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Information From the Voice Fundamental Frequency (*F*0) Region Accounts for the Majority of the Benefit When Acoustic Stimulation Is Added to Electric Stimulation

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Abstract

Objectives—The aim of this study was to determine the minimum amount of low-frequency acoustic information that is required to achieve speech perception benefit in listeners with a cochlear implant in one ear and low-frequency hearing in the other ear.

Design—The recognition of monosyllabic words in quiet and sentences in noise was evaluated in three listening conditions: electric stimulation alone, acoustic stimulation alone, and combined electric and acoustic stimulation. The acoustic stimuli presented to the nonimplanted ear were either low-pass-filtered at 125, 250, 500, or 750 Hz, or unfiltered (wideband).

Results—Adding low-frequency acoustic information to electrically stimulated information led to a significant improvement in word recognition in quiet and sentence recognition in noise. Improvement was observed in the electric and acoustic stimulation condition even when the acoustic information was limited to the 125-Hz-low-passed signal. Further improvement for the sentences in noise was observed when the acoustic signal was increased to wideband.

Conclusions—Information from the voice fundamental frequency (*F*0) region accounts for the majority of the speech perception benefit when acoustic stimulation is added to electric stimulation. We propose that, in quiet, low-frequency acoustic information leads to an improved representation of voicing, which in turn leads to a reduction in word candidates in the lexicon. In noise, the robust representation of voicing allows access to low-frequency acoustic landmarks that mark syllable structure and word boundaries. These landmarks can bootstrap word and sentence recognition.

INTRODUCTION

It has been well documented that low-frequency information, which is not well transmitted by cochlear implants, can be provided to patients through residual low-frequency acoustic hearing in the implanted ear or in the nonimplanted ear (Shallop et al. 1992; Armstrong et al. 1997; Tyler et al. 2002; Ching et al. 2004; Gantz & Turner 2004; Gstoettner et al. 2004; Kiefer et al. 2004; Turner et al. 2004; Kong et al. 2005; Mok et al. 2006; Gifford et al. 2007; Dorman et al. 2008). Both speech understanding in quiet and noise are improved significantly when patients have access to both electrically and acoustically stimulated (EAS) information.

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The aim of this study was to determine the minimum amount of low-frequency acoustic information that is required to achieve speech-perception benefit in listeners who have access to EAS. The results are of interest because a description of the minimum information constrains hypotheses about mechanisms that allow speech perception scores to increase in quiet and in noise with EAS.

EAS in Noise

One accounts for better speech recognition in noise with EAS and the others on an improved representation of pitch ($F0$) (Turner et al. 2004; Kong et al. 2005; Chang et al. 2006; Qin & Oxenham 2006). From this point of view, the low-frequency acoustic signal available to EAS patients provides a good representation of $F0$, and, when signals are presented in noise, listeners are able to segregate better the target voice from speech maskers.

Recent studies using acoustic simulations of EAS have suggested an alternative account. Kong and Carlyon (2007) suggested that it is the availability of low-frequency phonetic information, including (1) $F1$ cues below 500 Hz, (2) coarticulation cues such as formant transitions, and (3) low-frequency consonant cues, including the nasal formant and voicing, which is responsible for improved performance in noise with EAS. Kong and Carlyon suggested, without elaboration, that “glimpsing cues” may also play a role in EAS benefit.

Another perspective on the information relevant to EAS benefit in noise is provided by an EAS simulation by Brown and Bacon (2009). Large gains in speech understanding in noise were obtained when the low-frequency acoustic signal was replaced by a frequency- and amplitude-modulated sine wave. In some conditions, a tone carrying $F0$ and the low-frequency amplitude envelope provided the same intelligibility as low-passed (LP) speech. Brown and Bacon suggested that voicing, amplitude envelope, and pitch change cues can contribute independently to speech intelligibility in simulated EAS. Both Kong and Carlyon (2007) and Brown and Bacon point to glimpsing as an account for the benefit to speech understanding in noise when an acoustic signal is added to a simulated electric signal. In Brown and Bacon’s view of glimpsing, both $F0$ and the amplitude envelope could provide listeners with an indication of when to listen in noise.

EAS in Quiet

The glimpsing hypothesis, described above for the improved recognition of speech in noise, does not speak to the issue of improved word recognition in quiet. However, it is likely that the stimulus attributes glimpsed in noise are the same attributes that are responsible for improved word recognition in quiet. For signals presented in quiet, Ching (2005) reported that information transfer for both consonant voicing and manner was significantly improved when low-frequency acoustic information was added to information provided by a cochlear implant. Thus, the multiple acoustic cues to voicing and manner (Lisker & Abramson 1970; van Tasell et al. 1987; Faulkner & Rosen 1999) are good candidates for the cues added in quiet and glimpsed in noise. Dorman et al. (2008) suggested another possibility. In both quiet and noise, acoustic information about $F1$ could provide a frequency-appropriate reference against which higher-frequency information provided by the implant could be integrated. This suggestion stems from the observation that the cochlear place of electric stimulation is likely to be upshifted relative to the cochlear place of stimulation in the normal ear because of the limited insertion depths of electrode arrays. If EAS patients have a “correct” $F1$ value because of the acoustic signal, this could assist them in interpreting the upshifted information about $F2$ and $F3$.

The Present Study with EAS Patients

Much of the discourse about mechanisms underlying EAS benefit has come from the results of acoustic simulations of EAS. Simulations are aptly named—they are a proxy, using normal-hearing listeners, for testing patients who experience both electric and acoustic stimulation (EAS). Simulations are useful but are not a substitute for assessing the performance of EAS patients.

In this study, adult patients, who were fit with a cochlear implant in one ear and who had low-frequency acoustic hearing in the nonimplanted ear, were presented consonant nucleus vowel consonant (CNC) words in quiet and AzBio sentences in a competing babble noise at +10 dB. Performance was evaluated in three listening conditions: acoustic stimulation alone, electric stimulation alone, and EAS. The acoustic stimuli presented to the nonimplanted ear were either wideband, or LP filtered at 125, 250, 500, or 750 Hz. At issue was the minimum acoustic frequency band, and associated information, which allowed EAS benefit in quiet and in noise.

PATIENTS AND METHODS

Listeners

Nine, adult, postlingually deafened, cochlear implant users, were recruited. Eight listeners were fitted with a conventional implant electrode in one ear and with a hearing aid in the nonimplanted ear. S8 was fitted with a 20-mm implant (Duet, Med-El device) in one ear and with hearing aids in both ears. All nine listeners had residual hearing in the nonimplanted ear with thresholds ≤60 dB HL at 500 Hz and below and thresholds ≤60 dB HL at 1000 Hz and above. The audiogram from each listener's nonimplanted ear is shown in Figure 1. Table 1 displays demographic information for each listener. At the time of testing, all listeners had at least 4 months of experience with electric stimulation (range = 4 months to 5 years), and all listeners except S6 had at least 5 years of experience with amplification before implantation. Informed consent procedures were approved by the Institutional Review Board at Arizona State University.

Speech Stimuli and Test Conditions

Monosyllabic word recognition was tested using the CNC word lists (Peterson & Lehiste 1962). The materials include 10 phonemically balanced lists of 50 monosyllabic words recorded by a single male talker. $F0$ was extracted from one 50-word list using commercial software (WaveSurfer, version 1.8.5). The mean $F0$ was 123 Hz with an SD of 17 Hz.

Sentence recognition was tested using the AzBio sentences (Spahr & Dorman 2005) organized into 33 lists of 20 sentences (Gifford et al. 2008). Sentences comprising 6 to 10 words were recorded by four talkers (two men and two women) using a casual speaking style. The sentence lists were constructed to have an equal number of sentences spoken by each of four speakers (two men and two women) and to have a consistent overall level of intelligibility. $F0$ was extracted from 80 sentences. The mean $F0$ of the male talkers was 131 Hz (SD = 35 Hz). The mean $F0$ of the female talkers was 205 Hz (SD = 45 Hz).

The recognition of CNC words in quiet and AzBio sentences in the presence of competing 20-talker babble at +10 dB was evaluated in three listening conditions: (1) electric stimulation alone (E-alone), where signals were presented via direct input to the cochlear implant; (2) acoustic stimulation alone (A-alone), where signals were presented via earphone to the nonimplanted ear; and (3) combined EAS, where signals were presented simultaneously to the implanted ear, via direct input, and to the nonimplanted ear, via earphone.

In both the E-alone and EAS conditions, signals presented to the cochlear implant were unprocessed. In the both A-alone and EAS conditions, acoustic signals were LP-filtered at 125, 250, 500, or 750 Hz, or were unprocessed (wideband). The A-alone conditions are described by the filter cutoff frequency (i.e., 125 LP, 250 LP, 500 LP, 750 LP, and wideband), whereas the EAS conditions include a reference to the electric (E) signal presented to the implanted ear (i.e., E + 125, E + 250, E + 500, E + 750, and E + wideband). Thus, both monosyllabic word understanding in quiet and sentence understanding in noise were evaluated in a total of 11 conditions. Testing in all the three listening conditions began with the wideband stimuli. Within each filtered condition tested in the A-alone or EAS condition, the condition order was randomized and counterbalanced among listeners.

For both words and sentences, the list-to-condition assignments were randomized for each listener. However, with 10 CNC word lists and 11 conditions, the word list used in the A-alone 125 LP condition, where recognition scores were near 0% correct, was also assigned to another listening condition. A novel sentence list was used in each condition. Before testing, listeners were allowed a brief practice session in each condition.

Signal Processing

LP filters were implemented in MATLAB by specifying a 256th order finite impulse response filter to achieve a 90-dB/octave roll off. To document the effect of the filters on the stimulus material, 50 CNC words and 20 sentences were processed through each of the filter conditions (MATLAB, version 7.0). Then, a frequency analysis was conducted by using the fast Fourier transform. The average long-term spectra of the LP-filtered and wideband CNC words are shown in Figure 2. The average long-term spectra of the male and female speakers in the AzBio sentences are shown in Figure 3a, b, respectively.

Presentation of Speech Stimuli

Direct input to the cochlear implant in the E-alone and EAS conditions was accomplished using the standard external audio patch cables provided by the cochlear implant manufacturing company. Listeners were tested using their “everyday” speech-coding program, configured to accept an auxiliary input. The presentation level of the electric stimuli was verified as being “comfortably loud” by each listener.

Signals were presented to the nonimplanted ear in both the A-alone and EAS conditions via an insert earphone (Etymotic ER-1). To accommodate the different degrees of hearing loss in our population, acoustic signals were subjected to the frequency-gain characteristic prescribed by NAL-R formula (see Appendix). The maximum gain applied to acoustic stimuli was limited to 50 dB at any frequency.

The final presentation level of the acoustic stimuli was determined by a loudness matching procedure to equate the electric and acoustic signals. This was accomplished by alternating the presentation of an unprocessed, wideband signal to the cochlear implant with the presentation of an amplified, wideband signal to the earphone. Listeners used a response card to indicate whether the sound presented through the earphone was louder or softer than the signal presented to the cochlear implant. The response card was a continuous scale labeled with “softer” and “louder” at the end points and “same” at the midpoint. The overall gain applied to the signal presented to the earphone was adjusted until the listener reported similar loudness in the two ears. The overall gain setting that yielded the equal loudness rating in the wideband setting was applied to all acoustic stimuli in filtered conditions for both the A-alone and EAS conditions.

RESULTS

CNC Words

Figure 4a shows recognition accuracy for CNC words as a function of the stimulation condition and filter cutoff frequency. A repeated-measures analysis of variance revealed that the effect of condition was statistically significant ($F_{[10, 80]} = 101.36$, $p = 0.000008$ with Geisser-Greenhouse adjustment).

In the A-alone condition, the mean scores in the 125 LP, 250 LP, 500 LP, 750 LP, and wideband conditions were 0, 1, 7, 19, and 46% correct, respectively. A post hoc pairwise comparison (Fisher's least-square difference [LSD], $p < 0.05$) revealed that the scores in the 125, 250, and 500 LP conditions were not significantly different from each other and were all lower than the scores in the 750 LP and wideband conditions. The scores in the 750 LP and wideband conditions were significantly different.

Listeners achieved a mean score of 56% correct in the E-alone condition. There was no significant difference between performance in the A-alone wideband condition and the E-alone condition.

In the EAS condition, the mean scores for the E + 125, E + 250, E + 500, E + 750, and E + wideband conditions were 78, 81, 84, 86, and 88% correct, respectively. A post hoc pairwise comparison (Fisher's LSD, $p = 0.05$) indicated no significant improvement for word recognition when the acoustic information increased from 125 Hz to wideband. The level of performance achieved in each EAS condition was significantly higher than was achieved in the E-alone or A-alone wideband conditions.

AzBio Sentences at +10 dB SNR

Figure 4b shows recognition accuracy as a function of the stimulation condition and filter cutoff frequency. A repeated-measures analysis of variance revealed that the effect of condition was statistically significant ($F_{[10, 80]} = 62.4$, $p = 0.000048$ with Geisser-Greenhouse adjustment).

In the A-alone condition, the mean scores in the 125 LP, 250 LP, 500 LP, 750 LP, and wideband conditions were 0, 0, 6, 22, and 44% correct. A post hoc pairwise comparison (Fisher's LSD, $p < 0.05$) revealed that the scores in the 125, 250, and 500 LP conditions were significantly different from the scores in the 750 LP and wideband conditions. The scores in the 750 LP condition were significantly different from the scores in the wideband condition.

Listeners achieved a mean score of 40% correct in the E-alone condition. There was no significant difference between the performance in the A-alone wideband condition and the E-alone condition.

In the EAS condition, the mean scores for the E + 125, E + 250, E + 500, E + 750, and E + wideband conditions were 70, 71, 77, 82, and 87% correct, respectively. A post hoc pairwise comparison (Fisher's LSD, $p < 0.05$) revealed that the scores in the 125 LP condition were significantly different from the scores in the 750 LP and wideband conditions. The scores in the 250 LP condition were significantly different from the scores in the wideband condition. The level of performance achieved in each EAS condition was significantly higher than the level achieved in the E-alone or A-alone wideband conditions.

DISCUSSION

Word Recognition in Quiet

Word recognition increased significantly when patients had access to a low-frequency acoustic signal in addition to the signal provided by their cochlear implant. The addition of the 125-Hz LP signal increased scores by 22 percentage points, and the addition of the wideband signal increased scores by 32 percentage points. Word recognition in the E + wideband condition did not differ significantly from the performance in the E + 125 LP condition.

For the male speaker in our study, the 125-Hz-LP signal contained (1) the first harmonic ($F0$) and a much attenuated second harmonic and (2) an amplitude envelope that reflected the energy in voiced speech. It is presumably this information that provided the benefit to word recognition.

How would the information described above benefit word recognition in quiet for a cochlear implant patient? In the standard view, vowels and consonants, the constituent units of words, are specified by the location and changes in the location of the first, second, and third formants ($F1$, $F2$, and $F3$) (Liberman 1996). Pitch per se has a small, or no, role in specifying vowel and consonant identity (an exception is the vowel recognition theory of Miller [1989] in which $F0$ plays a role in defining one dimension of a three-dimensional perceptual space). However, the presence of the $F0$ (i.e., voicing) and an envelope that marks the onset and duration of voicing play a critical role in labeling a consonant as voiced or voiceless (see Faulkner & Rosen 1999 for a discussion of these cues in the context of auditory and audiovisual speech perception).

In one view of consonant recognition by implant patients, cues in the amplitude envelope provide enough information for the recognition of consonant voicing and consonant manner (Shannon et al. 1995). If that is the case, why would the addition of voicing information from the acoustic signal be of use to an implant patient who should receive a good representation of envelope information from their implant?

Implant patients receive the envelope features of manner and voicing relatively well, but not perfectly. For a sample of 39 implant patients with average or above average scores on CNC words, Spahr et al. (2007) reported that consonant place of articulation was received with 59% accuracy, voicing with 73% accuracy, and manner with 86% accuracy. Thus, there is ample room for an acoustic signal to enhance voicing and a little room to enhance manner. Indeed, Ching (2005) reported improved recognition of both voicing and manner in children and adults who combine EAS. Correct decisions about consonant manner and voicing provide phonotactic constraints that can narrow potential word candidates in a lexicon (Zue 1985) and can lead to improved word recognition in quiet.

Sentence Recognition in Noise

Similar to word recognition in quiet, our data for sentence recognition in noise indicate that the information in the 125-Hz LP signal provides the majority of the information leading to better speech recognition when acoustic stimulation is added to electric stimulation. In noise, performance increased by 47 percentage points in the E + wideband condition versus the E-alone condition. The E + 125 condition accounted for the majority of the improvement. Another portion of the benefit was caused by the information about formants that became detectable as the cutoff frequency of the LP filter increased to 750 Hz and wideband (Kong & Carlyon 2007).

Glimpsing

Kong and Carlyon (2007) noted, from their results with acoustic simulations of EAS, that glimpsing cues could play a role in improved speech understanding when patients combine EAS in noise. Li and Loizou (2008) provided a detailed view of glimpsing as an account for EAS benefit in noise (see also a discussion by Brown and Bacon [2009]). A glimpse, according to Cooke (2006), is “a time-frequency region that contains a reasonably undistorted ‘view’ of local signal properties.” Li and Loizou suggested that the low-frequency acoustic spectrum available to EAS patients provides excellent glimpses of important speech cues when speech is embedded in noise. This is because the portion of the spectrum below 500 Hz is masked to a lesser degree than high-frequency regions (Parikh & Loizou 2005) and the $F1$ component (and presumably $F0$) of the signal can be detected even in poor signal to noise ratios. Parikh and Loizou (2005) also noted that listeners are best able to integrate information when the glimpses are taken from the same frequency region over time. For EAS patients, the most favorable signal to noise ratios are consistent in the low-frequency acoustic spectrum, and this should facilitate the integration of information.

Voicing as a Landmark

The results from our study of word recognition in quiet pointing to the importance of voicing were marked by the acoustic $F0$ signal and amplitude envelope, as an aid to lexical access for EAS patients (see Spitzer et al. 2009 for a study of lexical segmentation with EAS patients). And, in our view, this is the principal acoustic information detected in noise. Li and Loizou (2008b) proposed that speech recognition in noise is facilitated when listeners have access to robust, low-frequency acoustic landmarks (Stevens 2002), such as the onset of voicing, which mark syllable structure and word boundaries. For EAS patients, the low-frequency acoustic spectrum, even when corrupted by noise, should provide robust acoustic landmarks that can bootstrap word and sentence recognition.

Limitations

Most of our patients had steeply sloping audiograms from 250 to 750 Hz. Currently, the majority of EAS patients are likely to have poorer, not better, auditory thresholds in low frequencies than the patients tested in this study. However, even patients with very poor, unaided auditory thresholds in low frequencies, for example, average thresholds at 250 Hz of 89 dB HL, show benefit when acoustic stimulation is added to electric stimulation (Ching et al. 2004). If EAS patients in the future have better thresholds up to 1000 or 1500 Hz, then it is possible that more benefit will be obtained from the information contained in bands higher than the 125-Hz low-frequency band.

Our scoring algorithm did not allow a separate tally of the patients’ responses to the AzBio sentences produced by male and female talkers.* In the 125-Hz LP condition, the first harmonic of the female voice was severely attenuated. Had the responses to the male and female speakers been tallied separately, the magnitude of the improvement in performance in the 125-Hz LP condition for the male voice could have been larger than that reported here, and the magnitude for the female voice was smaller than that reported here.

Summary

Information from $F0$ and the associated amplitude envelope accounts for the majority of the speech-perception benefit when acoustic stimulation is added to electric stimulation. We propose that, in quiet, low-frequency acoustic information leads to improved representation

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*An inadvertent change in the software that scored the sentence material prevented us from scoring male and female talkers separately.

of voicing and manner, which in turn leads to a reduction in word candidates in the lexicon. In noise, the robust representation of voicing allows access to low-frequency acoustic landmarks that mark syllable structure and word boundaries. These landmarks can bootstrap word and sentence recognition.

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APPENDIX

National Acoustic Laboratories (NAL)-R formulas for calculating required real-ear insertion gain (REIG) as a function of frequency modified for severe/profound hearing losses (hearing threshold level [HTL]; Byrne & Dillon 1986; Byrne et al. 1990). The REIG values were not full-on gains but were prescribed gains with the use of overall volume control.

1. Calculate $X_{\mathrm{dB}} = 0.05 \times (\mathrm{HTL}_{500} \times \mathrm{HTL}_{1000} \times \mathrm{HTL}_{2000}$ up to 180 dB) + 0.116 × combined HTL in excess of 180 dB.
2. Calculate the prescribed REIG at each frequency:

$$\begin{gathered}
\mathrm{REIG250\,(dB)}=X+0.31\ \mathrm{HTL250}-17\\
\mathrm{REIG500\,(dB)}=X+0.31\ \mathrm{HTL500}-8\\
\mathrm{REIG750\,(dB)}=X+0.31\ \mathrm{HTL750}-3\\
\mathrm{REIG1000\,(dB)}=X+0.31\ \mathrm{HTL1000}+1\\
\mathrm{REIG1500\,(dB)}=X+0.31\ \mathrm{HTL1500}+1\\
\mathrm{REIG2000\,(dB)}=X+0.31\ \mathrm{HTL2000}-1\\
\mathrm{REIG3000\,(dB)}=X+0.31\ \mathrm{HTL3000}-2\\
\mathrm{REIG4000\,(dB)}=X+0.31\ \mathrm{HTL4000}-2\\
\mathrm{REIG6000\,(dB)}=X+0.31\ \mathrm{HTL6000}-2\\
\mathrm{REIG8000\,(dB)}=X+0.31\ \mathrm{HTL8000}-2
\end{gathered}$$

3. When the 2000-Hz HTL is 95 dB or greater, add the following gain (dB) values to prescribe more gain in the low frequencies and less gain in the high frequencies.

Frequency (Hz) HTL 2 kHz	**250**	**500**	**750**	**1000**	**1500**	**2000**	**3000**	**4000**	**6000**
95	4	3	1	0	−1	−2	−2	−32	−2
100	6	4	2	0	−2	−3	−3	3	−3
105	8	5	2	0	−3	−5	−5	−5	−5
110	11	7	3	0	−3	−6	−6	−6	−6
115	13	8	4	0	−4	−8	−8	−8	−8
120	15	9	4	0	−5	−9	−9	−9	−9

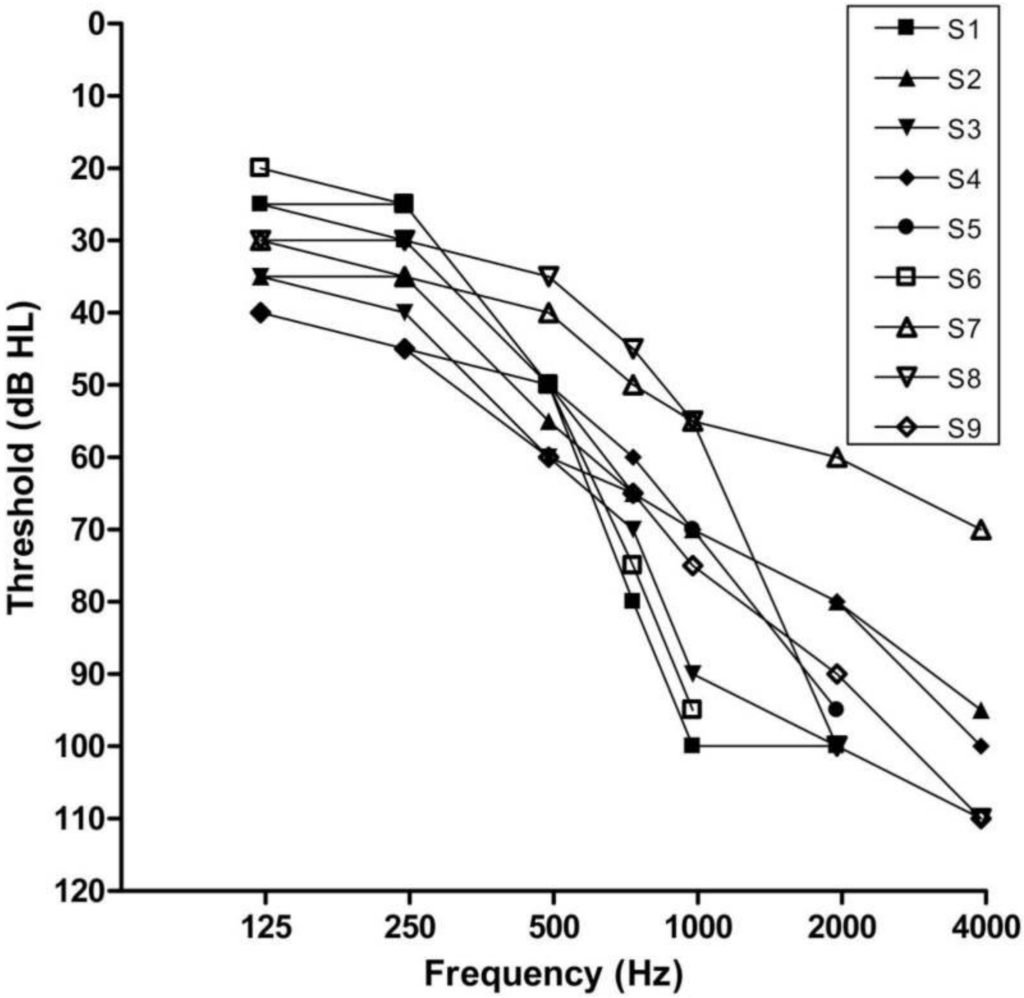

Fig. 1.
Individual audiograms for the nonimplanted ear.

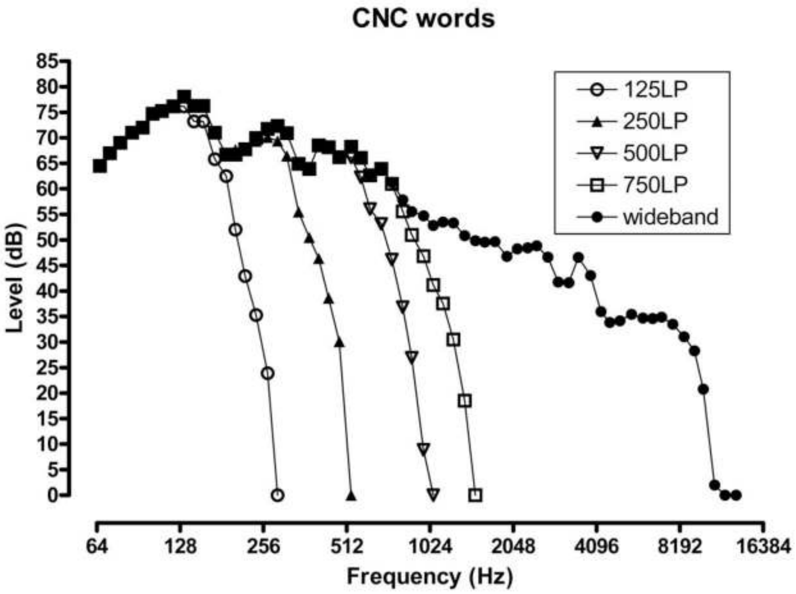

Fig. 2.

Averaged spectra of CNC words presented acoustically in the 125 LP, 250 LP, 500 LP, 750 LP, and wideband conditions.

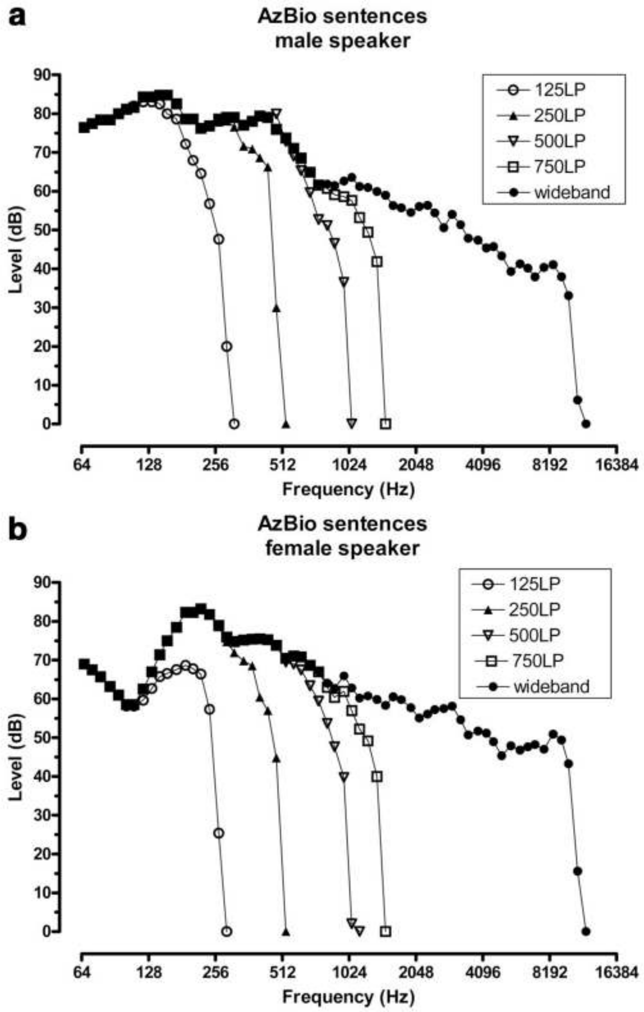

Fig. 3.

Averaged spectra of male talkers (a) and female talkers (b) from the AzBio sentences presented acoustically in the 125 LP, 250 LP, 500 LP, 750 LP, and wideband conditions.

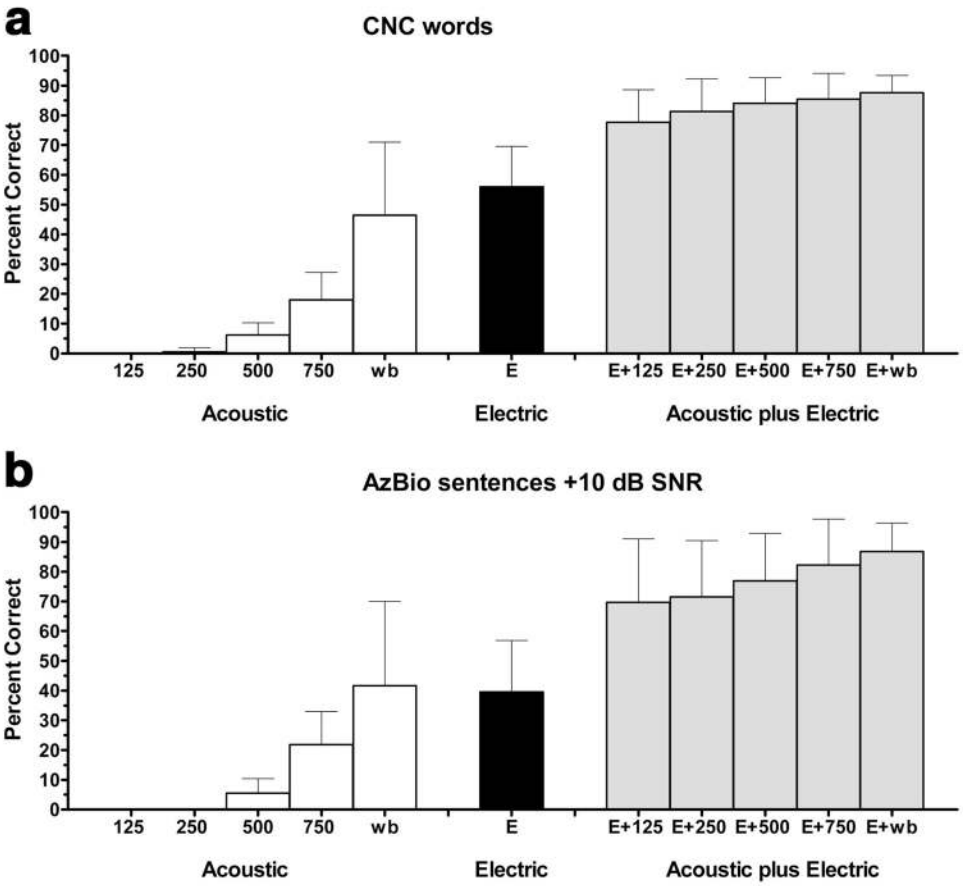

Fig. 4.

Performance as a function of stimulus condition (acoustic, electric, and acoustic plus electric) and LP filter setting for (a) CNC words and (b) AzBio sentences.

TABLE 1

Listener demographics including age, sex, etiology of hearing loss, duration of hearing loss in the implanted and nonimplanted ear, processor type and strategy, duration of experience with the implant and hearing aids, hearing aid device in the nonimplanted ear, and postoperative hearing aid use in the nonimplanted ear

Listener	Age	Gender	Etiology	Duration of hearing loss* (NIE)	Duration of hearing loss* (IE)	CI experience	CI device	HA experience (NIE), yrs	HA model	HA usage, % waking hours
1	69	M	Unknown	40	40	4 mo	Harmony	25	Starkey CE	100
2	70	M	Unknown	23	23	4 mo	Harmony	21	Senso Diva BTE	100
3	79	M	Unknown	35	35	2 yr	Freedom	18	Oticon BTE	100
4	82	M	Unknown	40	40	2 yr	Freedom	23	Starkey Sequel II BTE	100
5	49	F	Unknown	35	35	5 yr	ESPrit 3G	15	Beltone D71 Polara	100
6	64	M	Unknown	44	44	6 mo	Harmony	N/A	N/A	N/A
7	58	M	Ménière	4	14	3 yr	Combi 403	2	Oticon BTE	100
8	61	M	Genetic	47	47	1 yr	Duet	25	Danalogic BTE	100
9	62	M	Unknown	40	40	8 mo	Harmony	24	Virtue Audibel BTE	100

[*] Duration of hearing loss was defined as duration of time since patients first noticed incapability of understanding a conversation on the telephone as an indication of significant hearing loss.

NIE, nonimplanted ear; IE, implanted ear; CI, cochlear implant; HA, hearing aid; N/A, not applicable.