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Effect of Linear Frequency Transposition on Speech Recognition and Production of School-Age Children

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Abstract

Purpose: To investigate the clinical efficacy of linear frequency transposition (LFT) for a group of school-age children.

Research Design: A nonrandomized, within-subject design was implemented to investigate vowel and consonant recognition and fricative articulation of school-age children utilizing this feature.

Study Sample: Ten children, aged 6 years and 3 months, to 13 years and 6 months from a special education school district participated in this study. Individual hearing thresholds ranged from normal to moderate in the low frequencies and from severe to profound in the high frequencies. Average language age of children was within 2.2 years of chronological age.

Data Collection and Analysis: Phoneme recognition and fricative articulation performance were compared for three conditions: (1) with the children's own hearing aids, (2) with an advanced hearing instrument utilizing LFT, and (3) with the same instrument without LFT. Nonsense syllable materials were administered at 30 and 50 dB HL input levels. Fricative articulation was measured by analyzing speech samples of conversational speech and oral reading passages. Repeated measures general linear model was utilized to determine the significance of any noted effects.

Results: Results indicated significant improvements in vowel and consonant recognition with LFT for the 30 dB HL input level. Significant improvement in the accuracy of production of high-frequency (HF) fricatives after six weeks of use of LFT was also observed.

Conclusions: These results suggest that LFT is a potentially useful hearing aid feature for school-age children with a precipitous HF sensorineural hearing loss.

Key Words: Frequency transposition, hearing aids, speech recognition

Abbreviations: FC = frequency compression; HA = hearing aid; HF = high frequency; LFT = linear frequency transposition

Audiologists working with children are frequently confronted by precipitously sloping sensorineural hearing loss such as that resulting from treatment with ototoxic agents. Since the achievable high-frequency amplification for conventional hearing aids (HAs) is limited even with today's advanced technology, this audiometric configuration is particularly challenging to fit. The bandwidth of the hearing aid

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may not be sufficiently broad (Stelmachowicz et al, 2007). The most advanced feedback cancellation mechanisms may not completely eliminate acoustic feedback. The child's hearing loss may reflect a degree of damage to the inner ear structures to the point where tuning characteristics are significantly broadened and frequency discrimination is impaired even when high-frequency (HF) cues are made available, that is, cochlear "dead region" (Ching et al, 1998; Hogan and Turner, 1998). The child's access to HF acoustic cues is therefore limited, which may interfere with the ability to learn to categorize sounds into their morphological contexts and to eventually reproduce them.

Elfenbein et al (1994) examined the speech and language of children with various degrees of hearing loss. They found that even children with a mild hearing loss exhibited misarticulation of fricatives and demonstrated corresponding semantic and syntactic errors in morphology such as plural markers and verb tense (e.g., *cow* vs. *cows* and *jump* vs. *jumps*). Kortekaas and Stelmachowicz (2000) examined the effect of bandwidth on performance for several auditory tasks. Included was speech detection performance of normal-hearing adults and children ranging in age from five to ten years. They utilized low-pass filtering of speech to examine perception of the final /s/ in the context of a plural marker, that is, *truck* versus *trucks*, *drink* versus *drinks* in the presence of low-pass filtered speech-shaped noise. Significantly higher detection thresholds were reported for children than for adults. Hearing-impaired children exhibited significantly poorer performance on a picture identification task examining plurality, that is, *duck* versus *ducks* when the speaker was female. This is likely because the frequency range of the plural marker /s/ and /z/ was considerably higher in frequency for a female speaker than that for a male speaker (Stelmachowicz et al, 2002). More recently, Stelmachowicz et al (2007) examined the effect of bandwidth of both normal-hearing and hearing-impaired children on various types of assessments including word and phoneme recognition. They found significantly improved word scores for hearing-impaired children utilizing a broader bandwidth for /s/ and /z/. These authors concluded that the need to ensure audibility of the HF information is especially critical for children and that there is support for the use of extended HF bandwidths in amplification for hearing-impaired children.

Various others have examined alternate acoustic means to achieve audibility of the HF information. One such approach is the use of frequency lowering where the high-frequency sounds are heard as a lower-frequency substitute. A more detailed description of the various forms of frequency lowering and studies pertaining to this processing strategy can be found in Braida et al (1979). More recently, Korhonen and Kuk (2008) also provided a description of the distinction between frequency compression and frequency transposition. Briefly, in a frequency-compression (FC) scheme, frequency lowering is accomplished by compressing the bandwidth of the original signal by a predetermined ratio. Frequency transposition differs from FC approaches in that spectral shifting occurs without compression of the bandwidth. In true frequency transposition, spectral information is shifted but not compressed in bandwidth. For example, if the source is 4000 Hz, sounds in the 4000 Hz region will be lowered to the 2000 Hz region while maintaining the original bandwidth.

Parent et al (1998) studied speech recognition of four severely hearing-impaired adults using a first-generation wearable FC system. They used phoneme, word, and sentence materials. The frequency compression system identified spectral peaks above 2500 Hz as voiceless and spectral peaks below 2500 Hz as voiced as criteria for activation of the frequency compression algorithm. Once activated, the algorithm compressed the full spectra by predetermined ratios. Speech recognition and subjective impression were assessed with the frequency compression device after three to six weeks of use and compared with baseline performance with the participants' own hearing aids. Results indicated that all four participants experienced better audibility as measured by aided sound field thresholds with the frequency compression strategy. However, no patient experienced significant improvements in speech recognition at the word or phoneme level. Subjective measurements also indicated a lack of preference for the FC device. The authors concluded that frequency compression may be efficacious for some, but not for all, patients with considerable hearing losses. However, they were encouraged since none of the four individuals performed significantly poorer with the strategy than with their own conventional hearing aids.

McDermott et al (1999) examined performance in a group of five adults fit monaurally with the same FC device used in the Parent et al (1998) study. In a 12-week period, systematic changes in the amount of FC were made in order to investigate whether performance differences might be the result of fitting parameters or training effects. This enabled investigators to determine whether any significant performance improvements were attributable to FC or to the frequency response of the study instrument compared to that of the subjects' own hearing aids (HAs). Performance on speech recognition tasks with the subjects' own conventional hearing aids was compared to that with the study hearing aids. Results indicated that FC did significantly improve recognition of HF phonemes for two of the five individuals. However, for two individuals, sentence test results were significantly improved over their own hearing aids not because of the frequency lowering but because of the low-frequency amplification.

McDermott and Knight (2001) reported preliminary findings for three adults with a second-generation version of the instrument mentioned above. The three adults were assessed at two and four weeks with their own hearing aids and with the study hearing aids. Because it was not possible to selectively enable or disable the FC algorithm on the study aid, the investigators matched the low-frequency response between the individuals' own hearing aids and the study aids. Examiners administered a variety of assessment tasks including aided threshold measurements, monosyllabic word, consonant identification, and sentences presented in competing noise. Results showed that aided thresholds were improved with the study instrument. However, no significant improvements were identified for the word and phoneme recognition scores with FC. Additionally, significantly poorer sentence recognition in noise was obtained.

Miller-Hansen et al (2003) retrospectively examined the performance of a large group of children (N = 78) for an instrument utilizing FC. Although this study did not control for the possibility that any improvements in performance were due to the LF response of the study HA as in the McDermott et al (1999) study, it is one of few studies reporting results of FC use in children. The aided thresholds, word recognition performance and parent impressions of the study instrument were examined. Aided thresholds were better with FC compared to both the unaided condition and to those obtained with the children's own conventional hearing aids. For 24 children in the group, similar data with their own conventional HAs were available. They found a significant improvement of 12% on monosyllabic word recognition over the unaided and own aid conditions for these 24 children. The greatest improvements were seen for children with the poorest word-recognition scores. This led the authors to speculate that FC, by relaying HF speech information to low-frequency regions of the cochlea, may indeed allow utilization of missing HF speech cues. In addition, the authors also suggested that children who derive limited benefit from conventional amplification strategies may be able to make better use of cues provided by frequency lowering. Parent reports did not correlate with the measured improvements in speech-recognition testing. Furthermore, they did not suggest that there was a difference in performance with FC compared to conventional approaches. Interestingly, a significantly greater incidence of hearing aid repairs was also found with the FC device.

In summary, past and recent studies indicate that HF acoustic information may be more critical for normal-hearing and hearing-impaired children than for adults. The use of frequency lowering by means of FC has resulted in limited performance improvements for adults and children. In the decade or so since these studies were performed, the technology available to perform frequency lowering has undergone significant advancement including the means to perform linear frequency transposition.

LINEAR FREQUENCY TRANSPOSITION

Linear frequency transposition (LFT) is another example of frequency lowering (Andersen, 2006). This approach is utilized in the Audibility Extender^{TM} feature of the Widex Inteo hearing aid. LFT is designed such that a frequency region (called the source frequency) above a particular "start" frequency is targeted for transposition. Typically, the source frequency is either unaidable or unreachable (because of inadequate gain/output). The start frequency can be selectively determined for each individual based on hearing loss configuration.

Once activated, the spectral peak within the source region is identified and transposed down in frequency by one octave. Transposing to a region one octave below the start frequency shifts the HF information to the slope of the hearing loss where it may be better utilized due to finer tuning characteristics along the slope (Moore, 2004). Additionally, temporal and spectral characteristics of the input signal below the start frequency are unaffected. In this manner, HF cues can be made available to the listener without introducing unnecessary distortion. For a more detailed description of LFT, see Kuk, Korhonen, et al (2006).

Korhonen and Kuk (2008) investigated whether or not an LFT algorithm provided usable HF acoustic cues and whether training was important. Participants were normal hearing subjects with a simulated hearing loss obtained by low-pass filtering of the test materials at 1600 Hz. Recognition of voiceless consonants was assessed utilizing nonsense syllable stimuli in the CV, VCV, or VC format recorded by a female speaker through the hearing aid with and without LFT active. The nine participants were presented with the stimuli via headphones. Stimuli were randomized so that the stimuli recorded through the LFT were mixed with those recorded without the LFT feature. The consonant test was administered four times within a session, and a 15-minute self-paced training exercise was provided between test presentations. For training, participants selected specific syllables from among several options displayed on a computer screen.

Initial results indicated that consonant identification scores were the same for the LFT-on and the LFT-off conditions. However, a significant improvement in consonant identification scores was obtained after training. Performance for the LFT-off condition improved by an average of 14% after 30 minutes of training. A slight decrease in performance was seen after 45 minutes of training probably indicating fatigue of the listeners. This study showed that, for this group of normal-hearing listeners with simulated HF hearing loss, LFT created acoustic cues that were made usable with training.

Kuk, Peeters, et al (2007) reasoned that adults with a precipitous HF sensorineural hearing loss fit with thin-tube, open-fit BTEs might be good candidates for LFT because of limited audibility in the high frequencies. Use of a thin tube relative to a #13 tubing would result in a lower-frequency resonance peak and reduced HF output (Kuk, Peeters, et al, 2007). Open-ear fittings would also result in less available HF gain before feedback and possibly poorer aided sound field thresholds and poorer word recognition at low input levels (Kuk and Keenan, 2006). Consonant recognition and subjective preference for frequency transposition were examined in 13 individuals with a precipitous high-frequency hearing loss. The LFT start frequency was typically set at 4000 Hz. Nonsense syllable testing was performed immediately after fitting at 30 and 50 dB HL presentation levels in the default and LFT-on conditions with the same instrument. Individuals went through a two-week trial period with two programs, LFT and the default program, after which testing was repeated and results of program usage were determined via data logging. As much as 10–15% improvement in consonant scores was realized at both presentation levels. Vowel identification improved slightly at both presentation levels. When first fit with LFT, participants preferred the default program for speech stimuli. Their preference changed in favor of the LFT program after two weeks of use. These results suggested that adult users of LFT need time to acclimate to the new cues provided by LFT.

Thus it appeared that LFT provided usable acoustic cues and that training may be helpful to optimize its performance in aiding consonant identification. However, the same evidence is not available in children. If it can be shown that usable acoustic cues are made available to children and that they utilize these cues, the expectation would not only be improved speech perception but also speech production and language use. Thus, frequency transposition may benefit children more than it would hearing-impaired adults. A study of LFT in children would be useful in developing guidelines for fitting children with HF sensorineural hearing loss and setting appropriate expectations for progress with such an algorithm.

The purpose of this study was to investigate the effect of LFT on audibility, speech recognition, fricative articulation, and subjective preference of a group of school-age children. Because previous results with frequency lowering approaches have been lackluster in comparison to results with subjects' own conventional hearing aids, and because we wanted to ensure that performance with LFT was at least as good as the children's present performance, we felt it was important to include an assessment with the children's own HAs. In this study, we compared the phoneme recognition and fricative articulation performance of children using (1) their own hearing aids, (2) an advanced hearing instrument utilizing LFT, and (3) the same instrument without LFT. Additional goals were to assess whether auditory training enhanced performance, to assess the children's subjective preference for the LFT program, and to evaluate the effect of LFT on nonspeech environmental sounds.

METHOD

Study Participants

Data were collected from children at the Special School District in St. Louis, MO, with the approval of the protocol by the school board. A database at the study site consisting of over 500 hearing-impaired students was reviewed to find possible candidates to meet the study criteria. Ten hearing-impaired children age 6 years and 3 months to age 13 years and 6 months with a sloping sensorineural hearing loss were recruited to participate in this study. The required number of participants was determined based on the results of a power analysis using the data from the Kuk, Peeters, et al (2007) study of LFT for adults. The recruitment criteria included hearing thresholds indicative of no worse than 60 dB HL in the low frequencies (*below* 500 Hz) but poorer than 70 dB HL above 4000 Hz. The individual audiometric configuration of the ten participants is shown in Figure 1.

All children were experienced amplification users of digital technology ranging from low-end to high-end products that had been fit utilizing the desired sensation level (DSL 5.0) target. One child wore instruments utilizing a frequency compression scheme; the other nine utilized traditional nonlinear amplification. The FC approach was utilized by a 10.5-year-old child. He realized limited success with FC as measured by speech, language, and hearing assessments. Therefore, clinicians felt that this child also met the criteria for candidacy and could potentially benefit with the LFT. Nine children used FM systems along with their hearing aids in the classroom. Table 1 shows the amplification information for the ten participants.

All children were proficient English speakers, met developmental milestones, were partially or fully mainstreamed in regular classrooms, and used oral-aural communication. Age-equivalent language performance on standard receptive and expressive language and vocabulary assessment tools varied for the ten children from 0.1 to 3.9 years of chronological age. On

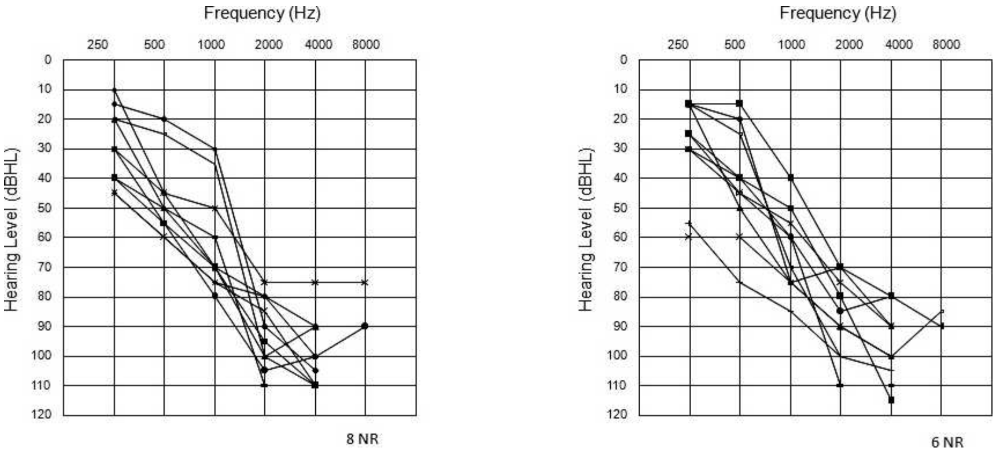

Figure 1. Individual audiogram configurations, N = 10.

average, the age-equivalent language performance was within 2.2 years of chronological age; however, all children continued to make progress academically. The primary goal was to assess consonant recognition and fricative articulation as a function of amplification strategy. Children were all able to repeat nonsense syllables, answer questions about pictures, and read a first-grade reading passage.

Consent was discussed with the parents along with each individual child. In addition, the nature of the study was explained without mentioning specific features of the hearing aids. That is, parents and children were informed that two different hearing aid settings would be assessed to determine which would result in the most improvement in auditory access to HF sounds. Examples of HF sounds were provided. Families were further informed that they could withdraw from the study at any time. Families were not paid for participation in this study; however, children received the hearing aids free for their permanent use.

Hearing Instruments

The Inteo hearing aid is a 15-channel instrument utilizing primarily slow-acting, wide dynamic range compression with a compression threshold of 0 dB HL and an active feedback cancellation system (Kuk and Keenan, 2006). Two models of the hearing aid were used in this study, the IN9 and the IN19. The two models differed mainly in the receiver used. The IN9 was a miniature BTE with 51 dB average gain and an output SPL90 peak of 125 dB SPL. The IN19 instrument utilized a larger receiver with 59 dB average gain and an OSPL90 peak of 131 dB SPL. The two study models used the same LFT feature previously described.

Hearing Aid Fitting

Model selection was based on hearing thresholds at 500 Hz and 2000 Hz. The IN9 was selected if thresholds at 500 Hz were less than 35 dB HL and thresholds at 2000 Hz were less than 70 dB HL. The IN19 was selected if the threshold was greater than 35 dB HL at 500 Hz and greater than 70 dB HL at 2000 Hz. All but one child were fit with the IN19. Children utilized custom-made skeleton-style, soft material earmolds with the study hearing aids. The vent diameter was chosen based on audiometric thresholds at 500 Hz. Specifically, if the threshold at 500 Hz was less than 25 dB HL and space permitted, a 2.5 mm vent diameter was utilized. If the threshold at 500 Hz was

Table 1. Demographic Information for All Children, Including Hearing Aid History and FM Usage

Participant #	Age	Own Aid Make/Model (Right)	Own Aid Make/Model (Left)	Widex Model R&L	FM Used
1	9.1	Phonak Supero 412	Phonak Supero 412	IN-19M	Yes
2	8.2	Phonak Maxx 411	Phonak Maxx 411	IN-19M	Yes
3	10.3	Phonak Maxx 411	Phonak Maxx 411	IN-19M	Yes
4	12.4	Phonak Claro 311	Phonak Claro 311	IN-19M	No
5	7.7	Starkey Destiny 1200	Starkey Destiny 1200	IN-19M	Yes
6	6.3	Widex P38	Widex P38	IN-19M	Yes
7	13.5	Oticon Adapto P	Oticon Adapto P	IN-9M	Yes
8	10.8	AVR Nano XP-D	AVR Nano XP-D	IN-19M	Yes
9	7.8	Phonak Maxx 411	Oticon Adapto P	IN-19M	Yes
10	13.6	Widex Bravo B-32	Widex Bravo B-32	IN-19M	Yes

between 25 and 40 dB HL and space permitted, a 2 mm vent was utilized. Every 10 dB increase in threshold would lead to a 0.5 mm reduction in vent diameter.

Fitting of the study hearing aids included measuring the in-situ threshold or "Sensogram" (Ludvigsen and Topholm, 1997) and completing a feedback test to set the maximum gain parameters. The sensogram method utilizes signals transduced through the hearing aid receiver via the child's own earmold to determine threshold. Thus, these thresholds considered the child's individual ear-canal volume and impedance. These thresholds were then used to calculate gain/output characteristics of the hearing aid. In-situ thresholds were found to have high test-retest reliability (Smith-Olinde et al, 2006).

Feedback testing was performed in order to estimate the initial feedback path and to determine the maximum amount of available gain in each channel. Active feedback cancellation was enabled for all hearing aids. The feedback cancellation feature utilized in the study instrument provided an average of 15 dB additional gain (Kuk, Jessen, et al, 2006).

Two hearing aid "programs" were utilized in the study hearing aids: the default program in which the LFT was "off" and an additional program in which LFT was "on." The same frequency response and gain settings were utilized in both programs. In addition, multiband fully adaptive directionality and classic noise reduction were activated in both programs. On the other hand, while active feedback cancellation was activated in the default program, it was "off" in the LFT program. A gain limitation feedback mechanism was used in the LFT program. It was reasoned that the likelihood of feedback would be minimal in the LFT program.

Simulated real ear responses for soft (55 dB SPL) and moderate (70 dB SPL) speech inputs were examined in the default program. Hearing aid gain parameters were adjusted so that the outputs matched DSL 5.0 targets for soft and moderate speech inputs to within 5 dB. Because of the extent of the hearing loss, no attempts were made to match the output above 3000 Hz. Age appropriate RECD values were incorporated into the simulated real ear measurements.

Start frequencies for the LFT program were determined on an individual basis (Kuk, Keenan, et al, 2007). The initial start frequency was set to the maximum allowable value, that is, 6000 Hz. The audiometer was set at 30 dB HL for CD playback of recorded female /s/. The child was asked to indicate when the stimulus was heard. The audibility of the transposed signal was examined using the SoundTracker feature on the Inteo hearing aid. In essence, this feature turned the hearing aid into a sound level meter (SLM) and allowed direct measurement of sound pressure at the hearing aid microphone position (Kuk et al, 2004). The LFT gain parameter was adjusted in 2 dB steps until the child reported hearing the /s/ sound, and its level was 5–10 dB SL on the SoundTracker. If the LFT gain was at its maximum and the child did not detect the stimulus consistently, the start frequency was set to the next lower frequency and the LFT gain parameter was reset back to 0 before its level was readjusted. The above steps were repeated until the highest start frequency and the lowest LFT gain yielded the perception of /s/. In situations where the /s/ could not be detected consistently either because of the severity of the hearing loss (or possibly because it was a novel auditory experience), a recorded /ʃ/ sound at a 30 dB HL input level was used as the stimulus instead. It is important to note that in the eight cases where /ʃ/ was used to set the transposition parameters, higher frequency information (including /s/) was still transposed.

Simulated real ear measurements were also performed following fitting with the LFT program. Since frequencies above the LFT start frequency were transposed only, the real ear output reflected the lack of amplification above the start frequency and an increase in output at frequencies slightly below the start frequency.

Since the LFT program was expected to provide children with new auditory access to HF fricatives such as /s/, we wanted to ensure that children heard soft speech and speech at conversation and higher input levels without discomfort for both the default and the LFT programs. To this end, a connected speech passage was presented at soft (35 dB HL), conversational (50 dB HL), and loud (70 dB HL) input levels. Children were asked to report whether the speech was "soft," "medium," "loud," or "too loud." Increases in insertion gain parameters were made for one child who reported that speech at the 50 dB HL presentation level was "soft." This procedure was performed in order to ensure subjective audibility and comfort. A reading titled "Summer in Sweden" (Plant, 2006) was selected for this purpose because of the prevalence of fricative sounds.

Materials

The efficacy of LFT for soft and conversational speech intelligibility was assessed at 30 and 50 dB HL input levels using nonsense syllables from the CUNY Nonsense Syllable Test (Edgerton and Danhauer, 1979, Form A, Lists 1 through 6). The full recorded, 25-item lists of CVCV from its original commercial compact disc were administered for each test condition.

The *DIBELS Oral Reading Fluency* passages were utilized to record accuracy and fluency with connected text (Good and Kaminski, 2002). The "Ice Cream" passage is a four-paragraph passage written at the first grade level with words that emphasized the /s/ and /z/ phonemes. These passages were based on the program of Research and Development of Curriculum-Based Measurement of Reading by Stan Deno and colleagues at the University of Minnesota.

For the conversational speech sample, the children were shown pictures describing actions and objects. Key words in the pictures utilized /s/ and /z/ sounds in various word positions. The conversation sample was obtained by asking the children questions about these pictures. Pictures and interview topics were the same for each child in order to evoke more homogeneous responses from the group and the use of the same key words. These pictures were obtained from *Spotlight on Articulation /s/* (Truman, et al, 2006). Each sample contained at least 50 instances of /s/ and /z/ and was approximately five minutes in length. Samples were videotaped and analyzed for /s/ and /z/ production accuracy. A speech-language pathologist with 15+ years experience working with hearing-impaired children obtained the speech sample and later analyzed the results to determine the accuracy rate. This examiner did not see the children for speech-language services on a regular basis and was not involved in weekly auditory training sessions.

A checklist of environmental sounds was utilized (Appendix 1) in order to assess the children's inventory of "nonspeech" sounds under each hearing aid test condition. This was performed to ensure that awareness of environmental sounds was not adversely affected by the use of LFT. This checklist included a list of environmental sounds typically occurring in everyday environments such as sounds in the kitchen, dining room, bathroom, and so forth. This material was developed at the Widex in-house research laboratory for the purpose of assessing awareness of environmental sounds. It was administered in survey/interview format with the audiologist interviewing the students in the presence of their parents at each assessment visit. Parents were asked to participate in order to confirm children's responses. Parents' decisions overruled those of children.

The children's subjective preference for the LFT program for speech and nonspeech stimuli was evaluated by comparing the percepts between the default program and the LFT program presented in a pairwise format. The test materials included bird, music, and speech stimuli that were recorded on a compact disc. Ten samples for each stimulus category were used. Each stimulus was edited to be approximately 10 sec in duration.

Procedures

All testing was conducted in a double-wall sound-treated test suite at the study facility. A GSI 61 audiometer was used for all audiometric tests. Daily biological calibration for audiometer linearity was performed. In addition, the output from each loudspeaker was confirmed prior to all testing.

Children were seated 1 m directly in front of the test loudspeaker. Performance on the test materials described above was assessed with the children's own hearing aids prior to other test conditions. The order of experimental conditions was identical for all children. Initially, children were assessed with their own HA. Next, children were assessed with the default program. They wore the default program for three weeks and were then evaluated after the three-week use period. They were then evaluated with the LFT program and wore it exclusively for three weeks after which a similar evaluation took place. They were evaluated again after an additional three week use of the LFT program (i.e., six weeks of LFT use). This test sequence was used in order to avoid the potential ethical dilemma from the discontinued use of the LFT program. Based on studies of the same LFT instrument with adults, Kuk, Peeters, et al (2007) and Korhonen and Kuk (2008) showed that improvements for syllable identification were noted with the LFT only after extended use (as little as two weeks) of the LFT. This suggests that if we were to counterbalance or randomize the test conditions, we would have started some children in the LFT program then provided them with new HF information only to take the new cues away when the children were presented with the default program. This could potentially affect the children's consistent use of auditory cues and result in undesirable changes in academic and/or social behaviors. Thus, we did not feel counterbalancing or randomizing test conditions would be appropriate. Instead, we felt that the current sequence—own aid, default, LFT—was an acceptable solution to the potential ethical dilemma.

In order to allow us to examine any potential learning effect alone, we tested the children in both the default program and the LFT program at their initial fittings as well as after each program was used for three weeks. As mentioned above, this time period was chosen because Kuk, Peeters, et al (2007) showed that in adults two weeks use of the LFT program was sufficient to demonstrate a measurable benefit. Although the study design may have benefited by implementing a control group by evaluating both default and LFT conditions at the initial fitting session as well as after three-week use periods, we were able to partly circumvent this limitation by evaluating both default and LFT conditions at the initial fitting sessions as well as after three-week use periods. Since auditory training was provided in both conditions, we are reasonably confident that improvements in one condition but not the other would be attributed at least in part to the hearing aid condition (i.e., extra HF cues). An additional three-week trial was extended for the LFT program to explore whether the novelty of the LFT cues might require a longer time course for full benefits.

Neither parents nor children were aware of the specific features being assessed during each trial period. However, the study clinicians were not blind to the child's hearing aid settings. The order of presentation of each of the four CUNY Nonsense Syllable Test lists was counterbalanced across participants. Presentation order of the paired comparisons was randomized across all participants.

Auditory training sessions were provided when the children were wearing the study hearing aid in its default program and in the LFT program. If an effect were seen after three weeks of LFT use but not after three weeks of master program use, or if the improvement were greater for the LFT program than for the master program, we could attribute the improvement to the cues provided by the LFT feature and not solely to training effects. Obviously, this reasoning assumes that the effect of training is linear and additive.

Auditory training sessions were not included for the own HA condition because the children had been receiving speech, language, and hearing services with their own hearing aids and would have had ample opportunity to become familiar with the acoustic cues provided by their own hearing aids. Additionally, the own HA condition was included primarily as a means of enabling clinicians to ensure that performance with the study HA was at least as good as that with their own HA.

Auditory training was conducted by an audiologist with approximately three years of auditory training experience. The training sessions were conducted once weekly, each lasting about 30 minutes with one to two children per session. Sessions consisted of games and activities using materials geared toward detection, discrimination, and articulation of "target" sounds including /s/, /z/, /ʃ/, /tʃ/, /dʒ/, /f/, /θ/, and /v/. The clinician focused on one target sound at each session; however, sounds covered at previous sessions were always reviewed at the end of each session. No homework or additional activities were provided for the families or children. Test materials were not utilized during the auditory training sessions. The speech assessments were conducted by a different clinician with approximately 20 years of diagnostic experience. She was not familiar with any of the study children.

Each participant attended six visits to complete data collection. Prior to each fitting and test session, the hearing aids were evaluated electroacoustically (American National Standards Institute, 2003) to ensure that they were working properly. The children's air conduction thresholds were measured at the start of each visit to monitor potential fluctuating hearing losses. A decrease in air conduction thresholds by more than 10 dB would lead to a suspension of the child's participation in the study while further audiological testing and follow-up were performed. The specifics of each visit were as follows.

The first visit was an assessment using the CUNY Nonsense Syllable Test in an aided condition using the child's own hearing aids at 30 and 50 dB HL. The environmental HF sound survey was administered. Baseline speech samples were also collected.

At the second visit, the child was fit with the study hearing aid programmed to the default (no LFT). Baseline nonsense syllable assessment with the default program at 30 and 50 dB HL was also performed at this visit. At the end of this session, clinicians instructed the child and family member on the use and care of the hearing aids. They were also asked to pay attention to how well the hearing aids performed in various environments. Parents were informed that the environmental sound survey would be repeated following three weeks of use so that they should pay attention to any new auditory experiences reported by their children. Additionally, children were given hearing aid diaries and were instructed to make notes of any other sound experiences in their diaries with the help of their parents. This visit was followed by three weekly half-hour auditory training sessions. At visit three the Nonsense Syllable Test was repeated with the default program along with a review of the environmental sound survey and collection of speech samples.

The LFT program was fit and evaluated using the Nonsense Syllable Test at visit four. Additionally, subjective preference for the transposition program over the default program for bird, music, and speech stimuli were evaluated at this visit. The children wore the hearing aid home with the LFT program for three weeks during which they received three weekly auditory training sessions.

Children returned for visit five after three weeks of use of the LFT program. The same evaluation tools that were discussed in the previous sections were administered. An additional three-week use period of the LFT program (along with auditory training) followed and children returned at visit six for a final assessment.

RESULTS

Aided Sound-Field Thresholds

The individual monaural aided sound-field thresholds obtained with the study hearing aid in the default program and in the LFT program are displayed in Figure 2 and Figure 3 respectively. The averaged thresholds are indicated by the darker solid line in each figure. With the default program, the average threshold was improved to 20 dB HL at 1000 Hz and

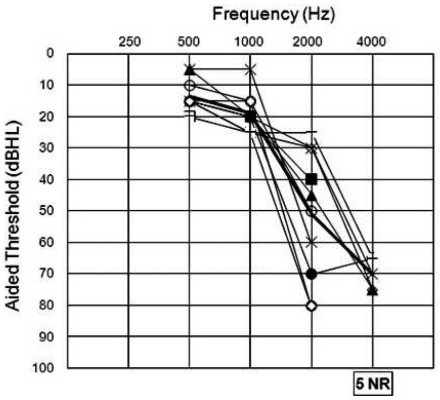

Figure 2. Monaural aided sound-field thresholds for the right and left ear with the default (no transposition) program. The averaged thresholds are represented by the bold line.

50 dB HL at 2000 Hz. Six "no responses" ($n = 6$) were noted at 4000 Hz.

Figure 3 shows that with the LFT, the aided threshold was improved to 20 dB HL at 1000 Hz and 30 dB HL (left) and 40 dB HL (right) at 2000 Hz. In contrast to the default program condition, aided thresholds of 30 dB HL were obtained at 4000 Hz in all ears. The aided thresholds obtained with the LFT program were considerably better than those measured with the default program and during the unaided conditions.

Nonsense Syllable Identification in Quiet

Phoneme identification scores were measured using the Nonsense Syllable Test at two input levels (30 and 50 dB HL) in six aided conditions (own aid, 2 times with default, 3 times with LFT). The raw scores were transformed using a rationalized arcsine transform (Studebaker, 1985). A repeated-measures ANOVA was used to test the significance of the three within-subjects effects, namely, level (30 or 50 dB HL) × aided conditions (six) × phoneme position (two, initial and medial) for consonant identification and vowel identification separately.

Significant main effects for consonant scores for level ($F(1,9) = 48.228$, $p < 0.001$, $\eta_p^2 = 0.84$) and aided condition ($F(5,45) = 20.005$, $p < 0.001$, $\eta_p^2 = 0.69$) were observed. However, the effect of phoneme position was not significant: ($F(1,9) = 1.864$, $p = 0.205$, $\eta_p^2 = 0.17$). Therefore scores for the initial and medial consonants were averaged for reporting. In addition, the analysis of vowel identification scores showed that the effects of level ($F(1,9) = 12.721$, $p = 0.006$, $\eta_p^2 = 0.59$) and aided condition ($F(5,45) = 16.066$, $p < 0.001$, $\eta_p^2 = 0.64$) were significant. The effect of vowel position was not significant: ($F(1,9) = 0.044$, $p = 0.839$, $\eta_p^2 = 0.01$). Consequently, the averaged consonant scores and the averaged vowel scores were reported in all subsequent figures.

Nonsense Syllable Test Performance at 30 dB HL

Figure 4 shows the averaged consonant and vowel scores measured across time/hearing aid conditions at the 30 dB HL presentation level. The error bars (for 1

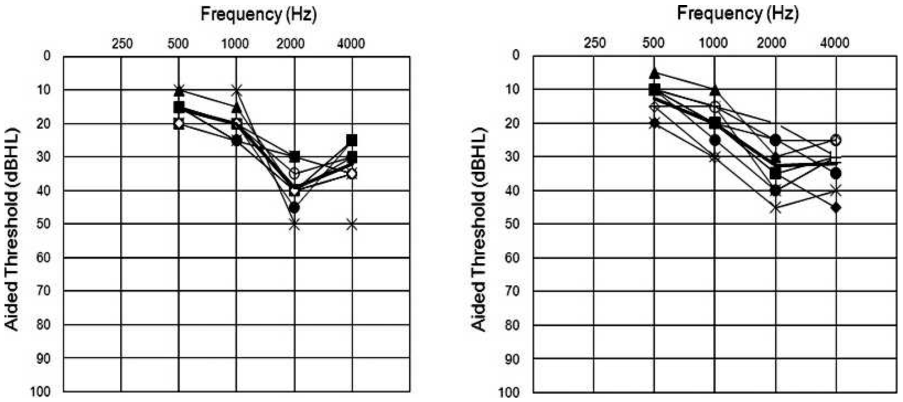

Figure 3. Monaural aided sound-field thresholds for the right and left ears with the linear frequency transposition (LFT) program. The averaged thresholds are represented by the bold line.

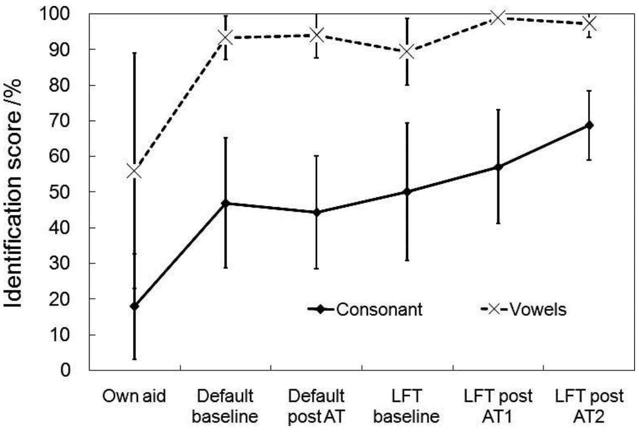

Figure 4. Consonant and vowel scores on the Nonsense Syllable Test presented at a 30 dB HL input level and measured with the participants' own aids (Own aid), with the study hearing aid in the default program at the initial fitting (Default baseline), with the default program after three weeks of auditory training (Default post-AT), with the study hearing aid in the LFT program at baseline (LFT baseline), with the study LFT program after three weeks of auditory training (LFT post-AT1), and after six weeks of auditory training (LFT post-AT2).

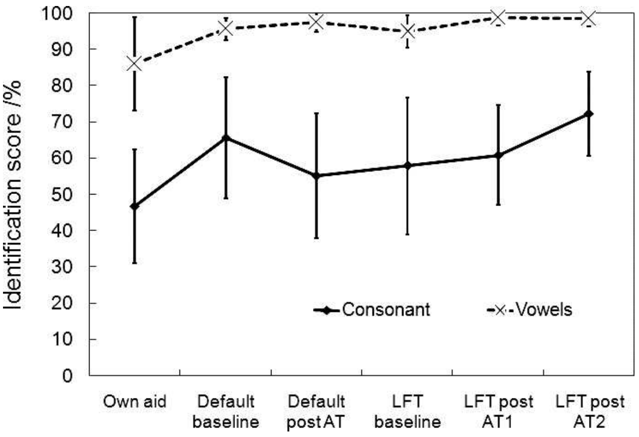

Figure 5. Consonant and vowel scores on the Nonsense Syllable Test presented at a 50 dB HL input level and measured with the participants' own aids (Own aid), with the study hearing aid in the default program at the initial fitting (Default baseline), with the default program after three weeks of auditory training (Default post-AT), with the study hearing aid in the LFT program at baseline (LFT baseline), with the study LFT program after three weeks of auditory training (LFT post-AT1), and after six weeks of auditory training (LFT post-AT2).

standard deviation) were also included to reflect participant variability. For consonant identification, the average participant achieved a score of 18% with their own hearing aids and 47% with the study hearing aid in its default program (no LFT) during the initial fitting. Auditory training in the default program did not seem to improve identification as reflected by the similar identification scores (44%) measured after the three-week training.

Performance with the LFT program took a slightly different course. Although the initial identification score with the LFT program (LFT baseline) was similar to that for the default program, scores measured with the LFT program improved to 57% after three weeks of auditory training with the LFT (LFT post-AT1) and to 69% after six weeks of training with the LFT (LFT post-AT2).

Vowel identification also improved with the use of the study hearing aid in the default condition. This was reflected by the increase in identification score from 56% with the children's own hearing aids to over 90% with the study hearing aid at the initial fitting. Interestingly, the initial vowel score for LFT (LFT baseline) decreased slightly (89%), only to improve to almost 100% during subsequent testing with the LFT program (LFT post-AT1 and -AT2).

A post-hoc analysis using paired-samples t-test with Bonferroni adjustment for multiple comparisons was performed. Results revealed that consonant recognition performance in both the default program and the LFT program (with or without training) were better than that with the children's own hearing aids ($p < 0.05$). The performance with the LFT program after six weeks of training (i.e., AE-AT2) was significantly better than that with the default program (with and without training). Performance after six weeks of training in the LFT program was significantly better than baseline LFT performance ($p < 0.05$). All other comparisons were nonsignificant ($p > 0.05$).

For vowel scores, significant differences were noted between the study hearing aid (both default and LFT programs) and the children's own hearing aids ($p < 0.05$). Performance with the LFT program after three weeks of training was significantly better than that in the default program at the baseline ($p < 0.05$). Performance with the LFT program after three weeks of training was significantly better than baseline LFT performance ($p < 0.05$).

Nonsense Syllable Test Performance at 50 dB HL Input Level

Figure 5 shows the averaged phoneme identification scores measured at 50 dB HL. A trend similar to that shown in Figure 4 was evident. Namely, identification scores measured with the study hearing aids were higher than those of the children's own hearing aids. In addition, there was a gradual improvement in the performance with the LFT program over time (e.g., consonant performance improved from 58% from baseline to 60% at AT1 and 72% at AT2).

The magnitude of the change was less dramatic at this presentation level than at the 30 dB HL level. A post-hoc analysis using paired-samples t-test with Bonferroni adjustment for multiple comparisons was performed. Results indicated that performance for

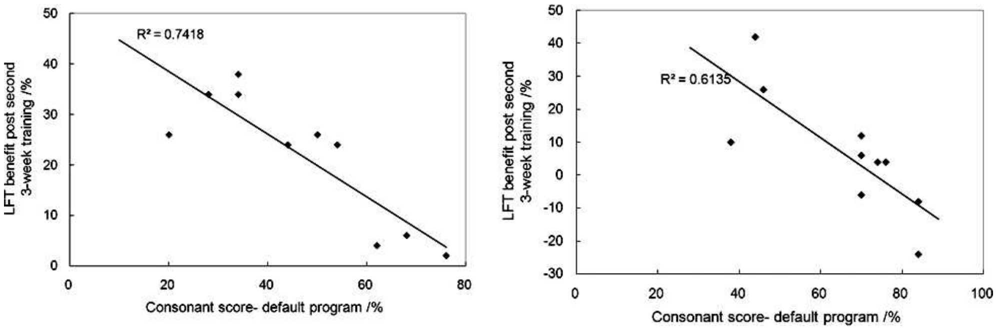

Figure 6. Scatterplots showing the correlation between individual consonant LFT benefit and the hearing loss at 1 kHz. The result for an input level of 30 dB HL is shown on the left, and that for 50 dB HL is shown on the right.

consonant recognition in the default program at the baseline was significantly better than that with the children's own HA ($p < 0.05$). Performance after six weeks of training in the LFT program was significantly better than that with the children's own HA. ($p < 0.05$). Comparisons in other test conditions were nonsignificant. Use of a larger sample of study participants may result in more instances of significance. No significant differences were noted in vowel identification among the default, LFT, and the children's own HA condition.

Correlation of Default Performance and LFT Benefit

Figure 6 shows scatterplots of the children's consonant identification scores measured with the LFT program at the end of the use period (y-axis) plotted against their scores with the default program at the beginning of the evaluation (x-axis). Improvements in consonant recognition scores measured for the LFT condition were greatest for children with the poorest baseline scores. Correlation is significant for both intensity levels (at 30 dB HL, $r = -0.861$; 50 dB HL, $r = -0.783$; $p < 0.01$); where r is the Pearson correlation coefficient. This suggests that children who perform poorly with conventional amplification would probably benefit most from the LFT algorithm.

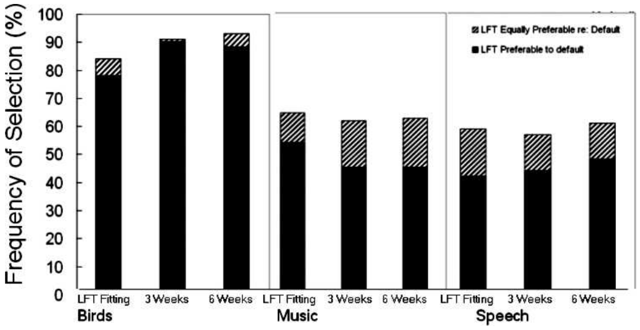

Figure 7. Preference for the LFT program compared to preference for the default program at various assessment sessions (LFT fitting, three weeks after fitting LFT, and six weeks after fitting LFT) for speech (female) and nonspeech stimuli (bird songs and music). The height of the solid black bar represents the percent of time the LFT program was preferable to the default program. The hatched portion of the bar represents the percent of time the LFT program was equally preferable to the default program. The total height of the bar represents the percent of time the LFT program was preferable to or equally preferable to the default program.

Subjective Preference for Speech and Nonspeech Stimuli

The relative subjective preference for the LFT program and the default program for bird, music, and female discourse stimuli over time is summarized in Figure 7. The height of the black portion of each bar represents the percentage of time the LFT program was preferred over the default program, while the hatched portion of the bar represents the instances in which equal preference was reported. Consequently, the total height of the bar represents the frequency at which the LFT program was as preferable as, if not more preferable than, the default program. Thus, the preference for the default program would be 100% minus the total height of the bar.

Figure 7 shows that almost 90% of the children preferred the LFT program over the default program when the stimuli were bird songs. The preference was approximately 60% when music and female discourse were used as the stimuli. These preferences did not change over time as reflected by the similar percentages at the baseline (LFT fitting) and post–auditory training periods (three and six weeks).

Accuracy of /s/ and /z/ Production

The children's accuracy of articulation of the /s/ and /z/ phonemes during the reading task and the conversation task is shown in Figure 8. The percent accuracy was calculated by dividing the instances in which the target phoneme was articulated accurately by the total instances in which the target phoneme was produced or could have been produced.

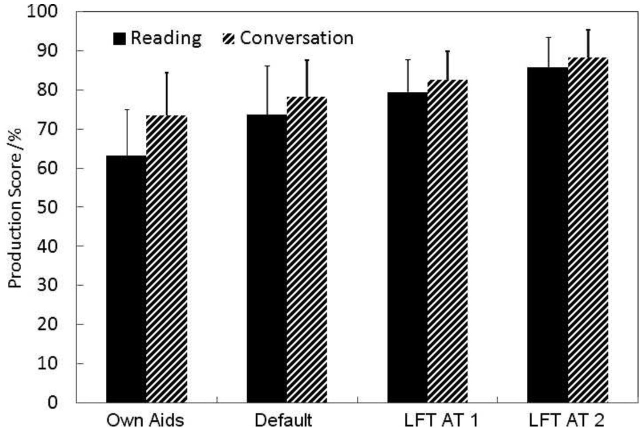

Figure 8. Accuracy of the /s/ and /z/ production measured on a reading task (solid) and a conversational task (hatched) with the children's own hearing aids, the study hearing aid in the default program after training, and the study hearing aid in the LFT program after three (LFT AT 1) and six (LFT AT 2) weeks of training.

Figure 8 showed that on the reading task, the average performance of children improved from an accuracy of 63% with their own hearing aids to 74% with the study hearing aid in the default program (default assess) after the three-week training. Continued improvement was noted with the use of the LFT program, with the performance after six weeks of LFT use at 86% (LFT assess 2). A similar trend was also noted for the conversational task.

The speech production data were also arcsine transformed, and a repeated-measures ANOVA was used to test the significance of the two within-subjects effects, namely, speech production task (reading or conversation) × aided conditions (own aid, default assess, LFT assess 1, and LFT assess 2). The results suggest that the effects of speech production task ($F(1,9) = 6.766$, $p = 0.029$, $\eta_p^2 = 0.43$) and aided condition were significant ($F(3,27) = 27.727$, $p < 0.001$, $\eta_p^2 = 0.76$). Post-hoc analysis using paired-sample t-tests with Bonferroni adjustment for multiple comparisons for the "reading" task showed that performance with the children's own hearing aids was significantly poorer than with the study hearing aid in both the default and LFT conditions ($p < 0.05$). Furthermore, performance in the LFT program was significantly better ($p < 0.05$) than the default program after the second three-week training period (i.e., LFT assess 2). A similar trend was seen with the "conversation" task, although the comparison between the children's own aids and the default assess condition was not significant ($p > 0.05$).

Subjective Questionnaires—Environmental HF Sounds

Figure 9 displays the percentage of sounds reported as detectable in each hearing aid condition (i.e., own aids, default program, LFT program) for each sound category (e.g., dining, kitchen, etc.). Children experienced greater awareness of environmental sounds when fit with the study hearing aid in the default program and in the LFT program as compared to their own HAs. A repeated-measures ANOVA was used to test the significance of the two within-subjects effects, namely, aided condition (own aid, default, LFT assess 1, LFT final) × sound category (kitchen, dining, bathroom, office, other, children, pets, sounds in public, sounds outdoor, and car) after the data were arcsine transformed. Results showed that aided condition was

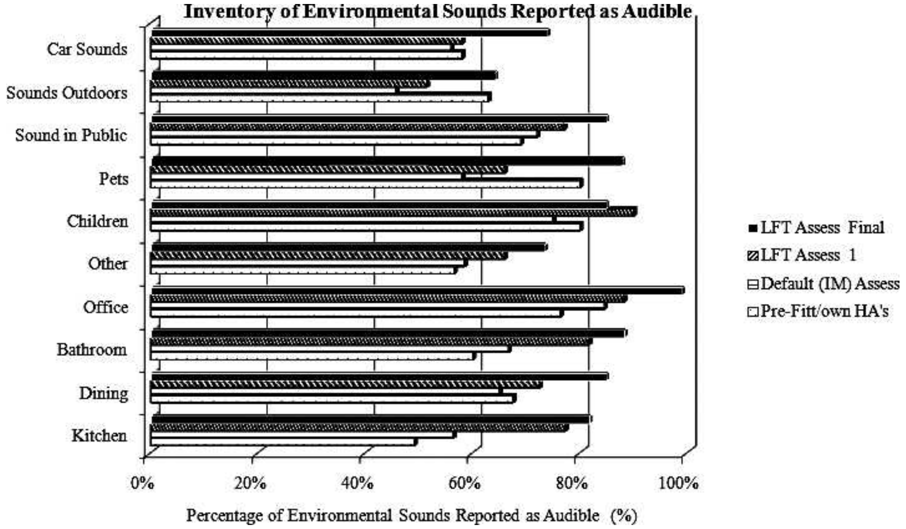

Figure 9. Percent of sounds reported as detectable (for all ten children) from Environmental High-Frequency Sound Survey in each hearing aid condition and in each sound category. (LFT Assess Final = after six weeks of use of LFT program; LFT Assess 1 = after three weeks of use of LFT program; Default = after three weeks of use of study hearing aid in default program; and Pre-Fitt/own HAs = at the onset of the study with children's own HAs).

significant ($F(3,27) = 5.378$, $p = 0.017$, $\eta_p^2 = 0.37$). Results also showed that sound category was significant ($F(9,81) = 12.474$, $p < 0.001$, $\eta_p^2 = 0.57$). A post-hoc analysis with Bonferroni adjustment for multiple comparisons of the different aided conditions indicated that the LFT final condition was significantly better ($p < 0.05$) than the own aids and default conditions but not the LFT assess 1 condition ($p > 0.05$).

It is also of interest to note that all ten children accepted the LFT program immediately when they were fit initially, and continued to use the study hearing aids in the LFT program after completion of the study.

DISCUSSION

The present study compared the speech perception and articulation of school-age children using the same hearing aid with and without LFT. The results support the efficacy of linear frequency transposition as implemented in the study hearing aid. Significant performance improvements with LFT were observed compared to that with the default program for vowel and consonant identification in quiet at a presentation level of 30 dB HL. Significant correlations were identified between baseline performance in the default program and improvements in speech recognition scores after six weeks of use of LFT at both 30 and 50 dB HL input levels. The results also showed a significant improvement in the accuracy and consistency of /s/ and /z/ articulation during a reading and a conversational task. The availability of additional cues and the extended use of the algorithm, along with auditory training, may have contributed to the improvement.

In this study we also examined subjective preference of children for LFT and the impact of LFT on awareness of environmental sounds. Results indicated that for speech stimuli, children report the LFT program is preferred or equally preferable to the default program 60% of the time at the initial fitting. That preference remains relatively stable after three and six weeks use of the LFT. This was not the case for adult users of LFT who initially preferred the default program over LFT and whose preference changed only after two weeks of use time (Kuk, Keenan, et al, 2007). Awareness of environmental sounds was significantly improved after six weeks of use of LFT compared to the own HA and default conditions.

Is Linear Frequency Transposition Efficacious?

Comparison with Previous Studies

Previous studies have evaluated the efficacy of commercial hearing aids utilizing frequency lowering techniques. Several of these studies were discussed in the introduction. Briefly, the majority of these studies were conducted utilizing a frequency compression hearing aid that operated by compressing the whole spectrum by a fixed ratio once a decision on "voiced" versus "voiceless" sounds was made. The results of these studies showed a lackluster effect of frequency compression (Parent et al, 1998; McDermott and Dean, 2000; McDermott and Knight, 2001; MacArdle et al, 2001). The only exception was the Miller-Hansen et al's (2003) retrospective review where the performance with frequency compression was compared to that of the subjects' own hearing aids. However, differences in the electroacoustic characteristics between the study hearing aids and the children's own hearing aids could have accounted for the improvement.

In the current study, the comparison of efficacy was made not only to the children's own hearing aids but also to the same hearing aid in its "nontransposition" mode, that is, default program. This ensured identical settings on the hearing aids and allowed a separate estimation of the effect of transposition. In this case, despite the relative appropriateness of the children's own hearing aids, the study hearing aid in the default program (i.e., no transposition) yielded significantly higher consonant identification scores than the children's own hearing aids at the 50 and 30 dB HL presentation levels. The vowel score also improved significantly over the children's own hearing aids.

Greater Loss, Greater Benefit

Frequency transposition achieves its objective by lowering sounds in an unaidable frequency region into another frequency region where it can be aided. If one assumes that speech understanding is proportional to how much aidable hearing the wearer has, one may expect greater benefits with frequency transposition in children who have poorer speech identification scores than those who have better speech identification scores with traditional amplification. Results of this study support this as significant correlations were identified between baseline performance in the default program and improvements in speech recognition scores after six weeks of use of LFT at both the 30 and 50 dB HL input levels.

What Is the Role of Training?

The improvement seen with LFT was not immediate on all evaluative measures other than the aided sound-field thresholds and subjective preference for speech and environmental stimuli. A period of three to six weeks was required to realize the benefits of LFT for consonant identification and /s/ and /z/ articulation.

One may question whether the final performance with the LFT after the six-week training was the result of auditory training alone. This possibility is not likely given that the Nonsense Syllable Test scores measured with the default program at the time of fitting and three weeks after training were similar. Training with the LFT program for the same duration resulted in improvements in consonant (and vowel) identification at both the three-week and six-week evaluations. Additional HF cues from the transposition algorithm had to have led to the enhanced identification scores.

On the other hand, the consonant scores obtained in the LFT program during initial fitting were not statistically different from the default program. Also, the vowel scores at the 30 dB HL input level were slightly depressed at the initial LFT fitting. Nonsense Syllable Test scores with LFT did not improve until the children were trained. Thus, one has to conclude that while the availability of the transposed HF cues is important, auditory training enhances the effective use and interpretation of the transposed speech cues.

Despite the significant improvements in consonant and vowel identification with LFT, the highly redundant nature of speech stimuli may preclude speech recognition test materials from fully illustrating the benefit achieved by children utilizing this strategy in real-life situations. Results of the environmental sound survey showed that LFT resulted in awareness of significantly more environmental sounds than either the children's own HAs or the study HAs in the default condition. Therefore, when evaluating strategies such as LFT, it may be beneficial to consider other measures to assess progress, such as awareness of nonspeech environmental sounds.

Another reason for the positive outcome in this study is that the children were fitted with a start frequency that was individually determined. Additionally, children accepted the LFT program immediately, and their preference for listening to speech and other environmental sounds via LFT was constant over the three- and six-week assessment periods. They used the LFT program exclusively in their daily environments prior to the evaluation. If such real-life adaptation to the new acoustic percepts were not available, it may not have been possible for the children to realize the benefits measured in this study. For example, McDermott and Dean (2000) evaluated the word identification score in quiet of four hearing-impaired subjects with a precipitously sloping HF loss with and without "frequency compression" using a compression factor of 0.6. Although the children were provided with training on the compressed signals (not the actual test materials) for ten one-hour sessions, they did not receive any extended, real-life exposure to the processed sounds because the device was not available in a wearable form. Consequently, no improvements were noted in the participants' word identification scores. The difference in outcomes between studies may reflect the differences in the processing algorithm itself; however, the lack of continued experience with the frequency lowered sounds may also have contributed to the difference in findings.

CONCLUSIONS

The current study showed that linear frequency transposition did improve consonant identification in quiet for children with a severe-to-profound hearing loss in the high frequencies. Improvement was also seen in the perception of speech and nonspeech sounds, as well as in the articulation of /s/ and /z/ phonemes during reading and conversation. Although the availability of the HF acoustic information (from transposition) is the main explanation for such improvements, the importance of auditory training and the consistent use of the algorithm in real life cannot be understated.

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Appendix 1. Environmental High-Frequency Sound Survey

Check the box next to each sound you hear under the appropriate listening situation when that sound was heard.

Sounds at home	Program 1	Program 2
Kitchen:		
1. Dripping faucet	☐	☐
2. Gas stove ignition	☐	☐
3. Microwave buttons	☐	☐
4. Microwave alarm	☐	☐
5. Breaking glass	☐	☐
6. Cracking ice	☐	☐
7. Aluminum foil	☐	☐
8. Candy wrappers	☐	☐
9. Whistling tea kettle	☐	☐
10. Refrigerator magnet	☐	☐
11. Plastic bag/wrap	☐	☐
Dining:		
12. Silverware	☐	☐
13. Spoon stirring a drink	☐	☐
14. Glasses clinking for a toast	☐	☐
15. Tapping glass with a spoon	☐	☐
16. Hitting chopsticks together	☐	☐
17. Soda fizzing	☐	☐
18. Other people eating	☐	☐
19. Chair scraping the floor	☐	☐
Bathroom:		
20. Dripping faucet	☐	☐
21. Urination	☐	☐
22. Clothes rustling	☐	☐
23. Zipper	☐	☐
24. Moving the seat up or down	☐	☐
25. Brushing hair	☐	☐
Office:		
26. Keyboard buttons	☐	☐
27. Rustling paper	☐	☐
28. Paperclips on hard surface	☐	☐
29. Clicking a pen	☐	☐
30. Scissors	☐	☐
31. Stapler	☐	☐
32. Computer sounds	☐	☐
33. Computer mouse click	☐	☐
34. Phone ring (in same room)	☐	☐
35. Phone ring (in other room)	☐	☐
36. Phone button tones	☐	☐
Other:		
37. Shaking keys	☐	☐
38. Squeaky furniture	☐	☐
39. Door hinge	☐	☐
40. Jewelry (ring on hard surface, noisy bracelet, etc.)	☐	☐
41. Ticking clock	☐	☐
42. Cuckoo clock	☐	☐
43. Adjusting window blinds	☐	☐
44. Watch alarm	☐	☐
45. Tapping fingernails	☐	☐
46. Fire crackling in fireplace	☐	☐
47. Hearing aid held in hand	☐	☐
48. Doorbell	☐	☐
49. Snap closures	☐	☐

Appendix 1. Continued

Sounds at home	Program 1	Program 2
50. Door locking	☐	☐
51. Wind blowing outside (when you are inside)	☐	☐
52. Rain on the roof	☐	☐
53. Various light switches		
a. Pull chain	☐	☐
b. Standard flip switch	☐	☐
c. Switch on a lamp	☐	☐
Children:		
54. Child's squeaky toy	☐	☐
55. Child's toy that plays music or beeps	☐	☐
Pets:		
56. Pet toenails on tile	☐	☐
57. Pet collar tags	☐	☐
58. Whining dog	☐	☐
59. Meowing cat	☐	☐
60. Pet toys with bell or squeak	☐	☐

Sounds in Public	Program 1	Program 2
61. Salvation Army bell	☐	☐
62. Elevator bell	☐	☐
63. Coins jingling	☐	☐
64. Wet shoes on tile	☐	☐
65. Shopping carts	☐	☐
66. Instruments (ex: piccolo)	☐	☐
67. Car turn signal	☐	☐
68. Cash register printing receipt	☐	☐
69. Music in stores over intercom (doctor's office/waiting area)	☐	☐
70. High heel shoes on hard floor	☐	☐

Sounds outdoors	Program 1	Program 2
71. Cracking ice	☐	☐
72. Rustling leaves	☐	☐
73. Birds	☐	☐
74. Crickets	☐	☐
75. Whistling	☐	☐
76. Wind chimes	☐	☐
77. Bicycle bell	☐	☐

Car sounds	Program 1	Program 2
78. Left key in ignition with door open (warning ding)	☐	☐
79. Door locking	☐	☐
80. Screeching tires	☐	☐
81. Checking air in tires (hiss)	☐	☐
82. Washing window or mirror	☐	☐