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Efficacy of Linear Frequency Transposition on Consonant Identification in Quiet and in Noise

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Abstract

Background: Frequency transposition has gained renewed interest in recent years. This type of processing takes sounds in the unaidable high-frequency region and moves them to the lower frequency region. One concern is that the transposed sounds mask or distort the original low-frequency sounds and lead to a poorer performance. On the other hand, experience with transposition may allow the listeners to relearn the new auditory percepts and benefit from transposition.

Purpose: The current study was designed to examine the effect of linear frequency transposition on consonant identification in quiet (50 dB SPL and 68 dB SPL) and in noise at three intervals—the initial fit, after one month of use (along with auditory training), and a further one month of use (without directed training) of transposition.

Research Design: A single-blind, factorial repeated-measures design was used to study the effect of test conditions (three) and hearing aid setting/time interval (four) on consonant identification.

Study Sample: Eight adults with a severe-to-profound high-frequency sensorineural hearing loss participated.

Intervention: Participants were fit with the Widex m4-m behind-the-ear hearing aids binaurally in the frequency transposition mode, and their speech scores were measured initially. They wore the hearing aids home for one month and were instructed to complete a self-paced "bottom-up" training regimen. They returned after the training, and their speech performance was measured. They wore the hearing aids home for another month, but they were not instructed to complete any auditory training. Their speech performance was again measured at the end of the two-month trial.

Data Collection and Analysis: Consonant performance was measured with a nonsense syllable test (ORCA-NST) that was developed at this facility (Office of Research in Clinical Amplification [Widex]). The test conditions included testing in quiet at 50 dB SPL and 68 dB SPL, and at 68 dB SPL in noise (SNR [signal-to-noise ratio] = +5). The hearing aid conditions included no transposition at initial fit (V1), transposition at initial fit (V2), transposition at one month post-fit (V3), and transposition at 2 months post-fit (V4). Identification scores were analyzed for each individual phoneme and phonemic class. Repeated-measures ANOVA were conducted using SPSS software to examine significant differences.

Results: For all test conditions (50 dB SPL in quiet, 68 dB SPL in quiet, and 68 dB SPL in noise), a statistically significant difference ($p < 0.05$ level) was reached between the transposition condition measured at two months postfitting and the initial fitting (with and without transposition) for fricatives only. The difference between transposition and the no-transposition conditions at the 50 dB SPL condition was also significant for the initial and one-month intervals. Analysis of individual phonemes showed a decrease in the number of confusions and an increase in the number of correct identification over time.

Conclusions: Linear frequency transposition improved fricative identification over time. Proper candidate selection with appropriate training is necessary to fully realize the potential benefit of this type of processing.

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In the interest of full disclosure, it should be noted that the authors are employees of Widex Hearing Aid Company, the manufacturer of the evaluated device.

Key Words: Linear frequency transposition, nonsense syllable test, training effect

Abbreviations: BTE = behind-the-ear hearing aid; LFT = linear frequency transposition; NST = nonsense syllable test; ORCA = Office of Research in Clinical Amplification (Widex); SNR = signal-to-noise ratio

People with a precipitously sloping high-frequency hearing loss may not be able to access information in the high frequencies from the use of conventional amplification. Such a difficulty may be the direct result of inadequate high-frequency amplification from the hearing aids either because of a low maximum power output level, limited bandwidth, or acoustic feedback before the desired gain is reached. More recently, it is acknowledged that such a hearing loss may result from a complete depletion of inner hair cells in the cochlea that renders the high-frequency region nonfunctional or "dead" (Moore, 2004). Acoustic stimulation of these "dead regions" may not improve performance and may even negatively affect sound quality and speech understanding (Ching et al, 1998; Turner and Cummings, 1999; Moore, 2004).

Frequency lowering has been proposed as an alternative processing strategy to restore audibility of the high-frequency sounds that are either unaidable or unreachable. The basic premise of frequency lowering is to deliver the acoustic information originally located in the high-frequency region as a lower frequency substitute (Braida et al, 1979). Thus, the lower-frequency hair cells decode the higher frequency information.

One variant of frequency lowering is *frequency transposition*. In this approach, only the high frequencies are lowered, sparing the lower frequencies (Johansson, 1961, 1966; Velmans, 1974). Typically, the high-frequency region is filtered and shifted to the lower frequency region, which is delivered to the listener without modification. This method aims to preserve the original signal in the lower frequencies as much as possible while providing audibility of the high-frequency cues. This scheme could potentially minimize the artifacts from frequency lowering such as a lower pitch perception. Unfortunately, previous studies with frequency lowering have been disappointing. The readers are urged to review Braida et al (1979) for a summary of the studies and the potential reasons for the disappointing findings such as inadequate technology, too much hearing loss, obliteration of the original speech cues, and insufficient training.

Widex Hearing Aid Company reintroduced frequency lowering as an optional signal processing feature in its Inteo family of hearing aids several years ago (see Andersen, 2006). This feature uses linear frequency transposition (LFT) to lower information above a programmable start frequency to a lower frequency region. In this algorithm, the most prominent peak located in the *source octave* (above start frequency) is identified and transposed linearly by one octave. Sounds below the start frequency are left amplified. The transposed signal is then band-pass filtered around the transposed peak with a one octave bandwidth to limit any potential masking effects. Finally, the transposed sounds are amplified and mixed with the original signal as the final output.

The LFT algorithm used is unique in several ways. First, the amount of frequency displacement at any instant in time is directly related to the location of the highest spectral peak of the original signal in the source octave. This was done to ensure that the harmonic relationship of the transposed and the original signal remains at exactly one octave for the most dominant frequency. This could preserve the naturalness and pleasantness of the output signal delivered to the listener. Second, the processing is unconditional, that is, it is active all the time. This ensures that the lowering of any high-frequency information is not dependent on the reliability of any activation criteria such as voicing detection. These design criteria may help to minimize any discontinuities in the output signal, reduce artifacts, and provide consistent processing.

A series of studies aimed at understanding the use of the LFT algorithm had been conducted. These studies were targeted at understanding how transposition may work in an ideal situation using normal hearing subjects with a simulated high-frequency hearing loss, and at how the transposition actually worked for hearing-impaired listeners. In the first study (Korhonen and Kuk, 2008), nine normal-hearing adults with a simulated hearing loss at and above 1600 Hz were tested on the identification of transposed voiceless consonants /s/, /ʃ/, /θ/, /f/, /tʃ/, /t/, /p/, and /k/ before and after they completed three 15-minute self-paced training. Transposition improved the identification scores of the stimuli by 14.4% over nontransposed stimuli after 30 minutes of training with the transposed stimuli. This study showed that frequency transposition produced acoustic cues that can be utilized by young, normal hearing subjects with a simulated hearing loss. Furthermore, the importance of auditory training was demonstrated.

In another study, Kuk, Peeters, et al (2007) reasoned that adults with a precipitous high-frequency sensorineural hearing loss fit with thin-tube, open-ear BTEs (behind-the-ear hearing aids) might be good candidates for LFT because of the potential compromise in available high-frequency output in such fittings. The authors investigated consonant recognition and subjective impressions of 13 individuals with such a hearing loss who wore binaural thin-tube, open-ear BTEs. The nonsense syllable test (NST) from Edgerton and Danhauer (1979) was used to evaluate performance at 30 dB HL and 50 dB HL input levels between the LFT and no-LFT conditions. Results indicated significant improvements of 10–15% in consonant identification in the LFT condition at both input levels. However, such benefits were not realized until after a two-week trial. These results supported the benefits of LFT in such a patient population and alluded that benefits may not be immediately realized and that a learning period is needed to reveal the potential benefits of this signal processing strategy.

More recently, Auriemmo et al (2009) studied the efficacy of LFT in 10 children between 6 and 13 years of age who had a severe-to-profound hearing loss at and above 3000 Hz. Phoneme recognition on the NST test (Edgerton and Danhauer, 1979) and /s/, /z/ articulation performance were compared among the children's own hearing aids and the study hearing aids with and without LFT. The results indicated significant improvements in vowel and consonant recognition and accuracy of fricative production after six weeks of LFT use. These results suggest that LFT is a potentially useful feature for school-aged children with a severe-to-profound high-frequency sensorineural hearing loss.

These studies pointed to the potential efficacy of LFT in quiet after the participants had used the feature in their daily lives. However, two lingering questions remain. First is the potential usefulness of such a feature in noisy situations. One may argue that with LFT, high-frequency noise that may not have been audible to a hearing-impaired person may become audible with transposition. This could increase the potential noise masking on the low-mid frequencies and result in poorer speech recognition in noise with LFT than without LFT. Unfortunately, the available evidence on this issue is limited and mixed at best. For example, Gengel and Foust (1975) reported that subjects showed no more decrement in performance compared to conventional amplification when tested with sentence materials at an SNR (signal-to-noise ratio) of +30, +15, and 0 dB. However, McDermott and Knight (2001) reported that understanding of sentences in competing noise was significantly poorer with the ImpaCt (a hearing aid that used frequency compression) than the subjects' own aids (three subjects only).

A second question relates to the mechanism of LFT. Inherent to all frequency lowering methods is that the spectrum of the input signal will be altered when the absolute positions of the peaks and valleys of the spectral envelope were changed. This raises the question on the distinctiveness of the lowered sounds from other phonemes in the nontransposed state. A consequence of that will be perceptual overlap (i.e., same acoustic cues for different phonemes). For example, a /ʃ/ that has dominant energy between 2000 Hz and 4000 Hz may be confused with a transposed /s/, which may have the same spectral content after frequency lowering (typical /s/ has energy above 4000 Hz).

In addition, the potential masking of the lower-frequency acoustic cues by the transposed high-frequency sounds (or noise) may be problematic. For example, a listener could have used the lower frequency cues to identify relatively wideband fricatives such as /ʃ/. However, transposition may move the dominant high-frequency cues into these regions and mask or distort the remaining spectrum. This could result in poorer performance with LFT than without LPT. Such possibilities had been reported in previous studies (e.g., Braida et al, 1979; Bakent and Shannon, 2006) and had been blamed for the lackluster effect of frequency lowering. On the other hand, these studies had not examined if such confusion may be reduced with training. One may speculate that as long as the high-frequency information is available, the initial confusion that may occur can be overcome with extended use of the transposed signals. The identity of the phonemes that may be affected and the changes over time may be of interest to clinicians.

The objective of the current study was to examine the efficacy of the LFT algorithm on adult hearing-impaired persons who had a severe-to-profound degree of hearing loss in the high frequencies. Specifically, their ability to identify nonsense syllables in quiet and in babble noise (eight-talker babble) will be monitored over a two-month adjustment period to examine any training/learning effect. A secondary objective was to identify the phoneme classes that may be especially sensitive to the action of LFT for this group of participants.

METHOD

Study Participants

The G*Power 3 power analysis package was used (Faul et al, 2007) to estimate the required number of participants. The data collected from the Kuk, Peeters, et al (2007) study on the use of LFT were used for estimation. Assuming that the results of this study will also show an effect size of $>13.3\%$ (the mean difference between LFT on after training and LFT off) and a standard deviation of $<10.3\%$, it was estimated that a

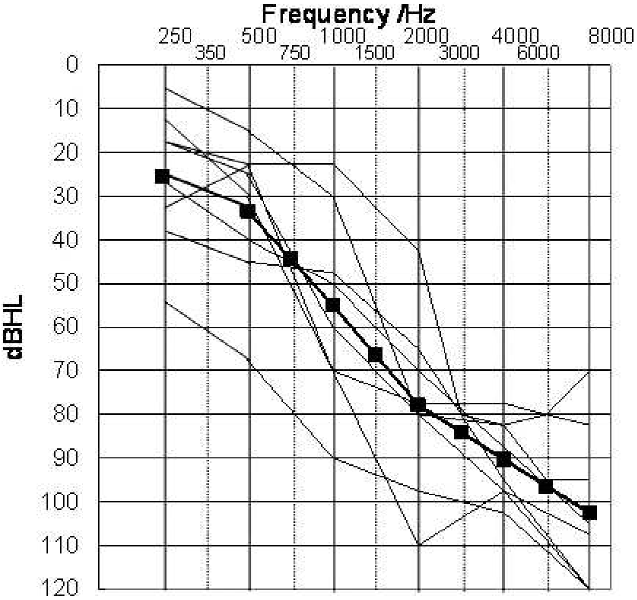

Figure 1. Averaged insert earphone thresholds for left and right ears plotted for each participant. The black line with squares shows the average of all participants.

minimum of seven participants were needed to reach statistical significance at the 0.05 level with a power greater than 0.8.

The participants were recruited from our research center database. None had participated in any studies involving frequency lowering. The criterion for selection was at least a severe-to-profound hearing loss above 2000 Hz (with one exception) but no more than a moderate-to-severe hearing loss in the low-to-mid frequencies. Using this criterion increased the likelihood that the hearing loss in the high frequencies was not aidable but that the hearing loss in the low-mid frequencies may be appropriately amplified and could use the transposed sounds. Ten participants met the requirement and were recruited into the study. However, the current data set was based on eight participants because one died during the course of the study and one withdrew because he refused to wear behind-the-ear hearing aids.

All eight remaining participants were native English speakers who had some hearing aid experience through previous hearing aid research or with their own hearing aids. Two participants did not own any hearing instruments; three had stopped using their own instruments due to a lack of perceived benefit; and three were using amplification consistently. The hearing aids worn by these three participants were all conventional multichannel digital compression hearing aids. All participants were explained the purpose of the study, their tasks, their risks, and their benefits prior to signing their consent. They were financially compensated for their participation.

All hearing losses were sensorineural in nature and were within ±10 dB between ears at any frequency. Thus, the audiograms for the right and left ears of each participant were averaged and displayed in Figure 1. The average of all participants was shown as the black line with squares.

Hearing Instrument

The current study was conducted using the Widex Mind440 (m4-m) digital micro BTE hearing aid (one participant used the m4-19 model, which was a power BTE with the same features). This hearing aid incorporated 15-channel slow-acting compression with a 107 dB SPL input dynamic range. The frequency bandwidth extended from 100 to 7450 Hz (ANSI S3.22-2003). The audio sampling rate was 32 kHz with a 32-bit sample resolution. The hearing aid had two noise reduction options. The directional microphone was fully adaptive in all its 15 channels. In addition, active feedback cancellation in both microphone paths as well as a vent estimation and compensation algorithms were available. Because these features were meant to be activated during daily use of the hearing aids, they were left activated during the data collection. These features should not affect the comparison between the LFT and no-LFT conditions.

The optional linear frequency transposition algorithm on the study hearing aid had two clinician adjustable parameters, *start frequency* and *LFT gain*, to meet the needs of individual hearing aid wearers. The start frequency had ten values between 630 and 6000 Hz in 1/3-octave intervals. The LFT gain was an additional gain applied to the transposed sounds. It could be increased by 14 dB or decreased by 16 dB relative to the default level. The LFT algorithm also included an option for clinicians to extend the source octave to include two octaves above the start frequency, thus allowing wider frequency coverage when low start frequencies were used.

To facilitate the ease of clinical fitting, the LFT program defaulted automatically to a start frequency based on the individual's hearing threshold. Specifically, the start frequency was taken as the lowest frequency where the aided long-term average speech spectrum intersected with the in-situ threshold (i.e., sensogram) of the wearer. It is recognized that this consideration is based simply on the audibility of the aided speech spectrum. Practical experience with this algorithm suggested that, especially for adult wearers, individual differences in subjective preference/acceptance for the transposed sounds should also be considered in the final choice of the start frequency. Thus, we took a custom approach to set the start frequency and the LFT gain in this study (Kuk, Keenan, Peeters, Korhonen, et al, 2007). Briefly, a recorded, interrupted /s/ sound was played through the audiometer at a dial reading of 30 dB HL. The participants, while wearing the study hearing aids at their default gain settings (without LFT) would indicate if the /s/ sound was audible and distortion-free. If the /s/ sound was not audible, or audible with distortion, the study clinician would activate the LFT program at the highest start frequency (i.e., 6000 Hz) and repeat the presentation. A positive identification of the /s/ sound would leave the start frequency at 6000 Hz; whereas a negative response would lead to a lower start frequency and/or increase in LFT gain. The highest start frequency (and the lowest LFT gain) where the participant can first identify the /s/ sound was taken as the start frequency and LFT gain setting. For start frequencies at or below 2500 Hz, an expanded transposition was used where two octaves of sounds in the source region were transposed (rather than one octave). The specific parametric settings for each of the eight participants were shown in Table 1. The start frequency selected by the individual approach was typically the same or one step higher than the default start frequency (i.e., less transposition when individual preference was considered).

Table 1. Parametric Settings Used by Participants in the Study

Participant #	Default SF (Hz)	Expanded LFT?	LFT Gain (dB)
1	2500	No	0
2	3200	No	6
3	2000	Yes	10
4	2000	Yes	0
5	2000	Yes	8
6	3200	No	0
7	3200	No	0
8	3200	No	4

Test Materials

Nonsense Syllable Test Developed at Widex Office of Research in Clinical Amplification (ORCA-NST)

An objective of the study was to identify the types of phonemic errors made by the participants with and without LFT over time. Because of the number of times that the test will be repeated for the different test conditions, a test that exhibits minimal learning effect will be desirable. The test should ideally include all phonemes in all word positions so that an analysis of the phonemic errors may be possible. Because the intended actions of a frequency-lowering algorithm involve the high-frequency sounds, the test materials must include phonemes that have sufficient high-frequency output. This would suggest that a computer-controlled, randomized nonsense syllable test that includes all phonemes read by a female talker may be desirable. Because such a test was not commercially available, we created our own test for this evaluation.

Details on the development of the nonsense syllable test (ORCA-NST) were reported in another article (Kuk et al, 2009). Briefly, the full version of the ORCA-NST included 23 consonantal phonemes (/m/, /n/, /ŋ/, /j/, /b/, /d/, /g/, /v/, /w/, /r/, /l/, /z/, /dʒ/, /ð/, /θ/, /f/, /ʒ/, /s/, /ʃ/, /tʃ/, /p/, /t/, /k/), each appearing in the initial, medial, and final positions of a CVCVC (consonant-vowel-consonant-vowel-consonant) syllable (unless it was impossible, such as having the /ŋ/ in the initial or medial positions). Five vowels (/ʊ/, /æ/, /i/, /Λ/, /a/) representing the range of the F1–F2 formant chart were used. This combination of consonants and vowels in the specific phoneme positions resulted in 115 unique nonsense syllables. In order to shorten the evaluation time for this study, the number of items on the test was reduced to 32 while keeping the relative ratios of each class of phonemes between the original and simplified versions of the ORCA-NST. Obviously, not all the phonemes would appear with the same frequency or in every word position as in the full version. The simplified list took approximately five to seven minutes to complete. A complete listing of the test syllables is included in Appendix 1.

These syllables were spoken by a female native English speaker and recorded in a low-noise ($L_{A,\ slow}$ = 22 dB SPL) double-walled audiometric test booth (3 m × 3 m × 2 m). The audio sampling frequency used for these recordings was 44.1 kHz. All the stimuli were normalized to the same maximum peak RMS level using a 50 msec sliding window. A custom program using Visual Basics was written to randomly present these nonsense syllables and to score the participants' responses. The automatic phonemic scoring provided us an immediate appreciation of the types of confusion that the listeners experienced with the study hearing aids under different test conditions and intervals.

Babble Noise

The babble noise was generated in house in order to ensure that it has the desired properties. The source material, which originated from audiobooks in the public domain, was read by two male and two female talkers. The original recordings were sampled at 44.1 kHz. Their spectra were analyzed to ensure that they have energy up to 16 kHz. Each passage was 30 sec long and was equalized for maximum RMS level in a 50 msec sliding window. A custom Matlab script was written to generate various versions of speech babble (i.e., 4 talkers, 8 talkers, 16 talkers, etc) from these source materials. An informal subjective listening test indicated that using 8 talkers (4 talkers × 2 streams) created a speech babble that allowed

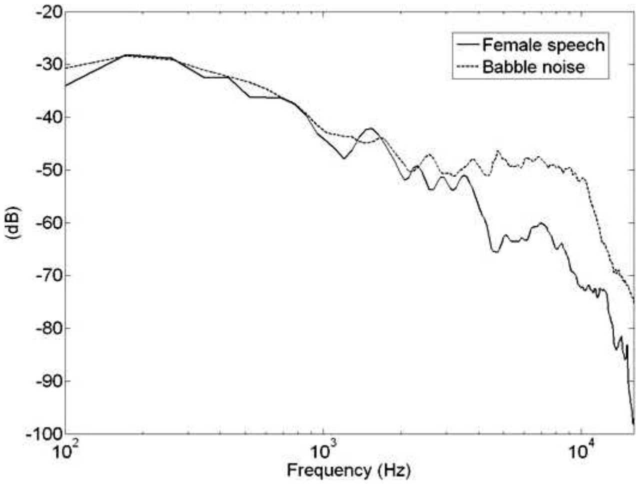

Figure 2. Speech (ORCA-NST) and noise (eight-talker babble) spectra used in the study.

occasional identification of individual words but disallowed comprehension of any individual talker. This was subsequently confirmed by analyzing its modulation spectra using a tool developed for Matlab at Interactive Systems Design Laboratory at University of Washington (http://isdl.ee.washington.edu/projects/modulationtoolbox/). Figure 2 shows the spectra of the speech and noise stimuli.

Training Materials

We developed a self-training program to facilitate the use of the LFT program (Kuk, Keenan, Peeters, Lau, et al, 2007). The program was PC-based and provided its users with directed "bottom-up" training on voiceless consonant and vowel sounds. Each day the participants' attention was directed to a different sound. The speech sounds that were targeted include /p/, /t/, /k/, /s/, /f/, /θ/, /ʃ/, /tʃ/, and all the English vowels. Each sound was trained at the syllable level, the word level, and the sentence level. The materials chosen were judged to have a sixth-grade reading level and were presented in various interactive activities. To increase the generalizability of the training, three different speakers (2 female and 1 male) were used to record the training materials. It took about 20–30 min per day for the participants to complete the daily exercises.

Test Conditions

All participants were tested on the ORCA-NST in quiet at 50 dB SPL and at 68 dB SPL with the speech materials presented from a loudspeaker placed 1 m in front of the participant. In addition, the ORCA-NST was also tested at a 68 dB SPL with the eight-talker babble noise presented from the sides and back (90°, 180°, and 270°) at an SNR of +5 dB. All testing was conducted in the double-wall sound-isolated booth.

Procedures

Each participant spent a minimum of four separate sessions to complete the data collection. During the first session, the audiometric thresholds of the participants from 250 to 8000 Hz were measured using insert earphones. The participant's in-situ thresholds (i.e., sensogram) at 500, 1000, 2000, and 4000 Hz were determined with the study hearing aids coupled to thin-tube, instant occluding earmolds. Afterwards, a feedback test was performed to establish the initial estimate of the feedback path and to limit the maximum available gain on the hearing aids to minimize feedback. The appropriateness of the default fitting (without LFT) was verified by viewing the simulated real-ear output on the fitting software. Adjustments were made to ensure that the criteria for acceptable performance were made. The participants' performance with the default program (no LFT) in the binaural fitting was evaluated by administering the ORCA-NST at 50 and 68 dB SPL in quiet, and at 68 dB SPL in noise at an SNR of +5 dB. The test conditions were counterbalanced across participants.

Participants returned for a second visit (after approximately one week), during which the parameters for the transposition program was selected. The LFT program assumed the same frequency response characteristics of the default master (no LFT) program. It also assumed the fully adaptive directional microphone, active feedback cancellation, and classic noise reduction of the no-LFT program. It is not expected that these features would affect the efficacy of the LFT algorithm. Although the LFT program had its own default LFT settings, we customized the start frequency and the optimal gain for the LFT program. The participants' performance with the LFT program was evaluated with the ORCA-NST at 50 and 68 dB SPL in quiet and at 68 dB SPL at a +5 dB SNR with the babble noise.

Afterward, the hearing aids were set so that the only available program on the hearing aids was the LFT program. The study clinician instructed the participants on the use of the hearing aids and asked that they pay attention to everyday sounds. To direct their attention to sounds, a checklist of 86 everyday sounds was provided to each participant, and they were asked to seek out the specific situations and experience the new sound percept with the LFT program. To further maximize the impact of the LFT program, all participants were also provided with the training CDs for take-home use. The clinicians reviewed with the participants the tutorial on installing the CD on their home computers, and demonstrated how each exercise may be completed. A training schedule was given to the participants detailing when to be trained in quiet and when to use background noise with the training. A more detailed description of the instructions and training can be found in Kuk, Keenan, Peeters, Lau, et al (2007).

The participants returned in one month for evaluation (third visit). Again, they were tested on the LFT program with the ORCA-NST at 50 and 68 dB SPL in quiet and in noise at a +5 dB SNR. Afterward, they were sent home with the LFT program and asked to use the LFT program and to return in one month. They were instructed not to go through any training exercises.

The participants returned after another month's use of the LFT program (a total of two months altogether, fourth visit), where they were tested on the LFT program with the ORCA-NST at 50 and 68 dB SPL in quiet and in noise at a +5 dB SNR.

RESULTS

Scoring on the ORCA-NST was done on a phoneme level. Appendix 2 summarizes the absolute individual consonant scores averaged for each of the four hearing aid conditions (default, LFT initial, LFT one-month, and LFT two-months) under the three test conditions (50 dB SPL in quiet, 68 dB SPL in quiet, and 68 dB SPL at SNR = +5). To make the results more meaningful, consonant scores were displayed according to the manner of articulation (stop, fricative, nasal, approximant, and affricate). Statistical significance was examined using the SPSS software (version 12.0). A Kolmogorov-Smirnov Test for normality was first conducted to ensure normal distribution of data. General Linear Model (GLM) analysis of variance for repeated measures was performed and followed up with Bonferroni post-hoc analyses with adjustments for multiple comparisons.

A factorial repeated-measures ANOVA was used to study the effect of three independent variables: test condition (three) × hearing aid setting/time (four) × manner of articulation (five). Results showed that significance was reached in all three variables: test conditions ($F(2,14) = 20.943$, $p < 0.001$, $\eta^2 = 0.74$, power = 1.0), hearing aid/time settings ($F(3,21) = 7.382$, $p = 0.004$, $\eta^2 = 0.51$, power = 0.9), and manner of articulation ($F(4,28) = 8.434$, $p < 0.001$, $\eta^2 = 0.54$, power = 1.0).

Effect at 50 dB SPL in Quiet

Figure 3 summarizes the absolute consonant scores grouped by the manner of articulation (fricatives, affricate, stops, nasals, approximants/laterals) for the four hearing aid conditions. One observed that scores for the stops, nasals, and approximants with the LFT were slightly poorer than the default no-LFT program at the initial fitting. However, scores with the LFT gradually improved over time such that at the end of the two months, the absolute scores measured with the LFT were the same or higher than the default program for all consonant classes.

Fricatives and affricates, on the other hand, showed a different pattern. The fricative scores at the initial LFT were higher than the default master program (20% vs. 35%). This advantage increased to around 43% at the end of 2-month use of the LFT program. A Repeated-Measures ANOVA was performed to study these two within-subjects factors: consonant class (5) x HA setting (4). Results showed that consonant class was significant ($F(4,28) = 6.804$, $p = 0.001$, $\eta^2 = 0.49$, power = 0.9), and HA setting was also significant ($F(3,21) = 5.467$, $p = 0.009$, $\eta^2 = 0.43$, power = 0.8).

A post-hoc analysis using Bonferroni adjustment for multiple comparisons showed that the LFT program measured at all visits (initial, one month, and two months) was significantly different than the default no-LFT program ($p < 0.05$) only for fricative sounds. Furthermore, the comparison on the stop consonants between the LFT program measured at two months and the LFT program measured at the initial fit was significantly different ($p < 0.05$). All the other comparisons were non-significant.

Effect at 68 dB SPL in Quiet

Figure 4 summarizes the absolute consonant scores for the 4 hearing aid conditions at a conversational input level. An immediate observation is that consonant scores for the nasals and approximants were similar between the LFT and the default programs. However, consonant scores for the stops were slightly poorer with the LFT program than the master program at the initial fitting. However, the scores with the LFT gradually improved over time so that at the end of the two-month use, the absolute scores measured with the LFT were the same or higher than the default program for all consonant phoneme classes.

Fricative scores measured during the initial use of LFT were higher than the default master program (38% vs. 42%). This advantage increased to around 52% at the end of the 2 month use of the LFT program. Results of a Repeated-Measures ANOVA showed that consonant class was significant ($F(4,28) = 7.395$, $p < 0.001$, $\eta^2 = 0.51$, power = 1.0) and HA setting was also significant ($F(3,21) = 3.446$, $p = 0.035$, $\eta^2 = 0.33$, power = 0.7).

A post-hoc analysis with Bonferroni adjustment for multiple comparisons revealed that the scores measured on the stop consonants with the LFT program during initial fit were significantly poorer than that of the

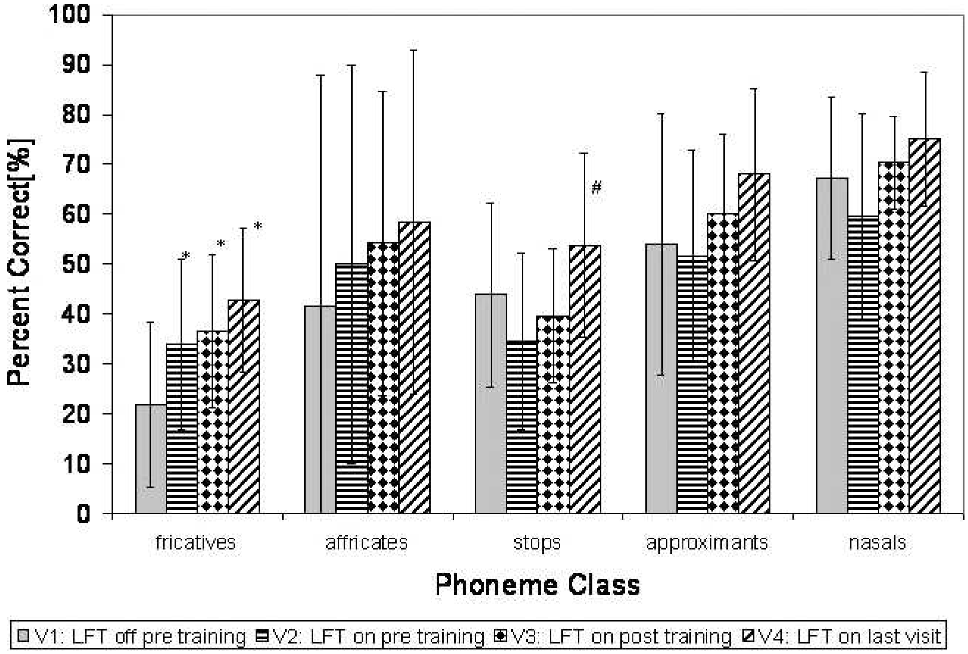

Figure 3. Consonant scores measured at a 50 dB SPL input level and grouped according to manner of articulation and measured with the default master program (V1, gray bar) and the LFT program at initial visit (V2), after one month's use (V3), and after two months' use (V4). The magnitude of the standard deviation is also included.

default program. However, the fricative scores measured with the LFT program at the end of the 2-months trial were significantly higher than the scores measured with the default program ($p < 0.05$). The consonant scores measured on the stops and fricatives with the LFT program at the end of two months were also significantly higher than the same scores measured with the LFT at initial fit. All the other comparisons were non-significant.

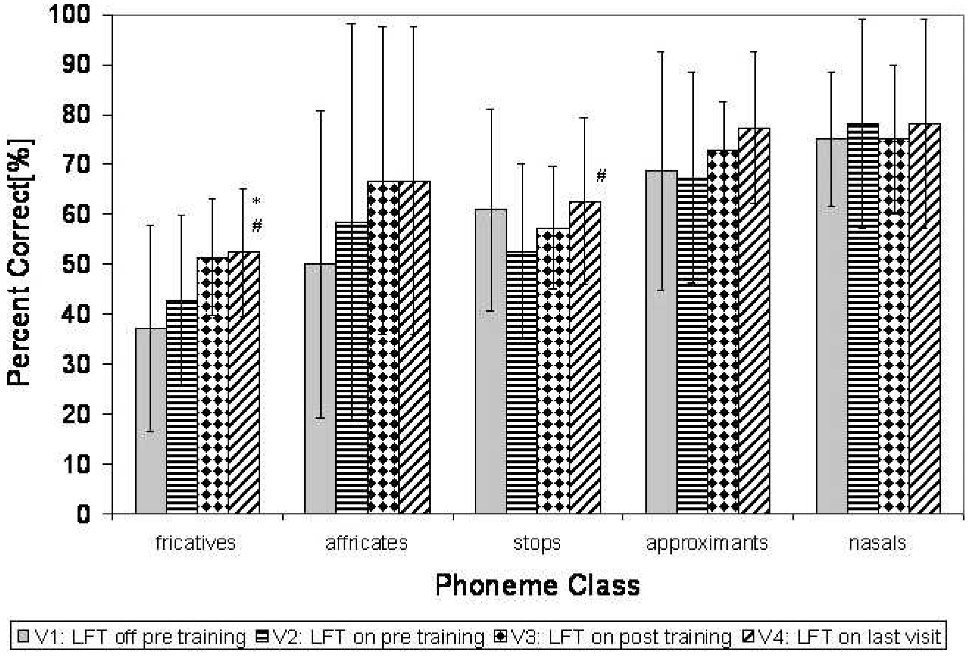

Figure 4. Consonant scores measured at a 68 dB SPL input level and grouped according to manner of articulation and measured with the default master program (V1, gray bar) and the LFT program at initial visit (V2), after one month's use (V3), and after two months' use (V4). The magnitude of the standard deviation is also included.

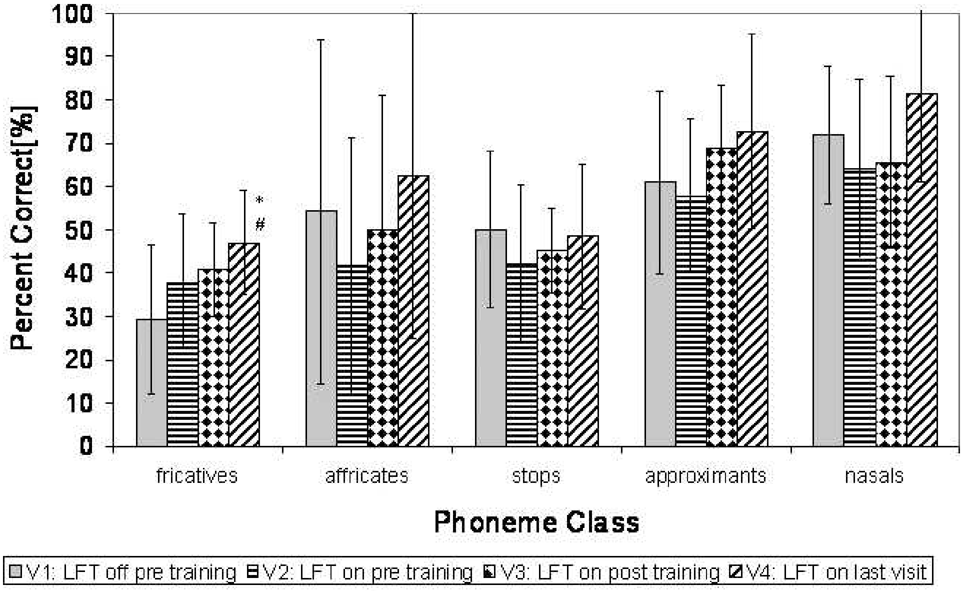

Figure 5. Consonant scores measured at a 68 dB SPL input leveling noise and grouped according to manner of articulation and measured with the default master program (V1, gray bar), the LFT program at initial visit (V2), and the LFT program after one month's use (V3) and after two months' use (V4). The magnitude of the standard deviation is also included.

Effect in Noise

Figure 5 summarizes the absolute consonant scores in noise for the 4 hearing aid conditions. An immediate observation was that consonant scores for all but the fricatives were initially poorer than the default program. However, these scores gradually improved over time so that at the end of two months, the absolute scores measured with the LFT were similar to or better than the default program. The initial fricative scores measured with the LFT was higher than the default master program (28% vs. 38%). This advantage increased to around 45% at the end of the 2 month use of the LFT program. A Repeated-Measures ANOVA showed that consonant class was significant ($F(4,28) = 7.956$, $p = 0.008$, $\eta^2 = 0.53$, power = 0.9) and HA setting was also significant ($F(3,21) = 8.483$, $p = 0.001$, $\eta^2 = 0.54$, power = 0.9).

A post-hoc analysis using Bonferroni adjustment for multiple comparisons showed that the LFT program measured at the two month visit was significantly different from the default program and the LFT program at the initial fit ($p < 0.05$) only for fricatives. All the other comparisons were non-significant.

Changes in Phoneme Identification over Time

In order to identify the specific phonemes that were affected by LFT at various test conditions and at various times, we adopted a criterion difference of greater than 10% to reflect a significant change in performance between the default (no-LFT) and LFT programs. This percentage criterion was chosen to ensure that the observed changes were larger than the magnitude of the test-retest variability of the nonsense syllable test used in this study. Phonemes that were affected by LFT at each test condition were clustered within a circle. Those that improved were identified by their symbols only; while those that became poorer were circled. Phonemes that were included within the intersection region of the circles represented those that were affected under both (or all) test conditions. A separate graph (or Venn diagram) was used to reflect the effect at each visit (LFT-initial, LFT-one month, and LFT-two months).

Figure 6 shows the phonemes that were affected at the initial fitting of the LFT. As reflected in the figure, the phonemes /ʒ/, /ʃ/ improved by more than 10% for all three test conditions (50 dB quiet, 68 dB quiet, and 68 dB noise) with LFT while the phoneme /p/ decreased for the three test conditions. The phoneme /wh/ improved for both quiet conditions, while the phoneme /v/ improved for the 50 dB quiet and 68 dB noise conditions. On the other hand, the phoneme /d/ was worse off for both quiet conditions, while the phoneme /ŋ/ was poorer for the 50 dB quiet and 68 dB noise conditions. Those phonemes that were outside the intersection region of the circles, for example, /dʒ/ and /s/ for the 50 dB condition, /dʒ/, /k/, /j/, /h/, /z/, /ŋ/ and /tʃ/ for the 68 dB condition, and /z/ and /tʃ/ for the +5 SNR conditions, represented the phonemes that were only affected under the specific condition. It is evident that while LFT resulted in improvements in identification of some phonemes, other phonemes may

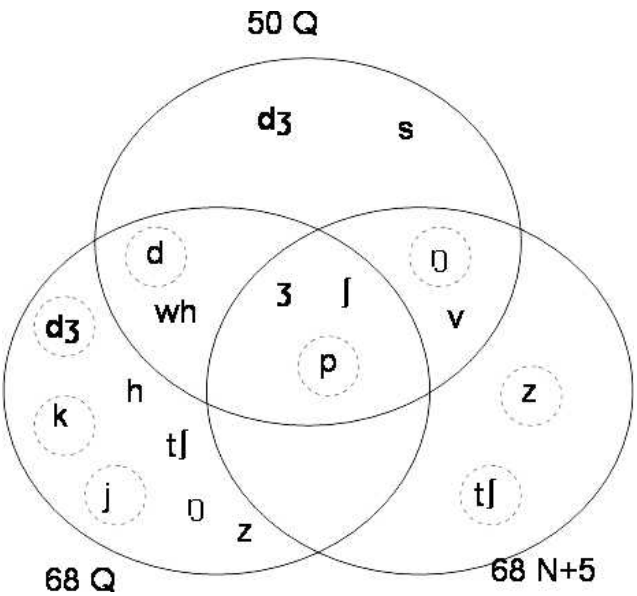

Figure 6. Venn diagram showing the phonemes that exhibited more than 10% change between the LFT and the default (no-LFT) programs during the initial visit. Symbols by themselves represent those that showed higher scores with the LFT. Symbols in a circle represent those that showed lower scores with the LFT.

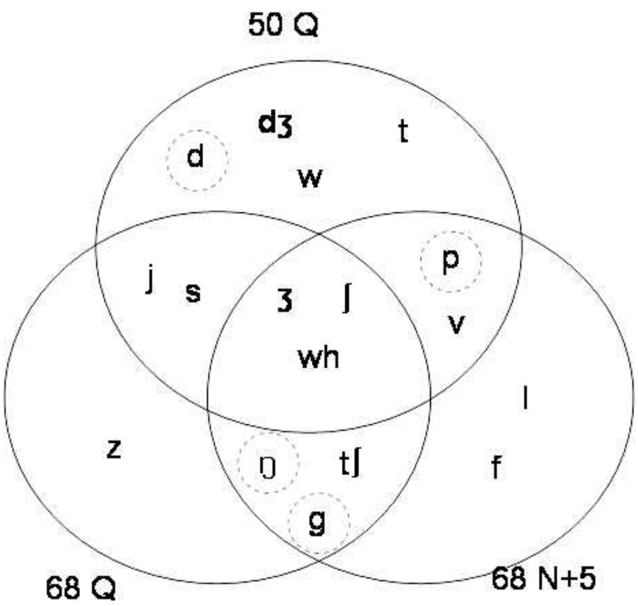

Figure 7. Venn diagram showing the phonemes that exhibited more than 10% change between the LFT and the default (no-LFT) programs at the one month visit. Symbols by themselves represent those that showed higher scores with the LFT. Symbols in a circle represent those that showed lower scores with the LFT.

have been affected negatively. In all, eight phonemes across the three test conditions were negatively affected. In addition, the phonemes that were affected varied depending on the test condition even though some phonemes such as /ʒ/, /ʃ/ and /p/ were affected in all three test conditions.

Figure 7 shows the phonemes that exhibited the criterion change between the LFT and the default programs after one month of LFT use. Similar to the observations made at the initial use of the LFT, the phonemes /dʒ/ and /ʃ/ still showed the criterion improvement across all three test conditions. Another phoneme, /wh/, was also seen to have improved under all three test conditions. On the other hand, the phonemes /j/ and /s/, /v/ and /p/, and /g/, /ŋ/, /tʃ/ were seen to change significantly at the 50 dB quiet and 68 dB quiet conditions, 50 dB quiet and 68 dB noise condition, and 68 dB quiet and 68 dB noise conditions respectively. The number of phonemes that showed significant changes was higher than that seen at the initial LFT use. But more importantly, the number of phonemes that were identified more poorly with LFT during its initial use decreased from 8 to 4 after one month's use of LFT.

Figure 8 shows the comparison after the LFT program was worn for two months. An immediate observation is that the number of phonemes that showed an improvement increased dramatically in the 50 dB quiet and 68 dB noise conditions; while those that showed a decrease was reduced to zero (0). This suggests that use of the LFT program for two months continued to improve consonant identification by (1) making more sounds more audible and meaningful (thus an increase in the number of phonemes identified), and (2) reducing the confusion brought forth by LFT (thus a reduction in number of phonemes misidentified). It is also of interest to note that the phonemes /dʒ/ and /ʃ/ continued to be correctly identified under all three test conditions. However, as was seen in the previous two figures, the phoneme /s/ did not improve in the noise condition even though it improved in the 50 dB and 68 dB quiet test conditions.

In summary, this section showed that the phonemes /dʒ/ and /ʃ/ had shown consistent improvement across all three test conditions. The number of phonemes that were better identified with LFT increased with the use of LFT; while those that were negatively affected by LFT during initial use decreased with its use.

DISCUSSION

This study showed that linear frequency transposition (LFT) as implemented on the current study hearing aid improved nonsense syllable identification, especially fricatives, in quiet and in noise, over a non-LFT program that used the same frequency-gain characteristics and processing features. On the other hand, the speech benefit was not immediately obvious for all phoneme classes at the initial visit. For some phonemes, there was a slight and non-significant decrease in identification which was temporary and resolved within two months.

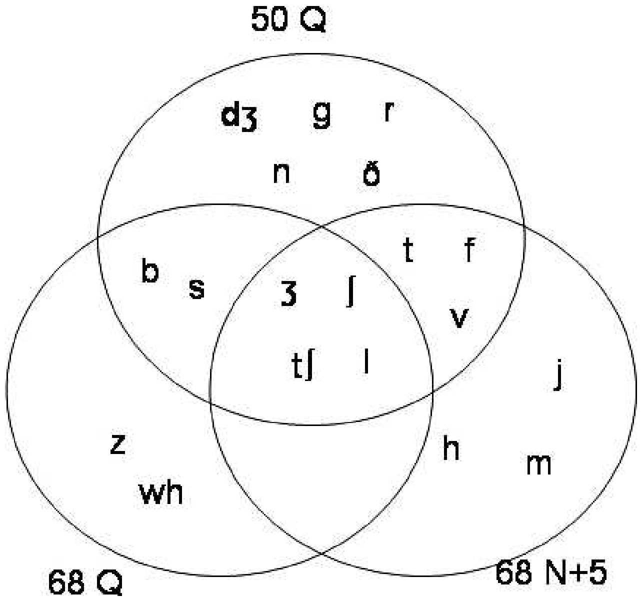

Figure 8. Venn diagram showing the phonemes that exhibited more than 10% change between the LFT and the default (no-LFT) programs at the final (two-month) visit. Symbols by themselves represent those that showed higher scores with the LFT. Symbols in a circle represent those that showed lower scores with the LFT.

Benefits of LFT

Comparison to Previous Studies

The improvement in identification scores for high-frequency phonemes was anticipated because studies conducted by other groups and by our group had reported similar findings. For example, Robinson et al (2007) found that detection of word-final /s/ and /z/ was significantly improved under frequency transposition processing. They also reported improvement on /ʃ/, /tʃ/, /dʒ/ and /t/. Fraga and Marotta (2004) found transposition to be beneficial in the identification of /f/, /ʒ/, /v/, /ʃ/ and /z/ but they also reported that improvement required individually adjusted parameters for different phonemes. Our group has consistently reported between 5% and 15% improvement in nonsense syllable identification in quiet with LFT in young adults with a simulated hearing loss (Korhonen and Kuk, 2008), adult hearing-impaired persons using an open-ear, thin-tube fitting (Kuk, Peeters, et al, 2007), and 8–12 years old children with a severe-to-profound hearing loss in the high frequencies (Auriemmo et al, 2009). In these studies, LFT significantly improved the hearing of nature's sounds (such as bird's songs, warning signals such as alarm, timer etc) while improving the identification of consonant sounds. In the study with children (Auriemmo et al, 2009), it was also demonstrated that the use of LFT improved speech production accuracy of /s/ and /z/ during reading and conversation tasks.

There are also differences in the results between this study and previous studies. Robinson et al's (2007) frequency transposition method also showed adverse effects on identification of /d/ and /z/. They did not find significant effects with /v/ and /w/. In our study, we reported initial confusion with the consonants /d/ and /p/, but improvement on /d/, /z/ and /v/ with use of the LFT. While McDermott and Knight (2001) reported that understanding of sentences in competing noise was significantly poorer with the ImpaCt than the participants' own aids, we observed similar performance between the LFT in quiet and in noise. Our results showed almost 20% improvements in consonant identification.

Obviously, the differences in the observations among studies may be explained by the differences in the algorithms used, subject selection, parametric settings, and study methodology. As described elsewhere (Kuk, Keenan, Peeters, Korhonen, et al, 2007), the appropriateness of the start frequency could affect the observed benefit of LFT (or any frequency lowering algorithms) and the kinds of confusion errors. In our study, we individualized the start frequency based on the participants' subjective response and no amplification was provided above the start frequency.

LFT May Not Be Just for Dead Region

The magnitude of the improvement from LFT was greater for the 50 dB SPL input level than for the 68 dB SPL input level. For example, 23% improvement in fricative score (20% vs. 43%) was noted at the 50 dB SPL input level versus 14% improvement (38% versus 52%) at the 68 dB SPL input level. Similar observation was also noted in other studies conducted by our group (Kuk, Peeters, et al, 2007; Auriemmo et al, 2009). The almost 10% additional benefit seen with LFT at a low input level is not likely due to better LFT effectiveness at a low input level; but rather the limited audibility at a low input level. With LFT, what were typically inaudible because of limited amplification became audible, albeit as a lower frequency substitute. This suggests that the application for a frequency lowering program may not only be appropriate for a "dead" region per se; but may also be considered for increasing the audibility of soft sounds where audibility is marginal. Admittedly, this is a non-conventional application of LFT and its use may be considered when all other avenues of achieving such audibility have been exhausted.

LFT Does Not Degrade Performance in Noise

The clinicians must remember that the objective of frequency lowering is not to improve speech understanding in noise; rather, it is to provide audibility of the unreachable high-frequency information as a lower frequency substitute. Rather than removing parts of the input signals like a noise reduction algorithm or a directional microphone, a frequency lowering algorithm adds to the overall audible input to the ear. This may result in a louder output and some even speculated that it could lead to a poorer performance in noise. In this study, we showed that consonant identification in noise revealed a slightly different error pattern than that in quiet. While the /p/, /g/, /ŋ/ were negatively affected by LFT during the initial and one month LFT use, an affricate /tʃ/ was also noted to be negatively affected by LFT during the initial and one month use of LFT. In addition, fewer phonemes were identified better with the LFT than with the default program during initial use (versus the conditions in quiet). Fortunately, as with the LFT use in quiet, no phonemes were found to be identified more poorly after two months' use of the LFT program. Thus, the results of this study showed that LFT does not make speech understanding in noise more difficult, and that the benefit of LFT in noise remains similar to that in quiet. The finding of no negative effect of LFT in noise is as important a finding as a positive effect of LFT in noise. This suggests that other effective noise reduction approaches, such as a directional microphone and noise reduction algorithm may be used in conjunction with LFT without compromising the effectiveness of each algorithm. One can expect each algorithm to provide its own unique benefits.

Is Improvement Unique to LFT?

The current study design compared the LFT scores measured at various time intervals to the no-LFT score measured at the initial visit. While it demonstrated that LFT performance improved over time, some may question if the same improvement can be expected of the no-LFT program if it were measured also. In that case, the speech benefit that can be attributed to LFT per se will be negligible. This possibility is not likely for the following reasons. First, the literature in the area of hearing aid acclimatization and adaptation (e.g. Arlinger et al, 1996; Humes and Wilson, 2003) suggested that the magnitude of improvement in speech identification scores with traditional hearing aid use (as long as 3 years) was small, typically less than 1–2%. An exception was the study reported by Kuk et al (2003) in a group of twenty people with a severe-to-profound degree of hearing loss. In this study, the authors reported a mean improvement in speech identification score of 4% between the initial fit and after one month's use of the digital power compression hearing aids. There was no additional improvement between the one-month and three-month use periods. This suggests that the use of the default, no-LFT program would likely not result in more than 4% change in speech identification scores.

Secondly, the possibility of the no-LFT program improving speech recognition was considered in a previous study. In Auriemmo et al (2009) we fit the 10 hearing-impaired students first with the default (no-LFT) program for three weeks before we fit them with the LFT program for two, 3-week periods. Weekly auditory training was provided during the course of the nine-week period. While the LFT program resulted in an improvement of speech identification score at the end of the three-week and six-week training period, the use of the no-LFT program did not improve the overall speech identification scores. This observation is in line with the literature on hearing aid acclimatization, and suggests that training (or use of hearing aids alone) cannot improve speech identification if the critical speech cues are not available (as in the no-LFT case).

These observations suggest that the magnitude of no-LFT improvement over time, if existed, would be several magnitude smaller than the magnitude of the improvement (20%) shown by the LFT. Thus, we feel confident that the improvement in speech understanding observed with the LFT is unique to the LFT processing, and not a general improvement common to both LFT and no-LFT processing.

Are the Benefits Provided by LFT Worthwhile?

When one considers that the use of LFT may result in initial confusion and its benefits may require some training, it is reasonable to question if the speech benefits warrant the extra effort (and cost) of adapting to this type of processing. After all, almost half of the participants also commented on the unnatural sound quality when they were initially introduced to the LFT program. Similar observations were made in Kuk, Peeters, et al (2007) and Auriemmo et al (2009) who reported that only 60% of the wearers reported the LFT program to be the same or better than the no-LFT program when music was used as the stimuli and 30% when speech discourse was evaluated. This need for adaptation raises the possibility that some wearers may not immediately accept the sound quality of the LFT program.

To assess its worthiness, one has to recognize that the unnaturalness in sound quality is dependent on the spectral complexity of the stimuli. In the Kuk, Peeters, et al (2007) and Auriemmo et al (2009) studies, almost 90% of the participants reported immediate preference for the LFT when bird songs were used as the stimuli. In addition, their subjective impression of the LFT program for music and discourse speech improved over time. Indeed, the use of LFT to gain additional awareness of everyday sounds and of hearing nature's sounds (such as birds, leaves rustling etc) has been documented to be both immediate and confusion-free. The subjective benefit is appreciated especially by people with a severe-to-profound hearing loss even without any noticeable improvement in speech understanding. An evaluation of speech understanding is only part of the benefit portfolio of an LFT algorithm.

Even if one considers an improvement in speech identification as the only yardstick to measure benefit, one has to accept that the current LFT not only improved the identification of /ʃ/, /tʃ/, /ʒ/, /l/ under all three test conditions, but it has also enhanced the identification of /dʒ/, /s/, /f/, /v/, /t/, /b/, /z/, /wh/, /h/, /m/, /j/, /g/, /r/, /n/, and /ð/ in one or more of the three test conditions, including noisy ones. This suggests that not only would LFT improve voiceless fricative identification, but it may also improve identification of other phoneme categories. And considering this type of processing is the only approach (other than cochlear implantation) that can currently result in audibility of the lost high frequencies for people with an unaidable or unreachable high- (to mid-) frequency hearing losses, the benefit of LFT is unique and irreplaceable.

The potential to improve the audibility of fricative sounds like the /s/ and /z/ phonemes is not trivial. This is because fricative sounds such as /s/ and /z/ are extremely important in the English language. For example, grammatical distinctions such as plurality, possessives and tense are often indicated by the phonemes /s/ and /z/, and context may not always provide this information to the listener. For example, Elfenbein et al (1994) reported that children with a mild-to-moderate hearing loss exhibited increased errors in both noun and verb morphology (e.g. cow vs. cows and jump vs. jumps) because of the reduced audibility of the fricatives from the hearing loss. When the audibility of the /s/ and /z/ sounds is restored, one may expect an improvement in the speech production accuracy of those sounds in children (Auriemmo et al, 2009).

The initial phonemic confusion on some phonemes may not be disconcerting for the following reasons. First, all the initial confusions were resolved at the end of the two- month use of LFT. Secondly, none of the participants reported any negative experiences with the daily use of the LFT. Rather, they reported hearing more sounds with the LFT hearing aids. They also reported increased awareness of their hearing world and being more comfortable with the LFT activated. They also reported greater speech understanding (and not a decrease in speech understanding in real-life as one may expect based on the objective speech tests findings). Reports of differences seen between the laboratory test results and real-life experience are not unusual. Researchers have reported similar discrepancy between laboratory tests and real-life measures (Cord et al, 2004). In this case, the discrepancy probably resulted from the contextual cues that study participants were able to decipher during their communication. Although one may expect children to be less able in making use of contextual cues, our previous study (Auriemmo et al, 2009) with children (8–12 years old) did not support that speculation. Rather, these children immediately accepted the LFT and reported no dissatisfaction with LFT use during the whole course of the study.

One may question if the benefits of LFT can only be realized with intervention, i.e., formal training or rehabilitation. The data in this study (as well as from other studies by our group) showed that formal training for one month (20–30 minutes daily) improved the wearers' performance over the initial use of LFT. But the data also showed that even after the training, performance continued to improve at the two-month interval. These observations support the idea that initial training would at least serve a facilitating role and increase the wearer's sensitivity and adaptation to LFT sounds. Unfortunately, the current study cannot conclude that formal training is important or if the training materials used in this study were effective. Nonetheless, we believe that use (and experience) of LFT in real-life (with or without formal training) is needed to reveal its true potential.

While the benefit of LFT is real, one has to remember that LFT is not intended for every person with a hearing loss who can be effectively managed by conventional amplification. Indeed, frequency lowering should be restricted to those where conventional amplification failed to provide audibility of the high-frequency sounds (Kuk et al, 2008). Thus we recommend that it be reserved only to those with a severe-to-profound loss in the mid-to-high frequencies. This is so we can be sure that they cannot receive amplification in a conventional way. We also recommend using the individual /s/ approach to determine the need for frequency transposition and individualize the start frequency (as described in the Method section). Given the lack of any alternative solution for this group of listeners (other than a cochlear implant), the benefit provided by LFT definitely warrants the cost and potential inconvenience of using this type of algorithm.

Implications

The evidence reported in this study suggests that LFT could potentially improve the audibility of high-frequency consonant sounds and improve their identification. It also suggests the potential of initial confusion and the need for an adjustment period. It means that candidates for this type of processing must be selected carefully. Individuals who have no other acoustic means to access the high frequency information should be considered for this type of algorithm. Individuals who can access the high frequencies through a hearing aid with a higher output or extended bandwidth should attempt those alternatives first. Additional research that focuses on minimizing the initial confusion is warranted.

Another implication is that listeners using this type of processing must be willing to try it for one to two months before improvements in speech understanding may be realized. While all the participants in this study showed some degree of improvement over time, it was indicated earlier that almost half commented of the "different" sound quality during the initial LFT fit. The clinicians must recognize that such behaviors are normal, and that they will be overcome with the consistent use of the device. The clinician should be reasonably certain of the goodness of the LFT settings, and must insist that the listeners try the algorithm for over two months before deciding their benefit (or lack thereof) from such an algorithm. It also suggests that one should delay on concluding the efficacy of such an algorithm until the wearer has used it for at least one to two months. When the proper candidate is selected and proper fitting, counseling and training are provided, it is reasonable to expect that linear frequency transposition can improve the identification of consonant (especially fricatives) sounds in quiet and in noise.

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Appendix 1. Nonsense Syllables Used in the ORCA-NST (one randomization)

	C1	V1	C2	V2	C3
1	t	æ	v	u	s
2	f	u	z	æ	b
3	g	ə	dʒ	æ	v
4	w	u	ʃ	i	b
5	ʃ	ə	k	u	
6	v	æ	d	æ	k
7	ɹ	ɑ	m	u	ð
8	ð	ɑ	d	ɑ	
9	f	i	θ	ə	l
10	k	i	ɹ	ə	v
11	p	i	ʃ	ə	m
12	w	æ	ʃ	ɑ	
13	ɹ	u	d	i	θ
14	s	ə	ɹ	u	tʃ
15	p	ɑ	f	u	n
16	j	æ	θ	u	ʒ
17	ʃ	ɑ	tʃ	u	l
18	p	u	n	u	θ
19	m	u	p	u	v
20	ð	i	j	æ	t
21	n	ə	l	ɑ	z
22	wh	æ	p	æ	f
23	s	ɑ	w	i	
24	m	ə	p	ə	θ
25	l	i	v	ə	ʃ
26	s	u	f	æ	l
27	d	ɑ	p	ɑ	ʒ
28	g	u	ð	ə	
29	h	ɑ	k	ə	ŋ
30	ð	æ	b	u	
31	h	æ	w	æ	p
32	b	ɑ	s	u	

Appendix 2. Averaged Individual Phoneme Scores (%) for Each of the Four Hearing Aid Conditions

	50 dB SPL	LFT off	LFT initial	LFT training	LFT final	68 dB SPL	LFT off	LFT initial	LFT training	LFT final	Noise	LFT off	LFT initial	LFT training	LFT final
Fricatives	ʒ	13	63	63	81	ʒ	25	69	81	88	ʒ	25	75	75	88
	∫	15	52	73	79	∫	52	77	96	96	∫	46	75	85	88
	s	28	40	40	45	s	43	43	53	58	s	30	33	35	38
	f	35	38	30	50	f	48	45	45	50	f	33	38	43	53
	v	31	44	48	44	v	44	46	56	52	v	25	42	42	48
	ð	8	5	8	18	ð	20	13	13	25	ð	15	13	13	18
	θ	5	3	5	8	θ	13	3	13	8	θ	10	5	5	10
	z	31	38	25	31	z	19	38	56	38	z	50	31	38	38
	h	44	44	38	31	h	69	81	75	75	h	50	44	44	69
Affricates	dʒ	50	75	75	75	dʒ	75	63	88	75	dʒ	63	75	75	75
	tʃ	38	38	44	50	tʃ	38	56	56	63	tʃ	50	31	38	56
Stops	g	25	31	19	63	g	75	69	50	75	g	69	56	56	63
	b	50	47	56	72	b	59	69	69	75	b	59	66	59	66
	t	25	31	50	44	t	50	50	38	44	t	44	38	50	56
	d	84	63	69	94	d	81	63	91	91	d	75	69	81	72
	k	34	31	34	38	k	63	47	53	56	k	41	38	34	47
	p	34	17	22	33	p	50	39	44	47	p	34	17	22	23
Approximants/ laterals	wh	38	63	63	88	wh	50	75	88	88	wh	75	50	75	75
	r	53	50	56	69	r	69	63	66	66	r	66	59	63	75
	l	60	58	63	73	l	68	75	75	88	l	55	63	73	78
	w	53	44	72	63	w	72	69	81	78	w	59	53	69	63
	j	50	50	38	56	j	75	50	56	69	j	63	56	63	75
Nasals	n	54	54	63	67	n	71	71	67	71	n	71	63	67	79
	m	78	72	78	84	m	81	84	88	88	m	72	66	69	88
	η	63	25	63	63	η	63	75	50	63	η	75	63	50	63