Cochlear Implant Combined with a Linear Frequency Transposing Hearing Aid

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Abstract

Background: Adults with cochlear implants (CIs) are usually implanted unilaterally. To preserve binaural advantages, a noninvasive method involves maintaining the hearing aid (HA) on the contralateral ear; the choice of HA for this purpose is therefore crucial. In recent years, the use of frequency transposition has gained a renewed interest in clinical practice. This type of processing records information from the high-frequency region and conveys it to a low-frequency region where there is still some residual hearing.

Purpose: To conduct an investigation and examine whether adults with unilateral CI derive benefits from a HA utilizing linear frequency transposition (LFT) on the contralateral ear.

Research Design: A two-period, single-blind, repeated-measures crossover design was conducted to examine the combination of LFT in conjunction with a CI. Speech recognition tests were performed in quiet and in noise with LFT either activated or deactivated. The Speech, Spatial and Qualities of Hearing Questionnaire (SSQ) was used to measure subjective benefit.

Study Sample: The participants were nine frequent bimodal users, five males and four females, with a moderate to profound high-frequency sensorineural hearing loss in the nonimplanted ear.

Intervention: The current study was conducted using the Widex Mind440 power (m4-19) behind-the-ear HA. The participants acted as their own control in a total of seven conditions: (1) bimodal with own HA, (2) CI only, (3) own HA alone, (4) bimodal new HA LFT-off, (5) new HA LFT-off, (6) bimodal new HA LFT-on, and (7) new HA LFT-on.

Data Collection and Analysis: Monosyllabic words in quiet and the Swedish version of Hearing in Noise Test (HINT) were used as speech test materials. Stimuli were presented in sound field at a speech level of 65 dB sound pressure level (SPL) via a loudspeaker at a distance of 1 m from the participant in a sound-treated room. The SSQ was administered in each session evaluating the three bimodal conditions. SPSS software was used for statistical analyses. General linear model (GLM) analysis of variance for repeated measures was performed and followed with Bonferroni-adjusted post hoc pairwise comparisons.

Results: Participants performed better with CI only than with HA alone, and the bimodal conditions were superior to the CI alone. No significant differences (p > .05) were observed when comparing the LFT-on with LFT-off regardless of whether the use of CI was included in the different listening conditions in objective and subjective measurements.

Conclusions: The results suggest an advantage for CI patients with a HA in the opposite ear, and that the LFT neither degraded nor enhanced speech performance in conjunction with a CI in quiet or in noise in comparison to when it was deactivated.

Key Words: Binaural hearing, bimodal stimulation, cochlear implant, hearing aid, linear frequency transposition, speech recognition

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Today it has become evident that cochlear implantation is a safe and reliable treatment for people with profound hearing loss (Brown et al., 2009; Gosepath et al., 2009). Improvements have been demonstrated in auditory-oral performances with cochlear implants (CIs) compared to hearing aids (HAs), and implanted patients report a significantly better quality of life (Geers, 1997; Hallberg and Ringdahl, 2004). As the criteria have become more lenient, infants and adults with severe hearing loss are now accepted as candidates. However, implantations in adults are usually unilateral. To provide binaural advantages, a noninvasive method involves continued use of a HA on the opposite ear. This combination of acoustic and electric input is called “bimodal stimulation.” Conclusive evidence has been demonstrating binaural advantages for people with this type of stimulation. As with bilateral HA fittings, bimodal stimulation provides benefits in terms of better speech recognition and localization ability. Collectively, studies have clearly indicated support for continued use of the HA on the opposite ear after unilateral implantation (Ching et al., 2004; Hamzavi et al., 2004; Morera et al., 2005; Ching et al., 2006).

Even though a conventional HA provides low-frequency sounds to the nonimplanted ear, it often fails to restore audibility to normal levels on high-frequency components of speech, such as softer phonemes (consonant sounds), for people with high-frequency sensorineural severe-to-profound hearing losses. On the contrary, too much amplification may lead to deterioration of speech understanding (Ching et al., 1998; Hogan and Turner, 1998). Different sound processing schemes have been developed over the past decades dedicated to solve this matter. One alternative method is to record information from the high-frequency region and convey it to a low-frequency region where there is still some residual hearing. This method is referred to as frequency lowering. Frequency lowering technologies can be divided into two groups: frequency transposition and frequency compression.

The first hearing device with frequency lowering was the Oticon TP 72. This device was a body-worn HA designed by Bertil Johansson at the Karolinska Institute, Stockholm, Sweden, and introduced in the 1960s. At that time, it was the only commercially available HA with frequency transposition. The device converted signals between 4 and 8 kHz into a low-frequency noise below 1.5 kHz, thus making high-frequency sounds audible for the listener. This type of processing was not always optimal as low-frequency cues could sometimes be partially masked by the converted noise. This problem also increased due to the system’s sensitivity for high-pitched noise, especially movement of clothing. Transposition could therefore occur for all high-frequency sounds regardless of level and whether it originated from speech or noise. Consequently, even unwanted background noise in the high-frequency region was transposed (Johansson, 1966; Foust and Engel, 1973).

Linear frequency transposition (LFT) is incorporated in a feature called Audibility Extender, manufactured by Widex. Like traditional transposition, the goal is to shift unaidable high-frequency sounds to lower aidable frequency regions. Based on the audiogram, a start frequency (SF) is automatically chosen at which the LFT begins. Generally, sounds one octave above the SF will be transposed. The region of sounds that will be transposed is called the source region. When activated, the LFT picks a frequency in the source region with the highest spectral peak (peak frequency) and locks it for transposition. Once identified, the peak frequency will be shifted downward linearly by one octave and the sounds surrounding it will be transposed down by the number of Hertz that corresponds to one octave for the peak frequency. In other words, as the peak frequency changes, the transposed frequency also changes.

In a preliminary study by Korhonen and Kuk (2008), LFT was tested on nine normally hearing adults with a simulated high-frequency hearing loss. The aim of the study was to demonstrate whether using LFT-on compared to when it was off could provide acoustic cues. The results showed that overall identification scores improved with LFT over the nontransposed stimuli by 14.4 percentage points. It is concluded that listeners may not always show an improvement immediately with LFT activated. As a matter of fact, some listeners may even be confused by it.

Kuk et al. (2009) also conducted a single-blind study where eight adults with severe-to-profound hearing loss were fitted with the Widex Mind440 (m4-m). The purpose of the study was to examine the effect of LFT on consonant identification in quiet and noise at speech levels of 50 and 68 dB sound pressure level (SPL). The results indicated a statistically significant improvement for fricatives in both conditions with the LFT-on after 2 mo compared to the initial fitting with and without LFT. It was concluded that LFT does not make speech understanding in noise more difficult, and that proper training, of at least 1 or 2 months, is recommended.
Another processing scheme is nonlinear frequency compression (NFC). This scheme aims to provide high-frequency speech information to the listener while preserving low- and mid-frequency information in a narrower low-frequency range. Based on a chosen cutoff frequency, frequency lowering occurs by applying compression for relatively high-input frequencies. This method reduces the bandwidth of the speech signal and has the advantage of no spectral overlap between the shifted and unshifted signals. However, NFC in the high frequencies also means that frequency ratios are not preserved in that particular region. One possible disadvantage of such a scheme could, therefore, be that speech might be adversely affected. NFC that is utilized in commercially available HAs is Sound Recover (SR), manufactured by Phonak.

McDermott and Henshall (2010) evaluated the effects on speech recognition in eight adults with a unilateral CI using NFC simultaneously on the contralateral ear. The results showed that there were no significant differences when comparing SR activated or deactivated in conjunction with a CI. Interestingly, the participants readily accepted the NFC even though there was no perceptual benefit related to the use of SR.

Since the studies of LFT have shown relatively positive effects and no published study has examined the use of CI in conjunction with LFT, we decided to examine whether adults with bimodal hearing devices would derive benefits from a HA utilizing LFT.

METHODS

Study Participants

To estimate the required study sample, the G*Power 3.1.2 power analysis package was used. Data for estimation were collected from our pilot experiment conducted prior to the current study. Assuming that the results will show an effect size of >7% (mean difference between LFT-on and LFT-off in the bimodal condition in quiet) and a standard deviation of 5.7%, it was estimated that a minimum of eight participants were needed to reach a statistical significance at the 0.05 level with a power greater than 0.8. Ten participants were recruited to the study. However, the results are based on nine participants because one participant decided to withdraw due to a lack of motivation. The current study sample consisted of five males and four females who were between 55 and 81 yr old (mean: 63.3). Participants were selected from the records of Sahlgrenska University Hospital based on the following criteria: age >18 yr, CI in one ear, and severe-to-profound sensorineural hearing loss in the opposite ear with residual hearing at the low-frequency region due to cochlear dysfunction. All the participants were frequent bimodal users, had Swedish as a first language, and a severe-to-profound hearing loss (>70 dB HL) above 2 kHz in the nonimplanted ear. Frequent HA users were included because no benefit from LFT was observed in nonfrequent bimodal users from our pilot study. In the low-frequency region, the participants were all within the fitting range of the HA that was being used in the present study. All participants were implanted in the ear with poorest hearing, had at least 1 yr of CI experience and stable-fitting parameters in their CI processors before the inception of the trial. Table 1 gives the demographic information of the participants. The hearing thresholds of the nonimplanted ear of each participant were measured using standard audiological procedures. Table 2 shows the individual hearing threshold levels (HTLs), mean, standard deviation, and range of HTL in the low-frequency region.

An information letter was sent to the participants before the start of the trial. Before signing the consent form, the participants were informed of and thus were aware of the risks, their tasks, and how collected data would be handled. None of the participants were paid for their participation, but they received the HA for their permanent use after the trial. Ethical approval for the study was obtained through the local ethics committee.

Table 1. Demographic Data for All Participants

<table>
<thead>
<tr>
<th>Participant no.</th>
<th>Gender</th>
<th>Age, yr</th>
<th>Etiology</th>
<th>HA/CI experience, yr</th>
<th>Ear with HA</th>
<th>Own HA model</th>
<th>Implant type</th>
<th>CI processor type</th>
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<tbody>
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<td>64</td>
<td>Unknown</td>
<td>54/8</td>
<td>L</td>
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<td>Nucleus CI24R</td>
<td>ESPrit 3G</td>
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<td>2</td>
<td>M</td>
<td>69</td>
<td>Unknown</td>
<td>16/3</td>
<td>R</td>
<td>Phonak Perseo 311</td>
<td>MED-EL Sonata</td>
<td>OPUS 2</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>81</td>
<td>Unknown</td>
<td>21/1</td>
<td>L</td>
<td>GN Resound Canta 780D</td>
<td>MED-EL Sonata</td>
<td>OPUS 2</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>55</td>
<td>Hereditary</td>
<td>48/2</td>
<td>L</td>
<td>Widex C18</td>
<td>Nucleus CI24RE</td>
<td>Freedom</td>
</tr>
<tr>
<td>5</td>
<td>F</td>
<td>80</td>
<td>Unknown</td>
<td>22/6</td>
<td>R</td>
<td>GN Resound Viking</td>
<td>Nucleus CI24RE</td>
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<tr>
<td>6</td>
<td>M</td>
<td>57</td>
<td>Unknown</td>
<td>20/5</td>
<td>R</td>
<td>Phonak Claro 311</td>
<td>Nucleus CI24RE</td>
<td>Freedom</td>
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<td>7</td>
<td>M</td>
<td>81</td>
<td>Unknown</td>
<td>20/4</td>
<td>R</td>
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<td>Nucleus CI24RE</td>
<td>Freedom</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>66</td>
<td>Postmeningitic and ototoxicity</td>
<td>60/4</td>
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<td>MED-EL Pulsar</td>
<td>OPUS 2</td>
</tr>
<tr>
<td>9</td>
<td>M</td>
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<td>39/5</td>
<td>L</td>
<td>Oticon Sumo DM</td>
<td>MED-EL Pulsar</td>
<td>OPUS 2</td>
</tr>
</tbody>
</table>

Note: HA = hearing aid; CI = cochlear implant; M = male; F = female; L = left; R = right.
Hearing Device

The study was conducted using the Widex Mind440 power (m4-19) BTE HA. This HA is a 15-channel instrument utilizing slow-acting wide dynamic range compression and has an active multidirectional feedback cancellation. The directional microphone and the feedback cancellation were activated throughout the study. The HA had a frequency range from 100 to 7100 Hz and an OSPL90 peak of 136 dB SPL (ear simulator data, IEC 60118-0). To minimize the acoustic differences between the test aid and their own HA, the participants’ own earmolds were used in the current study if possible.

Speech Recognition Tests

Two speech recognition tests were used to compare speech performances in each testing condition. All sound materials were presented at a fixed level of 65 dB SPL in a sound-treated room through a loudspeaker located 1 m directly in front of the participant. One different set of lists was used for each testing condition in a counterbalanced order for each speech test. The Swedish phonemically balanced (SPB) word lists were used as speech test material in quiet (Liden, 1954). Each list was composed of 50 monosyllabic words for recognition scoring and was presented with a carrier phrase produced by a male speaker with a Swedish native accent. The participants were instructed to repeat the word that followed the carrier phrase, and they were encouraged to guess. Performance was scored as proportion of correctly identified words.

The Swedish Hearing in Noise Test (HINT) was used to determine speech recognition threshold (SRT) in noise (Hållgren et al, 2006). Sentences recorded with a female speaker were presented at a fixed level of 65 dB SPL, with the level of the competing noise started at 57 dB SPL and adapted according to the accuracy of the participants’ responses. Scoring was based on whole sentences correctly or incorrectly repeated. The participants were encouraged to guess if they experienced difficulty in perceiving the spoken sentence. The adaptive protocol used in the administration of the HINT was employed with a 2 dB step size for 20 sentences (two lists), which means the competing noise was decreased by 2 dB for incorrect responses and increased by 2 dB if the response was correct. The competing noise was presented continuously between sentences, and the level adjustments were made so that the noise was presented at the new level for 3 s before the next sentence began. The HINT scoring rule was used to determine the final SRT; the average of the signal-to-noise ratios (SNRs) for sentences 5 to 20 and additionally the SNR at which sentence 21 would have been presented on the basis of the participant’s response to sentence 20.

Subjective Assessment

The Speech, Spatial and Qualities of Hearing Questionnaire (SSQ) was used to measure subjective benefit (Gatehouse and Noble, 2004). This questionnaire comprises 14 scored items including speech hearing, 17 items on spatial hearing, and 18 items on other qualities and features of hearing, which can be reported in terms of the average for the three subscales. The SSQ was administered by an audiologist in each session, and the participants were instructed to ask him if any question was unclear. The participants evaluated three bimodal conditions using SSQ: bimodal own HA, bimodal new HA LFT-off, and bimodal new HA LFT-on.

Hearing Aid Fitting

The m4-19 was fitted by using the manufacturer’s own software. An in situ measurement of the audimetric thresholds (sensogram) was performed in 13 channels.

<table>
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<th>0.75</th>
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<th>3</th>
<th>4</th>
<th>6</th>
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<td>65</td>
<td>70</td>
<td>80</td>
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<td>&gt;110</td>
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<tr>
<td>Mean</td>
<td>55.6</td>
<td>65.0</td>
<td>82.2</td>
<td></td>
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<td></td>
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<tr>
<td>SD</td>
<td>14.9</td>
<td>11.7</td>
<td>12.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Range</td>
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<td>50-80</td>
<td>70-100</td>
<td></td>
<td></td>
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</tbody>
</table>

Note: HTL = hearing threshold level; SD = standard deviation.
This method makes use of the HA acting as an audiometer, and the resulting configuration of the sensogram is used to calculate the appropriate gain and compression characteristics in the HA. A feedback test was also performed to make sure the HA would not whistle and to estimate maximum available gain in each channel. Insertion gain was measured, and the gain was adjusted to approximate the National Acoustic Laboratories Revised for Profound hearing loss (NAL-RP) target in the LFT-off program. In cases where the subject was to go home with LFT activated, a simulated real ear measurement was performed. Since only frequencies above the SF were transposed, the real ear output showed the lack of gain above the SF and a slight increase in output for the area below the SF.

If activated, the transposition algorithm in the HA had two adjustable parameters: the SF and the LFT-gain. The SF extended from 0.63 to 6 kHz with 1/3-octave band intervals that could be manually selected by the clinician. The LFT-gain could be decreased by 16 (minimum) or increased by 14 (maximum) dB relative to the default LFT-gain (0 dB). The difference between LFT-gain and the general gain was that LFT-gain only focused on the transposed signal, whereas the general gain was used when the participant thought that the sounds in general were too loud or too soft in the HA. To ease the clinical fitting, these parameters are automatically set by the software after performing the sensogram. Another optional function in the LFT was the extension of the source octave. If the SF is below or at 2500 Hz, an extended source region can be optionally selected, including two octaves above the SF instead of just one, resulting in an expanded range of transposed sounds. In this study, since there is no definitive protocol on how to set LFT, the SF was determined on an individual basis by an audiologist. In cases where expanded transposition was an option, this was selected in the aid. Table 3 shows the parametric setting for the LFT used by each participant. After the HA fitting, the participants were instructed to switch on their CI and determine whether the final setting of the gain was acceptable and whether overall loudness in the HA was similar to that of the CI.

Procedure

Each participant had to spend a minimum of three separate sessions, each lasting 1–1.5 hr, spaced over 16 wk to complete the data collection. At the first appointment (week 1), the audiogram of the nonimplanted ear was measured. Afterward, speech recognition tests in quiet and noise were carried out in three conditions: (1) bimodal own HA, (2) CI alone, and (3) own HA alone. The participants were also instructed to evaluate the bimodal with own HA condition using SSQ. After the tests, a two-period, single-blind crossover trial with an 8-wk interval was conducted where the nine participants were randomly divided into two groups. Fitting of the m4-19 was performed; the first group went home with the LFT activated for the first 8 wk and deactivated for the second 8 wk, whereas the order was reversed for the second group.

At the second session (week 8), four new speech recognition tests in quiet and noise were carried out in two conditions: bimodal with m4-19 and m4-19 alone. The participants had to evaluate the bimodal condition using SSQ once again, but this time the evaluation concerned the HA fitting performed in session 1. After the tests, the LFT was deactivated for the first group and activated for the second group.

At the third session (week 16), the groups performed the same speech tests in the same conditions used at the previous appointment. The only differences were that group one performed the tests with LFT-off and group two with LFT-on. Subjective assessment with SSQ was also conducted one last time evaluating the fitting from session 2. To make sure the participants only used the intended program during the 8 wk of use with each of the two experimental programs (LFT-on vs. LFT-off), the program control was deactivated so the participants could not switch between different programs after each fitting. The participants were encouraged to use the m4-19 in conjunction with the CI at all times during the 16 wk of the trial and they were instructed to contact the audiologist if they wanted to make adjustments in amplification during the trial. At the appointments, the participants were always tested with their best expected condition (bimodal) first, then CI alone, and finally HA alone to counteract any practice effect.

### Table 3. Parametric Settings in the Hearing Aid Used by the Participants in the Study

<table>
<thead>
<tr>
<th>Participant no.</th>
<th>SF</th>
<th>Expanded LFT</th>
<th>LFT Gain</th>
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<tr>
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<td>1600</td>
<td>Yes</td>
<td>+2</td>
</tr>
<tr>
<td>2</td>
<td>800</td>
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<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1250</td>
<td>Yes</td>
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<tr>
<td>4</td>
<td>1600</td>
<td>Yes</td>
<td>+2</td>
</tr>
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<td>5</td>
<td>1600</td>
<td>Yes</td>
<td>-2</td>
</tr>
<tr>
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<tr>
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<td>Yes</td>
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</table>

Note: SF = start frequency; LFT = linear frequency transposition.
RESULTS

The participants acted as their own controls in a total of seven conditions: (1) bimodal with own HA, (2) CI only, (3) own HA alone, (4) bimodal new HA LFT-off, (5) new HA LFT-off, (6) bimodal new HA LFT-on, and (7) new HA LFT-on. SPSS software was used for statistical analysis. A Kolmogorov-Smirnov test for normality was first conducted to ensure a normal distribution. The results of the test showed that all variables were nonsignificant \((p > .05)\). To analyze significant differences between the other experimental conditions, general linear model (GLM) analysis of variance (ANOVA) for repeated measures was performed and followed with Bonferroni-adjusted post hoc pairwise comparisons.

Speech Recognition in Quiet

The average speech recognition scores in quiet for each condition are summarized in Figure 1. The average performance with the participants’ own HA in quiet was relatively low (14%) when compared to the other two new HA alone conditions with LFT-off (28%) and LFT-on (30%). A one-way repeated-measures ANOVA showed that there were significant differences in the three HA alone conditions \([F (2, 16) = 22.9, p = .001, \eta_p^2 = 0.74, \text{power} = 1.0]\). A post hoc analysis using Bonferroni-adjusted pairwise comparisons revealed that the mean own HA performance was significantly lower than the new HA LFT-on \((p = .001)\) and new HA LFT-off \((p = .004)\) performance. No significant difference was noted between LFT-on and LFT-off \((p > .05)\). That is, the protocol HA yielded significantly higher speech recognition scores in quiet than the participants’ own HAs, and LFT did not influence the average performance.

The CI only and bimodal conditions showed similar patterns. The best recognition score was achieved in the bimodal, with new HA LFT-on (67%) and with new HA LFT-off (64%), conditions, whereas the bimodal with own HA (56%) and CI only (35%) yielded poorer performance. A one-way repeated-measures ANOVA conducted on the four mean scores revealed that there were significant differences between the average recognition scores \([F (3, 24) = 15.53, p < .001, \eta_p^2 = 0.66, \text{power} = 1.0]\). A post hoc analysis using Bonferroni-adjusted pairwise comparisons revealed that the results in the bimodal performances were significantly higher than with CI only \((p < .05)\). However, no significant differences were observed when comparisons between the three bimodal conditions were made \((p > .05)\). Thus, bimodal stimulation gave better results than using CI only, and the three bimodal conditions showed no difference in performance when the own HAs or new HA, with LFT enabled or disabled, were used in conjunction with a CI.

Figure 1. Average speech recognition scores in quiet for the listening conditions (error bars denote the 95% confidence interval). The asterisks denote significant differences compared with own HA in HA-only conditions, and significant differences compared with CI only in the bimodal conditions.
Speech Recognition Threshold in Noise

Figure 2 provides a summary of the average speech recognition thresholds in noise, when sentences were presented at 65 dB SPL, for each condition. Low SNR indicates better perceptual performance. The average SRTs were approximately 24 dB for all the HA alone conditions in noise. These results are due to a floor effect as most participants were not able to reach the 50% threshold; for this reason, data from these conditions were not analyzed.

The average SRTs in the CI only and bimodal conditions also showed a pattern similar to the performances in quiet, where bimodal with new HA LFT-on (8.8 dB) and with new HA LFT-off (9.9 dB) yielded the best score, and bimodal with own HA (11.5 dB) and CI only (18.8 dB) represented poorer performance. A one-way repeated-measures ANOVA revealed that there were significant differences in the CI only and bimodal conditions [F (3, 24) = 10.5, p = .001, η₂ = 0.57, power = 1.0]. Post hoc analysis with Bonferroni-adjusted pairwise comparisons showed that, in noise, the bimodal conditions were significantly better than the CI-only condition (p < .05). Comparisons made between the bimodal conditions were nonsignificant (p = 1.0). That is, using HA in combination with a CI generated higher recognition performance in noise, independently if the participants changed their own HAs to the new HA with and without LFT.

Speech, Spatial and Qualities of Hearing Questionnaire

Figure 3 shows the SSQ mean scores for each subscale for the three bimodal conditions. A higher score indicates less difficulty with the questions in that subscale. As may be seen, just like the objective measurements, there are no distinct patterns of difference between the three conditions in each subsection. The average scores in the speech section showed that the bimodal with own HA scored lowest (3.1), and that the bimodal new HA LFT-on (3.4) and new HA LFT-off (4.0) scored slightly better. The greatest increase was observed in the spatial section when comparing the scores between bimodal own HA (3.1) with the bimodal new HA LFT-on (4.2) and LFT-off (4.4). The quality section was approximately 5.3 for all the three conditions. A repeated-measures ANOVA conducted on the average subscale scores revealed no significant differences between the three bimodal conditions in each subsection [F (4, 32) = 2.4, p = .07, η₂ = 0.23, power = 0.62]

DISCUSSION

The aim of the current study was to investigate whether adults with bimodal hearing devices would derive benefits from a new HA utilizing LFT. To do this, the participants’ own HAs with and without the CI were included as listening conditions, and the HA only and bimodal conditions also involved the activation and
deactivation of the LFT. The present results suggest that adults with one CI benefit from using a HA on the contralateral ear. The best speech recognition performance was observed in the bimodal condition with LFT-on in quiet and in noise. However, no significant difference was noted between the LFT-on and LFT-off regardless of whether the listening condition included the use of CI. Significant improvements were noted in the HA alone condition in quiet when comparing the m4-19 with the participants’ own HA, but this effect was not observed in the bimodal conditions or in noise. Subjective data were also in contrast with the objective measurements where no difference was noted between LFT-on and LFT-off when the new HA was used with a CI.

Our results are in agreement with previous studies regarding bimodal stimulation where adults with unilateral CI benefit from using a HA on the contralateral ear (Ching et al, 2004; Morera et al, 2005; Ching et al, 2006). Even though there were small individual variations within the study sample, the group as a whole performed better in the bimodal conditions than in the CI or HA alone conditions. Furthermore, the current results agree with the results McDermott and Henshall (2010) reported when combining unilateral CI with NFC on the contralateral ear. They found no significant improvement between the NFC enabled or disabled in the HA-only and bimodal conditions, and a significant improvement when comparing the participants’ own HA with the new HA that was being used in the study. These results might not come as a surprise as comparing an old HA with a new HA would have naturally generated a greater benefit for the newer one regardless of whether transposition was present or not. It is also important to remember that the CI, bimodal stimulation, and frequency lowering all serve different purposes with different aims for the individual. CI users already have access to high-frequency components of speech via the implant, and the purpose of bimodal stimulation is to preserve or gain binaural benefit and complementary acoustic input. The LFT by itself might not necessarily provide a direct significant improvement in speech recognition for each participant with bimodal stimulation in a clinical/laboratory setting, but rather act as a support to the acoustically aided ear, making sound more clear and providing additional high-frequency cues to the listener. In addition, when looking at the results, it is obvious that the CI is superior to the HA only. It is therefore doubtful whether the LFT has enough functionality to generate a significant difference in speech recognition in the bimodal condition, as the CI user already has access to high-frequency sounds.

Kuk et al (2009) evaluated the efficacy of LFT over a period of time extending to 2 mo with training and clearly observed an improvement with further use. In the current study, the acclimatization period was also 2 mo and the participants readily accepted the LFT.
at the initial fitting even though some of them reported it sounding somewhat confusing and unnatural at first. Data logging of the protocol HA showed that the use of bimodal transposition was 11-15 hr per day for five participants and 6-8 hr for the other four. Interestingly, when the participants came back at the end of the 8-week period with LFT-on (still single-blinded during session 2 or 3 depending on which group they started out in) most of them reported that the LFT was easier to listen to after 8 wk of normal use than at the initial fitting. No interference between the CI and the new HA with LFT-on was noted in the objective and subjective measurements, and seven of nine participants decided to go home with the LFT activated in conjunction with the CI after the trial. This indicates that acclimatization of LFT can occur and one might speculate that with an acclimatization period even longer than 8 wk, different results might have been obtained. No significant difference was noted between LFT-on and LFT-off when using SSQ as subjective assessment, and the lack of statistical difference from these data might be due to the small number of participants in the trial. Cognitive factors might also have influenced the outcome since the study sample comprised some elderly participants. However, the current results are consistent with the results reported by Kuk et al (2009) and Auriemmo et al (2009) regarding subjective responses, where no participants reported negative experiences when using LFT. Instead, the participants in our study reported that they preferred to use the LFT in a quiet environment than in a noisy situation which seems reasonable since the main purpose of LFT is to make high-frequency sounds audible, and not enhance speech recognition in noise. Likewise, recently conducted studies have also shown that frequency lowering in general does not seem to significantly improve speech recognition in noise (Kuk et al, 2009; McDermott and Henshall, 2010; Wolfe et al, 2010).

Even though no significant difference was observed between the own HA and the protocol HA, neither for speech in noise nor with SSQ, all participants reported that the sound appeared to be clearer with the m4-19. These results might be due to the fact that no verification of the own HAs was performed in the current trial. However, the purpose of the current study was not to make comparisons with the own HA.

Standard clinical speech audiometric methods were used in this study. Monosyllabic words with a male speaker in quiet and the HINT sentences with a female speaker were used for evaluating the LFT and CI combination. While these parameters might not seem appropriate for this type of processing, they do reflect the actual clinical situation in Sweden where the SPB word lists and the HINT are the standard speech tests when evaluating the performance in users of CI. At present, there is a lack of evaluation tests for frequency lowering technologies in Swedish despite clinical use. It would be desirable if high-frequency consonant identification tests could be developed and used clinically in the near future to evaluate this type of processing scheme.

In our study, the SF for LFT was determined on an individual basis. We decided to do so because after performing the sensogram in our pilot study, the SF was usually set at a higher frequency than desired, thus generating almost no benefit for the listeners. It is, of course, possible that different settings of the SF and switching the extension of the source octave on/off could have generated different results at the end of the trial. We do, however, believe that having an individual setting of the LFT and using an extended LFT when possible was more justified than just following recommendations from the software manufacturer. To date there are no guidelines on how to select the appropriate candidates for frequency lowering. Most participants had residual hearing up to 1 kHz (around 80–95 dB HL) and almost no measurable hearing thresholds from 2 kHz, and as a result most SFs were set around 1.6 kHz or lower. The recruitment of participants with this cutoff between low- and high-frequency regions is appropriate since selecting candidates with even more residual hearing at higher frequencies would possibly generate a SF set too high up and, consequently, there would be no benefit of transposition for the listener. Moreover, the participants were asked if the loudness between the CI and HA with LFT was balanced at an informal test. Our previous experience has indicated that when the CI is mapped to a very high intensity level and the patients want to balance that level with the contralateral HA, this loudness balance might not turn out to be as good for the LFT-on condition. As mentioned before, one concern with frequency transposition is partial masking or distortion of low-frequency sounds. If the gain was adjusted to an unnaturally high intensity level for the sake of balancing, this might not benefit the LFT program. The clinician should keep this in mind when fitting a HA utilizing LFT in combination with a CI.

Although no significant difference was noted between LFT-on and LFT-off, the current results did not show any interference between the CI and HA with LFT; the bimodal LFT-on condition yielded the highest speech performance. Therefore, one interesting question to ask is whether bilateral stimulation, either HA with LFT and CI or bilateral CIs, offers the greatest chance for improvement of audition and speech recognition. Recent studies have pointed out the importance of preserving low frequency components of sound in CI patients in the nonimplanted ear (Chang et al, 2006; Cullington and Zeng, 2010; Zhang et al, 2010). With LFT restoring audibility in the high-frequency region, patients with one CI can now access both high- and
low-frequency components of sounds in the ear with HA. Further research on this topic identifying similarities and differences between bilateral CIs and bimodal stimulation with LFT would be interesting for different higher or lower auditory performance groups. Furthermore, no difference in performance was found based upon CI or personal HA type in the current results, and it would be of interest to conduct a future trial with a larger study sample to compare different CI or HA types with LFT benefit. Lastly, studies comparing adult listeners with either a congenital or late-acquired high-frequency sensorineural hearing loss, and their benefit when using frequency lowering would also be interesting to examine due to the unclear guidelines of appropriate candidates for this type of signal processing.

Taken together, the current results do not support or advise against the use of LFT in conjunction with a CI and should only be generalized for frequent users of bimodal stimulation with residual hearing at the low-frequency region in the nonimplanted ear. Until standard protocols regarding selection of candidates, evaluation methods, and fitting for LFT have been developed, LFT in the opposite ear should be selected for unilateral CI listeners on an individual basis in clinical practice.

CONCLUSIONS

In summary, the results of the present study showed auditory advantages for patients with a CI and a HA in the opposite ear. The study therefore supports previous literature regarding continued HA use on the nonimplanted ear after unilateral implantation. The participants scored the highest speech threshold and recognition performance in quiet and in noise for the bimodal condition with LFT activated. However, no significant improvement was observed when comparing the LFT-off with LFT-on regardless of whether the CI was included in the listening conditions. Even though none of the participants reported any negative responses when the LFT was used in conjunction with the CI, this study does not generally support or advise against the use of LFT in combination with a CI. Further research should focus on evaluation methods for this type of stimulation and develop more generalized fitting guidelines for LFT.

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