiple studies have shown no difference in performance in

noise with LFT and NFC compared to conventional processing (Kuk et al., 2009; McDermott and Dean, 2000; Robinson et al., 2009; Wolfe et al., 2010), while others have shown an improvement with NFC compared to conventional processing (e.g., Wolfe et al., 2011; McCreery et al., 2014). A consequence of FL is that it may make audible high frequency noise that would have otherwise been inaudible with conventional amplification, which could impair speech understanding (Wolfe et al., 2010). Further research is needed to understand the interaction between background noise and FL.

Acclimatization and Training

One potential limitation was that an acclimatization period was not provided for the listeners. There is conflicting evidence in the literature about the existence and role of auditory acclimatization post hearing aid fittings. Several of these studies suggest that full benefit from FL may not be evident until up to 6 months post fitting (Kuk et al., 2009; Auriemma et al., 2009; Wolfe et al., 2010, 2011) while other studies show no acclimatization effect (Turner et al., 1996; McDermott & Dean, 2000; Dawes et al., 2013). Acclimatization effects may depend on the listener (Glista et al., 2012), the task and stimulus (Wright & Zhang, 2009) and may vary according to measurement technique and practice effects (Glista et al., 2012). Although the current study did not include an acclimatization period, half of the participants had known previous experience with FL in their personal hearing aids: four with NFC and one with FT. Despite this familiarity, these individuals did not perform better with the FL strategy they were used to listening to, compared to the other FL strategies that they did not have previous experience with. Additionally, they did not show a preference for the FL strategy they were used to using, as was indicated by the subjective quality questionnaire data. Therefore, we have no evidence to suggest that acclimatization limited performance.

Candidacy for FL

Some studies have found that individuals with greater high frequency hearing loss are more likely to benefit from FL (Glista et al., 2009; Gou et al., 2011), while other studies have concluded the opposite (Simpson et al., 2006; McDermott & Dean, 2000). Our participants had gradually sloping hearing loss, and did not show significant improvements in speech perception with FL; therefore, our data is consistent with the hypothesis that individuals with less severe high frequency hearing loss will not benefit from FL. With more severe hearing losses, there is more information that needs to be lowered into a smaller available region of audibility. These individuals are also more likely to have high frequency dead regions (Vinay & Moore, 2007); therefore, some of the lowered signal may be presented in the dead-region. Individuals with generally better hearing over a wider frequency range, particularly low and mid frequencies, may be able to extract more speech information from the lowered signal than those with more steeply sloping losses. This question of candidacy is important because some manufacturers have FL as a default setting that is automatically turned on, regardless of hearing loss profile. Other manufacturers activate FL when a certain hearing loss profile is entered into the fitting software. If clinicians are not diligent and aware of these settings, they may inadvertently fit FL for individuals with hearing losses that are not appropriate for this technology.

CONCLUSION

Using the fitting method in this study, FL techniques may not provide benefit in background noise. Methods of FL that overlap the transposed frequencies with lower frequencies may degrade speech recognition. It is recommended to use caution when activating FL, as it may degrade speech understanding in noise for some listeners. Further research is needed to determine optimal FL settings for understanding speech in noise. Although audiometrically, individuals may appear to be candidates for FL strategies, it is important that benefit from FL be verified. Clinicians should be thoughtful about deciding when to use FL and take the time to verify whether it provides benefit.

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Abbreviations

NFC	Nonlinear frequency compression
LFT	Linear Frequency Transposition
FT	Frequency Transposition
FL	Frequency Lowering
WDRC	Wide Dynamic Range Compression
SII	Speech Intelligibility Index
SNR	Signal-to-Noise Ratio

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Figure 1. Mean (and standard deviation) hearing threshold levels averaged across all participants for each ear (O = right; X = left).

Figure 2.

Average output frequencies across subjects measured in the Audioscan Verifit for a given filtered speech signal (input frequency). Conditions were Non-Linear Compression (NLC), Linear Frequency Transposition (LFT), and Frequency Translation (FT). See text for measurement details.

Figure 3.

The mean and range of SNR-50 thresholds for each condition are displayed. Conditions were Non-Linear Compression (NLC), Linear Frequency Transposition (LFT), and Frequency Translation (FT). Labels of “on” or “off” designated whether frequency lowering was activated or not. Mean (and standard deviation) thresholds for each conditions were: -5.19 (1.64), -5.06 (1.56), -5.86 (1.31), -5.25 (1.70), -5.70 (1.44), and -4.19 dB (1.35) for NFC-off, NFC-on, LFT-off, LFT-on, FT-off, and FT-on, respectively.

Table 1

Participant demographics are shown, including age (years), sex (male/female), description of their personal hearing aids, length of hearing aid use, and whether frequency lowering (FL) was activated or not.

Subject	Age	Sex	Personal Aids	Aid Use	FL Use*
1	75	M	Phonak Naida Q RIC with custom ear molds	2 weeks	NFC
2	74	F	Phonak Ambra BTE with skeleton ear molds	10 years	NFC
3	71	M	Starkey Xino 90 RIC	10	2.5 years
4	70	F	Phonak Audeo XI with open domes	1 year	NFC
5	82	F	R: Manufacturer Unknown BTE, L: Phonak Audeo S RIC	6 years	Unknown
6	65	F	Danavox BTE with custom ear molds	13 years	Unknown
7	73	M	Oticon Vigo Pro BTE with skeleton ear molds	10 years	None
8	63	M	Unitron RICs with open domes	10 years	Unknown
9	72	F	Costco RICs with closed domes	5 years	Unknown
10	64	M	Phonak Audeo Q RICs with custom ear molds	6 months	NFC

Use of frequency lowering was determined by reading the programming out of the hearing aid(s), if the necessary software was available.

RIC = receiver in the canal, BTE = behind the ear, NFC = non-linear frequency compression, FT = frequency translation, R = right ear, L = left ear.

Table 2

For each item in the quality questionnaire, the mean, standard deviation, and range of responses are shown. The rating scale is displayed under each item.

	NFC			LFT			FT		
	WDRC	FL	WDRC	FL	WDRC	FL	WDRC	FL	FL
Question 1: How understandable were the words? 1 (poor) - 7 (excellent)	Mean	3.1	2.6	2.9	3	3.3	3.2		
	SD	1.4	1.3	1.2	1.2	1.4	1.1		
	Range	1-5	1-5	1-5	1-5	1-5	2-5		
Question 2: How much effort did it take to understand the words? 1 (too much) - 7 (little)	Mean	2.2	1.9	2.1	2.1	2	2		
	SD	0.6	0.8	0.9	0.7	0.5	0.6		
	Range	1-3	1-3	1-4	1-3	1-3	1-3		
Question 3: How would you describe the quality of the set of words? 1 (shrill/too sharp) - 7 (muffled)	Mean	5.7	5.6	5.7	5.3	5.7	5.4		
	SD	1.2	1.3	0.9	1.4	0.9	1.4		
	Range	3-7	3-7	4-7	3-7	4-7	3-7		
Question 4: How clear are consonant sounds? 1 (perfectly clear) - 7 (distorted)	Mean	5.2	4.8	5.2	5.2	5	5.1		
	SD	1.8	2	1.5	1.5	1.6	1.5		
	Range	2-7	2-7	2-7	2-7	2-7	2-7		
Question 5: How would you describe the gender of the speaker based on their voice? 1 (feminine) - 7 (masculine)	Mean	1.1	1.1	1.1	1.1	1.1	1.1		
	SD	0.3	0.3	0.3	0.3	0.3	0.3		
	Range	1-2	1-2	1-2	1-2	1-2	1-2		