ABSTRACT

Title of Dissertation:	THE BENEFITS OF ACOUSTIC INPUT TO COMBINED ELECTRIC AND CONTRALATERAL ACOUSTIC HEARING
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With the extension of cochlear implant candidacy, more and more cochlear-implant listeners fitted with a traditional-long electrode array or a partial-insertion electrode array have residual acoustic hearing either in the nonimplanted ear or in both ears and have shown to receive significant speech-perception benefits from the low-frequency acoustic information provided by residual acoustic hearing.

The aim of Experiment 1 was to assess the minimum amount of low-frequency acoustic information that was required to achieve speech-perception benefits both in quiet and in noise from combined electric and contralateral acoustic stimulation (EAS). Speech-recognition performance of consonant-nucleus vowel-consonant (CNC) words in quiet and AzBio sentences in a competing babble noise at +10 dB SNR was evaluated in nine cochlear-implant subjects with residual acoustic hearing in the nonimplanted ear in three listening conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. The results showed that adding low-frequency acoustic information to electrically stimulated information led to an overall improvement in speech-recognition performance for both words in quiet and sentences in noise. This improvement was observed even

when the acoustic information was limited down to 125 Hz, suggesting that the benefits were primarily due to the voice-pitch information provided by residual acoustic hearing. A further improvement in speech-recognition performance was also observed for sentences in noise, suggesting that part of the improvement in performance was likely due to the improved spectral representation of the first formant.

The aims of Experiments 2 and 3 were to investigate the underlying psychophysical mechanisms of the contribution of the acoustic input to electric hearing. Temporal Modulation Transfer Functions (TMTFs) and Spectral Modulation Transfer Functions (SMTFs) were measured in three stimulation conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. The results showed that the temporal resolution of acoustic hearing was as good as that of electric hearing and the spectral resolution of acoustic hearing was better than that of electric hearing, suggesting that the speech-perception benefits were attributable to the normal temporal resolution and the better spectral resolution of residual acoustic hearing.

The present dissertation research provided important information about the benefits of low-frequency acoustic input added to electric hearing in cochlear-implant listeners with some residual hearing. The overall results reinforced the importance of preserving residual acoustic hearing in cochlear-implant listeners.

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CONTRALATERAL ACOUSTIC HEARING

by

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Chapter 1: General Introduction

Cochlear implants have been shown to successfully restore partial hearing and provide considerable benefits to profoundly deaf individuals through electric stimulation. Although recent studies have reported that many implant users can recognize 70%-80% of sentences presented in quiet, understanding speech in noise and appreciation of the aesthetic qualities of sound (such as music and voice quality) remain challenges for most implant users. These deficits are most likely related to poor resolution of low-frequency information including voice pitch provided by current cochlear implants.

As the audiological criteria for implant candidacy have become less stringent, implant candidacy has now been extended to include individuals with moderate to severe bilateral hearing losses (e.g., Parkinson, Arcaroli, Staller, Arndt, Cosgriff & Ebinger, 2002). Consequently, an increasing number of individuals with a unilateral cochlear implant have residual hearing in the implanted and/or nonimplanted ear. With a full insertion implant (22-30 mm), patients receive electric stimulation from the implanted ear and acoustic stimulation from the contralateral ear (bimodal hearing). Many implant listeners with bimodal hearing have shown to receive significant speech-perception benefits from low-frequency acoustic information provided by residual acoustic hearing via a conventional hearing aid (e.g., Armstrong, Pegg, James & Blamey, 1997; Ching, Psarros, Hill, Dillon & Incerti, 2001; Ching, Incerti & Hill, 2004). Recently, interest has focused on the application of a relatively short insertion of electrode array (10, 16, or 20 mm) into the cochlea in patients with bilateral residual hearing without destroying low-frequency hearing in the implanted

ear. With a partial electrode insertion, patients receive acoustic stimulation from both the implanted and nonimplanted ears and electric stimulation from the implanted ear. In these patients, speech intelligibility both in quiet and in noise is significantly better in the combined-electric-and-acoustic-stimulation (EAS) condition than that in the electric-stimulation condition (e.g., Turner, Gantz, Vidal, Behrens & Henry, 2004**;** Kiefer, Gstoettner, Baumgartner, Pok, Tillein, Ye & von Ilberg, 2005**)**. Therefore, both groups of patients above have the opportunity to benefit from the combination of EAS and have shown to receive considerable benefits from low-frequency acoustic information in terms of appreciation of the aesthetic qualities of sound and understanding speech in background noise.

Goals and Aims

The principal goals of this dissertation research are (i) to investigate the benefits of low-frequency acoustic information to the speech-perception abilities of individuals with combined contralateral EAS, and (ii) to relate their speech-recognition performance to their underlying psychophysical abilities in the region of both acoustic hearing and electric hearing. The goals are met through experiments and analyses relative to two aims.

Aim 1. Assess the minimum amount of low-frequency acoustic information that is required to achieve speech-perception benefits both in quiet and in noise from combined contralateral EAS.

Aim 2. Determine the relationships among (i) the psychophysical measures of low-frequency acoustic hearing, electric hearing, and combined electric and contralateral acoustic hearing and (ii) measures of speech recognition.

Chapter 2: Low-pass Filtering in Speech-Perception Benefits from Contralateral

Acoustic Input in Listeners with Combined Contralateral EAS

Introduction

Limitations of current cochlear implants

Speech recognition of cochlear-implant listeners has improved significantly over the past decade and now the average scores of sentences in quiet are 70% - 80% (Osberger, Fisher & Kalberer, 2000) and the average score of monosyllabic words in quiet is approximately 50% (Dorman, 2000; Wilson, in press). However, understanding speech in noise and appreciation of the aesthetic qualities of sound (such as music and voice quality) remain challenges for most implant users due to the limitations of the electrode design and the signal processing schemes employed in current cochlear implants (e.g., Dorman, Loizou & Tu, 1998; Zeng & Galvin, 1999).

Poor speech perception in noise. In acoustic hearing, the cochlea performs an exquisite frequency analysis of a stimulus, resolving its frequency components into a spatially distributed array of activity. However, in electric hearing, an electric stimulus is not resolved into its spectral components because electric field spreads out from electrodes and activates nearby neurons and, therefore, electric stimulation bypasses all cochlear mechanisms that aid in separating the electric stimulus spectrally. In other words, cochlear implants generally have not been able to reproduce fine spectral analyses performed by the normal cochlea and can only provide coarse spectral information of the input signal. Even the most successful

implant users only realize perhaps 6 to 8 channels of distinct "place-frequency" information across the entire spectral range (Friesen, Shannon, Baskent & Wang, 2001). Nonetheless, today's cochlear implant users typically can understand speech remarkably well in quiet with limited spectral resolution (Skinner, Clark, Whitford, Seligman, Staller & Shipp, 1994; Osberger, Fisher & Kalberer, 2000; Garnham, O'Driscoll, Ramsden & Saeed, 2002). This is because speech is a very robust medium for communicating information due to the layers of acoustic, phonetic, and linguistic redundancies of speech information (Fletcher & Galt, 1950; Miller & Licklider, 1950; Remez, Rubin, Berns, Pardo & Lang, 1994). Therefore, only limited spectral resolution or little spectral information is necessary for implant users to understand speech in quiet. However, when the listening environment becomes more challenging, the limited spectral resolution provided by current cochlear implants is not adequate for understanding speech in noise for cochlear-implant listeners.

Although poor spectral resolution does not appear to be a limitation for understanding speech in quiet to the most successful implant users, the limited spectral resolution has a direct negative consequence on implant users' ability to understand speech in background noise. Understanding speech in background noise requires spectral resolution much finer than that required for understanding speech in quiet in order to separate speech from noise or to distinguish multiple talkers (Fu, Shannon & Wang, 1998). Implant listeners typically require higher target-to-masker ratios in broadband noise to achieve levels of speech-recognition performance comparable to normal-hearing listeners. Thus, even the most successful implant users still suffer from significant problems of understanding speech in background noise

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(Turner, Gantz, Vidal, Behrens & Henry, 2004; Stickney, Zeng, Litovsky & Assmann., 2004).

Loss appreciation of the aesthetic qualities of sound. While speech can be understood in the presence of severe degradation of spectral cues, music recognition and appreciation are compromised by even mild degradation (Shannon, 2005). Smith, Delgutte, and Oxenham (2002) have shown in normal-hearing listeners that increased spectral resolution is required to perceive harmonic pitch and to identify melodies and instruments. As many as 100 frequency bands are required to be resolved for music perception in normal-hearing listeners. A study by Oxenham, Bernstein, and Panagos (2004) demonstrated that fine place-specific frequency resolution is required to produce the harmonic pitch perception necessary for listening to complex acoustic signals.

Implant listeners using conventional long electrode implants have shown poorer performance than normal-hearing listeners on several pitch-related tasks, including detecting pitch change (frequency difference limens), perception of direction of pitch change (higher or lower), and discrimination of brief pitch patterns (Gfeller & Lansing, 1991; Gfeller, Turner, Mehr, Woodworth, Fearn, Knutson, Witt & Stordahl, 2002). Therefore, most cochlear-implant listeners are unable to perform a very basic listening task that normal-hearing people tend to take for granted, e.g., the ability to recognize familiar melodies such as holiday songs (Gfeller et al., 2002; Kong, Stichney & Zeng 2005). In addition, the aesthetic qualities of sound cannot be enjoyed by most cochlear-implant listeners. Many of them reported that the perception of sound became "mechanical" or "raspy" when compared to their

memories of acoustic hearing, and that many of the aesthetic qualities of sound were diminished (Gfeller et al., 2002).

Pitch perception in cochlear-implant listeners

It is widely believed that poor speech perception in noise and loss of appreciation of the aesthetic qualities of sound in cochlear-implant listeners are most likely related to poor resolution of low-frequency information including voice pitch (Gfeller et al., 2002). Voice pitch, or the fundamental frequency ($F0$) of voicing, has long been thought to be an important cue in the perceptual segregation of simultaneous and nonsimultaneous speech sources (e.g., Bregman, 1990; Darwin & Carlyon, 1995). Studies of normal-hearing listeners have found that when a competing voice is present, listeners generally find it easier to understand the target voice if the competing voice has a different $F0$ (e.g., Darwin & Carlyon, 1995; Bird & Darwin, 1998). Cochlear-implant listeners are unlikely to use the same $F0$ cues as normal-hearing listeners. Part of the difficulty experienced by cochlear-implant listeners in background noise may reflect their impaired abilities of extracting the $F0$s of two concurrent sounds to perceptually segregate the fluctuations of the target from those of the masker (Bregman, 1990; Darwin & Carlyon, 1995). Therefore, poor pitch perception is likely to be one of the important issues that limit cochlear-implant listeners to fully benefit from cochlear implantation. A discussion of pitch perception in cochlear-implant listeners follows.

Pitch is a subjective attribute of sound defined in terms of what is heard. It is related to the physical repetition rate of the waveform of a sound, which corresponds to the frequency for a pure tone and to the $F0$ for a periodic complex tone (Moor,

1998). In all languages, the pitch patterns of speech indicate which are the most important words in an utterance, they distinguish a question from a statement, and they indicate the structure of sentences in terms of phrases. In tonal languages, such as Mandarin Chinese, Zulu, and Thai, pitch can affect word meanings. Pitch also conveys nonlinguistic information about the gender, age, and emotional state of the speaker (Rosen, Fourcin & Moore, 1981). Pitch encoding in the normal auditory system involves both a temporal mechanism following the temporal fine structure of the input signal ("phase locking") and a place mechanism with resolved low-order harmonics ("place of excitation") (e.g., Plomp, 1967; Houtsma & Smurzynski, 1990; Smith, Delgutte & Oxenham 2002). However, both pitch encoding mechanisms fail in current cochlear implants.

Temporal codes. It is widely believed that auditory neurons are phase-locked to resolved frequency components and a correspondence between the temporal pattern of the neural firing and the place of excitation is important to derive pitch information from the lower harmonics (Loeb, White & Merzenich, 1983; Carlyon & Deeks, 2002). However, except for Simultaneous Analog Stimulation (SAS), all current processing strategies for cochlear implants remove temporal fine structures ("phase-locking" information) in stimulus waveforms and preserve only the slowly-varying temporal envelope. The envelopes are extracted from each of 6 to 22 frequency bands by full-wave rectification and low-pass filtering at a low frequency (<500 Hz). The envelope outputs are finally compressed and then used to modulate biphasic pulses. Trains of modulated biphasic pulses are then delivered to electrodes at a fixed rate. The temporal-fine-structure or "phase-locking" information is

eliminated in such processing schemes due to the usage of a fixed-rate carrier. Therefore, the temporal-fine-structure information of the input signal is not appropriately encoded by the speech processing strategies used in current cochlear implants.

Pitch perception in cochlear-implant listeners largely depends on deriving temporal pitch cues from temporal amplitude modulations corresponding to $F0$. The extent to which this is possible depends on two factors. First, the $F0$ must be passed by an envelope smoothing filter and a carrier pulse rate must be high enough to represent the modulations corresponding to the $F0$ (Green, Faulkner & Rosen, 2002; Moore, 2003). The average $F0$s of voicing are 125 Hz for adult males, 200 Hz for adult females and 300-400 Hz for children (Pickett, 1999). Both physiological and psychophysical evidences suggest that accurate representation of the temporal modulation envelopes requires the carrier pulse rate to be at least 4 to 5 times the frequency of the modulations to avoid aliasing (McKay, McDermott & Clark, 1994; Wilson, 1997). However, several widely used implant systems (e.g., Nucleus device) use a pulse rate of less than 1 kHz which is insufficient to cover much of the voice-pitch range. Second, there are limitations on the ability of the auditory system to perceptually encode the temporal amplitude modulations. Several psychophysical studies have reported that the ability of normal-hearing listeners to use temporal cues to derive a pitch perception from amplitude modulated noise is limited to frequencies below around 300 Hz (Pollack, 1969; Burns & Viemeister, 1976, 1981). Similarly, the ability of cochlear-implant listeners to detect the amplitude modulations in pulses applied to a single channel typically declines rapidly for modulation frequencies

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above 100–150 Hz (Shannon, 1992; Busby, Tong & Clark, 1993; Cazals, Pelizzone & Boex, 1994). Thus, the pitch salience associated with temporal modulations corresponding to the $F0$ is rather weak although the envelopes of the implant-processed stimuli can carry some periodicity information. Therefore, pitch perception in the temporal domain is expected to be severely limited in cochlear-implant listeners.

Place of excitation. Normal-hearing listeners derive pitch information primarily from lower (resolved) harmonics, whose frequencies are each encoded by a separate subset of auditory neuron fibers in the apical part of the cochlea. Unfortunately for cochlear-implant listeners, the shallow insertion of implant electrode arrays and the speech processing algorithms used in modern implants are unlikely to result in this information being encoded in the auditory neuron fibers. First, the average length of the human cochlea is about 32.4-37.1 mm (Sato, Sando & Takahashi, 1991). The electrode array is usually not fully inserted into the cochlea. The relatively shallow insertion severely limits the transfer of low-frequency spectral information. For example, Ketten, Skinner, Wang, Wannier, Gates, and Neely (1998), in a study of 20 patients implanted with the Nucleus Corporation implant, found that the average lower limit of frequency conveyed by the most apical electrode corresponds to the acoustic frequency of about 1000 Hz, according to Greenwood's (1990) equation. Therefore, the relatively shallow insertion depth of the implant electrode array does not reach the low-frequency place and the lower harmonics of pitch cannot be encoded appropriately in the "right place" of the cochlea. Even when the low-frequency spectral information is transferred to the apical electrodes, it is

encoded in the "wrong place", i.e., locations in the cochlea that are tuned to higher frequencies (Nadol, Young & Glynn, 1989; Linthicum, Fayad, Otto, Galey & House., 1991). Second, for all strategies, the input filters used to create "channels" are typically too broad to resolve individual harmonics. Furthermore, spread of current along and across the cochlea would increase the "mixing" of harmonics within individual auditory neuron fibers, even if implant devices were modified to have a larger number of electrodes each encoding a narrow range of frequencies (Frijns, de Snoo & ten Kate, 1996).

In summary, low-frequency information is not appropriately represented by the place of stimulation due to the shallow insertion depth of the electrode array, the spectral mismatch from the warped frequency-to-electrode allocation, and the relatively broad filters used in speech processing strategy to create "channels", combined with the spread of electric charge along and across the cochlea. This means that cochlear-implant listeners cannot extract the pitch of an electric input in a way analogous to that used by normal-hearing listeners for resolved harmonics (Friesen et al., 2001). Cochlear-implant listeners are most likely to have difficulty in hearing the pitch of a single voice even in quiet. They usually experience more difficulty in understanding speech in noise where they cannot use differences in the $F0$ to perceptually separate the voices of competing speakers.

Summary. Current cochlear implants preserve temporal/amplitude information and only provide coarse spectral information of the input signal. Poor pitch perception is a consequence of inadequate temporal and place encoding of low-frequency information provided by current cochlear implants. The loss of pitch

perception has unfortunate consequences for speech perception in noise and appreciation of the aesthetic qualities of sound in most implant listeners. However, preservation of residual low-frequency acoustic hearing in the implanted and/or nonimplanted ear can provide the valuable low-frequency information that is not well resolved by cochlear implants, leading to a substantial improvement in speech-recognition performance especially in noise and appreciation of the aesthetic qualities of sound in these cochlear-implant listeners.

Combined contralateral EAS

As the audiological criteria for implant candidacy have become less stringent and have extended to include people with a severe degree of hearing loss (Cohen, 2004), an increasing number of individuals with a unilateral cochlear implant have substantial residual low-frequency hearing in the nonimplanted ear. For these individuals implanted with a conventional long-electrode array, low-frequency acoustic information is available by combining electric hearing with acoustic hearing from the nonimplanted ear via a conventional hearing aid, whereas high-frequency information is provided by a cochlear implant (Dooley, Blamey, Seligman, Alcantara, Clark, Shallop, Arndt, Heller & Menapace, 1993; Tyler, Parkinson, Wilson, Witt, Preece & Noble., 2002). Such fitting of the cochlear implant in one ear and the hearing aid on the other is often called "bimodal fitting." The benefit that arises from wearing both the hearing aid and the cochlear implant compared to wearing the cochlear implant alone is referred to as a "bimodal benefit". While residual acoustic hearing present in these implant users is unlikely to contribute directly to speech intelligibility, the additional low-frequency cues from acoustic hearing may provide

sufficient information to compensate for the limitations encountered by current cochlear-implant listeners as noted above. These developments have led to the exploitation of combined contralateral EAS to provide information about the bimodal benefit and its underlying mechanisms.

Advantages of combined contralateral EAS

There are at least two advantages that individuals with electric hearing in the implanted ear and residual acoustic hearing in the nonimplanted ear benefit with combined contralateral EAS. The advantages are avoidance of auditory deprivation and provision of the complementary cues provided by combined contralateral EAS.

Avoidance of auditory deprivation. Providing an auditory input to the ear with residual acoustic hearing may help prevent neural degeneration that is associated with auditory deprivation. It is known that speech recognition ability gets worse in the unaided ear for individuals who have bilateral hearing losses but unilateral hearing aid amplification (Silman, Gelfand & Silverman, 1984; Hurley, 1999; Neuman, 1996). This deterioration is often attributed to a lack of auditory stimulation and reduced peripheral neural activity in the unaided ear. The stimulation provided by a hearing aid may help maintain spiral ganglion cell survival in the nonimplanted ear for future advances in hearing restoration or future cochlear implantation.

Provision of complementary cues. There is some evidence showing that a hearing aid and a cochlear implant can provide complementary information. Acoustic amplification with the hearing aid provides adequate low-frequency information whereas electric stimulation with the cochlear implant does not. Specifically, acoustic stimulation provided by the hearing aid may help the user access adequate

low-frequency information, which contains finer spectral and/or temporal cues in an input signal and is not well resolved by the cochlear implant. Better speech performance in quiet has been observed mainly due to better perception of voicing and manner information in consonant perception in the combined-contralateral-EAS condition when compared to that in the electric-stimulation-alone condition (Ching et al., 2001). Similar results have also been reported by Mok, Grayden, Dowell, and Lawrence (2006), suggesting that the speech-perception benefits in quiet arise from improved perception of the low-frequency components in the acoustic input from the hearing aid. In addition, low-frequency information relating to voice pitch in acoustic hearing may provide sufficient cues to aid in source segregation of competing voices and, thereby, contribute to the improved speech perception in noise for listeners with combined contralateral EAS (Kong, Stickney & Zeng, 2005).

Perceptual incompatibility. Little doubt exists regarding the advantages of combined contralateral EAS. However, there is a major concern arising from the "incompatibility" between sensations elicited by electric stimulation via an implant and by acoustic stimulation via a hearing aid (Dooley et al., 1993, Ching et al., 2001). There are perceptual dissimilarities between electric hearing and contralateral acoustic hearing because electric stimuli differ in several essential aspects from acoustic stimuli. For example, it is known that sounds processed by the cochlear implant and the hearing aid in opposite ears may elicit different pitch sensations because the cochlear implant stimulates the basal part of the cochlea, whereas the hearing aid stimulates the apical part of the cochlea (Blamey, Dooley, Parisi & Clark, 1996). In addition, the dynamic range and the shape of iso-loudness curves between

electric and contralateral acoustic hearing of the same person can also be quite different (Blamey, Dooley, James & Parisi, 2000).

Perceptual incompatibility between electric and contralateral acoustic hearing has been reported in some studies. Generally, cochlear-implant users described any acoustic sound they heard as being qualitatively very different from the sensations created by stimuli delivered through the implant system. Tyler et al. (2002) reported that one of their subjects heard the acoustic and electric stimuli as separate sound sources. Blamey et al. (1996, 2000) demonstrated a pitch mismatch and differences in the dynamic range and the shape of the iso-loudness curves between the acoustically and electrically stimulated ears. Dooley et al. (1993) also reported that some subjects discontinued using their hearing aids or cochlear implants after implantation.

Despite the potential "incompatibilities," many implant users who have some residual hearing in the nonimplanted ear have opted to use a hearing aid and a cochlear implant in opposite ears even though speech perception in the nonimplanted ear is often poorer than that in the implanted ear. A demographic study (Cowan & Chin-Lenn, 2004) reported 51% of adults with an unaided threshold of 90 dB HL or better at 500 Hz in the nonimplanted ear continued to wear the hearing aid together with the cochlear implant for at least 4 hours per day. For those patients who adapted to both devices, the perceptual incompatibility did not seem to interfere with their speech recognition both in quiet and in noise (Dooley et al., 1993; Tyler et al., 2002).

Summary. Two advantages benefit individuals with combined contralateral EAS. The acoustic amplification via a hearing aid to the nonimplanted ear may help prevent auditory deprivation. Improved speech perception both in quiet and in noise

for individuals with combined contralateral EAS may be related to the complementary information provided by the two devices. Acoustic stimulation provided by the hearing aid may help the individuals access adequate low-frequency information, which contains finer spectral and/or temporal cues in the speech signal and is not well resolved by current cochlear implants. Perceptual incompatibilities arise from differences in several essential psychophysical aspects in terms of encoding of electric stimuli and acoustic stimuli in the auditory system. Despite the potential incompatibilities, many cochlear-implant listeners with residual hearing in the nonimplanted ear have adapted to use both devices.

Previous reports on bimodal benefits

Bimodal benefits in adults. Studies conducted with adult listeners have shown that benefits can be obtained from using a cochlear implant with a hearing aid compared with using either device on its own (Shallop, Arndt & Turnacliff, 1992; Dooley et al., 1993; Armstrong, Pegg, James & Blamey, 1997; Blamey, Armstrong & James, 1997). Shallop et al. (1992) reported speech results in quiet from seven subjects whose mean hearing threshold at 500, 1000, and 2000 Hz (pure tone average (PTA)) was 104 dB in the nonimplanted ear. Vowel and consonant identification and sentence recognition were evaluated in each subject. The results showed a significant improvement in performance in at least one speech-recognition test in the combined-contralateral-EAS condition over the acoustic-stimulation condition or the electric-stimulation condition after 6 months of implant use, and the improvement continued to be observed at 12 months postoperatively. Dooley et al. (1993) evaluated four adults (mean PTA in the nonimplanted ear = 106 dB HL) and reported significantly

higher consonant scores in the combined-contralateral-EAS condition than those in the acoustic-stimulation condition or the electric-stimulation condition. Blamey, Armstrong, and James (1997) reported results from a group of 50 implant users (mean PTA= 107 dB HL in the nonimplanted ear) showing that continued use of the implant plus the hearing aid could provide a significant advantage in speech perception over the use of the implant on its own. Armstrong et al. (1997) tested four adults whose mean PTA in the nonimplanted ear was 103.5 dB HL. Speech perception was evaluated using CUNY sentences and CNC words in quiet and in background noise. Their results showed that speech scores in quiet and in noise at 5 and 10 dB SNRs were significantly higher with combined contralateral EAS compared to those with electric stimulation alone. Those individuals who were consistent hearing aid and implant users tended to receive greater bimodal benefits than others who normally wore the implant alone.

In more recent studies, the outcomes of research into combined contralateral EAS have been published, with the majority of listeners showing benefits in terms of speech recognition in quiet at a conversational level, speech recognition in noise, and localization ability. There have also been rare cases in which poorer speech recognition was reported for individuals using combined contralateral EAS compared to using electric stimulation alone (Tyler et al., 2002; Ching, Incerti. & Hill 2004; Hamzavi, Pok, Gstoettner & Baumgartner, 2004; Kong, Stickney & Zeng, 2005; Dunn, Tyler & Witt, 2005; Mok, Grayden, Dowell & Lawrence 2006). Tyler et al. (2002) tested three listeners (mean PTA in the nonimplanted ear = 86.5 dB HL) on CNC word and CUNY sentence recognition both in quiet and in noise and

localization tasks. They reported that two adult listeners received bimodal benefits in noise but only one listener received bimodal benefits for words in quiet. In addition, two listeners had improved localization ability. Ching, Incerti, and Hill (2004) tested 21 adults (mean PTA in the nonimplanted ear = 99 dB HL) with Bamford-Kowal-Bench (BKB) sentences in noise at + 10 dB SNR and found that seven subjects demonstrated better sentence and phoneme recognition performance in multi-talker babble noise at 10 dB SNR with combined contralateral EAS. They also found overall improved localization with combined contralateral EAS relative to monaural electric stimulation.

Further, a group benefit of combined contralateral EAS relative to electric-stimulation was reported by Hamzavi, et al. (2004) for speech recognition in quiet. Seven cochlear-implant listeners who continued to use their hearing aids in the opposite ear were tested. In the majority of subjects, the combined-contralateral-EAS condition was superior to the electric-stimulation condition with an average group improvement of 8.9% on a sentence test and 10.5% on a monosyllable test. Similar group benefits were also reported by Kong, Stickney, and Zeng (2005) for speech recognition in noise and melody recognition. Five implant subjects with moderate to profound hearing loss at frequencies from 125 to 8000 Hz in the nonimplanted ear were tested on sentence recognition at 0, +5, +10, +15, and +20 dB SNR. The results showed that residual low-frequency acoustic hearing produced essentially no speech recognition in noise but it significantly enhanced performance when combined with electric hearing. Performance of melody recognition in the same group of subjects was better than that with electric hearing. Mok et al. (2006) reported that 6 of 14

subjects with hearing loss less than 90 dB HL from 125 to 1000 Hz in the nonimplanted ear showed significant benefits on open-set speech tests and 5 showed benefits on close-set spondees. However, 2 participants showed poorer speech perception with combined contralateral EAS when compared to that with electric stimulation in at least one of the speech-perception tests. Results of information transmission analyses demonstrated that speech-perception benefits in quiet arose from the improved perception of the low-frequency components in speech.

Gifford, Dorman, McKarns, and Spahr (2007) reported bimodal effects in patients with bilateral hearing losses meeting candidacy for a partial-insertion cochlear implant ($\leq$ 65 dB HL up to 500 Hz) but who have chosen to receive a full-insertion cochlear implant. Scores on tests of monosyllabic word recognition in quiet and sentence recognition in quiet were obtained from 12 subjects and in noise at +10 and +5 dB SNR from 6 subjects. All subjects benefited significantly when low-frequency information from the nonimplanted ear was added to the implanted ear. Performance of the subjects was comparable to individuals with combined ipsilateral EAS as reported in the literature. Similar results were reported in the following study by Dorman, Gifford, Spahr, and McKarns (2008). The performance of 15 subjects with combined contralateral EAS, whose mean thresholds at 500 Hz and lower were 53 dB HL and better in the nonimplanted ear, increased by 17-23 percentage points on tests of CNC word and AzBio sentence recognition both in quiet and in noise from the electric-stimulation condition to the combined-contralateral-EAS condition.

Bimodal benefits in children. Pediatric data have also showed that some children benefit from using both a cochlear implant and a hearing aid. Chmiel, Clark,

Jerger, Jenkins, and Freeman (1995) evaluated six children between the ages of 4 and 13 yr who continued to wear their hearing aids in the nonimplanted ear after implantation in the contralateral ear. The mean PTA in the nonimplanted ear was 105 dB HL. Three children showed significant bimodal benefits in speech-perception tasks and in a speech-imitation task. The other three children did not show any significant speech-perception or speech-production difference between the combined-contralateral-EAS condition and the electric-stimulation condition. Simon-McCandless and Shelton (2000) studied four children and found that speech-perception scores for half of the children were higher in the combined-contralateral-EAS condition than those in the acoustic-stimulation or the electric-stimulation condition. Ching, Psarros, Hill Dillon, and Incerti (2001) reported benefits in speech perception, localization, and aural/oral function for 16 children and the results showed that open-set sentence and closed-set consonant recognition at +10 dB SNR was significantly better with combined contralateral EAS than that with electric stimulation due to the significantly improved transmission of voicing and manner cues but not due to the transmission of place cues. Further, 4 of 5 children in Ching et al.'s study (2001) had improved horizontal localization abilities in the combined-contralateral-EAS condition relative to the electric-stimulation condition.

At least one investigation did not find bimodal benefits in children. Waltzman, Cohen, and Shapiro (1992) reported that children who were deaf before age 5 yrs did not show better speech-recognition performance in the combined-contralateral-EAS condition over the electric-stimulation condition. This result may stem from language delays and much less residual hearing in the nonimplanted ear,

which may influence the amount of benefit they received from the acoustic input. This notion was supported by the study of Holt, Kirk, Eisenberg, Martinez, and Campbell (2005). Children with more residual hearing (severe degree of sensorineural hearing loss) in the nonimplanted ear were included in their study. Children were longitudinally tested on Phonetically Balanced-Kindergarten Word lists (PB-K) in quiet and Hearing-In-Noise Test-Children's Version (HINT-C) sentences at 6-month intervals. The results showed benefits from combined contralateral EAS particularly in background noise.

Summary. Previous research on bimodal benefits for speech perception has shown mixed results across studies as well as among individuals. Although most studies showed signs of benefits from combined contralateral EAS, some individuals obtained benefits whereas others did not. There have also been rare cases in which poorer speech perception with combined contralateral EAS compared to that with electric stimulation was reported for individuals. This could be related to the way in which bimodal benefits were measured, the divergent experience in hearing aid and implant usage among individuals, and the degree of hearing loss in the nonimplanted ear.

Combined ipsilateral EAS

There is a subpopulation of candidates fulfilling the newer criteria of cochlear implantation who have a significant amount of low-frequency residual hearing in both ears. These are extreme cases of the "ski-sloping" audiogram where pure-tone hearing threshold levels up to 500 Hz may be near normal or moderately impaired, but with severe or profound levels of hearing loss at 750 Hz and above. These individuals

usually have unsatisfactory speech understanding with hearing aids. One of the newest applications in cochlear implants that can be helpful for this group of individuals is to use a partial electrode array (10, 16, or 20 mm) and an improved atraumatic surgical technique to preserve low-frequency acoustic hearing in the implanted ear. With the partial electrode array, individuals receive acoustic stimulation from both ears and electric stimulation from the implanted ear. Initial reports of hearing preservation and speech recognition following the partial insertion of the electrode array have been very encouraging.

Previous reports on combined ipsilateral EAS in cochlear-implant listeners

Van Tassel, Greenfield, Logeman, and Nelson (1999) were the first to introduce the concept of acoustic stimulation in the low-frequency range in combination with electric stimulation in the mid-to-high frequency range for patients with rather well-preserved low-frequency hearing of 20-70 dB up to 1 kHz and severe-to-profound hearing loss of $\geq$ 70 dB in the mid-to-high-frequency range of $\geq$ 1 kHz. They showed that acoustic hearing could be preserved with the insertion of a 20mm electrode array into the cochlea reaching to approximately the 1000 Hz frequency place in the cochlea. Better speech recognition in quiet was observed with combined ipsilateral EAS when compared to that with electric stimulation. The range of improvement was 44% to 53% on the Hochmair-Schulz-Moser (HSM) sentence test and 20% to 35% on the monosyllables, depending on the training experience with combined ipsilateral EAS.

Gantz and Turner (2004) studied six patients with combined ipsilateral EAS who were fit with a "short" electrode array of either 6 or 10mm in length. Residual

low-frequency hearing was preserved to within 10 to 15 dB in all patients. Gantz and Turner found that combined ipsilateral EAS helped the patients with consonant identification as well as with monosyllabic word recognition. The 10 mm insertion depth allowed better performance than the 6mm insertion depth. A study by Turner, Gantz, Vidal, Behrens, and Henry (2004) on short-electrodes also showed significant benefits of additional low-frequency acoustic hearing in terms of speech recognition in noise. In this study, acoustic hearing was preserved up to frequencies of 500 to 750 Hz. They compared the speech reception thresholds of spondee words in different noise backgrounds (steady-state noise versus competing sentences) in implant users with "10mm short-electrodes" and traditional "18-20mm long-electrodes". They reported that speech reception thresholds improved by 15 dB in the competing talker background and 5 dB in the steady-state noise background in combined hearing recipients with the short-electrode implants when compared to the speech reception thresholds in combined hearing recipients with the traditional long-electrode implants. They concluded that the better speech-recognition performance in multi-talker babble noise with additional low-frequency acoustic hearing was attributed to the ability of the listeners to take advantage of the voice differences between the target and the masker speech.

Successful conservation of hearing after traditionally long-electrode cochlear implantation using the atraumatic electrode insertion technique to preserve residual low-frequency hearing was reported by Kiefer, Gstoettner, Baumgartner, Pok, Tillein, Ye, and von Ilberg (2004). The patients presented with low-frequency hearing of 20-60 dB up to 750 Hz. Insertion depths in the patients ranged from 19 mm to 24 mm

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with the majority of insertions at 19mm or 20mm. Hearing preservation in the implanted ear could be partially achieved in 1 2/14 subjects (86%). The patients' mean performance on Freiburg monosyllabic words in the acoustic-stimulation condition was 7% correct; in the electric-stimulation condition it was 54%; and in the combined-ipsilateral-EAS condition it was 62%. The patients' average performance on the HSM sentences in quiet in the acoustic-stimulation condition was 32%; in the electric-stimulation condition it was 78%; and in the combined-ipsilateral-EAS condition it was 86%. In noise, the improvement from the electric-stimulation condition to the combined-ipsilateral-EAS condition was 23%. A significant speech recognition improvement was shown in 7 of 13 patients in the combined-ipsilateral-EAS condition relative to the electric-stimulation condition. Similar results were also reported by Gstoettner, Kiefer, Baumgartner, Pok, Peters, and Adunka (2004). In their study, 21 subjects with considerable low-frequency hearing but with unsatisfactory speech understanding with hearing aids were implanted with 18-24 mm insertion depth of MED-EL COMBI-40+ cochlear implant electrode arrays. Hearing preservation in the implanted ear could be achieved in 18/21 patients (85.7%). Dramatic benefits for combined ipsilateral EAS compared to electric stimulation were observed in speech recognition tests. The long-term ipsilateral hearing preservation in patients who underwent cochlear implantation using the atraumatic technique was later reported by Gstoettner, Helbig, Maier, Kiefer, Radeloff, and Adunka (2006). Their study showed that complete and partial preservation of ipsilateral hearing after cochlear implantation was achieved in about 70% of 23 cases over an average period of 27.25 months.

James, Albegger, Battmer, Burdo, Deggouj, Deguine, Dillier, Gersdorff, et al. (2005) reported preliminary results from a prospective study investigating the benefits of combined ipsilateral EAS and the conservation of residual hearing after implantation with 17-19 mm insertion depth (300-430 degrees) of standard-length Nucleus Contour Advance perimodiolar electrode array by using a defined surgical protocol. Word recognition scores in quiet were improved from 10% in the electric-stimulation condition to 30% in the combined-ipsilateral-EAS condition in 3 out of 12 patients. Signal-to-noise ratio thresholds for sentence recognition were improved by up to 3 dB. Patients reported that they experienced greatly improved sound quality and preferred to use the two devices together. Similar benefits of combined ipsilateral EAS were reported in the following study of James, Fraysse, Deguine, Lenarz, Mawman, Ramos, Ramsden, and Sterker (2006). They investigated 10 adults implanted with 17 mm insertion depth (285-420 degrees Insertion depth angles) of Nucleus 24 Contour Advance perimodiolar electrode arrays. Mean postoperative scores improved from 56% in the electric-stimulation condition to 68% in the combined-ipsilateral-EAS condition. For sentences presented in multitalker babble noise at 5 dB SNR, mean scores improved from 61% in the electric-stimulation condition to 75% in the combined-ipsilateral-EAS condition.

Fraysse, Macias, Sterkers, Burdo, Ramsden, Deguine, Klenzner, and Lenarz (2006) assessed the conservation of residual hearing in recipients of the Nucleus 24 Contour Advance cochlear implant with 17 mm insertion depth, and the benefits of combined ipsilateral EAS. Hearing was preserved in 12 out of 27 conventional candidates for cochlear implantation where a recommended soft-surgery protocol was

strictly adhered. Group mean recognition scores for words improved from 45% in the electric-stimulation condition to 55% in the combined-ipsilateral-EAS condition. For sentences presented in noise at 5 dB SNR, combined ipsilateral EAS provided considerable benefits for speech recognition in noise, equivalent to between 3 and 5 dB SNR, when compared to electric stimulation.

Previous reports on simulation of combined ipsilateral EAS in normal-hearing listeners

In a simulation of cochlear-implant signal processing for combined ipsilateral EAS, the input signal is low-pass filtered at a certain frequency (e.g., 500 Hz) for acoustic stimulation. For electric stimulation, the input signal is divided into a number of frequency bands and the amplitude envelope of each band is extracted and modulated by either a noise-band, whose bandwidth is equal to the band of speech information it is representing, or a sine wave, whose frequency is equal to the center frequency of the band it represents (Shannon, Zeng, Kamath, Wygonski & Ekelid, 1995; Dorman, Loizou & Rainey, 1997). The low-pass filtered acoustic input and the processed electric input are added together to form a simulated signal of combined ipsilateral EAS. Acoustic simulation is applied to normal-hearing listeners to evaluate the potential benefits from the combination of EAS.

Dorman, Spahr, Loizou, Dana, and Schmidt (2005) tested 12 normal-hearing listeners with sentence stimuli through a five-channel, combined-ipsilateral-EAS condition. Insertion depths of 19, 17, 15, 13, and 11mm were simulated. Acoustic stimulation was allowed to 500 Hz. Using sentences for the test material, they found that all simulated insertion depths for combined ipsilateral EAS, whether shallow or

deep, gave better performance than electric stimulation alone. The best performance was found with depths of 19 and 17mm. A 19mm insertion depth allowed 40% better sentence understanding than an 11mm insertion depth.

In addition to testing implant patients, Turner et al. (2004) also tested normal-hearing listeners using a noise-excited envelope vocoder. They investigated the effect of introducing unprocessed low-frequency information on listeners' ability to recognize two-syllable words (spondees) in a background of either steady-state noise or two-talker babble. Using a 16-channel vocoder and steady-state noise interference, they found no effect of processing: vocoder processing did not degrade performance, relative to the unprocessed condition, and adding back unprocessed acoustic information below 500 Hz did not improve performance. In contrast, performance in two-talker babble was degraded by 16-channel vocoder processing and was partially restored by reintroducing the unprocessed signal below 500 Hz.

Qin and Oxenham (2006) investigated the benefits of adding unprocessed low-frequency information at different low-pass cutoff frequencies to an eight-channel noise-excited envelope vocoder in normal-hearing listeners. The results confirmed that the additional low-frequency information provided significant benefits in speech intelligibility in noise even when the cutoff frequency for the unprocessed acoustic information was reduced as low as to 300 Hz, suggesting the improved speech intelligibility in noise were attributed to the improvement in $F0$ representation. With the higher cutoff frequency of 600 Hz, part of the improvement in performance was likely due to the improved spectral representation of the first formant.

Chang, Bai, and Zeng (2006) used a 4 channel simulation of a cochlear implant and a 4-channel simulation with the addition of low-passed speech to investigate the minimum amount of the low-passed speech needed for achieving the speech-perception benefits from combined ipsilateral EAS. The speech was filtered at 250, 500 and 1000 Hz to simulate different degrees of hearing preservation. The addition of the low-passed speech information improved performance relative to the electric-stimulation condition. The 250 Hz low-pass condition allowed a 10-dB-SNR and the 500 Hz low-pass condition allows a 15-dB-SNR improvement, suggesting that the $F0$ of voicing played a major role in the speech-perception benefits. A larger 15-dB-SNR improvement was observed with the 1000 Hz low-pass condition, suggesting that the first formant could also play a role if listeners had hearing beyond 500 Hz.

Brown and Bacon (2007) investigated the contributions of $F0$ information and the amplitude envelope of speech from acoustic hearing to electric hearing under simulated ipsilateral EAS. They replaced the low-frequency speech with a tone that was modulated either in frequency to track the $F0$ of the speech, in amplitude with the extracted envelope of the low-frequency speech, or both. Speech tokens recorded by a female talker were combined with various backgrounds and processed with a four-channel vocoder to simulate electric hearing. Across all backgrounds, intelligibility improved significantly when a tone tracking $F0$ was added to vocoder stimulation and further still when both $F0$ and amplitude envelope cues were applied. These results are consistent with previous reports on the importance of $F0$ information in speech

understanding in noise, which enables listeners to use voice pitch to separate a target voice from a background of other voices.

Summary

Short-insertion cochlear implants stimulate only the basal end of the cochlea and leave the apical (low-frequency) end sufficiently intact to preserve low-frequency residual hearing. Studies in both real and simulated implant listeners have shown that speech intelligibility both in quiet and in noise is significantly better in the combined-ipsilateral-EAS condition than that in the electric-stimulation condition. The benefits of adding low-frequency acoustic information to electrically stimulated information may be mostly derived from the improved representation of voice pitch.

Questions remained for combined contralateral/ipsilateral EAS

Amount of acoustic information necessary for achieving EAS benefits

The results from the previous studies above suggest that combined contralateral/ipsilateral EAS can lead to a substantial improvement in speech-recognition performance over electric stimulation. However, little is known about the underlying mechanisms of the speech-perception benefits from residual acoustic hearing. Implant listeners with contralateral/ipsilateral residual hearing may benefit from the combination of EAS because the additional low-frequency information provided by acoustic hearing may contain finer spectral and/or temporal cues that are particularly useful to help implant listeners identify important acoustic cues for speech perception. For example, the additional spectral and/or temporal pitch cues from acoustic hearing may help resolve the lowest harmonics of a complex sound to

identify voices of two concurrent sounds, which may lead to an improved ability to perceptually segregate the fluctuations of the target from those of the masker. This additional low-frequency information is mostly absent from electric hearing. It is possible that the auditory system can integrate the complementary information provided by combined EAS, resulting in improved speech perception (Ching et al, 2001; Mok et al, 2006).

Low-frequency acoustic information (<1000 Hz) contains different amount of speech cues. Therefore, the questions remaining are: (i) How much low-frequency acoustic information or residual low-frequency hearing is required to achieve the speech-perception benefits from combined contralateral EAS? (ii) What is the additional acoustic information attributed to the observed speech-perception benefits both in quiet and in noise? There are studies that have investigated the amount of low-frequency acoustic input in order to achieve the speech-perception benefits by using acoustic simulation of combined ipsilateral EAS on normal-hearing listeners (e.g., Chang, Bai & Zeng, 2006; Qin & Oxenham, 2006). The results showed that significant benefits were observed even when the acoustic input was limited to a range containing only the $F0$. Up-to-date, no study has been done on actual cochlear-implant listeners with combined contralateral/ipsilateral EAS. The acoustic simulation of normal-hearing subjects involves 'ideal' residual hearing, with no hearing loss and accompanying deficits, such as broadened auditory filters. At issue is whether cochlear-implant listeners, who have significant hearing loss and accompanying disorders of auditory processing, are able to access and benefit from limited low-frequency information – as did normal-hearing listeners.

In Experiment 1, nine, adult, postlingually-deafened, cochlear-implant subjects with some residual acoustic hearing in the nonimplanted ear were recruited to assess the minimum amount of low-frequency acoustic information that was required to achieve the speech-perception benefits both in quiet and in noise from combined contralateral EAS (Aim 1). Speech-recognition performance of CNC words in quiet and AzBio sentences in a competing babble noise at +10 dB SNR was evaluated in three listening conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. The acoustic stimuli presented to the nonimplanted ear were wide band or low-pass filtered at 125 Hz, 250 Hz, 500 Hz, or 750 Hz. The electric stimuli presented to the implanted ear were wide band. These selected cutoff frequencies were used to assess the minimum amount of low-frequency acoustic information for achieving the speech-perception benefits from combined contralateral EAS.

Frequency overlap on the speech-perception benefits

Consider the case of patients with a standard cochlear implant electrode in one ear and low-frequency, residual hearing in the other ear. If the cochlear implant signal processor is configured in the usual manner, the band pass of the input filters will be 250-350 Hz at the low-frequency end and 5-7 kHz at the high frequency end. Additionally, low frequency information below 750-1000 Hz may be available from the ear contralateral to the implant depending, of course, on the extent of low frequency hearing. Because there are perceptual dissimilarities between the acoustically and electrically stimulated information (e.g., Dooley et al., 1993; Ching et al., 2001), it is reasonable to wonder if EAS patients would benefit from keeping

information from the two stimulation modalities separate to facilitate the perceptual integration of the acoustic signal and the electric signal. This can be accomplished by high pass filtering the electric signal and low-pass filtering the acoustic signal.

Previous research into the benefit from the division of frequency content between the acoustic signal and the electric signal in EAS patients has shown mixed results across studies as well as among individuals. Some studies have found no significant difference in speech perception between conditions in which frequency ranges overlap or do not overlap (Gantz & Turner, 2003; Kiefer et al., 2005). Other studies, however, have found that some individuals benefited from reduced overlap between acoustic and electric stimulation. For example, Wilson, Woford, Lawson, and Schatzer (2002) examined identification of consonants and identification of words in CUNY sentences in noise at +5 and +10 dB SNR in five patients in test conditions in which the analysis bands of cochlear implant signal processing extended from 350 Hz to 5500 Hz, from 600 Hz to 5500 Hz, or from 1000 Hz to 5500 Hz. The patients had different amounts of residual hearing -- both in their implanted ear and in the contralateral ear. One of five subjects showed significant benefit from the use of the 600-5500 Hz (i.e., reduced overlap) frequency range. This patient benefited both when the acoustic signal was in the ear contralateral to the implant and in the ear ipsilateral to the implant. A larger effect has been reported by Vermeire, Anderson, Flynn, and Van de Heyning (2008). These researchers investigated the influence of different cochlear implant and hearing aid fittings on sentence recognition in noise at +5, +10 and +15 dB SNR in four subjects with electric and acoustic hearing in the same ear. The hearing aid amplification gain was systematically manipulated and the

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frequency range of the cochlear implant was either a full range or a reduced overlap with acoustic hearing. The results showed that the reduced overlap of cochlear-implant stimulation and hearing-aid amplification allowed the best scores in three out of four subjects.

The issue of overlap in information provided by electric and acoustic stimulation was revisited in Experiment 1 as a minor topic. Speech-recognition performance of CNC words in quiet and AzBio sentences in a competing babble noise at +10 dB SNR was evaluated in three listening conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. The acoustic stimuli presented to the nonimplanted ear were wide band or low-pass filtered at 250 Hz, 500 Hz, or 750 Hz. The electric stimuli presented to the implanted ear were wide band or high-pass filtered at 250 Hz, 500 Hz, or 750 Hz. These selected cutoff frequencies were used to assess, for patients with combined contralateral EAS, whether reducing the overlap in frequency representation in the input filters of the cochlear implant and in acoustic hearing would be beneficial to speech recognition.

To set a reference for the newly processed speech stimuli in Experiment 1, speech-recognition performance of ten normal-hearing subjects was evaluated when listening to the low-pass or high-pass filtered speech stimuli listed above.

Hypotheses

The operating hypotheses of Experiment 1 were: (1) the amount of low-frequency acoustic information from the nonimplanted ear available to cochlear-implant listeners would affect the speech-perception benefits both in quiet and in noise from combined contralateral EAS; and (ii) reducing the overlap in frequency

representation in the input filters of the cochlear implant and in acoustic hearing would be beneficial to speech recognition for listeners with combined contralateral EAS.

Summary and predictions based on literature review

Understanding speech in noise and appreciation of the aesthetic qualities of sound (such as music and voice quality) are the two main challenges for most implant users. These deficits are most likely related to the poor resolution of low-frequency information including voice pitch. With the extension of cochlear implant candidacy, individuals with some residual hearing have received cochlear implants with a traditional long-electrode array or a short-electrode array. Low-frequency acoustic information is available by combining electric hearing with acoustic hearing from the implanted and/or nonimplanted ears. Residual acoustic hearing in the implanted and/or nonimplanted ear provides these implant listeners with a unique opportunity to access low-frequency information, which contains finer spectral and/or temporal speech cues and is not well resolved by cochlear implants. Studies on speech perception both in quiet and in noise with combined contralateral/ipsilateral EAS have shown significantly better speech-recognition performance than that with electric stimulation.

The goal of the present experiment is to assess the minimum amount of low-frequency acoustic information that is required to achieve the speech-perception benefits both in quiet and in noise from combined contralateral EAS. It is expected that the additional low-frequency information would provide significant speech-perception benefits both in quiet and in noise even when the acoustic information is

limited down to 250 Hz, which is consistent with the results from the previous studies of acoustic simulation on normal-hearing listeners (Chang, Bai & Zeng, 2006; Qin & Oxenham, 2006). In addition, it is also expected that reducing the overlap in frequency representation in the input filters of the cochlear implant and in acoustic hearing may be beneficial to speech recognition for listeners with combined contralateral EAS.

Methods

Experimental Design

Experiment 1 used a within-subject design with stimulation mode (e.g., acoustic stimulation, electric stimulation, and combined contralateral EAS) and filter cutoff frequency (e.g., 125 Hz, 250 Hz, 500 Hz, 750 Hz, and wide band) as independent variables. Dependent variables were the speech recognition scores of CNC words in quiet and AzBio sentences in a competing babble noise at +10 dB SNR. A repeated-measures analysis of variances (ANOVA) was applied to the results and the effects of the stimulation mode and the filter cutoff frequency on the speech-recognition performance were evaluated and analyzed to (i) assess the minimum amount of acoustic low-frequency information that was required to achieve the speech-perception benefits both in quiet and in noise from combined contralateral EAS (Aim 1); and (ii) assess whether reducing the overlap in frequency representation in the input filters of the cochlear implant and in acoustic hearing would be beneficial to speech recognition for listeners with combined contralateral EAS.

Subjects

Nine, adult, postlingually-deafened, cochlear implant users were recruited as study participants in the present experiment. Eight subjects were fitted with a traditional long-electrode implant in one ear and with a hearing aid in the nonimplanted ear and they participated in a complete series of performance measurements. S8 was fitted with a short-electrode (20mm) implant (Duet, Med-El device) in one ear and with two hearing aids in both ears, and he only participated in the conditions to assess the minimum amount of acoustic low-frequency information necessary to achieve the speech-perception benefits from combined contralateral EAS. All nine subjects demonstrated large amount of speech-perception improvement (20-40%) from the electric-stimulation-alone condition to the combined-contralateral-EAS condition and, therefore, were recruited into the present experiment to avoid a possible flooring effect on the measurement of speech-perception benefits in the conditions in which acoustic information was reduced from wide band to 125 Hz. All nine subjects had residual hearing in the nonimplanted ear with thresholds at 500 Hz and below at ≤ 60 dB HL and thresholds at 1000 Hz and above at ≥ 55 dB HL. Table 1 displays individual audiometric thresholds. Table 2 displays demographic information for each subject including age, sex, etiology of hearing loss, duration of hearing loss both 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 hearing aid usage post operatively in the nonimplanted ear. At the time of testing, all subjects except for S6 had at least 4 months experience with electric stimulation (range of 4 months to 5 years) and at least 5 years experience with amplification prior to implantation. S6 had 6 months experience with electric

Subject	125 Hz	250 Hz	500 Hz	750 Hz	1000 Hz	1500 Hz	2000 Hz	3000 Hz	4000 HZ	6000 Hz	8000 Hz
1	25	30	50	80	100	100	100	100	NR(115)	NR(110)	NR(110)
2	35	35	55	65	70	75	80	90	95	NR(110)	NR(110)
3	35	40	60	70	90	95	100	NR(110)	NR(115)	NR(110)	NR(110)
4	40	45	50	60	70	80	80	90	100	85	80
5	25	25	50	65	70	80	95	NR(110)	NR(115)	NR(110)	NR(110)
6	20	25	50	75	95	NR (110)	NR(110)	NR(110)	NR(115)	NR(110)	NR(110)
7	30	35	40	50	55	55	60	65	70	70	70
8	30	30	35	45	55	90	100	110	115	NR(110)	NR(110)
9	40	45	60	65	75	85	90	100	110	110	110

Note. NR = no response at audiometer limits. The limits in the audiometers are listed in parentheses.

Table 1. Individual audiometric thresholds (dB HL) in the nonimplanted ear.

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

Note. NIE = nonimplanted ear; IE = implanted ear; CI = cochlear implant; HA = hearing aid; N/A = not applicable
[a]Duration of hearing loss was defined as duration of time since patients first noticed incapable of understanding a conversation on the telephone as an indication of significant hearing loss.

Table 2. Individual subject demographic information, including age, sex, etiology of hearing loss, duration of hearing loss both 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 hearing aid usage post operatively in the nonimplanted ear.

stimulation and was not fitted with a hearing aid in the nonimplanted ear. Informed consents were approved by Institutional Review Board from both Arizona State University and University of Maryland College Park and were obtained from each individual subject after the nature of the study was explained.

Hearing aids

In the present experiment, all speech stimuli were delivered dichotically to both ears. The acoustic input of test materials was amplified based on a frequency-gain characteristic prescribed by NAL-NL1 formula and was presented through an insert earphone (Etymotic ER-1) to the nonimplanted ear (Ching, Inerti & Hill, 2004). Therefore, subjects' hearing aids were not used in present experiment.

Cochlear implants

The electric input of test materials was presented through a direct input cable to each subject's speech processor. Subjects were tested with their 'everyday' device settings and each subject's cochlear implant was checked before speech-recognition performance was evaluated at each test session. The volumes and sensitivity settings of the cochlear implant were not adjusted in order to maintain the same settings on the cochlear implant for both the combined-contralateral-EAS and the electric-stimulation conditions.

Speech stimuli

The CNC words. The CNC words were phonemically balanced to American English, each consisting of 50 words (Peterson & Lehiste, 1962). The speaker was a male and his average $F0$ was 123 Hz (S. D. = 17 Hz) (WaveSurfer software, version

1.8.5). To avoid a possible learning effect, no CNC word list was repeatedly used in the same test session and only the lists with poor scores (<20%) were used in the following session.

The Az Bio sentences. Lists of Az Bio sentences with equal intelligibility (33 lists in total) , each consisting of 20 sentences ranging in length from 6 to 10 words, were developed to evaluate the performance of cochlear-implant listeners in the Cochlear Implant Laboratory at Department of Speech and Hearing Sciences at Arizona State University (Spahr & Dorman, 2005). The speakers were instructed to speak in a casual style and a total of 5 speakers (2 male & 3 female) were used. The average F0s were 131 Hz (S. D. = 35 Hz) for the male voice and 205 Hz (S. D. = 45 Hz) for the female voice (WaveSurfer software, version 1.8.5). Because the average scores of Az Bio sentences at +5 dB SNR and at +10 dB SNR were 37 % and 66%, respectively, in the combined-contralateral-EAS condition (Gifford, et al., 2007), AzBio sentences at +10 dB SNR were selected in the present experiment to avoid a possible flooring effect.

Stimulus processing. All speech stimuli were recorded using waveform editing software (COOL EDIT PRO 2.0 at 44.1 kHz sampling rate) and then processed by a low-pass filter with cut-off frequencies of 125 Hz, 250 Hz, 500 Hz, and 750 Hz, or a high-pass filter with cut-off frequencies of 250 Hz, 500 Hz, and 750 Hz. The filters were designed with a FIR1 function in MATLAB (7.0).

Because speech stimuli were presented dichotically in the combined-contralateral-EAS condition, the acoustic input of all speech stimuli was presented through an insert earphone (Etymotic ER-1) and the electric input was presented

through a direct input cable to each subject's speech processor to avoid acoustic crosstalk. To make the speech stimuli audible to the nonimplanted ear with hearing loss, the acoustic input was subjected to a frequency-gain characteristic prescribed by NAL-R formula (Byrne & Dillon, 1986; Byrne, Parkinson & Newall, 1990) prior to presentation to the nonimplanted ear. The NAL-R formula was intended to make the average loudness of the speech the same for speech intelligibility. The goal of the frequency-dependent amplification was to restore audibility as far as possible, while avoiding excessive loudness. The gain specified by the NAL-R formula was calculated and applied to the nonimplanted ear for each subject. The maximum insertion gain applied was 50 dB. If the NAL-R formula called for an insertion gain greater than 50 dB, then the insertion gain was limited to 50 dB. The NAL-R formula filters were designed using a FIR2 function in MATLAB (7.0).

A Tucker-Davis Technologies (TDT system 3) Power digital-analog converter (DAC) with six digital signal processors was used to implement the low-pass/high-pass filters and the NAL-R formula filters for each condition and each subject. The low-pass/high-pass filters were implemented on one processor. A 90 dB/octave roll-off was chosen for the low-pass filter because it created an audiometric configuration similar to that found in the literature for many combined EAS patients. The NAL-R formula filters were implemented on the other five processors to give maximum cutoff sharpness. The TDT Power DAC was then connected to two attenuators (PA5) and the outputs were fed to a headphone driver, which presented the stimuli dichotically to each subject. The stimuli were calibrated daily.

Overall Procedure

Test conditions. Speech-recognition accuracy for CNC words (speech perception in quiet) and AzBio sentences in the presence of a competing babble noise at +10 dB SNR (speech perception in noise) was evaluated in three listening conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. The amount of the acoustic/electric input in three listening conditions was varied by filtering the speech stimuli at different cutoff frequencies.

In the acoustic-stimulation condition, all speech stimuli were either unprocessed with a full speech spectrum (Wide band) or processed by a low-pass filter with cutoff frequencies of 125 Hz (125 LP), 250 Hz (250 LP), 500 Hz (500LP), and 750 Hz (750LP). To document the effect of the low-pass filter on the speech stimuli, 50 CNC words and 20 AzBio sentences were processed through each of the filter conditions by using a waveform editing software (COOL EDIT PRO 2.0 at 44.1 kHz sampling rate) and then a frequency analysis was conducted for each of the filter conditions by using Fast Fourier Transform (FFT). The spectra of the low-pass-filtered speech stimuli are shown in Figure 1.

In the electric-stimulation condition, the speech stimuli were either unprocessed with a full speech spectrum (Wide band) or processed by a high-pass filter with cutoff frequencies of 250 Hz (250HP), 500 Hz (500HP), and 750 Hz (750HP).

In the combined-contralateral-EAS condition, the low-pass-filtered or the wide-band speech stimuli presented to the nonimplanted ear were combined with the wide-band speech stimuli presented to the implanted ear to assess the minimum

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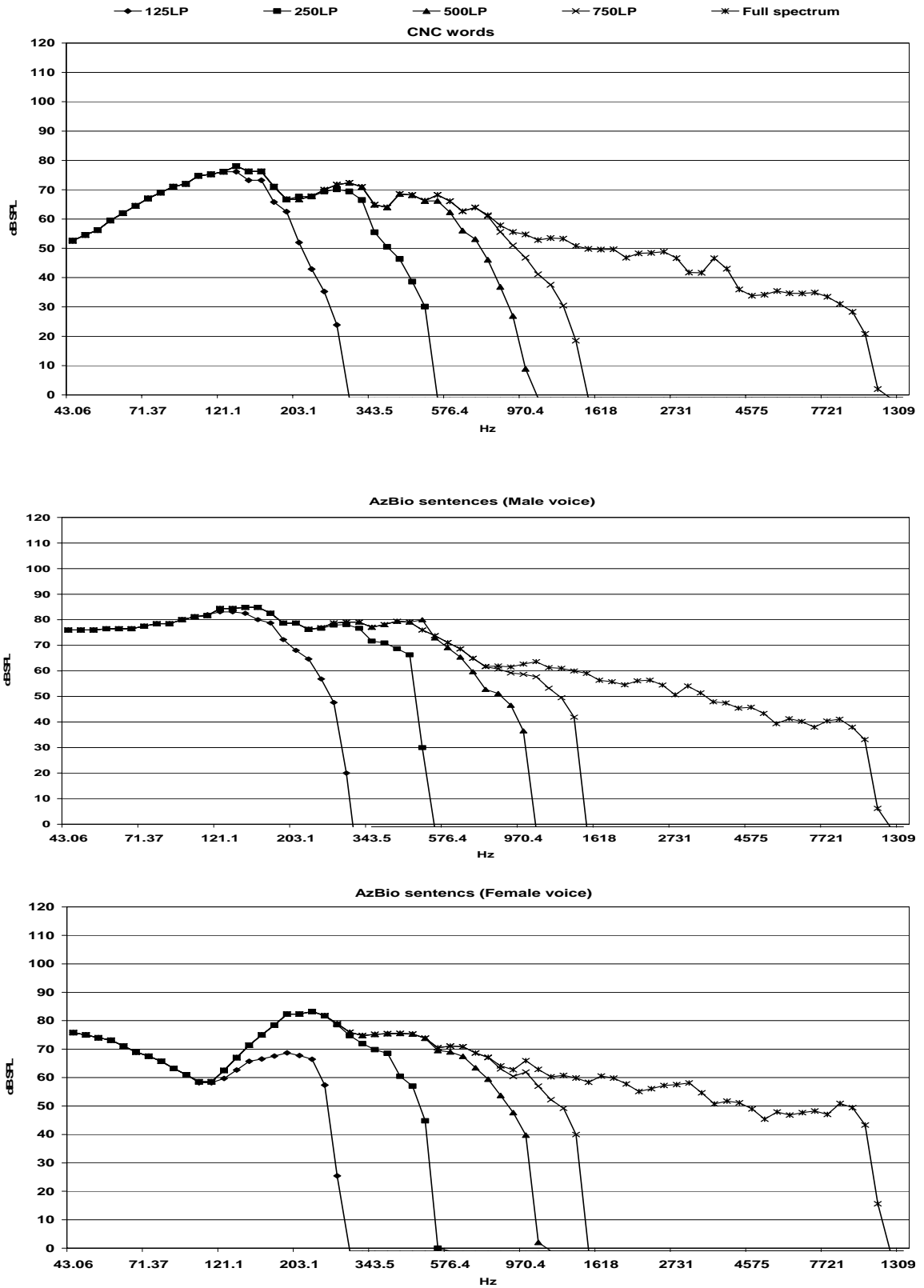
Figure 1. FFT outputs for the low-pass-filtered speech stimuli.

amount of low-frequency acoustic information that was required to achieve the speech-perception benefits from combined contralateral EAS. Then the low-pass-filtered acoustic stimuli (250LP, 500LP, and 750LP) were combined with high-pass-filtered electric stimuli (250HP, 500HP, and 750HP) to test whether reducing the overlap in frequency representation in the input filters of the cochlear implant and in acoustic hearing would be beneficial to speech recognition in listeners with combined contralateral EAS.

The total number of CNC word lists and AzBio sentence lists presented in three stimulation conditions was 5 for the acoustic-stimulation condition, 8 for the electric- stimulation condition, and 8 for the combined-contralateral-EAS condition. The total conditions and repeated measurements for each subject are represented in Figure 2.

All subjects were tested with CNC words and AzBio sentences in the presence of a competing babble noise at +10 dB SNR. No feedback was provided and they were instructed to guess if they were not sure. All tests were preceded by practice sessions with sentences and words. CNC words and sentences were scored as words correct. Performance was measured in the following conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. In each condition, performance was repeatedly measured with test materials listed above. Subjects were seated in a sound-attenuating chamber. Typically all speech tests included two sessions, 3-4 hours per session with frequent breaks. The entire procedure, including preliminary audiometric assessment and practice sessions, was completed in about 7-8
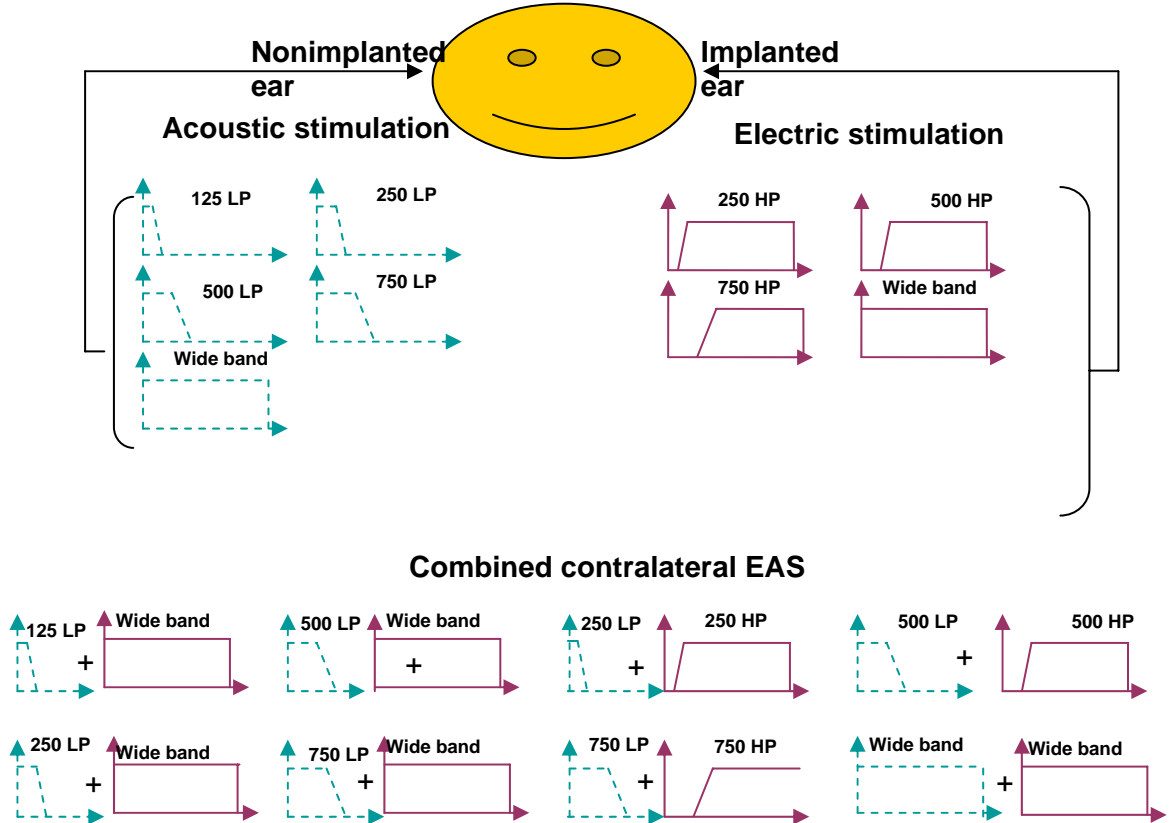
Figure 2. Schematic representations of speech stimuli (CNC words and AzBio sentences at +10 dB SNR). In the acoustic-stimulation condition, the stimuli presented to the nonimplanted ear were unprocessed (Wide band) or low-passed filtered at 125 Hz (125LP), 250 Hz (250LP), 500 Hz (500LP), or 750 Hz (750LP). In the electric-stimulation condition, the stimuli presented to the implanted ear were unprocessed (Wide band) or high-pass filtered at 250 Hz (250HP), 500 Hz (500HP), or 750 Hz (750HP). In the combined-contralateral-EAS condition, the low-pass filtered (125LP, 250LP, 500LP, or 750LP) or the wide-band acoustic stimuli were combined with the wide-band electric input. The low-pass filtered acoustic stimuli (250LP, 500LP, or 750LP) were also combined with the high-pass filtered electric stimuli (250HP, 500HP, or 750HP).

hours. The order of test conditions was counterbalanced across subjects. Subjects were reimbursed for their participation in the experiment.

Presentation level. In the acoustic-stimulation condition, the acoustic stimuli were presented to the nonimplanted ear through an insert earphone (Etymotic ER-1). All acoustic input of speech stimuli was presented at 70 dB sound pressure level (SPL) prior to the amplification based on a frequency-gain characteristic prescribed by NAL-R formula. Therefore, the presentation level was set on an individual basis for each subject, according to his/her audiometric thresholds.

In the electric-stimulation condition, the electric stimuli were presented to each subject's speech processor via a direct input cable. This was to defeat the headset microphone so that no external input occurred, while at the same time preserving the microphone pre-emphasis. All electric input of speech stimuli was presented at 70 dB SPL. The volume and sensitivity settings of the cochlear implant were not adjusted in order to maintain the same settings on the cochlear implant for both the electric-stimulation and the combined-EAS conditions.

In the combined-contralateral-EAS condition, the stimuli were output via an audio splitter connector with one connected to an insert earphone (Etymotic ER-1) and the other one connected to each subject's speech processor via a direct input cable. Adjustment of amplification gain of the acoustic input has been found to be useful because the relative effectiveness with which each ear transmits low-frequency versus high-frequency information may be different in listeners with combined contralateral EAS (Ching, et al., 2001). Therefore, to facilitate the perceptual fusion of the acoustic input and the electric input, a loudness matching method was used to

find the frequency gain of the acoustic input that amplified speech to the same overall loudness as the electric input. The speech stimuli used for loudness adjustment were AzBio sentences at +10 dB SNR, which were not used in the following speech-recognition test. The subject was instructed to listen to the speech stimuli first presented at 70 dB SPL with the implant alone and remember the loudness, then listen to the amplified speech stimuli with the insert earphone alone, and indicate on a response card whether the sound was louder or softer than that in the implanted ear. The response card was a continuous scale, labeled with "louder" and "softer" at the end points and "the same" halfway in between. The experimenter adjusted the frequency gain until the speech stimuli were rated to sound equally loud in both ears. The volume and sensitivity settings of the cochlear implant were not adjusted in order to maintain the same settings on the cochlear implant for both the electric-stimulation and the combined-EAS conditions.

Results

Results for normal-hearing listeners when listening to the processed speech stimuli

   Subjects. Ten normal-hearing subjects participated in the present experiment and they ranged in age from 20-53 years (mean age = 28.8 yrs; st. dev. = 10.7 yrs). All subjects had normal audiometric thresholds $\leq$ 15 dB HL for octave test frequencies from 250 to 8000 Hz (ANSI, 2004). All subjects provided written informed consent and were paid an hourly wage for their participation.

   Stimuli and Procedure. All speech stimuli were: (i) processed by a low-pass filter with cutoff frequencies of 125 Hz (125LP), 250 Hz (250LP), 500 Hz (500LP), 750 Hz (750LP), and 1000 Hz (1000LP); (ii) processed by a high-pass filter with

cutoff frequencies of 250 Hz (250HP), 500 Hz (500HP), and 750 Hz (750HP); or (iii) unprocessed with a full spectrum (Wide band). The signal processing schemes were followed as described above. All speech stimuli were presented via a loudspeaker directly in front of subjects at 70 dB SPL. The testing procedure was followed as described above.

Results. Figure 3 shows the identification accuracy of CNC words and AzBio sentences at +10 dB SNR, in percent correct, as a function of filter cutoff frequency. A single-factor repeated-measures ANOVA was conducted separately for CNC words and AzBio sentences with the filter cutoff frequency as a within-subject factor. The analysis revealed that the effect of the filter cutoff frequency was statistically significant for both CNC words ($F_{(8, 72)} = 1010.6$, $p < 0.001$) and AzBio sentences ($F_{(8, 72)} = 714.0$, $p < 0.001$). Post hoc pairwise comparison tests (Fisher's LSD) revealed that (i) the mean scores in the low-pass-filtered conditions (125LP, 250LP, 500LP, 750LP, and 1000LP) were significantly different from one another both for CNC words and AzBio sentences ($p < 0.05$); (ii) the mean scores in the high-pass-filtered conditions (250HP, 500HP, and 750HP) were not significantly different from one another ($p > 0.05$) and were not significantly different from the mean scores in the wide-band condition for both CNC words and AzBio sentences ($p > 0.05$); and (iii) the mean scores in the low-pass-filtered conditions were all significantly lower than those in the high-pass-filtered conditions ($p < 0.05$), and were significantly lower than the mean scores in the wide-band condition for both CNC words and AzBio sentences ($p < 0.05$).
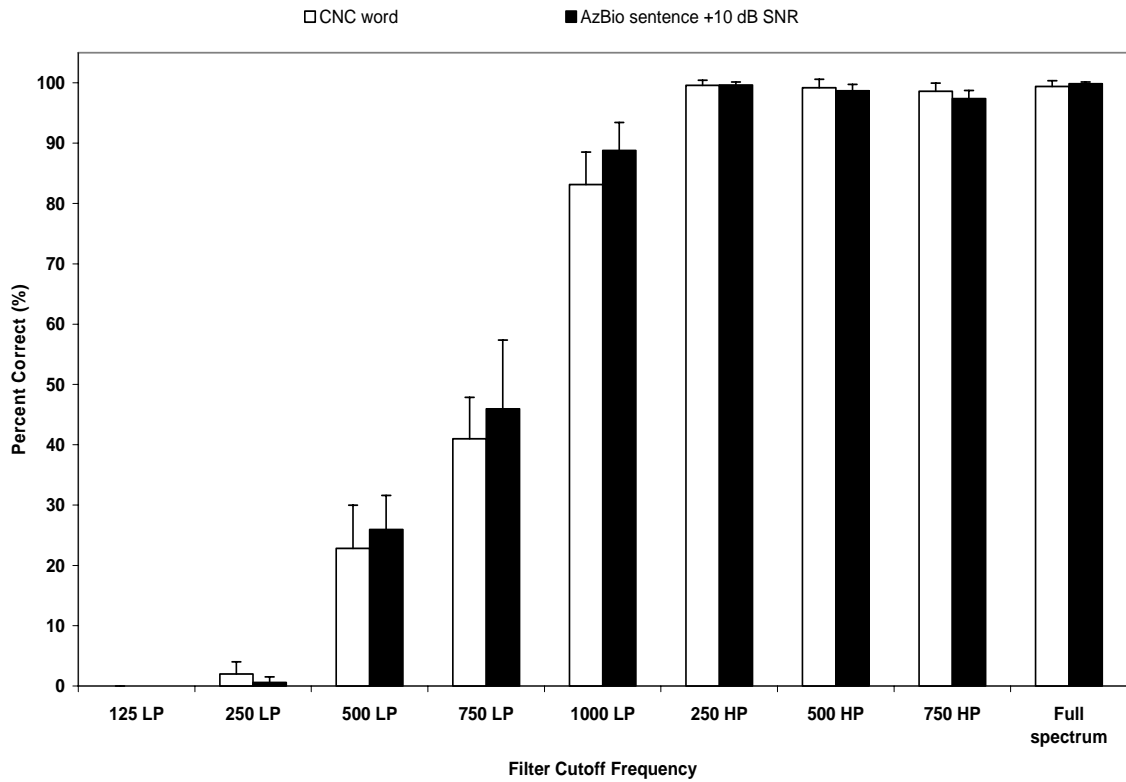
Figure 3. Group mean scores of CNC word (white bars) and AzBio sentence at +10 dB SNR (black bars) presented at 70 dB SPL for normal-hearing subjects. Error bars indicate +1 standard deviation.

Results for cochlear-implant listeners with combined contralateral EAS

Amount of acoustic information necessary for achieving EAS benefits

CNC words. Figure 4 shows recognition accuracy for CNC words as a function of filter cutoff frequency and as a function of stimulation condition. A repeated-measures ANOVA revealed that the effect of condition was statistically significant ($F_{(10, 80)}$ = 98.1, p < 0.0010). In the acoustic-stimulation conditions the mean scores in the 125LP, 250LP, 500LP, 750LP, and wide-band conditions were 0, 0.9, 6.7, 19.3, 46.4 percent correct, respectively. A post hoc pairwise comparison (Fisher's LSD) revealed that the scores in the 125LP and 250LP conditions were not significantly different from each other (p > 0.05) but were all lower than the scores in the 500LP, 750LP, and wide-band conditions (p < 0.05). The scores in the 500LP, 750LP, and wide-band conditions were significantly different from one another (p < 0.05).

In the electric-stimulation condition the mean score was 56% correct. This score was not significantly higher than the score in the wide-band, acoustic-stimulation condition (Fisher's LSD, p > 0.05).

In the EAS conditions the mean scores for the 125LP (A) + wide band (E), 250LP (A) + wide band (E), 500LP (A) + wide band (E), 750LP (A) + wide band (E), and wide (A) + wide band (E) conditions were 77, 82, 84, 85.5, and 86.2 percent correct, respectively. All scores were significantly higher than those in the wide-band, acoustic-stimulation condition and in the wide-band, electric-stimulation condition (Fisher's LSD, p < 0.05). Among the five EAS conditions, a post hoc pairwise comparison (Fisher's LSD) revealed that there was a significant improvement for word recognition when the acoustic information increased from 125 Hz to 250 Hz (p

Figure 4. Percent correct scores for CNC words and AzBio sentences at +10 dB SNR as a function of stimulation condition and low-pass filter setting. LP = low pass. WB = wide band.

< 0.05). No significant improvement was observed when the acoustic information increased from 250 Hz to 500 Hz, from 500 Hz and 750 Hz, and from 750 Hz to wide band ($p > 0.05$).

AzBio sentences at +10 dB SNR. Figure 4 shows recognition accuracy as a function of filter cutoff frequency and as a function of stimulation condition. A repeated-measures ANOVA revealed that the effect of condition was statistically significant ($F_{(10, 80)} = 62.4$, $p < 0.0010$). In the acoustic-stimulation conditions the mean scores in the 125LP, 250LP, 500LP, 750LP, and wide-band conditions were 0, 0, 6, 22 and 44 percent correct. A post hoc pairwise comparison (Fisher's LSD) revealed that the scores in the 125LP and 250LP conditions were not significantly different from each other ($p > 0.05$) but were all lower than the scores in the 500LP, 750LP, and wide-band conditions ($p < 0.05$). The scores in the 750LP and wide-band conditions were not significantly different from each other ($p > 0.05$) but were all significantly higher than that in the 500LP condition ($p < 0.05$).

In the E condition the mean score was 40 percent correct. This score was not significantly higher than the score in the wide-band, acoustic-stimulation condition (Fisher's LSD, $p > 0.05$).

In the EAS conditions the mean scores for the 125LP (A) + wide band (E), 250LP (A) + wide band (E), 500LP (A) + wide band (E), 750LP (A) + wide band (E), and wide band (A) + wide band (E) conditions were 69.8, 71.5, 76.8, 82.3 and 86.9 percent correct, respectively. All scores were significantly higher than those in the wide-band, acoustic-stimulation condition and in the wide-band, electric-stimulation condition (Fisher's LSD, $p < 0.05$). Among the five EAS condition, a post hoc

pairwise comparison (Fisher's LSD) revealed that there was a significant improvement for sentence recognition when the acoustic information increased from 250 Hz to 500Hz and from 500 Hz to750 Hz ($p < 0.05$). No significant improvement was observed when the acoustic information increased from 125 Hz to 250 Hz and from 750 Hz to wide band ($p > 0.05$).

Frequency overlap on the speech-perception benefits

CNC words. Figure 5 shows recognition accuracy for CNC words as a function of filter cutoff frequency and as a function of stimulation condition. A two-way repeated-measures ANOVA revealed significant main effects for the filter cutoff frequency ($F_{(3,21)} = 95.2$, $p < 0.001$) and for the stimulation condition ($F_{(2,14)} = 23.4$, $p < 0.001$) with a significant interaction ($F_{(6,42)} = 15.8$, $p < 0.0010$).

Subsequent analysis of simple main effects for the filter cutoff frequency revealed that the mean word recognition scores were influenced by the filter cutoff frequency for the acoustic-stimulation condition ($F_{(3, 5)} = 11.5$, $p < 0.05$) and the electric-stimulation condition ($F_{(3, 5)} = 7.1$, $p < 0.05$) but not for the EAS condition ($F_{(3, 5)} = 4.4$, $p > 0.05$). A post hoc pairwise comparison (Fisher's LSD) revealed that the mean word recognition scores in the 250LP, 500LP, 750LP, and wide-band conditions were significantly different from one another for the acoustic-stimulation condition ($p < 0.05$). The mean word recognition scores in the 250HP, 500HP, and 750HP conditions were significantly different from one another for the electric-stimulation condition ($p < 0.05$). When the scores in the 250HP, 500HP, and 750HP conditions were compared with that in the wide-band condition for the electric-stimulation condition, the score in the wide-band condition was not significantly

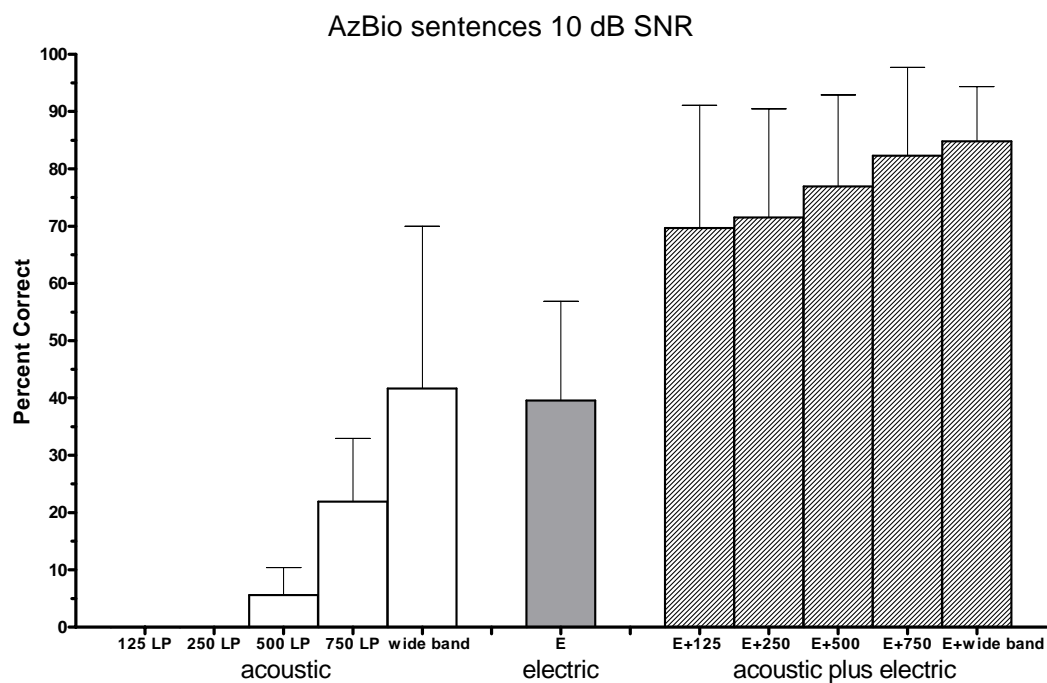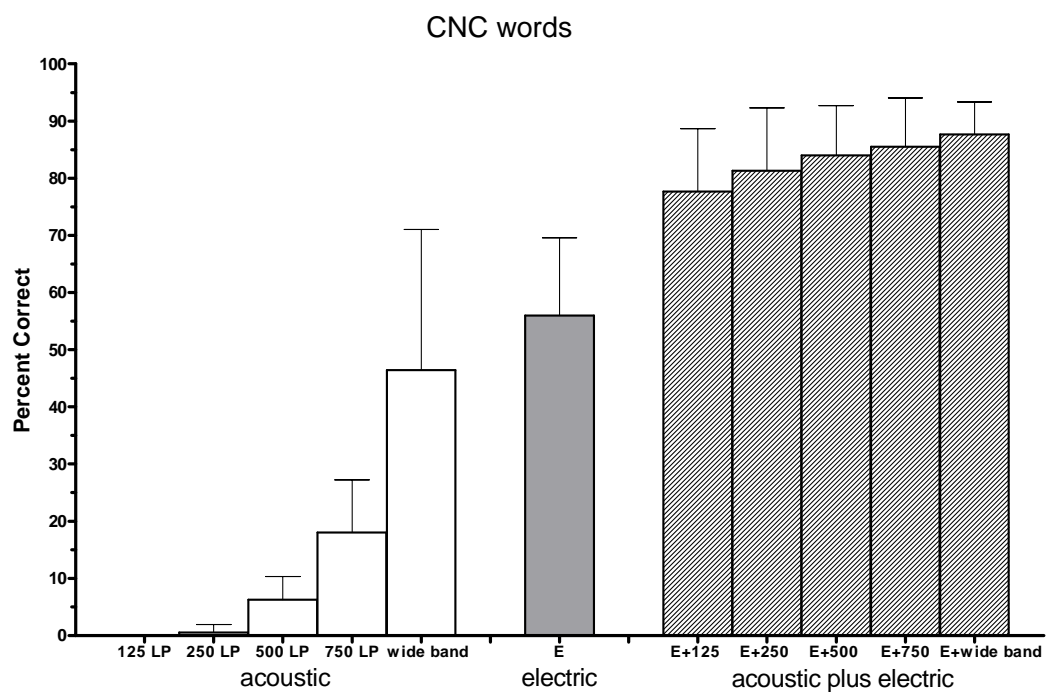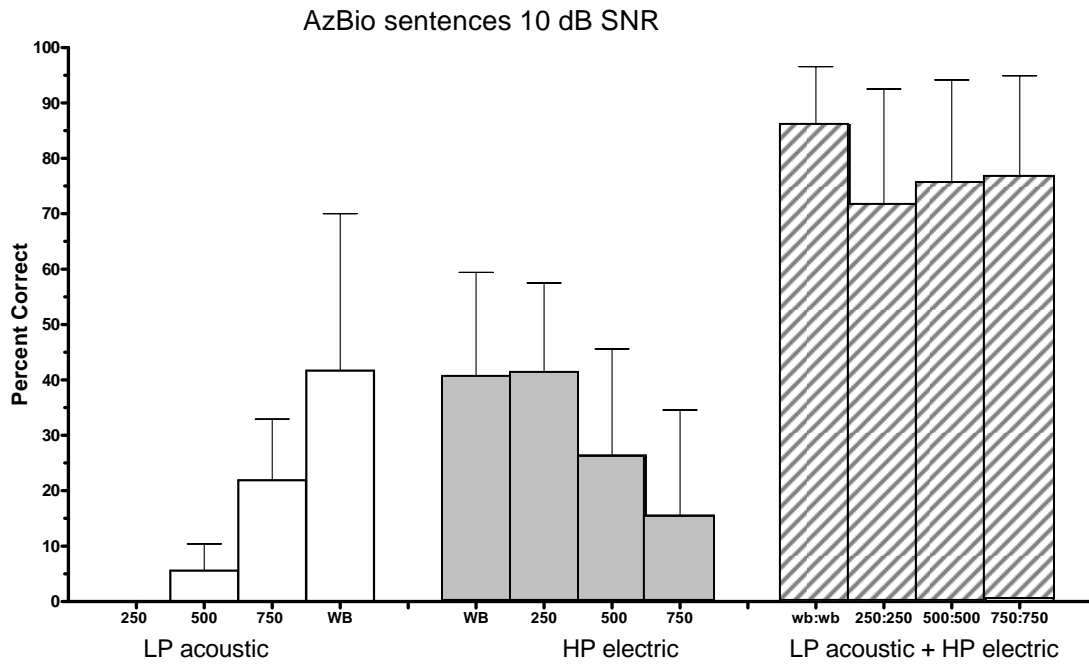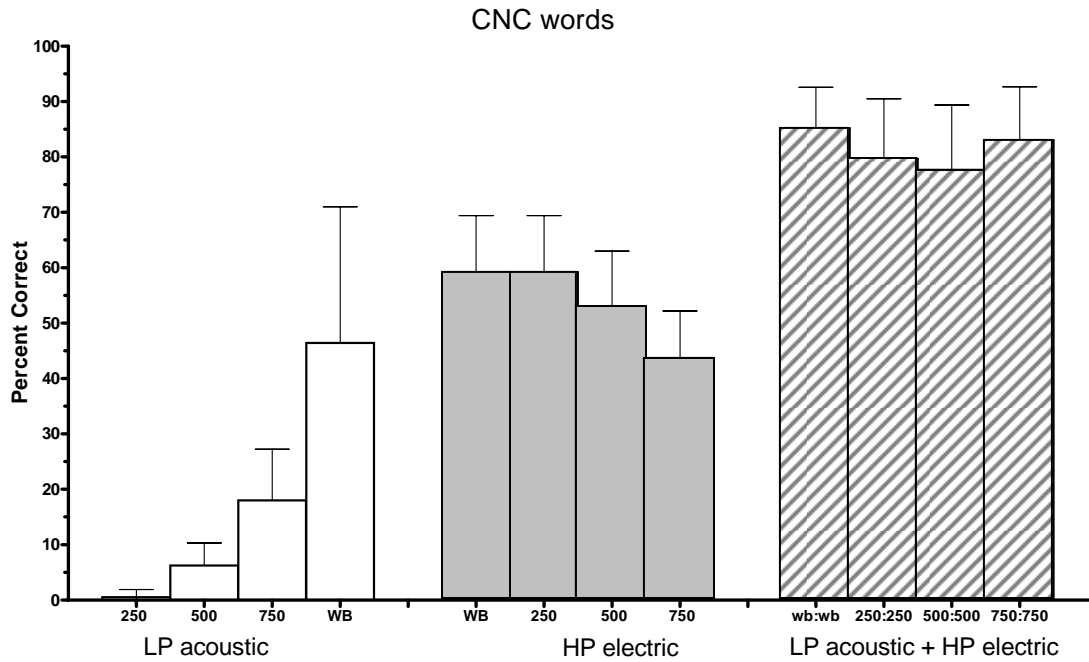Figure 5. Percent correct scores for CNC words and AzBio sentences at +10 dB SNR as a function of stimulation condition and filter condition. LP = low pass. HP = high pass. WB = wide band.

different from that in the 250HP condition ($p > 0.05$) but was significantly higher than those in the 500HP and 750HP conditions ($p < 0.05$).

Subsequent analysis of simple main effect for the stimulation condition revealed that the mean word recognition scores were influenced by the stimulation condition for all four filter-cutoff-frequency conditions (for 250 Hz: $F_{(2, 6)} = 152.1$, $p < 0.001$; for 500 Hz: $F_{(2, 6)} = 92.4$, $p < 0.001$; for 750 Hz: $F_{(2, 6)} = 135.4$, $p < 0.001$; for wide band: $F_{(2, 6)} = 112.8$, $p < 0.001$). A post hoc pairwise comparison (Fisher's LSD) revealed that the mean word recognition scores in the EA condition were significantly higher than those in the acoustic- and electric-stimulation conditions for all four filter-cutoff-frequency conditions ($p < 0.05$). The mean word recognition scores in the electric-stimulation condition were significantly higher than those in the acoustic-stimulation conditions for the 250-Hz, 500-Hz, and 750-Hz conditions ($p < 0.05$) but not for the wide-band condition ($p > 0.05$).

AzBio sentences at +10 dB SNR. Figure 5 shows recognition accuracy for AzBio sentences in noise at +10 dB SNR as a function of filter cutoff frequency and as a function of stimulation condition. A two-way repeated-measures ANOVA revealed significant main effects for the filter cutoff frequency ($F_{(3,21)} = 19.2$, $p < 0.001$) and for the stimulation condition ($F_{(2,14)} = 53.3$, $p < 0.001$) with a significant interaction ($F_{(6,42)} = 10.8$, $p < 0.001$).

Subsequent analysis of simple main effect for the filter cutoff frequency revealed that the mean sentence recognition scores were influenced by the filter cutoff frequency for the acoustic-stimulation condition ($F_{(3, 5)} = 8.1$, $p < 0.05$) and the electric-stimulation condition ($F_{(3, 5)} = 48.7$, $p < 0.001$) but not for the EAS condition

($F_{(3, 5)}$ = 2.7, p > 0.05). A post hoc pairwise comparison (Fisher's LSD) revealed that the mean sentence recognition scores in the 250LP, 500LP, 750LP, and wide-band conditions were significantly different from one another for the acoustic-stimulation condition (p < 0.05). The mean sentence recognition scores in the 250HP, 500HP, and 750HP conditions were significantly different from one another for the electric-stimulation condition (p < 0.05). When the scores in the 250HP, 500HP, and 750HP conditions were compared with that in the wide-band condition for the electric-stimulation condition, the score in the wide-band condition was not significantly different from that in the 250HP condition (p > 0.05) but was significantly higher than those in the 500HP and 750HP conditions (p < 0.05).

Subsequent analysis of simple main effects for the stimulation condition revealed that the mean sentence recognition scores were influenced by the stimulation condition for all four filter-cutoff-frequency conditions (for 250 Hz: $F_{(2, 6)}$ = 39.9, p = .000; for 500 Hz: $F_{(2, 6)}$ = 63.0, p = .000; for 750 Hz: $F_{(2, 6)}$ = 56.5, p = .000; for wide band: $F_{(2, 6)}$ = 136.8, p = .000). A post hoc pairwise comparison (Fisher's LSD) revealed that the mean sentence recognition scores in the EA condition were significantly higher than those in the acoustic- and electric-stimulation conditions for all four filter-cutoff-frequency conditions (p < 0.05). The mean sentence recognition scores in the electric-stimulation condition were significantly higher than those in the acoustic-stimulation conditions for the 250-Hz, 500-Hz, and 750-Hz conditions (p < 0.05) but not for the wide-band condition (p > 0.05).

Discussion

Discussion of results for normal-hearing subjects

Normal-hearing subjects were able to use limited low-frequency information (up to 1000 Hz) to get good speech recognition in quiet (83% percent correct for CNC words) and even in noise (89% percent correct for AzBio sentences at +10 dB SNR), and their speech-recognition performance was not affected when the low-frequency information was completely eliminated from the speech signal up to 750 Hz. These results reinforce the notion that speech contains layers of acoustic, phonetic, and linguistic redundancies and is a very robust medium for communicating information. These redundancies explain why good speech recognition in cochlear-implant listeners is possible given a severe reduction in the spectral cues and the elimination of the temporal-fine-structure information of the speech signal provided by current cochlear implants. The results also suggest that "ideal" residual hearing (up to 1000 Hz) with no hearing loss and accompanying deficits, such as broadened auditory filters, can produce good speech intelligibility both in quiet and in noise because of the speech redundancies.

Discussion of results for cochlear-implant subjects.

Amount of acoustic information necessary for achieving EAS benefits

The results can be summarized as follow. Adding low-frequency acoustic information from the nonimplanted ear to electrically stimulated information led to an overall improvement in the speech-recognition performance for both CNC words in quiet and AzBio sentences in noise at +10 dB SNR. This improvement was observed

even when the acoustic input was low-pass filtered at 125 Hz, suggesting that the speech-perception benefits are primarily attributed to the voice-pitch information (even one harmonic) from the acoustic input. A further improvement in speech-recognition performance for sentences in noise was observed when the low-pass cutoff frequency increased from 250 Hz to 750 Hz, suggesting that part of the speech-perception benefits are likely due to the improved spectral representation of the first formant.

The results from Experiment 1 are consistent with those of studies using acoustic simulations of EAS, which showed that additional low-frequency information led to a significant improvement in speech-recognition performance in noise with a greater improvement observed for higher low-pass cutoff frequencies e.g., 600 Hz in Qin and Oxenham's study (2006) and 1000 Hz in Chang, Bai, and Zeng's study (2006). The findings from Experiment 1 also extend the previous results in the following ways. First, speech recognition in quiet can improve with the additional low-frequency information. Second, the improvement can be observed with a low-pass cutoff frequency as low as 125 Hz, containing only one harmonic ($F0$) of voice-pitch information. Third, the benefits from the low-frequency acoustic input hold in real listeners with combined contralateral EAS, who have "real" residual hearing with hearing loss and accompanying deficits, such as broadened auditory filters. These findings further support the approaches that attempt to combine either contralateral or ipsilateral acoustic stimulation with electric stimulation in cochlear-implant listeners with some residual hearing.

Frequency extent of residual hearing necessary for speech-perception benefits

Because there is large variability in the amount of residual hearing available across the population of cochlear-implant listeners, at issue in this experiment is to assess the amount of low-frequency acoustic information (or the frequency extent of residual hearing) necessary to achieve the speech-perception benefits both in quiet and in noise from combined contralateral EAS. The results from Experiment 1 suggest that the low-frequency acoustic information from the contralateral ear can provide significant speech-perception benefits both in quiet and in noise when that information is from an extremely limited frequency range (<125 Hz) and when auditory thresholds in that limited frequency range are elevated. The subjects who participated in Experiment 1 presumably have relatively good frequency resolution at 125 Hz given a mild degree of hearing loss (mean threshold = 31 dB HL) (e.g., Glasberg & Moore, 1986). Therefore, care should be taken when interpreting the current findings in terms of the potential benefits for cochlear-implant listeners who have less amount of residual acoustic hearing, e.g., severe-to-profound hearing loss at 125 Hz and above. It should be of interest to further investigate whether the speech-perception benefits from adding limited acoustic information (< 125 Hz) to electrically stimulated information would be achieved in patients who have less amount of residual acoustic hearing.

One concern about the frequency extent of residual hearing for the speech-perception benefits in the present experiment is that most of the speech stimuli (all the CNC word lists and half of the sentences of each AzBio sentence list) were recorded

by a male voice and the frequency extent may be overestimated due to the lower $F0$ of a male voice than that of a female voice. The average $F0$ of the male voice was 123 Hz for the CNC words and 131 Hz for the AzBio sentences. The average $F0$ of the female voice was 205 Hz for the AzBio sentences. Therefore, little acoustic information of the female-spoken sentences was left after the acoustic input was low-pass filtered at 125 Hz. However, the sentence recognition score in the A(125LP) + E(Wide band) condition was still significantly better than that in the E (Wide band) condition, indicating that subjects were able to benefit from the acoustic input in the region of the slope (90 dB/octive) of the low-pass filter as demonstrated by the presence of a substantial amount of energy around the $F0$ of the female voice in the FFT output for the 125LP condition in Figure 1. Overall, the results suggest that the limited acoustic input that contains only the $F0$, even a harmonic, of the voice pitch contributes significantly to the speech-perception benefits in listeners with combined contralateral EAS.

Role of acoustic input in improving performance

The present experiment demonstrated that although low-frequency acoustic hearing produced negligible or even no intelligibility for speech recognition, it significantly improved speech-recognition performance both in quiet and in noise when combined with electric hearing. Cochlear-implant subjects in the present experiment had residual hearing up to 1 kHz except for Subject 7 who had a severe degree hearing loss above 1 kHz. This frequency range contains the acoustic cues for speech perception distributing over time mostly in the time and amplitude domains. Rosen (1992) divides speech information in the time and amplitude domains into

envelope cues, periodicity cues, and temporal-fine-structure cues. A detailed discussion of the contribution of each of the acoustic cues to the speech-perception benefits when combined with electric hearing follows.

Envelope cues and periodicity cues. The envelope of the signal typically can help segment speech into word-sized and, in some instances, phoneme-sized units in the signal. As shown in Figure 6, a sample sentence spoken by a male voice from AzBio sentences at +10 dB SNR is low-pass filtered at 125 Hz, 250 Hz, 500 Hz, or 750Hz. Word units and even phoneme-sized units are clearly recognizable even when the speech stimuli are low-pass filtered at 125 Hz. Additionally, the envelope also provides information about "manner" of consonant articulation, that is, whether a sound is from the category stop consonant, nasal, semivowel, or fricative. As shown in Figure 7, /aba/, /ama/, /asa/ are low-pass filtered at 125 Hz, 250 Hz, 500 Hz, or 750 Hz. Relative to the surrounding vowels, voiced stop consonants (e.g., /b/) are characterized by periodic energy before a period of silence in the signal. Nasals (e.g. /m/) are characterized by periodic energy connected with the vowels before and after. Fricatives (e.g., /s/) are characterized by a period of silence in the signal. All the acoustic signatures above are clearly recognizable even when the stimuli are low-pass filtered at 125 Hz. Therefore, the differences in envelopes between classes of consonants from the low-frequency acoustic input are sufficiently large to allow subjects to "sort" speech phonemes into possible categories and provide information about the consonant "manner".
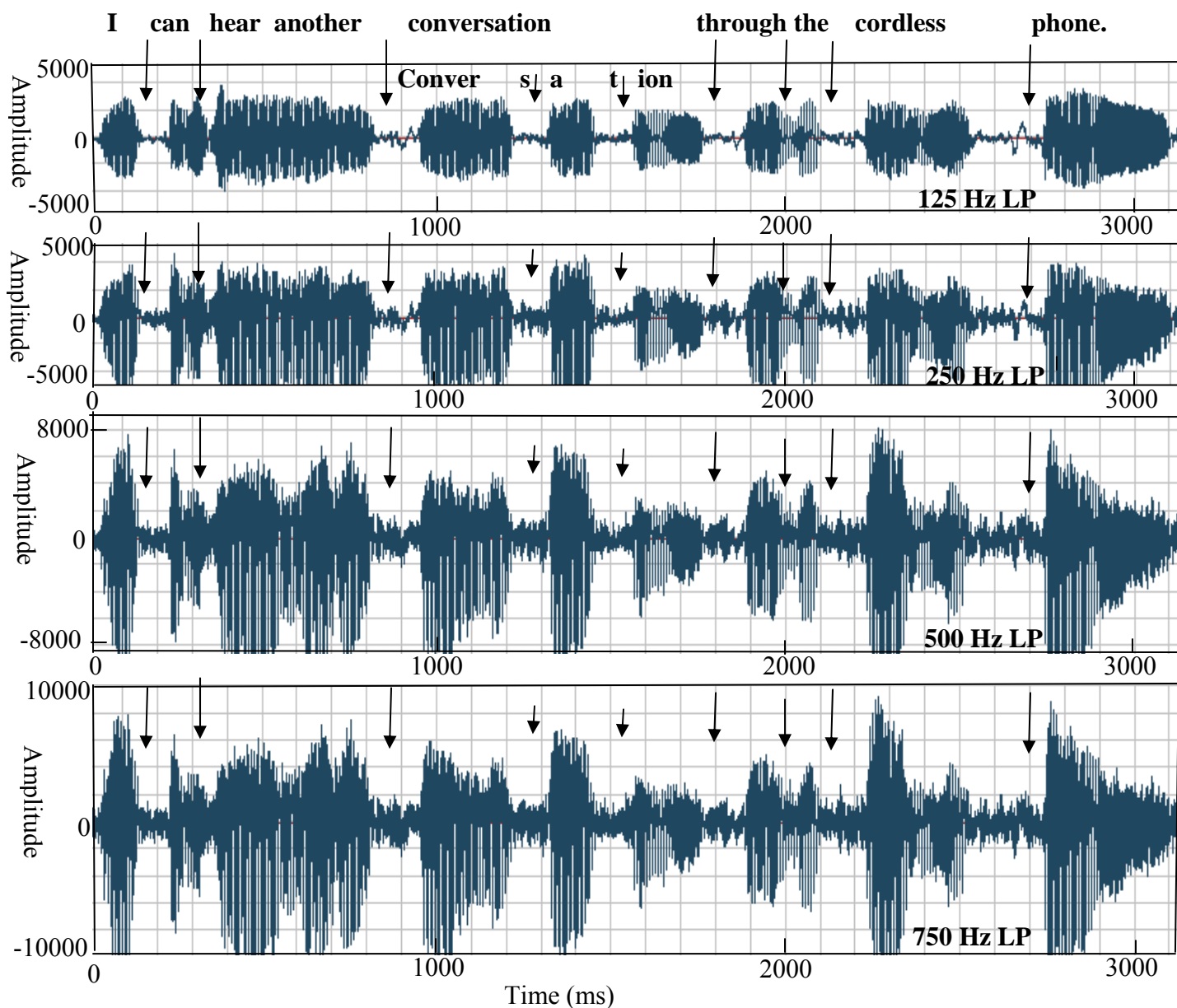
Figure 6. Time/amplitude display of "I hear another conversation through the cordless phone." low-passed filtered at 125 Hz, 250 Hz, 500 Hz or 750 Hz. Arrows indicate the location of word boundaries. For the word "Conversation", arrows indicate envelope-marked boundaries for the phonetic elements.
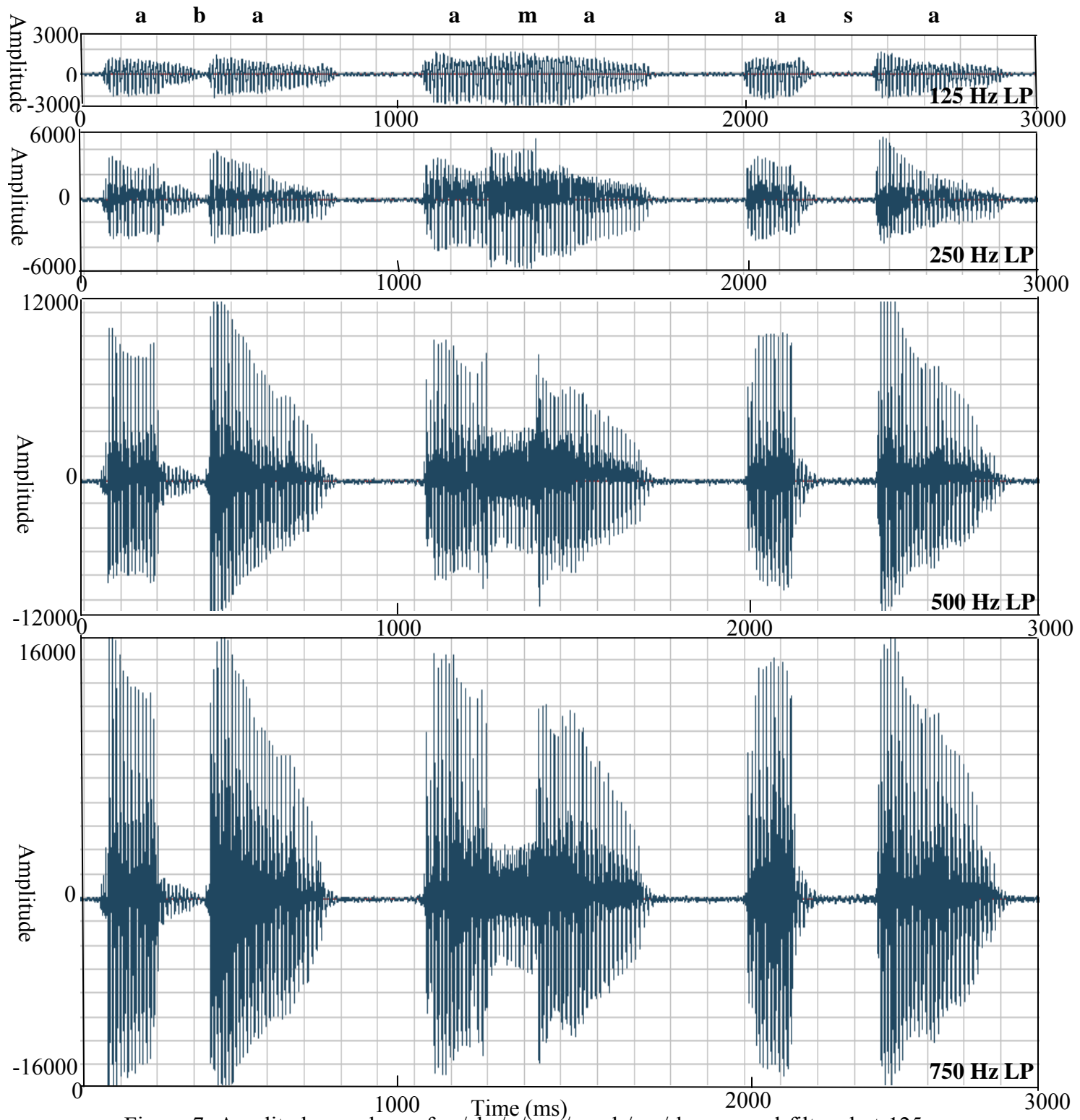
Figure 7. Amplitude envelopes for /aba/, /ama/, and /asa/ low-passed filtered at 125 Hz, 250 Hz, 500 Hz, or 750 Hz. The envelopes differ for each consonant category, providing information about the manner of consonant production, and the periodicity cues provide information about the voicing status of a consonant.

Periodicity cues provide information about the voicing status of a segment. As shown in Figure 7, voiced sounds (e.g., /b, m/) are periodic, whereas voiceless sounds (e.g., /s/) are characterized by a period of silence for the low-pass filtered stimuli. Therefore, the large differences in periodicity between the two classes of sounds from the low-frequency acoustic input also provide information about the consonant "voicing".

Although implants transmit envelope and periodicity cues with reasonable fidelity, scores for "voicing" and "manner" are far below asymptote for average cochlear-implant listeners. Spahr, Dorman, and Loiselle (2007) reported, for a sample of 39 patients with average and above scores on CNC words, that place was received with 59 percent accuracy, voicing with 73 percent accuracy and manner with 86 percent accuracy. Thus, there is ample room for the acoustic signal to enhance voicing and a little room to enhance manner. It appears as if the limited low-frequency acoustic hearing (<125 Hz) in the nonimplanted ear functions more like an additional "independent" channel, providing additional information about the consonant "manner" and "voicing", which are signaled by envelope and periodicity cues. A correct decision about consonant manner and voicing provides phonotactic constraints which can significantly narrow potential word candidates in a lexicon (e.g., Zue, 1985), leading to a substantial improvement in speech-recognition performance for both CNC words in quiet and AzBio sentences in noise.

Role of F0 representation in improving performance. As stated in the Introduction, voice-pitch information is poorly encoded by current implants due to the

fact that place–frequency cues are generally poor due to poor spectral resolution. The only pitch information available in the implants is from the temporal-pitch cues signaled in the temporal envelopes, which are only salient at lower frequencies (< 100-150 Hz). However, voice pitch is an important cue in the perceptual segregation of simultaneous and nonsimultaneous speech sources. Therefore, the pitch differences between the target and the masker in the temporal envelopes provided by the implants are not robust enough to reliably separate the target and the masker.

In Experiment 1, the recognition of sentences in noise benefited significantly from adding low-frequency acoustic information to electrically stimulated information even when the acoustic information was low-pass filtered at 125 Hz. With this level of acoustic input (residual acoustic hearing) which contains very little speech information (ANSI, 2004), the speech-perception benefits should be attributed mostly to the improvement in $F0$ representation alone. As shown in Figure 8, a portion of a vowel (/a/) is low-pass filtered at 125 Hz, 250 Hz, 500 Hz or 750 Hz. The acoustic realization of voice pitch is a series of high-amplitude components, or spikes, in the time/amplitude envelope and the $F0$ is clearly represented even when the acoustic input is low-pass filtered at 125 Hz. Better $F0$ information provided by the acoustic input aids the recognition of the target speech from the background noise by assisting the listener to "group" the various upper-frequency components of speech. Thus, it is reasonable to conclude that the additional low-frequency acoustic information (<125 Hz) improves the $F0$ representation and thus aids recognition of sentences in noise by improving speech segregation abilities of cochlear-implant listeners. This result is in line with those of EAS-simulation studies which showed
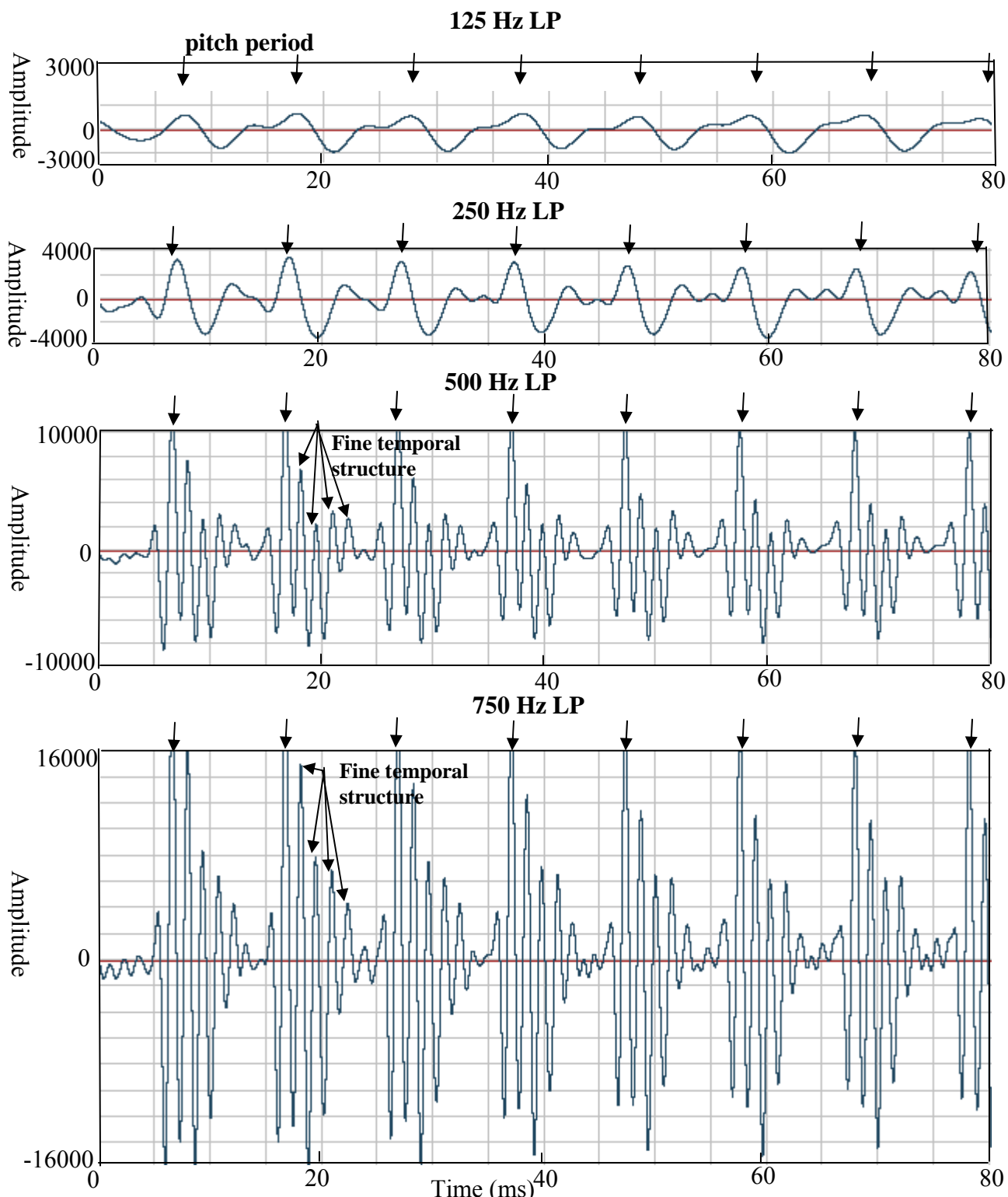
Figure 8. Envelope for a portion of a vowel low-passed filtered at 125 Hz, 250 Hz, 500 Hz, or 750 Hz. The interval between the arrows marks the pitch period. The temporal fluctuations within the pitch period in the 500-and 750-Hz conditions are the temporal fine structure cues.

that (i) the additional low-frequency information that contained only the *F*0 of the voicing significantly improved speech recognition performance in noise when combined with envelope-vocoder processed speech (Chang, Bai & Zeng, 2006; Qin & Oxenham, 2006), and (ii) an amplitude and/or frequency modulated sine wave at the frequency of the voice aided speech understanding in noise (Brown & Bacon, 2007).

Temporal-fine-structure cues. Temporal-fine-structure cues can provide information about the frequency of the first formant of the speech signal. As shown in Figure 8, the lower amplitude fluctuations (the temporal-fine-structure cues) between the large pitch "spikes" are clearly recognizable for a potion of a vowel (/a/) low-pass filtered at 500 Hz or 750 Hz. The interval between the lower amplitude fluctuations codes the frequency information of the first formant. Because the temporal fine structures are discarded in all current speech processing strategies due to the usage of a fixed-rate carrier, the temporal-fine-structure information is not well transmitted by electric stimulation. With the higher cutoff frequencies of 500 Hz and 750, part of the improvement in performance in the combined-EAS condition is likely due to the improved spectral representation of the first formant. This is suggested in the results of AzBio sentence recognition at 10 dB SNR by the fact that there was a significant improvement in sentence recognition performance when the acoustic input presented with the wide-band electric input was increased from 250 Hz to 500Hz and from 500 Hz to 750 Hz.

When speech in noise is transmitted electrically, the spectral representations of $F1$ and $F2$ are corrupted by noise. Even in quiet, $F1$ and $F2$ are not well specified by electrical stimulation due to the small number of functional channels of stimulation. Spahr, Dorman, and Loiselle (2007) report mean vowel scores ranging between 52 and 70% correct for a sample of patients with average and above levels of performance on CNC words. The same authors report a 59% transmission score for place of articulation – a feature specified, in large part, by the location and direction of change of $F2$ and $F3$. If formant location is minimally specified in quiet, and the location is further obscured by noise, then it is not surprising that a good representation of $F1$ from the acoustic signal can provide significant aid for EAS patients in noise. A good representation of $F1$ can aid in vowel recognition and can aid in the identification of consonant voicing (Liberman, Delattre & Cooper, 1958) and manner of articulation (e.g., Liberman et al. 1956). Again, a correct decision about consonant manner and voicing provides phonotactic constraints which can significantly narrow potential word candidates in a lexicon (e.g., Zue, 1985), leading to a substantial improvement in speech-recognition performance for AzBio sentences in noise.

Summary. When speech is presented both acoustically and electrically to patients who use an implant in one ear and who have low-frequency hearing in the other ear, information from the $F0$ of voicing is sufficient to provide a significant improvement in both word recognition in quiet and sentence recognition in noise. In addition, information from the first formant ($F1$) accounts for part of the improvement in sentence recognition in noise. A mechanism that is common to

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improvement both in quiet and in noise is proposed: The information in the acoustic signal aids in the recognition of consonant voicing and manner which leads to a large reduction of word candidates in the lexicon.

Frequency overlap on the speech-perception benefits

Another minor issue addressed in Experiment 1 was whether reducing the overlap in frequency representation in the input filters of the cochlear implant and in acoustic hearing would be beneficial to speech recognition for patients with a cochlear implant in one ear and low-frequency hearing in the contralateral ear. No significant benefit in reduced overlap was observed either at the group level or at the individual level. Thus, clinicians can use a standard cochlear implant programming with patients who have residual hearing on the ear contralateral to the implant.

The finding of no benefit from reduced overlap stems largely from the negative effect of high-pass filtering the electric signal. In the electric-stimulation condition (Figure 5), the scores for both CNC words and AzBio sentences in noise in the 500HP and 750HP conditions were significantly lower than that in the wide-band condition. This outcome documents a speech-recognition advantage for the full frequency range over the reduced frequency range of the electric signal. In other words, apical electrodes, which are effectively turned off by the action of the high-pass filtering, convey a significant amount of low-frequency information. This finding is consistent with the results of Wilson et al. (2002) who also showed a performance advantage for the widest overall analysis band for electric-only stimulation.

Row 1 of Tables 3 & 4 documents the EAS benefit observed when the electric signal high-pass filtered at 250 Hz is complemented by acoustic information below 250 Hz. High-pass filtering the electric signal at 250 Hz should be, and is, equivalent to presenting the wide-band electric signal because 250 Hz is about the low-frequency cut off of channel 1 in most cochlear implant signal processors. When acoustic information below 250 Hz is added to this signal, then speech-recognition performance improves significantly, demonstrating that the low-frequency acoustic signal below 250 Hz provides information that is (i) important for understanding, and (ii) not well represented in the electric signal.

Rows 2 & 3 of each table demonstrate the effect of transferring information above 250 Hz from electric hearing to acoustic hearing. As it should be expected, high-pass filtering the electric signal progressively degrades performance in the electric-stimulation condition. And, as it should be expected, opening up the low-pass filter allows incrementally better performance in the acoustic-stimulation condition. What is surprising is that the information loss in the electric-stimulation condition is offset by the information gain in the acoustic-stimulation condition. This suggests that, for the purposes of speech understanding, information between 250 Hz and 750 Hz is adequately represented in both the electric and acoustic case.

Finally, for electric and acoustic stimulation delivered to opposite ears, the large synergistic effects reported by others for electric and acoustic stimulation delivered to the same ear have been replicated in Experiment 1. For example, Gstoettner et al. (2004) reported a patient with a 6 % correct sentence score with a hearing aid, a 39 % correct score with a cochlear implant, and a 90 % correct score

Filter Settings		Speech Understanding Scores		
Electric Signal	**Acoustic Signal**	**E Only**	**A Only**	**EAS**
250 HP	250 LP	59%	.5%	80%
500 HP	500 LP	53%	6%	78%
750 HP	750 LP	44%	18%	83%
Wide band	Wide band	59%	45%	85%

Table 3. Scores for CNC words as a function of filter condition. LP = low pass. HP = high pass

Filter Settings		Speech Understanding Scores		
Electric Signal	**Acoustic Signal**	**E Only**	**A Only**	**EAS**
250 HP	250 LP	41%	0%	72%
500 HP	500 LP	26%	6%	76%
750 HP	750 LP	15%	22%	77%
Wide band	Wide band	41%	42%	86%

Table 4. Scores for AzBio sentences at +10 dB SNR as a function of filter condition. LP = low pass. HP = high pass.

when stimulation was from both the implant and hearing aid. As shown in Tables 3 and 4, similar synergy is found. Indeed, extreme cases of synergy in the 250 HP electric + 250 LP acoustic conditions are found. For CNC words, a mean score of 0% correct in the acoustic-stimulation condition combined with a mean score of 41% correct in the electric-stimulation condition produces a mean score of 72% correct in the combined-contralateral-EAS condition. For sentences in noise, a mean score of.5% correct in the acoustic-stimulation condition combined with a mean score of 59 % correct in the electric-stimulation condition produces a mean score of 80% correct in the combined-contralateral-EAS condition. Thus, acoustic signals that allow no speech intelligibility in isolation can provide large benefit to speech understanding when combined with electrical stimulation. Given this outcome clinicians should always aid the ear contralateral to an implant and assess speech intelligibility in the combined-contralateral-EAS condition.

Summary

A reduced frequency overlap between acoustic and electric stimulation is not beneficial for patients who use an implant in one ear and who have low-frequency hearing in the other ear, due to a speech-recognition advantage for the full frequency range over the reduced frequency range of the electric signal. For the purposes of speech understanding, information between 250 and 750 Hz is equally represented in both acoustic and electric stimulation. Although low-frequency acoustic information below 250 Hz, which isn't conveyed by implants, produces no speech-recognition intelligibility, it significantly improves cochlear-implant performance and accounts for the majority of the speech-perception benefits when combined with electric

stimulation. Therefore, clinicians should use a standard cochlear implant programming and always aid the ear contralateral to an implant for patients who have residual hearing on the ear contralateral to the implant.

Clinical relevance

The results from the present experiment have a significant clinical relevance in terms of determining how much residual hearing (i.e., different inherent "cutoff frequencies") is necessary to achieve the speech-perception benefits in listeners with combined contralateral EAS. This information helps estimate the potential benefits that listeners with different degrees of residual hearing in the nonimplanted ear will get after implantation. The results from the present experiment also provide insight to the potential benefits for listeners with combined ipsilateral EAS. To generalize the benefits of the acoustic input from combined contralateral EAS to combined ipsilateral EAS, it requires an assumption that the benefits of low-frequency acoustic stimulation of the contralateral ear should be equivalent to those of low-frequency acoustical stimulation of the same ear. However, both combined contralateral and ipsilateral EAS provide complementary information via a hearing aid (contralateral or ipsilateral to the implanted ear) and a cochlear implant, which should account for the major benefits of the acoustic input to combined EAS. Therefore, the present experiment also provides valuable information to estimate the potential benefits for listeners with combined ipsilateral EAS.

The results of the present study also provide an important guidance for cochlear implant candidates with different amounts of residual hearing when considering different options of implantation, e.g., unilateral implantation vs. bilateral

implantation; long electrode vs. partial-insertion implantation. As shown in the present experiment, even extremely limited acoustic input (< 125 Hz) provided substantial speech-perception benefits. Therefore, preserving residual hearing in the nonimplanted ear should be a better choice than taking a second implant with a traditional long electrode array, which may cause a complete loss of acoustic hearing after implantation. The residual hearing in the implanted ear should also be preserved as far as possible and, therefore, a partial-insertion implant should be a better choice than a long electrode implant if implant candidates meet the criteria for the partial-insertion implantation.

Conclusions

The overall pattern of results suggests that although low-frequency acoustic hearing (<125 Hz) produces no speech-recognition intelligibility, cochlear-implant listeners are able to benefit significantly from the limited residual hearing in improving speech-recognition performance both in quiet and in noise. It appears as if the limited low-frequency acoustic hearing in the nonimplanted ear functions as an additional "independent"channel, providing acoustic cues for speech perception distributing over time mostly in the time/amplitude envelope of the speech signal, which include envelope cues, periodicity cues and temporal-fine-structure cues. Envelope cues and periodicity cues are available for residual hearing down to 125 Hz, providing information about word- and phoneme-size units, "manner" and "voicing" of consonant articulation, and $F0$, which leads to a substantial improvement in speech-recognition performance for both CNC words in quiet and sentences in noise when combined with electrically stimulated information. Additional temporal-fine-

structure cues are also available for residual hearing up to 500- and 750-Hz, providing information of the first formant, which leads to a further improvement in speech-recognition performance for sentences in noise. A mechanism that is common to improvement both in quiet and in noise is proposed: The information in the acoustic signal aids in the recognition of consonant voicing and manner which leads to a large reduction of word candidates in the lexicon.

A reduced frequency overlap between acoustic and electric stimulation is not beneficial for patients who use an implant in one ear and who have low-frequency hearing in the other ear, due to a speech-recognition advantage for the full frequency range over the reduced frequency range of the electric signal.

Given the outcomes of significant speech-perception benefits from the limited acoustic input (<125 Hz) and no significant speech-perception benefits in the reduced frequency overlap between acoustic and electric stimulation, clinicians should always aid the ear contralateral to an implant and use a standard cochlear implant programming for patients who have residual hearing on the ear contralateral to the implant.

Chapter 3. Temporal Modulation Transfer Functions (TMTFs) in Listeners with

Combined Contralateral EAS

Introduction

As noted in Experiment 1, additional acoustic information can provide significant speech-perception benefits to listeners with combined contralateral EAS. In order to design improved speech processing strategies for combined contralateral EAS and to optimize these strategies for cochlear-implant listeners who meet the criteria of combined contralateral EAS, it is necessary to develop an understanding of the perceptual mechanisms of the benefits of the acoustic input to combined contralateral EAS. The following questions need to be addressed: (i) In which domains does the acoustic information add extra benefits, in the frequency domain, the amplitude/temporal domains (envelope cues), or both? (ii) Are the speech-perception benefits attributable to better temporal resolution and/or spectral resolution of residual acoustic hearing? The auditory psychophysical abilities of patients with combined contralateral EAS and the relation to their speech recognition abilities may provide insight to the perceptual mechanisms of the contribution of the acoustic input to electric hearing. Aim 2 of this dissertation research is to assess the differences among the psychophysical measures of low-frequency acoustic hearing, electric hearing, and combined EA hearing.

Literature review

Sound is defined in the intensity, temporal, and frequency domains. For a cochlear-implant listener to use his or her device successfully for speech perception,

environmental sound awareness, and/or music appreciation (if possible), a cochlear implant must encode each of the three domains of the sound. Although the electric stimulation of the auditory nerve can compensate to some degree for hearing sensation and frequency resolution of moderately-to-profoundly hearing-impaired listeners, current cochlear implants are still far from providing normal spectral resolution to cochlear-implant listeners due to the factors such as the problems of channel interaction and electrode-array placement that causes a frequency mismatch between the place of the electrodes and the characteristic frequency of the neurons at that location in an individual cochlear-implant listener (e.g., Shannon, Zeng & Wygonski, 1998; Skinner, Ketten, Holden, Harding, Smith, Gatges, Neely, Kletzker, Brunsde & Blocker, 2002). Therefore, the temporal-envelope cues, which are encoded in the amplitude and temporal domains, have been shown to be particularly important for transmitting speech information through cochlear implants (e.g., Van Tassel, Greenfield, Logeman & Nelson, 1992).

Temporal cues for speech perception

Temporal variations in amplitude over time occurring in different frequency bands are a common feature of many complex sounds such as speech. Rosen (1992) divided the time/amplitude waveform into three classes of cues that are important for speech perception. The major classes include the envelope cues, occurring at 2-50 Hz, the period or voice-pitch cues, occurring at 50-500 Hz, and the temporal-fine-structure cues, occurring at 600-10,000 Hz.

The low-frequency amplitude changes contained in the envelope of the speech signal convey information about consonant manner of articulation, consonant voicing, and vowel duration (Rosen, 1992). The envelope can also provide the most useful prosodic and segmental speech information in the signal (e.g., Drullman, Festern & Plomp, 1994a, b; Fu & Shannon, 2000).

Rosen (1992) also described speech contrasts appearing as higher rate modulations in the time and amplitude domains that represent voice-pitch cues. The voice-pitch cues appear as periodic oscillations in the time waveform at rates of 50 to 500 Hz. Because implanted electrodes do not typically stimulate cochlear regions below 1000 Hz and, therefore, provide limited voice-pitch cues, periodic temporal information (50-500 Hz) may be especially important for implant patients to derive pitch cues from the speech signal and contribute to perception of suprasegmental information, such as voice gender recognition (Fu, Chinchilla & Galvin, 2004) and tone recognition for tonal languages (e.g., Fu, Zeng, Shannon & Soli, 1998; Fu & Zeng, 2000).

The highest frequency component of the time-amplitude waveform is the temporal fine structure, which codes the frequency information of the first formant. According to Rosen (1992), listeners who can extract the temporal-fine-structure information (600 – 10,000 Hz) from the time-waveform are able to distinguish phonemes that share low-frequency voicing and manner characteristics, but differ spectrally. This level of resolution allows identification of vowels, classified by formant frequency relationships, and consonants that vary only by place of

articulation. Therefore, these temporal-fine-structure cues within each frequency band of a speech processor are also important for speech recognition in cochlear implant listeners (Wilson, Finley, Lawson, Wolford, Eddington & Rabinowitz, 1991).

All current processing strategies for cochlear implants divide the stimulus waveform into 6 to 22 frequency bands and extract the temporal envelope from each frequency band by full-wave rectification and low-pass filtering at a low frequency (<500 Hz). During this signal processing, the temporal-fine-structure information is removed from the stimulus waveforms and the envelope cues are preserved and used to modulate biphasic pulses. Therefore, current cochlear implants can only provide low-frequency envelope cues and limited periodicity cues. It is possible that residual hearing in the nonimplanted ear may provide additional periodicity cues (voice pitch) and temporal-fine-structure cues, which lead to a substantial improvement in speech-recognition performance in listeners with combined contralateral EAS. However, it is unknown (i) whether the perception of the temporal/amplitude variations in the nonimplanted ear is normal or close to normal so that residual acoustic hearing is capable of conveying the periodicity cues and the temporal-fine-structure cues of the input signal; and (ii) whether the temporal resolution of the hearing-impaired ear is better than that of the implanted ear. Therefore, it is important to first understand the temporal resolution abilities of hearing-impaired listeners and cochlear-implant listeners.

Temporal resolution in hearing-impaired listeners

Temporal resolution refers to the ability to detect amplitude changes over time and the resolution of the envelope of sound rather than the fine structure of sound (Moore, 1998). Gap detection and TMTF are two main methods to measure the temporal resolution.

Gap detection. In the task of gap detection, the duration of a gap in narrowband sounds (tones or bands of noise) is adjusted to find the point where it is just detectable. For normal-hearing listeners, the gap thresholds were generally constant, at 6-8 ms over a wide frequency range, except at very low frequencies (200 Hz and below) due to a smoothing effect produced by the auditory filters at very low frequencies (Shailer & Moore; 1987; Moore, Peters & Glasberg, 1993). Hearing-impaired listeners performed markedly worse in detecting gaps in narrowband stimuli than normal subjects when tested at the same SPLs, but only slightly worse at equal sensation levels (SLs) (Fitzgibbons & Wightman, 1982; Glasberg, Moore & Bacon, 1987; Nelson & Thomas, 1997).

Modulation detection. Gap detection experiments give a single number - the gap threshold - to describe the temporal resolution. A more general approach is to measure the threshold for detecting changes in the amplitude of a sound as a function of the rapidity of changes. The function relating the threshold amount of modulation to modulation frequency is known as a temporal modulation transfer function (TMTF: temporal modulation detection threshold (TMDT) as a function of modulation frequency). For normal-hearing subjects, the transfer functions have resembled a low-pass filter with a cutoff frequency of about 70 Hz, as detection

thresholds are relatively constant for modulation frequencies below about 70 Hz. Performance for this section is presumably determined mainly by the amplitude resolution of the auditory system. For modulation frequencies above about 70 Hz, the detection thresholds increase at a rate of 3-6 dB/oct (Bacon & Viemeister, 1985; Formby & Muir, 1988; Strickland & Viemeister, 1997). The decline is usually interpreted as a measure of the limited ability of the auditory system to follow rapid amplitude fluctuations. The shapes of TMTFs do not vary much with overall sound level, but the ability to detect the modulation does worsen at low SLs (Viemeister, 1979; Bacon & Viemeister, 1985; Formby, 1985).

Several studies measuring TMTFs for broad-band noise carriers (Lamoré, Verweiji & Brocaar, 1984; Bacon & Viemeister, 1985; Formby, 1986) showed that hearing-impaired subjects exhibited impaired temporal resolution as revealed by a decrease in sensitivity to amplitude modulation, often particularly for modulation frequencies above about 100 Hz. Poor sensitivity at higher modulation frequencies resulted in the TMTF with an abnormally steep high-frequency attenuation rate and the rates in hearing-impaired subjects could be more than twice of those in normal-hearing subjects (Bacon & Viemeister, 1985; Formby, 1987). In addition, the 3-dB cutoff frequencies of the TMTFs in many of hearing-impaired subjects were found to be lower than normal, indicating a longer time constant (Bacon & Viemeister, 1985; Formby, 1986). However, this may have been largely a consequence of the fact that high frequencies were inaudible to the hearing-impaired subjects (Bacon & Viwemeister, 1985). Bacon and Gleitman (1992) measured the TMTFs for broad-band noise using subjects with relatively flat hearing losses. They found that at equal

(high) SPLs performance was similar for hearing-impaired and normal-hearing subjects. At equal (low) SLs, hearing-impaired subjects tended to perform better than normal-hearing subjects.

TMTFs were also measured by using sinusoidal carriers (e.g., Strickland & Viemeister, 1997; Kohlrausch, Fassel & Dau 2000; Moore & Glasberg, 2001). Although the interpretation of the results is complicated by the fact that the modulation introduces spectral sidebands, which may be detected as separate components if they are sufficiently far in frequency from the carrier frequency (Seck & Moore, 1994; Kohlrausch et al., 2000), listeners with cochlear hearing loss have reduced frequency selectivity and, therefore, the temporal resolution can be measured with the sinusoidal carrier independently from the spectral resolution. The overall results from the previous studies suggest that the temporal resolution for deterministic stimuli is similar for both normal-hearing and hearing-impaired listeners (e.g., Moore & Glasberg, 2001).

To summarize the results above, hearing-impaired listeners often show reduced temporal resolution as a result of the low SL of the stimuli and/or the reduced audible bandwidth of the stimuli. When these factors are controlled, hearing-impaired listeners often perform as well as normal-hearing listeners.

Temporal resolution in cochlear-implant listeners

There have been a number of studies documenting the temporal resolution of cochlear-implant listeners with simple stimuli and reporting relatively normal temporal processing ability in cochlear-implant listeners.

Gap detection. Gap detection thresholds for postlingually-deafened implant patients, using high intensities, were 2-5 ms (Moore & Glasberg, 1988; Shannon, 1989). Thresholds for normal-hearing subjects using acoustic stimulation were 6-8 ms (Shailer & Moore; 1987; Moore, Peters & Glasberg, 1993). Thresholds increased when using stimuli at low SLs for both electric and acoustic stimulation. Gaps of 10-20 ms duration were often important in discriminating speech sounds and, therefore, cochlear-implant listeners should be as able to detect gaps of that duration as normal-hearing listeners (Dorman, 1993).

Modulation detection. TMTFs have been reported for electric stimulation in postlingually-deafened cochlear implant subjects. Shannon (1992) reported TMTFs for electric stimulation in postlingually-deafened adults that had some similarities to those obtained with acoustic stimulation in normal-hearing subjects. The shape of the transfer function resembled that of a low- or band-pass filter. The lowest thresholds were recorded at modulation frequencies of 80-100 Hz. Also, the attenuation rate of the transfer function for modulation frequencies above 100 Hz obtained with electric stimulation was steeper than that obtained with acoustic stimulation. Shannon (1992) observed that thresholds increased at lower SLs, whereas performance for normal-hearing subjects with acoustic stimulation was relatively unaffected by SL (Viemeister, 1979). Busby, Tong, and Clark (1993) measured amplitude modulation detection in cochlear implant subjects and indicated that their TMTFs often resembled a low-pass filter with a cutoff frequency of 50-150 Hz, which tended to be higher than that recorded for acoustic stimulation in normal-hearing subjects. Cazals, Pelizzone, Saudan, and Boex, (1993) compared amplitude modulation detection and

phonetic recognition in nine cochlear implant subjects who demonstrated open-set speech understanding ranging from excellent to poor. TMTFs showed clear low-pass filtering characteristics up to 100 Hz for subjects with better speech understanding, whereas little or no such characteristics were observed in subjects with poorer speech intelligibility.

While acoustic TMTFs are relatively homogeneous across normal-hearing listeners, there can be great variability in the shape and the overall modulation sensitivity of the TMTFs across cochlear-implant listeners. For instance, Shannon (1992) reported some cases where the transfer function resembled a band-pass filter with cutoff frequencies of 80 and 140 Hz. Busby et al. (1993) reported flat transfer functions for one of four postlingually-deafened subjects tested, as the very low detection thresholds did not vary over the range of modulation frequencies tested: 4-250 Hz. Transfer functions which did not markedly vary across modulation frequencies were also recorded by Cazals et al. (1994) although these were primarily found in cases where the detection thresholds were considerably elevated. In addition, Busby et al. (1993) recorded transfer functions which resembled an additional low-pass filter with a cutoff frequency of 4-5 Hz in two prelingually-deafened subjects. For the third prelingually-deafened subject, the transfer function resembled a filter with two pass bands at 4-5 and 100-125 Hz.

Many studies have also evaluated the relationship between cochlear-implant listeners' modulation sensitivity and speech performance (Cazals et al., 1994; Fu 2002). Cazals et al. (1994) found a moderate correlation between the phoneme recognition and the depth of high frequency rejection in the TMTFs of nine

postlingually-deafened Ineraid users. Fu (2002) showed a highly significant correlation between the modulation sensitivity and phoneme recognition. These results suggest that differences in speech recognition abilities of cochlear-implant listeners may be partly caused by differences in temporal processing capabilities.

To summarize the results above, cochlear-implant listeners have relatively normal temporal processing ability measured by gap detection. TMTFs for electric stimulation are similar to those obtained with acoustic stimulation in normal-hearing subjects but there can be great variability in the shape and the overall modulation sensitivity of the TMTFs across cochlear-implant listeners. Moderate to high relationships have been reported between temporal modulation sensitivity and speech-recognition performance in cochlear-implant listeners. Overall, the pattern of results on temporal resolution indicates that implant listeners can detect and discriminate temporal changes about the same as acoustic listeners.

Rationale

As noted in Experiment 1, additional acoustic information can provide significant speech-perception benefits to listeners with combined contralateral EAS. The temporal/amplitude resolution of low-frequency acoustic hearing in the nonimplanted ear may be better than that of electric hearing, which may account for the speech-perception benefits in listeners with combined contralateral EAS. Psychophysical measurements of TMTFs in the acoustic-stimulation, the electric-stimulation, and the combined-contralateral-EAS conditions would allow direct comparisons of the temporal/amplitude resolution among three stimulation conditions to test whether the temporal/amplitude resolution of the hearing-impaired ear is better

than that of the implanted ear. In addition, a comparison of the temporal/amplitude resolution between cochlear-implant subjects and normal-hearing subjects would answer the question of whether the temporal/amplitude resolution in three stimulation conditions is normal or close to normal. Furthermore, considerable individual variability of the speech-perception benefits both in quiet and in noise appears in many of the reported studies, revealing large differences in using additional acoustic information to help identify speech sounds in listeners with combined EAS. Therefore, an explanation of individual differences of the speech-perception benefits should include variations of basic psychophysical sensitivities to the temporal/amplitude modulations. Assessments of the correlation of the speech-recognition performance and the TMDT would provide insight to the relation of the speech-perception benefits with the temporal/amplitude resolution in three stimulation conditions.

Hypotheses

The operating hypothesis of this experiment was that the mechanism contributing to the speech-perception benefits in listeners with combined contralateral EAS would not be due to the improved temporal/amplitude representation of the input signal provided by residual acoustic hearing.

Summary and predictions based on literature review

Current cochlear implants can only provide coarse spectral resolution to cochlear-implant listeners. The temporal envelope cues, which are encoded in the amplitude and temporal domains, are particularly important for transmitting speech

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information through cochlear implants. Speech information in the amplitude and temporal domains can be divided into three classes for speech perception: envelope cues, periodicity cues or voice-pitch cues, and temporal-fine-structure cues. Current cochlear implants preserve the low-frequency envelope cues and remove the temporal-fine-structure cues in the stimulus waveforms. Residual hearing in the nonimplanted ear may have better temporal resolution than electric hearing in the implanted ear, which accounts for the speech-perception benefits in listeners with combined contralateral EAS. However, studies have shown that cochlear-implant and hearing-impaired listeners have relatively normal temporal processing abilities measured by gap detection and TMTF. Therefore, it is been expected that the mechanism contributing to the speech-perception benefits in listeners with combined contralateral EAS is not due to the improved temporal/amplitude representation of the input speech signal provided by residual acoustic hearing.

Methods

Experimental design

Experiment 2 used a within-subject design with stimulation mode (acoustic-stimulation alone, electric-stimulation alone, and combined contralateral EAS) and modulation frequency (16 Hz, 32 Hz, and 64 Hz) as independent variables, and TMDT as a dependent variable. A repeated-measures ANOVA was applied to the data and the effects of the stimulation mode and the modulation frequency on the TMDT were evaluated and analyzed. Speech recognition scores of CNC words in quiet and AzBio sentences in noise at +10 dB SNR from Experiment 1 with a wide-band input were used to correlate with the mean TMDTs. The results provided us

insight to the underlying mechanisms of the contribution of the acoustic input to combined contralateral EAS (Aim 2).

Subjects

All cochlear-implant subjects except for S8 who participated in Experiment 1 were recruited in the present experiment. S8 had a partial-insertion implant and the lower cutoff of the frequency range for his speech processor was set at 750 Hz so that the electrically stimulated information did not interfere with the acoustically stimulated information in the same ear. Therefore, S8 was not able to hear the 500 Hz carrier with his implant and did not allow a direct comparison of TMTFs between electric and acoustic hearing.

Ten normal-hearing subjects participated in the present experiment and they ranged in age from 20-53 years (mean age=28.8 yrs; st. dev. = 10.7 yrs). All subjects had normal audiometric thresholds $\leq$ 15 dB HL for octave test frequencies from 250 to 8000 Hz (ANSI, 1997).

All subjects provided written informed consent for their participation in the present experiment. The research protocol and informed consent statement were approved by the Institutional Review Board at the University of Maryland, College Park and Arizona State University. Subjects were paid an hourly wage for their participation.

Cochlear Implants

The electric input of stimuli was presented through a direct input cable to each subject's speech processor. Subjects were tested with their 'everyday' device settings

and each subject's cochlear implant was checked before modulation detection was evaluated at each test session. The volumes and sensitivity settings of the cochlear implant were not adjusted in order to maintain the same settings on the cochlear implant for both the combined-contralateral-EAS and electric-stimulation conditions.

Stimuli

Stimuli generation. Stimuli were generated using a Tucker-Davis Technologies (TDT II) system with a 16-bit digital-to-analog converter (DD1, 50-kHz sampling rate), attenuated (TDT PA4), passed through a headphone buffer (TDT HB6), and delivered to a double-walled sound attenuating booth. The time signal of a sinusoidally amplitude-modulated sinusoid was defined as follows:

$$s(t) = A(1 + m\cos(2\pi f_m t))\sin(2\pi f_c t). \qquad (1)$$

A indicates the overall amplitude, *m* is the degree of modulation taking values between 0 and 1, and f_m and f_c are the carrier frequency and the modulation frequency, respectively. The carrier frequency was 500 Hz. The modulation frequencies were 16, 32, and 64 Hz. Modulation detection thresholds indicated the just noticeable value of *m* [often expressed as 20 log(*m*)]. The spectrum of such a stimulus consisted of three components: the carrier frequency and the two sidebands which were spectrally separated from the carrier by the modulation frequency. The level of the sidebands relative to the carrier level can be derived by subtracting 6 dB from 20 log(*m*). Thus, for 100% amplitude modulation (20 log(*m*) = 0 dB), the sideband level is 6 dB lower than the carrier level. Each carrier burst lasted 540 ms,

including 20 ms raised-cosine rise/fall ramps. The interval between bursts within a trial was 500 ms. The overall level of the modulated and unmodulated stimuli was the same, regardless of modulation depth. The depth of the modulation—based on the modulation index, m— was varied adaptively. The modulated waveforms were attenuated by a factor of $(1+m^2/2)^{1/2}$ to ensure that the average level of each observation interval was equal.

Selection of carrier. A 500-Hz sinusoidal carrier instead of a noise carrier was used in the present experiment for the following reasons. The modulation of the sinusoidal carrier introduces two spectral sidebands with a spectral distance from the carrier that equals the modulation frequency. Therefore, it is impossible to control which detection cues are used by the subjects in discriminating a modulated sinusoid from an unmodulated sinusoid, especially at high modulation rates where sidebands are sufficiently far in frequency from the carrier frequency and become audible as separate tones (Kohlrausch, Fassel & Dau, 2000). Because of this disadvantage of sinusoidal carriers, a vast majority of studies measuring TMTFs have used noise carriers. However, a disadvantage of the noise carrier is that noise is a stochastic carrier that has intrinsic modulations, which may function as a masker in the task of modulation detection of a modulated noise from an unmodulated noise and limit the listener's ability of detecting the imposed modulation. These intrinsic fluctuations become particularly relevant for narrow-band-noise carriers (Dau, Kollmeier & Kohlrausch, 1997a, b; Dau, Verhey & Kohlrausch, 1999). Then, TMTFs obtained by using sinusoidal carriers provide a better measure of the inherent temporal resolution of the auditory system than by using noise carriers, provided that the modulation

frequency is within the range where spectral resolution does not play a major role. A look into the literature reveals that both carrier types reveal basically the same temporal processing, which is usually described by an initial flat portion up to around 50-60 Hz for broadband noise (Viemeister, 1979; Bacon & Viemeister, 1985; Formby, 1986) and around 100-130 Hz for sinusoid (Zwicker, 1952; Sek, 1994; Srickland & Viemeister, 1997; Yost & Sheft, 1997).

Because subjects with combined contralateral EAS have limited residual acoustic hearing ($\leq$ 60 dB HL up to 500 Hz), a 500-Hz sinusoidal carrier instead of a 1000-Hz sinusoidal carrier was used to ensure the audibility of the test stimuli presented to the nonimplanted ear. In addition, for the carrier frequency of 500 Hz, the equivalent rectangular bandwidth (ERB) of the auditory filter is about 80 Hz (Glasberg & Moore, 1990) and the "edge" components in complex tones need to be separated by more than about 0.75 ERB (60 Hz for the carrier frequency of 500 Hz) from neighboring components to be "heard out" as separate tones, even when all components have equal amplitude (Moore & Ohgushi, 1993). As mentioned above, the sideband level of the 500 Hz carrier is 6 dB lower than the carrier level for 100% amplitude modulation and even lower for less amplitude modulation. Thus, the effects of resolution of sidebands are likely to be small for modulation frequencies up to 64 Hz for the carrier frequency of 500 Hz. Several studies on modulation detection for sinusoidal carriers showed that modulation thresholds stayed much more constant at rates between 8 and 64 Hz for sinusoidal carrier frequencies above 1 kHz in both normal-hearing and hearing-impaired listeners (Sek, 1994; Stricklang & Viemeister, 1997; Yost & Sheft, 1997; Kohlrausch, Fassel & Dau, 2000; Moore & Glasberg,

2001). Therefore, the temporal resolution can be measured by TMTFs with the 500-Hz sinusoidal carrier and modulation frequencies up to 64 Hz independently from the spectral resolution both for acoustic hearing and electric hearing in the present experiment.

Presentation level. In the acoustic-stimulation condition, the stimuli were presented to the nonimplanted ear through an insert earphone (Etymotic ER-1). The presentation level was set at 30 dB SL (re: threshold at 500 Hz) on an individual basis for each subject. The mean threshold at 500 Hz for the subjects was 53 dB HL (S. D. = 9 dB). Therefore, the stimuli were presented at 70-90 dB SPL. The use of 30 dB SL presentation level of stimuli was to ensure the stimuli were presented at each subject's most comfortable level. The reason was that many of the previous studies (e.g., Busby et al., 1993; Cazals et al., 1993) showed that modulation detection by hearing-impaired listeners was much more sensitive to stimulation level as revealed by decreased absolute modulation sensitivity at lower SLs when compared to normal-hearing listeners (Shannon, 1992).

In the electric-stimulation condition, the stimuli were presented to each subject' speech processor via a direct cable. This was to defeat the headset microphone so that no external input occurred, while at the same time preserving the microphone pre-emphasis. The presentation level of the electric input was set at the same loudness level as the acoustic input on an individual basis for each subject to ensure the stimuli presented at each subject's most comfortable level. A loudness matching method was used to find the presentation level of the electric stimuli with

the same overall loudness as the acoustic stimuli presented at 30 dB SL. The subject was instructed to listen to the acoustic stimuli first with the insert earphone alone and remember the loudness, then listen to the electric stimuli with implant alone, and indicate on a response card whether the stimuli were louder or softer than those in the nonimplanted ear. The response card was a continuous scale, labeled with "louder" and "softer" at the end points and "the same" halfway in between. The experimenter adjusted the presentation level of the electric stimuli until they were rated to sound equally loud to the acoustic stimuli presented at 30 dB SL.

In the combined-contralateral-EAS condition, the stimuli were output via an audio splitter connector with one end connected to an insert earphone (Etymotic ER-1) and the other one connected to each subject's speech processor via a direct input cable. The presentation level of the acoustic stimuli was set at 30 dB SL. The level of the electric stimuli that sounded equally loud to the acoustic stimuli was used to facilitate the perceptual fusion of the acoustic input and the electric input. The volume and sensitivity settings of the cochlear implant were not adjusted in order to maintain the same settings on the cochlear implant for both the electric-stimulation and the combined-contralateral-EAS conditions.

Normal-hearing subjects were tested by using a level of 80 dB SPL, which was in a similar range to those for cochlear-implant subjects tested at 30 dB SL, i.e., 70-90 dB SPL. This level was chosen because Moore and Glasberg (2001) showed that for low modulation frequencies, the TMDTs obtained at low SLs (e.g., 15-30 dB SL) with a 1000-Hz carrier in hearing-impaired subjects were similar to those obtained at high carrier levels (e.g., 80 dB SPL) in normal-hearing subjects. Other

research measured TMTFs for broadband or narrowband noise also showed that performance was similar for hearing-impaired and normal-hearing subjects at equal (high) SPLs (Bacon & Gleitman, 1992; Moore, Shailer & Schooneveldt, 1992). Therefore, presenting the stimuli to cochlear-implant and normal-hearing subjects at equal (high) SPL instead of equal SL allowed a reasonable comparison of TMTFs between two groups of subjects.

Procedure

The measurements included the assessment of TMDT as a function of the modulation frequency in three listening conditions: acoustic stimulation alone, electric stimulation alone, and combined EAS. All subjects were tested in a double-walled sound treated room. Prior to actual psychophysical testing, training was provided for the TMTF measurements.

The TMDTs (dB) were estimated using a three-interval-forced-choice (3IFC) paradigm. Two intervals contained the standard (reference) stimulus, while the other interval, chosen at random, contained the comparison (test) stimulus. The comparison was always a modulated signal of variable modulation depth, while the reference was unmodulated. Three buttons were displayed on a subject response pad, corresponding to three intervals. A colored light was turned on and off above each button when presenting the stimuli. Subjects were instructed to press the button corresponding to the interval that sounded "different" (i.e., that contained the test stimulus), ignoring any loudness variation between intervals. Feedback was given after each trial by a flashing colored light above the button corresponding to the correct interval. Each run

began with the comparison clearly different from the reference with a 100% modulation depth (m =1 in the above formula), and the modulation depth was varied in a three-down, one-up procedure. The modulation depth of the comparison was reduced after three correct responses and increased after one incorrect response. This converged on the modulation depth that produced 79.4% correct responses (Levitt, 1971). A starting level of 100% modulation depth was used with a decreasing step of 5 dB for the first two reversals and the step size was reduced to 2 dB at the third and fourth reversals and remained fixed at 1 dB thereafter. Each run ended after 10 reversals and took about 5-6 minutes to complete. All threshold estimates were based on the average of even number of the last six reversals. For each subject measures were repeated two to four times at each selected modulation frequency to check reproducibility and the average was taken as a final measure.

Results

Temporal modulation detection

Figure 9 shows the mean TMDTs expressed as 20 log *m* (*m*: the modulation index at threshold) and +1 standard deviation, in dB, as a function of modulation frequency and as a function of stimulation condition. The mean TMDTs as a function of the modulation frequency for ten normal-hearing subjects are also shown in the figure with black bars. A repeated-measures ANOVA was performed on the raw data for the TMDTs with two within-subjects factors (the modulation frequency with four levels and the stimulation condition with three levels). The analysis revealed no significant main effects for the modulation frequency ($F_{(2,14)} = 0.6$, $p > 0.05$) and the

TMTFs
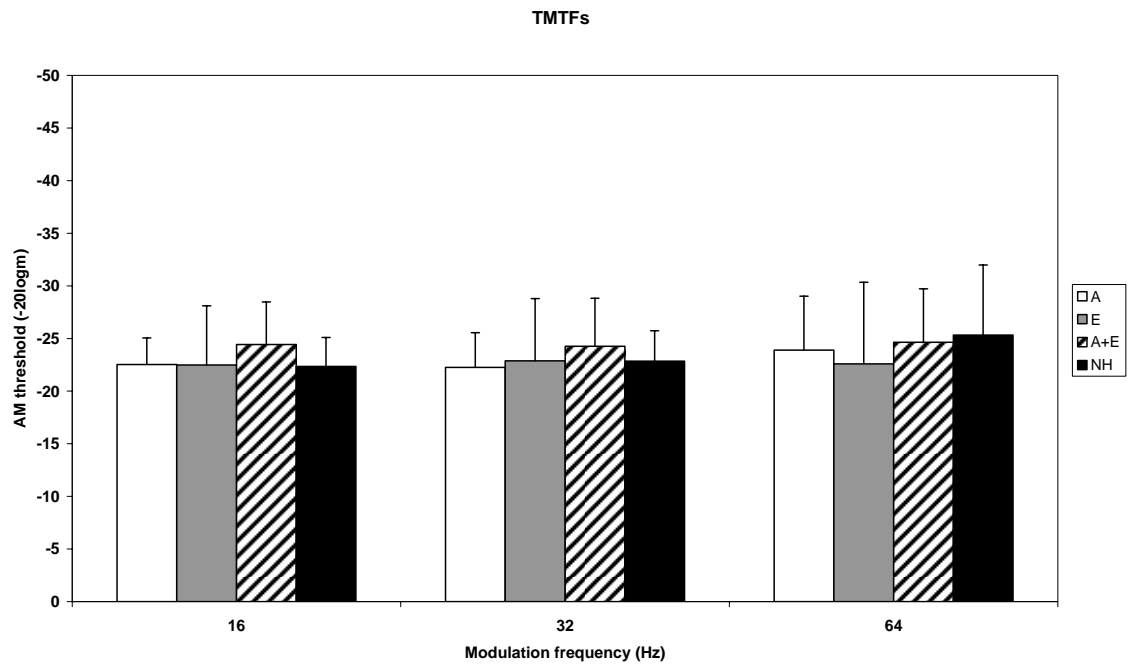
Figure 9. Group mean temporal modulation detection thresholds (TMDTs) as a function of modulation frequency (16 Hz, 32 Hz, and 64 Hz) for eight cochlear-implant subjects with combined contralateral EAS. TMDTs of ten normal-hearing subjects as a function of modulation frequency are shown with black bars. Error bars indicate +1 standard deviation.

stimulation condition ($F_{(2, 14)}$ =1.9, $p > 0.05$), and no significant interaction ($F_{(4,28)}$ = 1.2, $p > 0.05$).

To further investigate the difference of the temporal resolution between cochlear- implant subjects and normal-hearing subjects, the TMDTs in three stimulation conditions in eight cochlear-implant subjects were compared separately with the TMDTs in ten normal-hearing subjects. A repeated-measures ANOVA was conducted with a within-subject factor (modulation frequency with four levels) and a between-subject factor (subject group with two levels).

In the acoustic-stimulation condition, a repeated-measures ANOVA analysis revealed no significant main effects for modulation frequency ($F_{(2,32)}$ = 3.1, $p > 0.05$) and for subject group ($F_{(1, 16)}$ = 0.1, $p > 0.05$), and no significant interaction ($F_{(2,32)}$ = 0.3, $p > 0.05$).

In the electric-stimulation condition, a repeated-measures ANOVA analysis revealed no significant main effects for modulation frequency ($F_{(2,32)}$ = 1.5, $p > 0.05$) and for subject group ($F_{(1, 16)}$ = 0.1, $p > 0.05$), and no significant interaction ($F_{(2,32)}$ = 1.6, $p > 0.05$).

In the combined-contralateral-EAS condition, a repeated-measures ANOVA analysis revealed no significant main effects for modulation frequency ($F_{(2,32)}$ = 2.2, $p > 0.05$) and for subject group ($F_{(1, 16)}$ = 0.4, $p > 0.05$), and no significant interaction ($F_{(2,32)}$ = 1.4, $p > 0.05$).

Correlation

The mean TMDTs calculated across the modulation frequencies (16, 32 and 64 Hz) were used to correlate with the speech recognition scores. Relations between

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the mean TMDTs and the speech recognition scores of CNC words in quiet and AzBio sentences in noise at +10 dB SNR in three stimulation conditions with a wide-band input were assessed separately with a Pearson's correlation coefficient. Figure 10 displays the percentage correct for CNC word (left column) and AzBio sentence (right column) recognition as a function of the mean TMDT for the eight cochlear-implant subjects. The lines show the linear regression between the word/sentence recognition scores and the mean TMDTs in three stimulation conditions. Statistical analysis revealed no significant correlations between with temporal modulation sensitivity and speech recognition performance in all three stimulation conditions ($p >$ 0.05).

Discussion

Temporal modulation detection

The overall pattern of results suggests that the temporal/amplitude resolution of acoustic hearing, electric hearing, and combined electric and acoustic hearing is essentially normal in subjects with combined contralateral EAS. The speech-perception benefits observed in listeners with combined contralateral EAS are attributable to the normal temporal/amplitude resolution of residual acoustic hearing.

The TMDTs did not depend systematically on the modulation frequencies from 16 Hz to 64 Hz for all three stimulation conditions in cochlear-implant subjects and for the normal control condition in normal-hearing subjects. Unsystematic variations of the TMDTs were not greater than 2-3 dB at each individual modulation frequency. The TMDTs at modulation frequencies up to 64 Hz for three stimulation
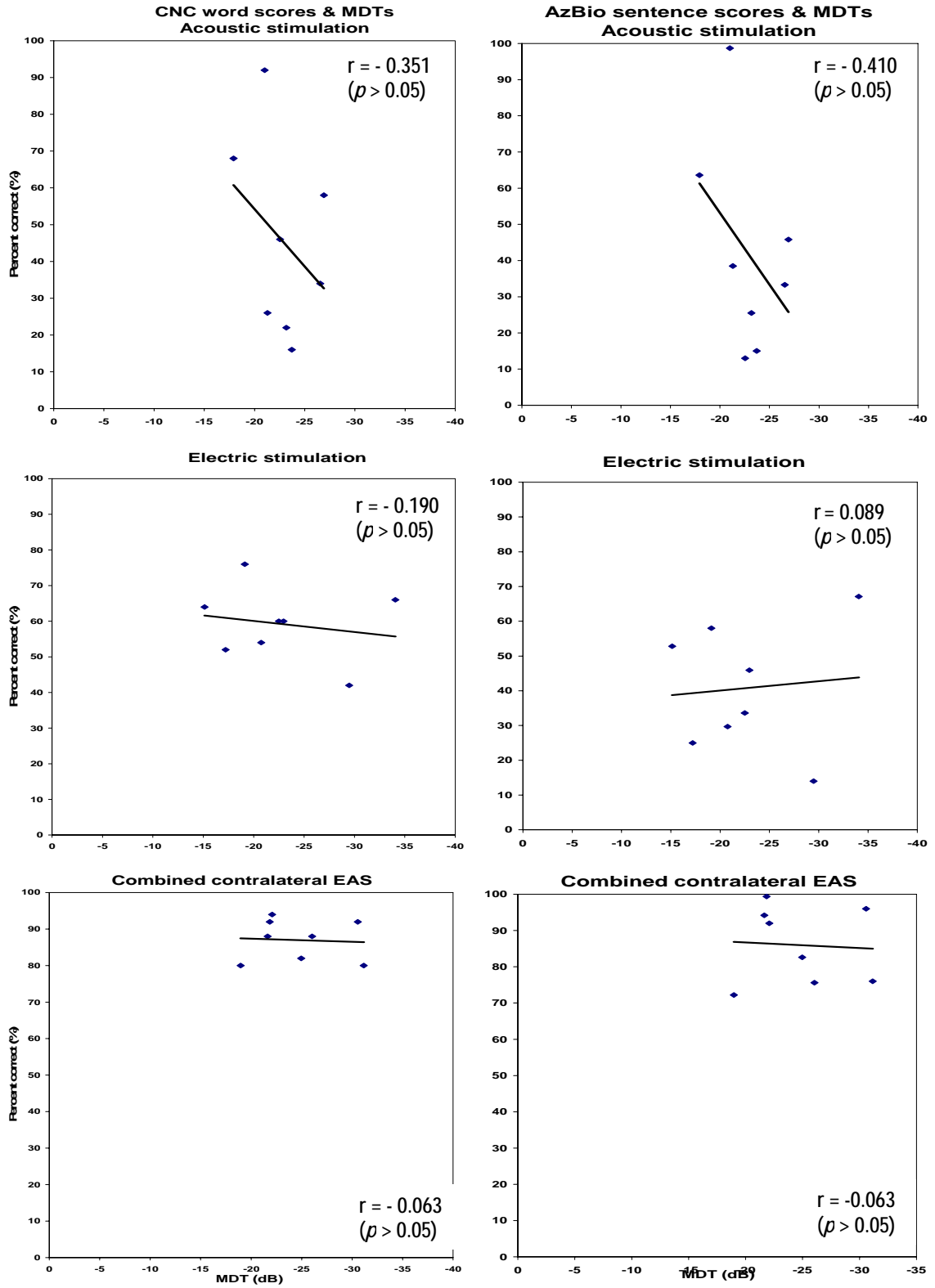
Figure 10. displays the correlation of CNC word (left column) and AzBio sentence (right column) scores with the mean TMDTs across the modulation frequencies of 16 Hz, 32 Hz, and 64 Hz.

conditions in cochlear-implant subjects were not significantly different from those in normal-hearing subjects. The general results above were similar to those previously reported for acoustic stimulation in normal-hearing and hearing-impaired listeners, and for electric stimulation in cochlear-implant listeners. For example, several studies on modulation detection for sinusoidal carriers showed that modulation thresholds stayed much more constant at frequencies between 8 and 64 Hz for sinusoidal carrier frequencies above 1 kHz in both normal-hearing and hearing-impaired listeners (Sek, 1994; Stricklang & Viemeister, 1997; Yost & Sheft, 1997; Kohlrausch, Fassel & Dau, 2000; Moore & Glasberg, 2001). Other studies also showed that implanted subjects were most sensitive to modulations of sinusoidal current up to 50-100 Hz (Shannon, 1992, Busby, Tong & Clark, 1993).

Age effect on the measurement of TMTFs. Although the mean TMDTs for three stimulation conditions in cochlear-implant subjects were not significantly different from those in normal-hearing subjects, there is a concern about a possible age effect on the measures of temporal resolution when considering the age difference between cochlear-implant (mean age = 66 yrs; st. dev. = 10.3 yrs) and normal-hearing groups (mean age = 28.8 yrs; st. dev. = 10.7 yrs).

A number of studies examining the age effect on measures of temporal resolution have shown that older listeners with normal or near-normal hearing demonstrate impaired temporal resolution as evidenced by elevated TMDTs (Takahashi & Bacon, 1992), longer modulation transfer function time constants (Bacon & Gleitman, 1992; Takahashi & Bacon, 1992), elevated gap detection thresholds (Moore, Peters & Glasberg, 1992; Schneider, Pichora-Fuller, Kowalchuk

& Lamb 1994; Snell, 1997; Schneider & Hamstra, 1999; Snell & Frisina, 2000), and poorer temporal discrimination performance in complex stimulus conditions (e.g., tonal duration discrimination, gap duration discrimination, and discrimination of temporal order) (Fitzgibbons & Gordon-Salant, 1995, 1998, 2001; Gordon-Salant & Fitzgibbons, 1999). Therefore, cochlear-implant subjects in the present experiment would have shown elevated TMDTs and a group difference of the mean TMDTs between cochlear-implant subjects and normal-hearing subjects would have been significant if the age effect had played a role in the measures of TMTFs. However, the between-group difference was not observed in the present experiment. In fact, the elevated TMDTs in the study of Takahashi and Bacon (1992) were likely due to the audibility issue in their older subjects. They found that once they factored out the potential influences of reduced audibility, there were no significant age effects. Other studies comparing gap detection performance for older and younger listeners with normal hearing also found little or no difference between the age groups (He, Horwitz, Dubno & Mills 1999; Bertoli, Smurzynski & Probst, 2002). Thus, it is possible that an age-related impairment in temporal resolution, completely independent of hearing, is observed for only those more complex temporal tasks (tasks involving discrimination) in which the auditory system is taxed more heavily than in the more traditional measures of temporal resolution (tasks involving detection). Therefore, it is reasonable to conclude that the possible age effect on the direct comparison of temporal resolution between cochlear-implant subjects and normal-hearing subjects is negligible in the present experiment.

Summary. In summary, the data were in solid statistical agreement for modulation frequencies between 16 Hz and 64 Hz, indicating that the temporal/amplitude resolution for the three stimulation conditions in cochlear-implant subjects is similar to that in normal-hearing subjects.

Correlation

In the present experiment, the correlations between speech recognition and absolute temporal modulation sensitivity in cochlear-implant subjects did not reach statistical significance in all three stimulation conditions for both CNC words in quiet and AzBio sentences in a competing babble at 10 dB SNR, suggesting that temporal modulation detection is not a strong predictor of speech recognition for acoustic, electric, and combined electric and contralateral acoustic hearing.

The electric-stimulation condition. Although there was substantial inter-subject variability in both cochlear-implant subjects' modulation detection sensitivity (-34 dB - -15 dB) and speech-recognition performance (42% - 76% for CNC words, 14% - 67% for AzBio sentences) in the electric-stimulation condition, the relation between the two measures did not reach a statistical significance. The lack of the significance in the present experiment differed from the results of several studies showing significant correlations between these two measures in cochlear-implant listeners (Cazals et al., 1994; Fu, 2002). Two factors may be responsible for the lack of the significant correlation found in the present experiment. One possibility was that different methods were used to calculate the correlation between temporal modulation sensitivity and speech recognition in the previous studies and in the present experiment. In the previous studies, the speech recognition performance was

moderately correlated with the rejection factor of the modulation transfer function, calculated as the difference between TMDTs at 71 and 400 Hz for the transfer function at a medium loudness level (Cazal et al., 1994) and was highly correlated with the mean TMDT at a sinusoidal modulation frequency of 100 Hz, calculated over each subject's entire dynamic range (Fu, 2002). In the present experiment, the mean TMDT, calculated across the modulation frequencies of 16, 32, and 64 Hz at a comfortable loudness level, was used to correlate with the speech-recognition performance. The distinct methodologies did not allow a direct comparison of the results from the previous studies and the present experiment.

The other factor responsible for the lack of the significant correlation found in the present experiment between temporal modulation sensitivity and speech-recognition performance may be that the mean TMDTs in the electric-stimulation condition, calculated across the three modulation frequencies, were not appreciably different among the eight subjects, and were also not significantly different from those in normal-hearing subjects. Therefore, the temporal resolution measured by modulation detection may be sufficient for implant listeners to perceive speech information coded in temporal/amplitude envelopes and may not be fully utilized in speech pattern recognition at all. In fact, many other studies have found no relation between speech-recognition performance and temporal resolution measured by gap detection because most of the gap thresholds obtained in cochlear-implant listeners are probably sufficient to perceive speech information coded by temporal gaps (Shannon, 1989; Busby & Clark, 1999). Therefore, the contribution of the temporal processing to speech perception may be much less than that from other electric

parameters and the performance of subjects predominantly reflects the processing of these other sources of speech information, such as spectral information which is coded by stimulation on the different electrodes.

The acoustic-stimulation condition. Although there is no study reporting relation between temporal modulation sensitivity and speech recognition in hearing-impaired subjects, several previous studies about amplitude modulation detection of acoustic stimuli by hearing-impaired subjects have reported variable results, including decreased sensitivities and steeper rejection slopes of the modulation transfer functions (Bacon & Viemeister, 1985; Formby & Muir, 1988; Bacon & Gleitman, 1992). These evidences of reduced temporal resolution are largely due to a result of the low SL of the stimuli and/or the reduced audible bandwidth of the stimuli. When these factors are controlled, hearing-impaired subjects typically perform the task of temporal modulation detection as well as normal-hearing subjects. In the present experiment, the modulation detection performance between the acoustic-stimulation condition in cochlear-implant subjects and the normal-control condition in normal-hearing subjects was not significant, indicating normal temporal resolution of the hearing-impaired ear, which is in agreement with the results from the previous studies. Again, the uniformity observed in overall temporal modulation detection performance in the acoustic-stimulation condition, ranging from -27 dB for subject S8 to -18 dB for subject S2, and the lack of the significant correlation between temporal modulation sensitivity and speech recognition suggest that the normal or close to normal temporal resolution of the hearing-impaired ear may not be fully utilized in speech recognition. The contribution of temporal processing to speech perception in

hearing-impaired subjects may be much less than those from other factors, such as loss of absolute sensitivity and a broadened auditory filter. Therefore, the temporal resolution is not a strong predictor of speech recognition in the acoustic-stimulation condition.

The combined-EAS condition. Similar to the uniformity observed in overall temporal modulation detection performance, ranging from -31 dB for subject S2 to -19 dB for subject S4, speech-recognition performance was also highly uniform among the eight cochlear-implant subjects, ranging from 80% to 94% for CNC words and from 72% to 98% for AzBio sentences in the combined-EAS condition. The lack of the significant correlation between these two measures was likely due to a ceiling effect of the speech-recognition performance. Again, the results suggest that the normal temporal resolution in the EAS condition is not a major limitation for cochlear-implant subjects with combined EAS to achieve a high level of speech understanding both in quiet and in noise.

Summary. Overall, the lack of any significant correlations between temporal modulation sensitivity and speech recognition in all three stimulation conditions in the present experiment suggests that the normal temporal resolution of electric, acoustic, and combined hearing seems to provide sufficient speech information linked to temporal envelope variations and may not be fully utilized in speech pattern recognition.

Conclusions

(1) The TMTFs obtained using sinusoidal carriers in cochlear-implant and normal-hearing subjects resemble those found by previous researchers.

Modulation detection thresholds for low modulation frequencies up to 64 Hz reflect the effects of both amplitude resolution and temporal resolution.

(2) The amplitude/temporal resolution of acoustic hearing, electric hearing, and combined electric and acoustic hearing is essentially normal in subjects with combined contralateral EAS. The speech-perception benefits observed in listeners with combined contralateral EAS are attributable to the normal amplitude/temporal resolution of residual acoustic hearing.

(3) The lack of any significant correlations between temporal modulation sensitivity and speech recognition in all three stimulation conditions suggests that the normal amplitude/temporal modulation resolution of acoustic, electric, and combined electric and acoustic hearing is sufficient to perceive substantial acoustic features of speech linked to temporal envelope variations and, therefore, is not a strong predictor of speech recognition.

Chapter 4. Spectral Modulation Transfer Functions (SMTFs) in Listeners with Combined Contralateral EAS

Introduction

Current cochlear implants can only provide coarse spectral resolution to cochlear-implant listeners. A direct perceptual consequence of reduced spectral resolution due to the use of a cochlear implant is that the internal representation of spectral envelopes may be "blurred", making it difficult for a listener to identify the spectral cues necessary for speech perception. Therefore, one psychophysical factor that is likely to contribute to the speech-perception benefits in listeners with combined contralateral EAS is the better spectral resolution of acoustic hearing in the nonimplanted ear when compared with that of electric hearing in the implanted ear. Although the presence of sensorineural hearing loss typically may decrease spectral resolution compared to normal hearing, listeners with sensorineural hearing losses still may have better spectral resolution than typical cochlear-implant listeners (Henry, Turner & Behrens, 2005). The better spectral resolution from the nonimplanted ear may optimize the transmission of the fine spectral details of the input signal. This additional information in the spectral domain combined with the spectral cues provided by cochlear implants may allow greater accuracy in the identification of the spectral cues necessary for speech perception. Also, understanding speech in the presence of background noise may be improved with the additional spectral information if the listeners are better able to spectrally separate the target from the masker. Therefore, it is important to first understand the spectral cues

for speech perception and the spectral resolution abilities of hearing-impaired listeners and cochlear-implant listeners. The detailed discussion follows.

Spectral cues for speech perception

Spectrally, vowels can be identified by relatively steady-state formants. The frequency of these formants varies as a function of the speaker's age and sex (Peterson & Barney, 1952). Resolution of the first (F1) and second (F2) formant is sufficient to allow a high level of vowel intelligibility (Delattre, Liberman, Cooper & Gerstman, 1952). The place-of-articulation contrasts, which differ by the position of the articulators in the vocal tract, e.g., /b/ vs. /d/ or /i/ vs. /a/, require resolution in the frequency domain. Within stop consonants, either voiced [b, d, g] or unvoiced [p, t, k,], place cues are identified by the frequency of the aspiration burst, relative to the vowel, and the transition of the second formant. Nasals can be distinguished by their 2nd formant transitions, with /m/, /n/, and /ŋ/ having successively higher starting frequencies for the vowel. Fricatives can be distinguished by their noise band frequencies and bandwidth, e.g., [s, z] have higher noise-band center-frequencies than [f, v]. Dipthongs (e.g., /aɪ/, /eɪ/), and semivowels (e.g., /w/, /j/, /r/) are distinguished not only by their changing formant frequencies, but also by the duration of formant movement (Liberman, Delattre, Gerstman & Cooper, 1956).

Spectral resolution in hearing-impaired listeners

Spectral resolution refers to the ability of the auditory system to separate or resolve the components in a complex sound (Moore, 1998).   Reduced spectral resolution in hearing-impaired listeners has been demonstrated in physiological

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studies, showing broader tuning curves measured from single neurons in the auditory nerve of anaesthetised animals with damaged cochleas (e.g., Dallos, Ryan, Harris, McGee & Ozdama, 1977; Liberman & Dodds, 1984). Reduced spectral resolution of listeners with cochlear loss is also demonstrated with measurements of psychophysical tuning curves (PTC's) (e.g., Zwicker & Schorn, 1978; Carney & Nelson, 1983) and measurements of auditory filter shapes using both ripple-noise maskers and notched-noise maskers (e.g., Wightman, McGee & Kramer,1977; Glasberg & Moore, 1986; Trees & Turner, 1986; Dubno & Dirks, 1989). Typically, in these experiments, the subject is required to detect a signal such as a sinusoid in the presence of a masking background. The results are used to provide a description of frequency selectivity (spectral resolution) in the auditory system.

The bandwidth of auditory filters in listeners with cochlear hearing loss has been shown to be up to three to four times greater than that in normal-hearing listeners (Glasberg & Moore, 1986). The reduced frequency selectivity or spectral resolution associated with sensorineural hearing loss produces a smearing of spectral details in the internal representation of complex acoustic stimuli at threshold/suprathreshold levels. As a result, hearing-impaired listeners have difficulty locating the spectral peaks within stimuli which are important in the identification of vowels, as well as consonants that vary only by place of articulation. In addition, the reduced frequency selectivity arising from a broadening of the auditory filters leads to poorer resolution of the lower harmonics of voice pitch. This has a direct effect on hearing-impaired listener's ability to use $F0$ differences to separate competing sounds, leading to poor speech perception in noise. Overall, the reduced spectral

resolution contributes significantly to the speech-recognition deficits observed in hearing-impaired listeners (Dubno & Dirks, 1989).

Spectral resolution in cochlear-implant listeners

Spectral resolution in cochlear-implant listeners depends first on the ability of a cochlear-implant system to provide spectral details in the signal. The number of stimulating channels in current cochlear-implant systems is generally limited to between 6 and 22, depending on the device and speech processing strategy, and, therefore, these speech processors do not preserve the fine spectral details in the speech signal. Second, spectral resolution depends on the ability of an individual cochlear-implant listener to perceive this electric representation of spectral information. For some listeners, presumably those with good nerve survival and good electrode placement, each electrode may be usable as a distinct channel with which to represent speech information. Other listeners who may have poor nerve survival and/or poor electrode placement may have many fewer effective channels than the number of electrodes in their implants. Studies on the effect of the number of channels on speech recognition in cochlear-implant listeners indicate that the effective number of channels perceived by these listeners is lower than the physical number of channels provided. Cochlear-implant listeners show an asymptote in speech recognition on average across listeners with between two and seven channels, depending on the degree of difficulty of the speech material presented (Dorman & Loizou, 1997; Fishman, Shannon & Slattery, 1997; Friesen et. al., 2001). Therefore, the limited number of stimulating channels (6 to 22) in current cochlear-implant systems is enough for cochlear-implant listeners to achieve high levels of speech

recognition both in quiet and in noise if they can perceive the coarse spectral information represented by electric stimulation across the electrodes. However, cochlear-implant listeners generally cannot utilize all of the spectral information that is provided by cochlear-implant speech processors and multiple electrode arrays. Poor spectral resolution is a major factor that limits cochlear-implant listeners from utilizing the spectral details of the speech signal for speech perception.

Reduced spectral resolution of electric stimulation has been demonstrated in physiological studies. Hartmann, Topp, and Klinke (1984) measured discharge patterns of cat primary auditory fibers with electric stimulation of the cochlea. The frequency tuning properties in response to electric stimulation were relatively broad. Similar results were also found in the studies of van den Honert and Stypulkowski (1984, 1987), in which spatial maps of electric excitation were constructed by comparing electric threshold with acoustic characteristic frequency for large populations of auditory nerve fibers in cats. Results showed that stimulation with even intracochlear bipolar electrodes produced a relatively broad threshold distribution adjacent to the electrodes, indicating poor spatial selectivity.

Psychophysical experiments also confirm that cochlear-implant listeners have reduced frequency selectivity. Chatterjee and Shannon (1998) measured forward masked excitation patterns in four users of the Nucleus Corporation 22-channel implant. The resulting excitation patterns were compared to the measurement obtained with acoustic stimulation of a normal-hearing listener. The excitation patterns of two implanted subjects were slightly broader than normal, whereas one subject showed a spatial extent that was more than twice as wide. A fourth showed

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excitation patterns that were sharp near the tip but which, for some electrode pairs, were nonmonotonic at wider masker-probe separations.

Other investigators examined place-pitch sensitivity (i.e., the ability to distinguish among electrodes on the basis of tonotopically mediated pitch or timbre) in cochlear-implant listeners, using psychophysical electrode pitch-ranking and electrode-discrimination tasks. The listeners' task was to listen to the pulse trains applied sequentially to each of two electrode channels and state which presentation produced the higher pitch, and an answer was scored as correct if this corresponded to the more basal channel. Townshend, von Compernolle, and White (1987) were the first investigators to examine place-pitch sensitivity in cochlear-implant listeners. They showed that some implant listeners exhibited relatively strong place-pitch sensitivity consistent with the normal tonotopic organization of the cochlea, whereas others perceived little change in pitch as a function of electrode location.

Nelson, Van Tasell, Schroder, Soli, and Levine (1995) used an electrode-ranking procedure to evaluate the ability to distinguish electric stimulation of different electrodes in 14 users of the Nucleus cochlear implant 22 device. Performance on the electrode-ranking task was defined in terms of d per mm of distance between comparison electrodes. Large individual differences were observed among cochlear-implant listeners. In some subjects, perfect performance was reached with as little as 0.75 mm between comparison electrodes. In other subjects, perfect performance was not reached until the spatial separation between comparison electrodes was over 13 mm, more than three quarters of the entire length of the electrode array, meaning poor place-pitch sensitivity to change in the frequency of an acoustic input.

Donaldson and Nelson (1999) evaluated the average place-pitch sensitivity across the electrode array as a function of electrode separation in 14 cochlear-implant listeners using the Nucleus MPEAK and SPEAK speech processing strategies. The results showed considerable variability in subjects' performance at all electrode separations. At the narrowest separation 0.75 mm, corresponding to the distance between adjacent electrodes in the Nucleus array, place-pitch sensitivity (d) ranged from 0.13 to 1.52. However, only 3 of 14 subjects achieved performance better than $d = 1$. Performance improved systematically as electrode separation increased from 0.75 to 4.5 mm for most subjects. Two subjects demonstrated unusually poor pitch-ranking performance.

To summarize the results above, reduced spectral resolution in electric stimulation has been demonstrated in physiological studies, showing broader tuning curves. Psychophysical studies also confirm poor place-pitch sensitivity with large individual differences among cochlear-implant listeners.

Measures of spectral profile resolution

The traditional psychophysical measures of spectral resolution in hearing-impaired listeners and cochlear-impaired listeners described above are generally assumed to underlie to some extent their ability to resolve the spectral aspects of the speech signal. However, these measures typically require a listener to detect a signal in the presence of a masker (hearing-impaired listeners) or to discriminate between stimulation on different electrodes activated individually (cochlear-implant listeners). The distinct methodologies do not allow a direct comparison of spectral resolution between hearing-impaired and cochlear-impaired listeners. In addition, these

measures are time-consuming to conduct since they are multi-point measures, which are made at multiple positions along the basilar membrane (hearing-impaired listeners) or the electrode array (cochlear-implant listeners). Furthermore, the knowledge obtained from a limited set of measures at multiple points across the electrode array is unable to predict the perception of a complex spectral profile of novel stimuli. Recently, investigators have used a more direct and one-point measure of cochlear-implant listeners' ability to perceive the complex spectral envelope or spectral contrast (the difference in amplitude between the peak and valley), which reflects the spectral profile resolution in hearing-impaired and cochlear-implant listeners.

A spectral envelope or the relative distribution of acoustic intensity across frequency is a principle physical characteristic that distinguishes one sound from another. These differences must be maintained in the internal representation of the acoustic spectra in order for the identification of vowels and consonants that vary only by place of articulation. The perception of spectral envelope or spectral contrast in cochlear-implant listeners is likely to be poor because the internal representation of the electric spectra of an input signal is smeared due to the reduced spectral resolution in cochlear-implant listeners as discussed above. Furthermore, this reduced complex spectral contrast is further compromised by the compression from the wide acoustic dynamic range to the small electric dynamic range (typically 3–30 dB) used in the most current speech processing strategies. This notion has been supported by the study of Loizou and Poroy (2001), who found that the minimal spectral contrast required for high levels of vowel identification accuracy was 4–6 dB for cochlear-

implant listeners, while normal-hearing listeners only require a spectral contrast of between 1 and 3 dB for reasonably accurate vowel identification (Leek, Dorman & Summerfield, 1987; Alcantare & Moore, 1995).

To investigate the perception of spectral envelope in cochlear-implant listeners, Henry and Turner (2003) used a method that involved the detection of sinusoidal spectral modulation. In their experiment, stimuli were broadband noise signals and the modulation was generated by systematically varying the amplitude of broadband noise signals in the spectral envelope. With this sort of spectral envelope, the number of cycles of modulation (modulation density) was increased or decreased with the modulation depth held constant. The task involved discriminating between two modulated noise stimuli in which the frequency positions of the peaks and valleys were interchanged. The minimum modulation density (ripple spacing) at which a reversal in peak positions can be detected was determined as the threshold for spectral peak resolution. The results showed a significant relationship between spectral peak resolution and vowel recognition in cochlear-implant listeners, indicating that listeners who can resolve more closely spaced peaks are better at recognizing vowels.

In Henry, Turner, and Behrens (2005), the measure of spectral peak resolution developed by Henry and Turner (2003) was applied in normal-hearing, hearing-impaired and cochlear-implant listeners. Spectral peak resolution was best, on average, in normal-hearing listeners, poorest in cochlear-implant listeners, and intermediate for hearing-impaired listeners. There was a significant relationship between spectral peak resolution and both vowel and consonant recognition in quiet across the three listener groups.

Spectral Modulation Transfer Function. Another method using stimuli very similar to those used by Henry and Turner (2003) to study the spectral envelope perception is to measure the spectral modulation transfer function (SMTF). The spectral modulation transfer function is defined as the minimal spectral contrast required for detecting sinusoidal spectral modulation as a function of spectral modulation frequency (Saoji, Litvak, Emadi & Spahr, 2005). The idea of SMTF is very similar in concept to the temporal modulation transfers function (TMTF) in the temporal domain. Figure 11 shows a 3-D schematic representation of TMTF and SMTF. The time and amplitude domains are modulated in TMTF while the frequency and amplitude domains are modulated in SMTF. Spectral modulation frequency is measured in units of cycles per octave (cyc/oct) and successive peaks and valleys are separated by multiples or fractions of an octave. Figure 12 shows the schematic representation of 1 cyc/oct spectral envelope. The carrier bandwidth is a 6-octave wide band of noise from 200 to 12800 Hz. The sinusoidal spectral envelope contains six cycles over the six-octave band of noise (i.e., 1 cyc/oct spectral modulation frequency). The peak-to-valley difference of the overlaying logarithmic sinusoid determines the amount of contrast in dB.

During the measurement of SMTF, the listener's task is analogous to the temporal modulation detection task, which involves discriminating between one modulated noise stimulus in which the modulation depth is varied (with the frequency positions of the peaks and valleys held constant) and one unmodulated noise stimulus with a flat spectrum. The minimum contrast or peak-to-valley difference necessary to discriminate between an unmodulated (flat spectrum) and a modulated spectrum is

3-D Schematic Representation of TMTF
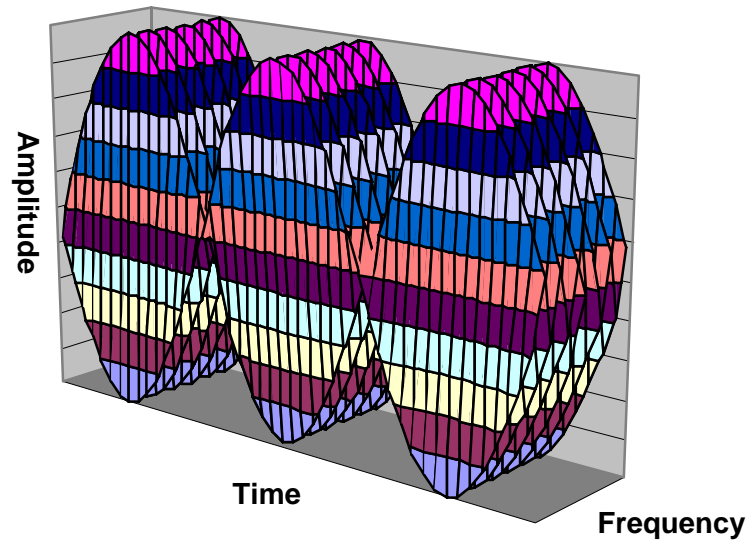
3-D Schematic Representation of SMTF
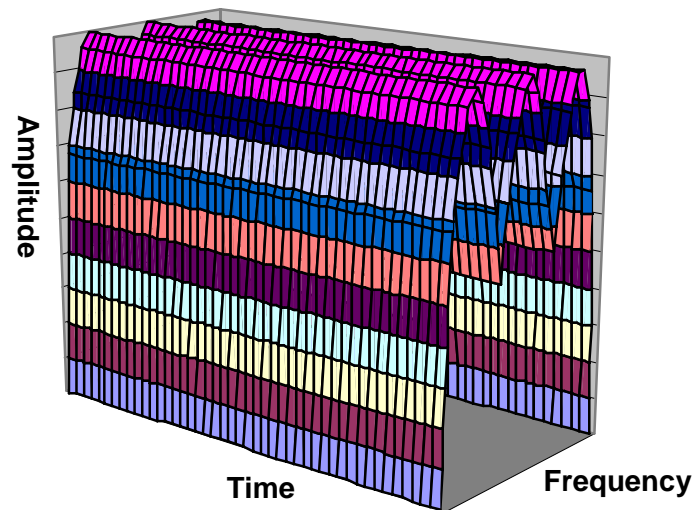
Figure 11. 3-D Schematic representations of TMTF and SMTF. The time/amplitude domains are modulated in the TMTF and the frequency/amplitude domains are modulated in the SMTF.
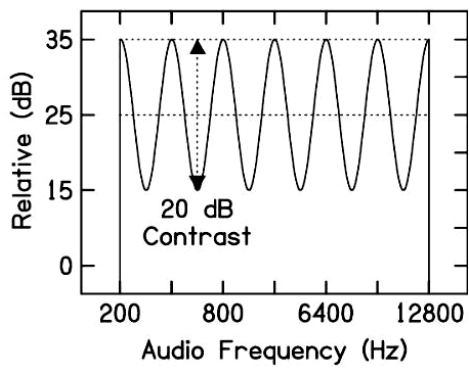
Figure 12. A schematic representation of a sinusoidal spectral modulation with a modulation frequency of 1 cyc/oct superimposed on a 6-octave wide band of noise (200 to 12800 Hz). The modulation contrast is 20 dB.

known as spectral modulation detection threshold (SMDT). It was hypothesized that low-frequency modulation would involve across-channel comparisons in the electric-frequency domain, requiring the listener to compare amplitude across the electrode array to build a representation of the envelope. But as the number of modulation cycles increased, a point would be reached where the peak and the valley of one or more cycles of the spectral modulation would be processed in the same functional channel. This would reduce the perceived contrast between the peaks and valleys. This test is to provide a direct measure of cochlear-implant listeners' ability to perceive the frequency locations of spectral peaks in a broadband acoustic signal.

Litvak, Spahr, Saoji, and Fridman (2005) reported SMTFs in cochlear-implant listeners. They measured SMTFs in cochlear-implant listeners at spectral modulation frequencies of 0.25, 0.5, 1, and 2 cyc/oct, and correlated the SMDTs with listeners' vowel and consonant recognition scores. The results showed that cochlear-implant listeners needed greater spectral contrast to detect the high spectral modulation frequencies than to detect the low modulation frequencies, and the spectral modulation thresholds corresponding to the lowest spectral ripple frequencies (0.25 and 0.5 cyc/oct) best related to speech recognition scores ($r = 0.76$ and $r = 0.9$, respectively). Therefore, SMTF can be used to relate spectral envelope perception to vowel and consonant recognition in cochlear-implant listeners.

The measure of SMTF is also applicable to listeners with acoustic hearing. Summers and Leek (1994) measured the threshold of detecting a stimulus containing a sinusoidal ripple across its frequency range from a flat-spectrum band-pass stimulus for normal-hearing and hearing-impaired listeners. The ripple frequencies ranged

from 1 to 9 cyc/oct. They also calculated the excitation patterns for sinusoidal modulations superimposed on a log-frequency axis. The results obtained in their study showed that the auditory systems with broadened auditory filter bandwidths (as in cochlear hearing loss) needed about 5 dB greater peak-to-valley difference or contrast than normal-hearing listeners to discriminate the rippled stimulus from the flat stimulus, which was consistent with the reduction in frequency selectivity revealed in the excitation pattern calculations. These findings suggested that the frequency resolution ability of the auditory system was critical to spectral envelope perception. Therefore, the measure of SMTF can be applied in the nonimplanted ear of listeners with combined EAS. As such, the measure of SMTF provides an opportunity to directly compare the spectral peak resolution of residual acoustic hearing with that of electric hearing.

Rationale

The spectral resolution of low-frequency residual acoustic hearing presumably is better than that of electric hearing (Henry, Turner & Behrens, 2005). This advantage of spectral resolution in low-frequency acoustic hearing may provide relative benefits in perceiving spectral features of speech sounds and, therefore, leading to improved speech perception both in quiet and in noise in listeners with combined contralateral EAS. Psychophysical measurements of SMTFs in the acoustic-stimulation, the electric-stimulation, and the combined-contralateral-EAS conditions would allow direct comparisons of the spectral resolution among three stimulation conditions to test whether the spectral resolution of acoustic hearing is better than that of electric hearing. In addition, a comparison of the spectral resolution

between cochlear-implant subjects and normal-hearing subjects would answer the question of whether the spectral resolution in three stimulation conditions is normal or close to normal. Furthermore, considerable individual variability of the speech-perception benefits both in quiet and in noise appears in many of the reported studies, revealing large differences in using additional acoustic information to identify speech sounds in listeners with combined EAS. Therefore, an explanation of individual differences in the speech-perception benefits should include variations of basic psychophysical sensitivity to spectral modulation. Assessments of the correlation of speech recognition and spectral profile resolution would provide insight to the relation of the speech-perception benefits with the spectral resolution in three stimulation conditions.

Hypotheses

The operating hypothesis of Experiment 3 was that the mechanism contributing to the speech-perception benefits in listeners with combined contralateral EAS would be due to the improved spectral representation of the input signal provided by residual acoustic hearing.

Summary and predictions based on literature review

Spectral information contributes primarily to the discrimination of the vowel formants and the consonant place-of-articulation features. For hearing-impaired listeners, reduced spectral resolution arises from a broadening of the auditory filters. For cochlear-implant listeners, reduced spectral resolution is due to the smeared activation pattern associated with electric stimulation, combined with a limited

number of "independent" function channels. The consequences of reduced spectral resolution in both clinical populations are likely to be very similar: a reduced ability to utilize the spectral cues for speech perception both in quiet and in noise.

Auditory scientists used different experimental procedures to study the perception of complex spectral envelope patterns in both hearing-impaired and cochlear-implant listeners. In the present experiment, measurement of SMTFs was used to characterize the spectral envelope perception of both acoustic and electric hearing in listeners with contralateral EAS, which would allow a direct comparison of the spectral profile resolution between residual acoustic hearing and electric hearing. The results would identify the general relationship between the spectral profile resolution and the speech-perception benefits in listeners with contralateral EAS. Although the spectral resolution of residual acoustic hearing is typically reduced in people with cochlea hearing loss, it may be still better than that of electric hearing. Therefore, it is expected that the mechanism contributing to the speech-perception benefits in listeners with combined contralateral EAS is likely due to the improved spectral representation of the input signal provided by residual acoustic hearing.

Methods

Experimental design

Experiment 3 used a within-subject design with stimulation mode (acoustic-stimulation alone, electric-stimulation alone, and combined contralateral EAS) and modulation frequency (0.5 cyc/oct. and 1 cyc/oct.) as independent variables, and SMDT as a dependent variable. A repeated-measures ANOVA was applied to the data and the effects of the stimulation mode and the modulation frequency on the SMDT were evaluated and analyzed. Speech recognition scores of CNC words in

quiet and AzBio sentences in noise at +10 dB SNR from Experiment 1 with a wide-band input were used to correlate with the SMDTs. The results provided us insight to the underlying mechanisms of the contribution of the acoustic input to combined contralateral EAS (Aim 2).

Subjects

All cochlear-implant subjects except for S5 who participated in Experiment 1 were recruited in the present experiment. S5 had difficulty in discriminating between the modulated and unmodulated noise stimuli and showed unstable performance after an extensive practice. Therefore, S5 was not included in the present experiment.

Ten normal-hearing subjects participated in the present experiment and they ranged in age from 20-53 years (mean age=28.8 yrs; st. dev. = 10.7 yrs). All subjects had normal audiometric thresholds ≤ 15 dB HL for octave test frequencies from 250 to 8000 Hz (ANSI, 2004).

Each observer provided written informed consent for their participation in this research. The research protocol and informed consent statement were approved by the Institutional Review Board at the University of Maryland, College Park and Arizona State University. Subjects were paid an hourly wage for their participation.

Cochlear implants

The electric input of stimuli was presented through a direct input cable to each subject's speech processor. Subjects were tested with their 'everyday' device settings and each subject's cochlear implant was checked before modulation detection was evaluated at each test session. The volumes and sensitivity settings of the cochlear implant were not adjusted in order to maintain the same settings on the cochlear

implant for both the combined-contralateral-EAS and the electric-stimulation conditions.

Stimuli

    Stimuli generation. Rippled noise stimuli of 125-5600 Hz bandwidth were generated using MATLAB software (Mathworks, 2006). The spectral modulation frequencies were 0.5 cyc/oct or 1 cyc/oct. The stimuli were generated in the frequency domain assuming a sampling rate of 44,100 Hz. First, the desired spectral shape was generated using the equation where $F(f)$ is the amplitude of a bin with center frequency

$$|F(f)| = \begin{cases} 10^{\frac{c}{2}\sin(2\pi f_c(\log_2 f - \log_2 350) + 2\pi\theta_0)/20}, & 125 < f < 5600 \\ 0 & \text{o.w.} \end{cases}$$

(2)

f Hz, f_c is the spectral modulation frequency (0.5 or 1 cyc/oct), and θ_0 is the starting phase. The desired noise band was synthesized by adding a random phase to each bin, and taking an inverse Fourier transform. The starting phases of the individual frequency components were randomized for each stimulus to avoid fine-structure pitch cues and local increment detection that may be perceptible to listeners. The flat noise stimuli were generated using a similar technique, except that spectral contrast C was set to 0. The amplitude of each stimulus was adjusted to an overall level of 65 dB sound pressure level (SPL). The spectral contrast (difference between spectral peaks

and valleys (in dB)) was varied adaptively. The stimuli were of 400 ms duration and were gated with each 400-ms observation interval. The rippled noise stimuli were output from a standard PC to an Audiophile sound card. The sound card output was attenuated separately in two output channels using an inline attenuator such that for the electric input of stimuli to the speech processor, the level was equivalent to a 65-dB-SPL acoustic input to the microphone of the speech processor and the acoustic input of stimuli was adjusted on an individual basis as explained below.

Presentation level. In the electric-stimulation condition, the rippled noise stimuli were presented to the each subject via a direct input into the speech processor, using a 3.5-mm mono phone plug, which defeated the headset microphone so that no external input occurred, while at the same time preserving the microphone pre-emphasis. The presentation level was set at 65 dB SPL. Up to now, there has been no study reporting that spectral modulation detection is sensitive to stimulation level. However, the spectral contrast across electrode arrays would have been reduced or lost due to either peak clipping (deletion of high intensity information) or center clipping (deletion of low intensity information) if the stimuli had been presented at either a high or low level and the sensitivity control of the cochlear implant had not been adjusted accordingly to capture the entire range of amplitude values in the stimuli. Therefore, presenting stimuli at 65 dB SPL, which is usually at a comfortable loudness level, is the best way to avoid possible effects of peak clipping and/or center clipping on the spectral modulation detection task during the measurement of SMTF. The volumes and sensitivity settings of the cochlear implant were not adjusted.

In the acoustic-stimulation condition, the rippled noise stimuli were presented to the nonimplanted ear through an insert earphone (Etymotic ER-1). The presentation level of the acoustic input was set at the same loudness level as the electric input on an individual basis for each subject. A loudness matching method was used to find the presentation level of the acoustic input with the same overall loudness as the electric input presented at 65 dB SPL. Subjects were instructed to listen to the electric stimuli first with the implant alone and remember the loudness, then listen to the acoustic stimuli with the insert earphone alone, and indicate on a response card whether the stimuli were louder or softer than that in the nonimplanted ear. The response card was a continuous scale, labeled with "louder" and "softer" at the end points and "the same" halfway in between. The experimenter adjusted the presentation level of the acoustic input until the stimuli were rated to sound equally loud to the electric input presented at 65 dB SPL.

In the combined-contralateral-EAS condition, the stimuli were output via an audio splitter connector with one end connected to an insert earphone (Etymotic ER-1) and the other one connected to each subject's speech processor via a direct input cable. The presentation level of the electric input was set at 65 dB SPL. The level of the acoustic input that sounded equally loud to the electric input was used to facilitate the perceptual fusion of the acoustic input and the electric input. The volume and sensitivity settings of the cochlear implant were not adjusted in order to maintain the same settings on the cochlear implant for both the electric-stimulation and the combined-contralateral-EAS conditions.

Procedure

The measurements included the assessment of SMDT as a function of modulation frequency in three listening conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. All subjects were tested in a double-walled sound treated room. Prior to data collection subjects received a few sample trials for any new condition to familiarize them with the stimuli.

The SMDTs (dB) were estimated using a cued, two-interval, two-alternative, forced-choice (2IFC) paradigm. For each set of three intervals, the first interval always contained the reference stimulus, and this cuing or reminder interval was helpful in cases where listeners could hear a difference between the signal and the standard stimulus but could not identify which was which. The test interval, chosen at random from the other two intervals, contained the comparison stimulus. The comparison was always a modulated signal with variable spectral contrast, while the reference was a flat spectrum noise with bandwidth extending from 125 to 5600 Hz. The modulated signal and the second reference were randomly presented in the other two intervals. There was an interstimulus interval of 400 ms. Three numerically labeled buttons were displayed on a computer screen, corresponding to the three intervals, and subjects were instructed to press the button corresponding to the interval that sounded "different" (i.e., the one that contained the test stimulus), ignoring any loudness variation between intervals. Feedback was given after each trial by flashing 'correct' or 'wrong' on the screen. A run consisted of 80 trials. Each run began with the comparison (modulation depth with a peak-to-valley ratio of approximately 20 dB) clearly different from the reference, and the modulation depth

was varied in a three-down, one-up procedure. The modulation depth of the comparison was reduced after three correct responses and was increased after one incorrect response. This converged on the modulation depth that produced 79.4% correct responses (Levitt, 1971). The initial step size of the change of the modulation depth was 2 dB and was 0.5 dB after three reversals. All threshold estimates were based on the average of the last even number of reversals, excluding the first three. Using the above procedure, SMDTs were obtained for the modulation frequencies of 0.5 cyc/oct and 1 cyc/oct. Each reported threshold was based upon the average of three consecutive runs. Each run of 80 trials of the cued 2IFC task took approximately 6-7 minutes to complete.

Results

Spectral modulation detection

Figure 13 shows the mean SMDTs and +1 standard deviation, in dB, as a function of modulation frequency and as a function of stimulation condition. The mean SMDTs as a function of the modulation frequency from ten normal-hearing subjects are also shown in the figure with black bars. A repeated-measures ANOVA was performed on the raw data for the SMDTs with two within-subjects factors (modulation frequency with two levels and stimulation condition with three levels). The analysis revealed significant main effects for the stimulation condition ($F_{(2, 14)} = 18.5$, $p < 0.001$) and for the modulation frequency ($F_{(1, 7)} = 19.9$, $p = 0.003$) without a significant interaction between these two effects ($F_{(2, 14)} = 2.3$, $p > 0.05$). Subsequent post hoc pairwise comparison (Fisher's LSD) revealed that the mean SMDTs in the electric-stimulation
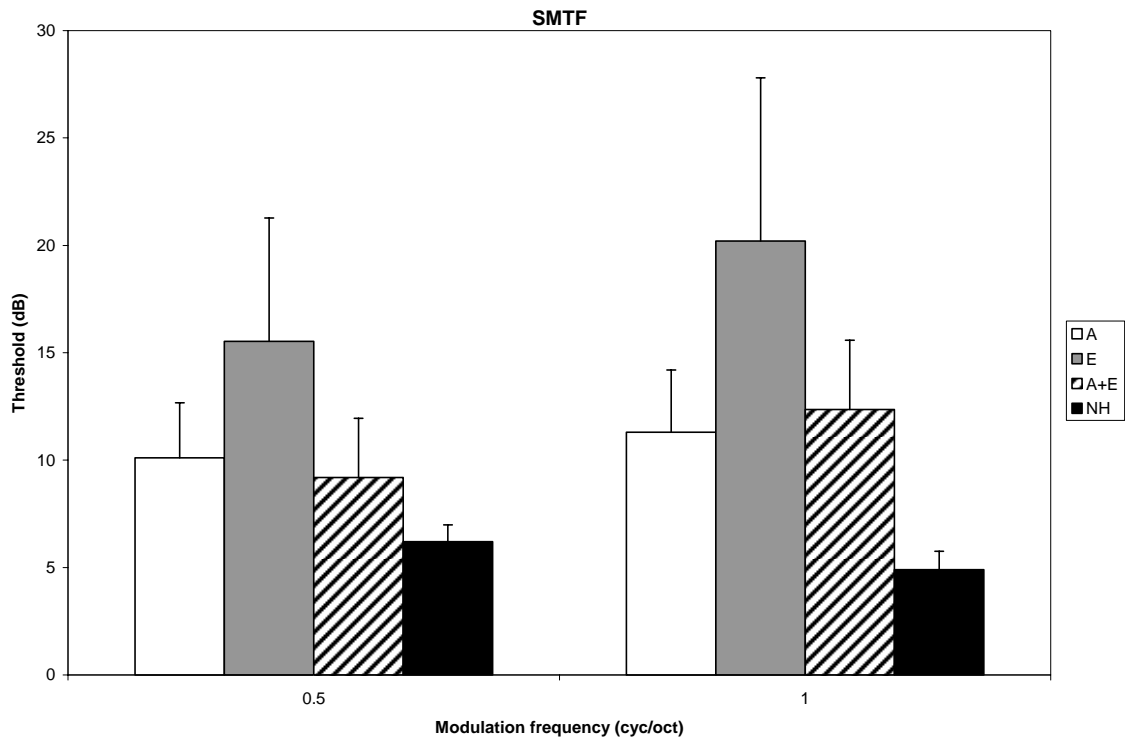
127

Figure 13. Group mean spectral modulation detection thresholds (SMDTs) as a function of modulation frequency (0.5 and 1 cyc/oct) for eight cochlear-implant subjects with combined contralateral EAS. SMDTs of ten normal-hearing subjects as a function of modulation frequency are shown with black bars. Error bars indicate +1 standard deviation.

Condition were significantly higher than those in the acoustic-stimulation and EAS conditions for both 0.5 and 1 cycle/octave modulation frequencies ($p < 0.05$).

To further investigate the difference of the spectral profile resolution between cochlear-implant subjects and normal-hearing subjects, the mean SMDTs of eight cochlear-implant subjects in three stimulation conditions were compared separately with the mean SMDTs of ten normal-hearing subjects. A repeated-measures ANOVA was conducted with a within-subject factor (modulation frequency with two levels) and a between-subject factor (subject group with two levels).

In the acoustic-stimulation condition, a repeated-measures ANOVA analysis revealed that there was a significant main effect for subject group ($F_{(1, 16)} = 41.5$, $p = 0.000$) but there were no effect for modulation frequency ($F_{(1, 16)} = 0.6$, $p > 0.05$) and no interaction between modulation frequency and subject group ($F_{(1, 16)} = 4.4$, $p > 0.05$).

In the electric-stimulation condition, a repeated-measures ANOVA analysis revealed that there were a significant main effect for subject group ($F_{(1, 16)} = 44.9$, $p < 0.001$) and a significant interaction between modulation frequency and subject group ($F_{(1,16)} = 20.8$, $p < 0.001$) but there was no effect for modulation frequency ($F_{(1,16)} = 3.8$, $p > 0.05$). When the mean SMDTs were collapsed across the two modulation frequencies, the mean SMDT in cochlear-implant subjects was significantly higher than that in normal-hearing subjects (Independent t-test, $p < 0.05$).

In the combined-contralateral-EAS condition, a repeated-measures ANOVA analysis revealed that there were a significant main effect for subject group ($F_{(1, 16)} = 15.1$, $p < 0.001$) and a significant interaction between modulation frequency and

subject group ($F_{(1,16)}$ = 23.5, $p < 0.001$) but there was no effect for modulation frequency ($F_{(1, 16)}$ = 0.3, $p > 0.05$). When the mean SMDTs were collapsed across the two modulation frequencies, the mean SMDT in cochlear-implant subjects was significantly higher than that in normal-hearing subjects (Independent t-test, $p < 0.05$).

Correlation

The SMDTs at the two modulation frequencies were used to correlate separately with the recognition scores of CNC words in quiet and AzBio sentences in noise at +10 dB SNR measured in Experiment 1 with a wide-band input in the acoustic-stimulation, electric-stimulation, and combined-contralateral-EAS conditions. Figure 14 displays the correlation of the CNC word and AzBio sentence scores with the SMDTs at 0.5 cyc/oct modulation frequency. Figure 15 displays the correlation of the CNC word and AzBio sentence scores with the SMDTs at 1 cyc/oct modulation frequency. There was a general trend of negative correlation between the speech recognition scores and the SMDTs at the two spectral modulation frequencies in the acoustic-stimulation and electric-stimulation conditions. However, due to the limited number of subjects included in the present experiment (eight subjects), only the AzBio sentence scores in the electric-stimulation condition were significantly correlated with the SMDTs at 1 cyc/oct modulation frequency ($r = -0.814$, $p = 0.007$).
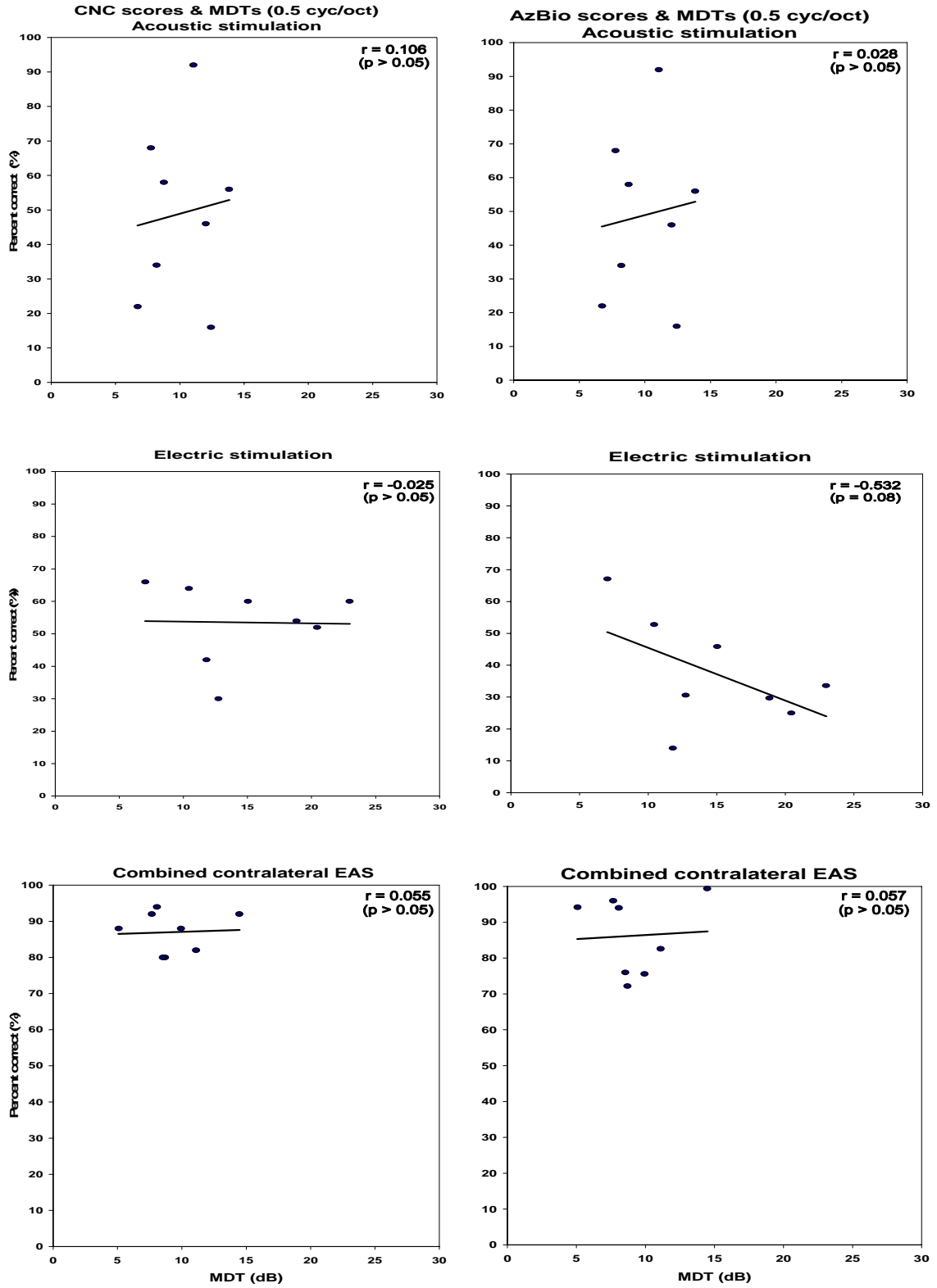
Figure 14. The correlation of CNC word (left column) and AzBio sentence (right column) scores with the mean SMDTs at 0.5 cyc/oct modulation frequency.
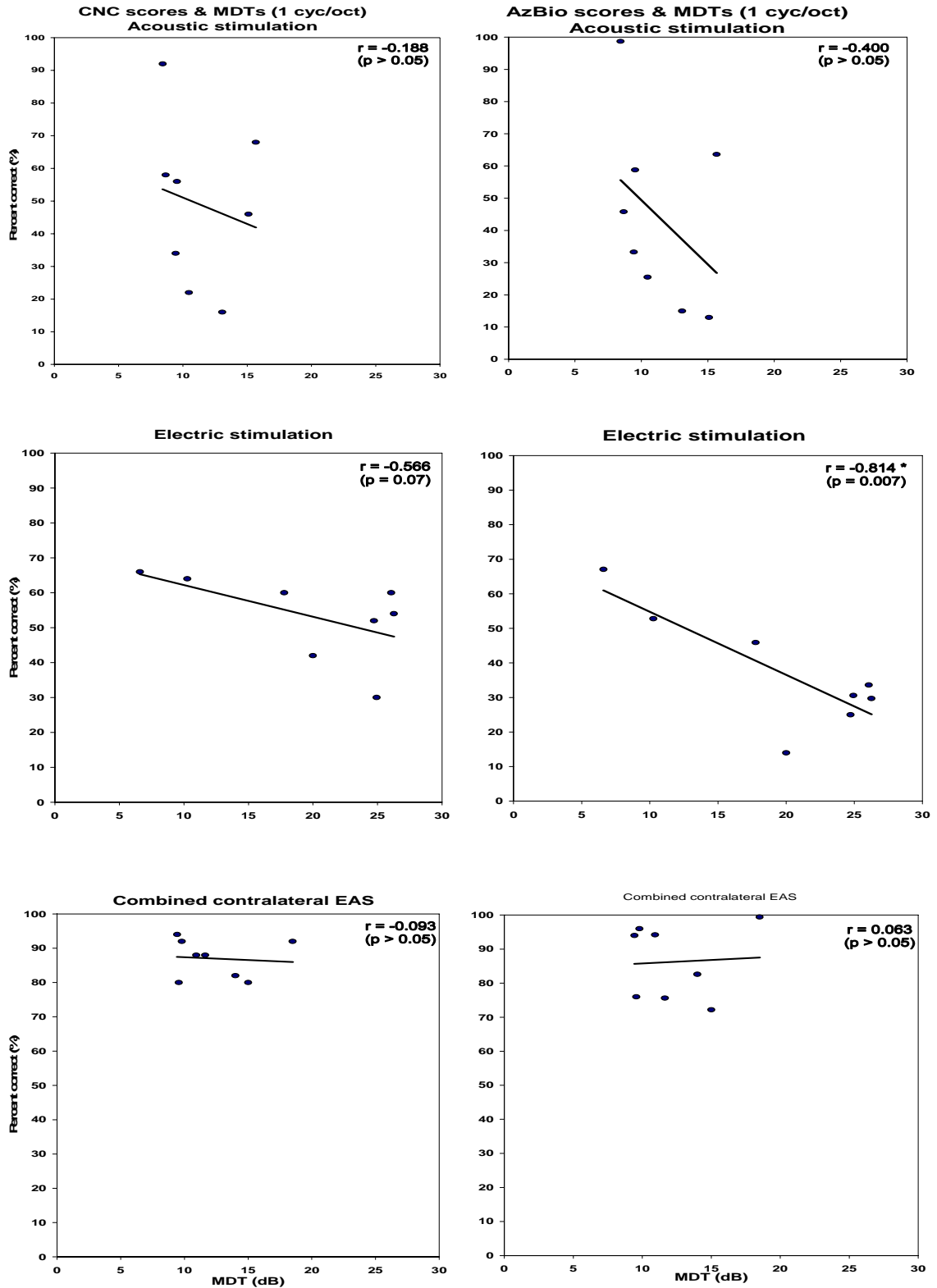
Figure 15. The correlation of CNC word (left column) and AzBio sentence (right column) scores with the mean SMDTs at 1 cyc/oct modulation frequency. "*" indicates significant coefficient correlation.

Discussion

Spectral Modulation Detection

The mean SMDTs at two modulation frequencies in the electric-stimulation condition were significantly higher than those in the acoustic-stimulation, combined-EAS, and normal-control conditions. In addition, the mean SMDTs of cochlear-implant subjects in the acoustic-stimulation condition were significantly higher than those of normal-hearing subjects. The overall pattern of results suggests that the spectral profile resolution of residual acoustic hearing is not as good as normal but is better than that of electric hearing, and the speech-perception benefits observed in listeners with combined contralateral EAS are attributable to the better spectral resolution of residual acoustic hearing.

In the electric-stimulation condition, spectral envelopes or spectral contrasts are represented by the relative amplitude across channels. During the spectral modulation detection task, implant subjects were required to compare amplitude across electrode arrays to build a global representation of the spectral profile or envelope in order to discriminate between the modulated and unmodulated stimuli. The significantly higher spectral SMDTs in the electric-stimulation condition when compared to those in the acoustic-stimulation and combined-EAS conditions indicate that larger spectral contrast (peaks and valley difference) is needed for cochlear-implant subjects in order to perform the spectral profile discrimination task in the electric-stimulation condition; in other word; the perception of spectral profile is poorer in the electric-stimulation condition than that in the acoustic-stimulation and combined-EAS conditions. It is likely that the internal representation of the electric

spectra of an input signal is smeared due to the reduced spectral resolution in cochlear-implant listeners, which is related to patterns of neural survival and function, and patterns of current distribution in the cochlea. Furthermore, the "blurred" internal representation of the spectral peaks in acoustic signals is further compromised by the compression from a wide acoustic dynamic range to a small electric dynamic range (typically 3–30 dB) used in most current speech processing strategies (see the Introduction). Depending on the neural survival, current distribution in the cochlea, and dynamic range of an individual, performance on the spectral modulation detection task varied widely among eight cochlear-implant subjects in the electric-stimulation condition, with the best-performing subject able to achieve a level of performance (6.6 dB) close to the range of normal-hearing subjects (4.2-7.5 dB), while at the other end of the performance range three subjects showed thresholds of approximate 26.3 dB. The overall poor spectral profile resolution observed in the electric-stimulation condition is generally consistent with the results of previous physiological studies, showing reduced spectral resolution of electric stimulation evidenced by broader tuning curves (e.g., Hartmann, Topp & Klinke, 1984), and psychophysical studies, showing poor place-pitch sensitivity evidenced by the inability of implant listeners to discriminate electrodes and to detect and discriminate changes (Donaldson & Nelson, 1999).

In the acoustic-stimulation condition, spectral envelopes or spectral contrasts are represented by the relative amplitude across internal auditory filters. The significantly higher spectral profile resolution thresholds in the acoustic-stimulation condition when compared to those in the normal-control condition indicate that the spectral

profile resolution of residual acoustic hearing is reduced compared to that of normal hearing due to a broadening of auditory filters associated with cochlear hearing loss and, therefore, produces a smearing of spectral detail in the internal representation of complex acoustic stimuli at threshold/suprathreshold levels. However, the mean spectral SMDTs in the acoustic-stimulation condition were significantly lower than those in the electric-stimulation condition, indicating better spectral profile resolution of residual acoustic hearing than that of electric hearing. Figure 16 displays the average residual hearing subjects had in the nonimplanted ear and the modulation cycles of the modulated noise carrier they had access to at a comfortable listening level. The residual acoustic hearing with a limited listening bandwidth had access to only one (for 0.5 cyc/oct. modulation) or two cycles (for 1 cyc/oct. modulation) of modulation but produced better performance on the spectral modulation detection task than electric hearing, which had a full range of listening bandwidth and had access to three or six cycles of modulation. The overall better spectral profile resolution (but not as good as normal) in the acoustic-stimulation condition observed in the present experiment was generally consistent with the results from the previous studies, which showed that spectral peak resolution was best, on average, in normal-hearing listeners, poorest in cochlear-implant listeners, and intermediate for hearing-impaired listeners (Henry & Turner, 2003; Henry, Turner & Behrens, 2005). Taken together, it is reasonable to conclude that the spectral profile resolution of residual acoustic hearing is not as good as normal but is better than that of electric hearing.

In the combined-EAS condition, the mean SMDTs were not significantly different from those in the acoustic-stimulation condition but were still significantly
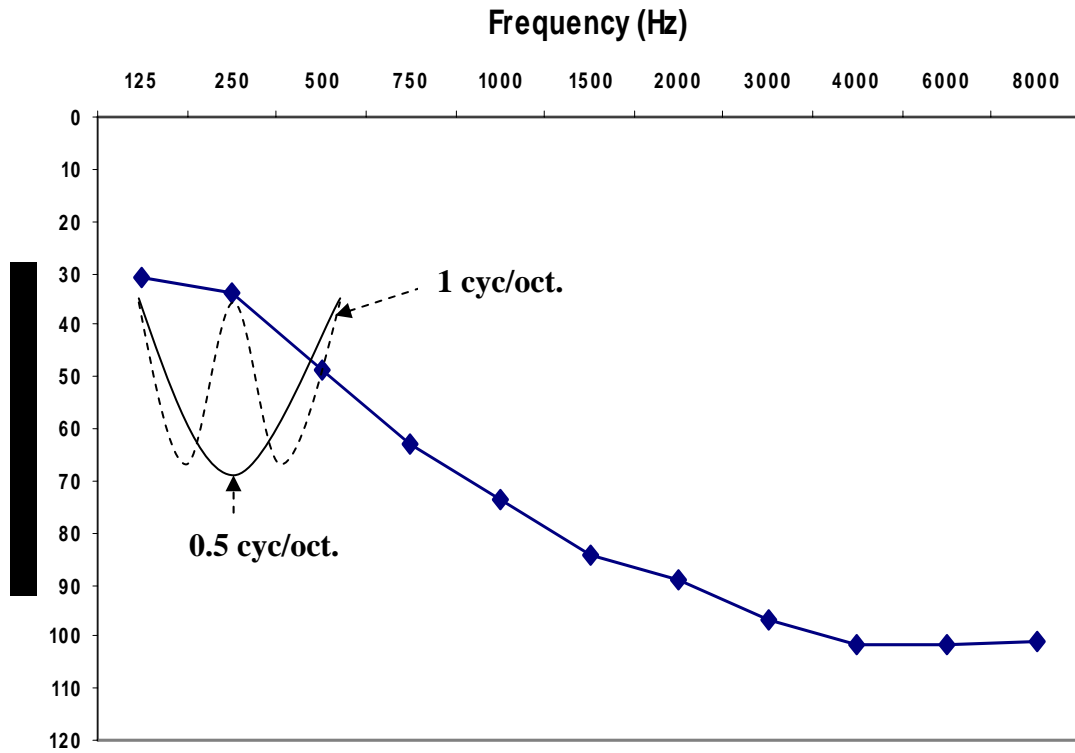
Figure 16. displays mean audiogram for eight subjects with low-frequency residual hearing and a schematic representation of spectral modulation cycles for modulation frequencies of 0.5 and 1 cyc/oct audible for residual acoustic hearing.

higher than those in the normal control condition, indicating that adding extra modulation information from electric hearing to residual acoustic hearing did not further improve the spectral profile resolution. Cochlear-implant subjects mostly relied on the region of residual acoustic hearing where the spectral resolution was relatively better to resolve the spectral profile difference in order to discriminate the modulated stimuli from the unmodulated stimuli. Therefore, accurate performance on the spectral profile resolution task did not require broadband analysis of the signal. The spectral resolution in the electric-stimulation condition may be overestimated by the spectral profile resolution task used in the present experiment. Further research using a narrow-band noise carrier is required to determine which frequency regions are used by individual listeners to perform the task in the electric-stimulation condition. Effective frequency regions may be associated with a higher specificity of neural populations activated in electrical stimulation. This may have a potential clinical application in terms of specifying the "functional channels" and improving the clinical programming of the cochlear implant speech processor.

Age effect on the measurement of SMTFs. There are histopathological and physiological evidences in animals and in humans, showing that aging adversely affects outer hair cell (OHC) functioning independent of hearing loss, which is responsible for cochlear nonlinearity, e.g., high sensitivity, sharp tuning, and enhanced spectral contrasts via suppression (McFadden, Campo, Quaranta & Henderson 1997a; McFadden, Quaranta & Henderson, 1997b; Satoh, Kanzaki, O-Uchi & Yoshihara, 1998; Dorn, Piskorski, Keefe, Neely & Gorga, 1998; Parham, Sun & Kim, 1999; Torre & Fowler, 2000). Therefore, there is a concern about a

possible age effect on the measures of spectral profile resolution given the age difference between cochlear-implant (mean age = 66 yrs; st. dev. = 10.3 yrs) and normal-hearing groups (mean age=28.8 yrs; st. dev. = 10.7 yrs) in the present experiment. However, most studies designed to examine the age effect on psychophysical estimates of cochlear nonlinearity have shown no significant age differences in nonlinear cochlear processing (Peters & Moore, 1992; Sommers & Gehr, 1998; Lentz, Richards & Matiasek 1999). In fact, a more central auditory deficit, likely related to temporal resolution, is a primary factor that contributes to the speech-perception difficulties experienced by older individuals (Fitzgibbons & Gordon-Salant, 1995, 1998, 2001; Gordon-Salant & Fitzgibbons, 1999). Therefore, a significant between-group difference of spectral profile resolution between cochlear-implant subjects in three stimulation conditions and normal-hearing subjects observed in the present experiment does not likely reflect an age effect but rather a reduced spectral resolution of electric and residual acoustic hearing when compared to that of normal hearing.

Correlation

The electric-stimulation condition. There was significant inter-subject variability in both subjects' spectral profile resolution (6.6 dB - 26.3 dB) and speech-recognition performance (42%- - 76% for CNC words, 14% - 67% for AzBio sentences) in the electric-stimulation condition. Sentence recognition was strongly correlated with the spectral profile resolution at 1 cyc/oct modulation frequency (r = -0.814, p = 0.007). For this fairly small sample of eight subjects, the spectral profile resolution can account for a substantial portion (r^2 = 66%) of the variance of speech-

recognition performance in cochlear-implant subjects. These results indicate that those listeners who are better able to determine the positions of the spectral peaks and valleys in the electric signal, as shown by lower spectral profile resolution thresholds, are, on average, more readily able to extract speech information from the signal.

Large variability in the ability to understand speech by cochlear-implant listeners is commonly reported (e.g., Firszt, Holden, Skinner, Tobey, Peterson, Gaggl, Runge-Samuelson & Wackym, 2004). This significant variability in speech understanding is thought to be a product of variations among cochlear-implant listeners in many factors. For example, identifying variables in postlingually-deafened adults related to pre-operative factors, including the duration of deafness, the duration of cochlear-implant use, etiology of deafness, and preoperative sentence scores, allows some level of prediction of postoperative speech perception ability (e.g., Dorman, Dankowski, McCandless, Parkin & Smith 1990; Blamey *et al.*, 1992; 1996; Gantz, Woodworth, Knutson, Abbas, & Tyler, 1993; Battmer *et al.*, 1995; Rubinstein, Parkinson, Tyler & Gantz, 1999). Also, there are several hypotheses that have been advanced to address the underlying causes of this variability, including the number and function of surviving spiral ganglion cells, the placement of the electrodes within the scala tympani (e.g., short or long electrode array), patterns of current distribution within the cochlea, the status of the central auditory system, and across-subject differences in spectral selectivity in cochlear-implant listeners (Glasberg & Moore, 1986; Summers & Leek, 1994; Baskent & Shannon, 2003; Boex, Kos & Pelizzone, 2003; Cohen *et al.*, 2003, 2004, 2005; Ferguson, Collins & Smith, 2003; Henry *et al.*, 2005). As discussed in the Introduction, spectral profile perception is one of the

measurements of spectral selectivity. A significant correlation between sentence recognition in noise and spectral profile resolution observed in the present experiment suggests that spectral resolution is a strong predictor of speech perception in cochlear-implant listeners. Therefore, the spectral profile resolution test may have a potential clinical application in terms of improving the predictive power of models which use variables such as duration of deafness and preoperative sentence scores (e.g., Rubinstein et al., 1999) to describe the variance in cochlear-implant speech recognition.

A significant correlation between speech recognition and spectral profile resolution observed in the electric-stimulation condition is generally consistent with the results from previous studies, which showed a significant correlation between spectral profile resolution and both vowel and consonant recognition in quiet in cochlear-implant listeners (Henry, Turner & Behrens, 2005; Litvak et. a.l, 2007). However, there are several differences observed in the present experiment. First, while previous studies reported a strong correlation between spectral resolution and speech recognition in quiet, CNC word recognition was moderately correlated with spectral profile resolution at 1 cyc/oct modulation frequency (r = -0.564, p = 0.07) in the present experiment. The weaker relationship in the present experiment may result from assessing the spectral resolution ability of cochlear-implant listeners in a relatively small sample size. The relation above would be expected to be strong and reach a statistical significance if more data were obtained in a wide range of individuals across the clinical populations. Second, a new finding observed in the present experiment is that the relation between speech recognition and spectral profile

resolution not only applies to recognition in quiet but also to recognition in competing backgrounds. In fact, it seems that AzBio sentence recognition in noise is more correlated with spectral profile resolution than CNC word recognition in quiet in the present experiment, indicating that the spectral profile resolution is likely to be a major factor that contributes to the deficits of speech perception in noise in cochlear-implant listeners. This finding supports the well-known notion that reduced spectral resolution in cochlear-implant listeners has a more detrimental effect on speech recognition in competing backgrounds than in quiet listening conditions (Turner, Gantz, Vidal, Behrens & Henry, 2004; Stickney et. al., 2004).

The acoustic-stimulation condition. The inter-subject variability in subject's spectral profile resolution in the acoustic-stimulation condition (6.7 dB - 15.7 dB) was relatively small compared to that in the electric-stimulation condition (6.6 dB - 26.3 dB). Although speech-recognition performance was highly variable among the eight implant subjects in the acoustic-stimulation condition (16% - 92% for CNC words, 13% - 99% for AzBio sentences), the relation between spectral profile resolution and speech recognition did not reach a statistical significance. The lack of the significant correlation between speech recognition and spectral resolution differs from several studies that have shown significant correlations between these two measures in hearing-impaired listeners (e.g., Festen & Plomp, 1983; Lutman & Clark, 1986; Henry et al., 2005). It seems likely that other perceptual factors except for the spectral profile resolution may contribute to the speech-perception deficits in the acoustic-stimulation condition. In fact, except for the spectral profile resolution, the loss of absolute sensitivity in hearing-impaired listeners is another major factor

affecting speech perception. Amplification via the use of hearing aids compensates for this only to some extent, especially for those hearing-impaired listeners with moderate-to-profound high-frequency hearing losses. Implant subjects in the present experiment only had limited residual hearing up to 1000 Hz (except for S7) in the nonimplanted ear. Therefore, the lack of the significant correlation may result from the factor of audibility, which may be the primary factor limiting speech perception in the acoustic-stimulation condition.

The combined-EAS condition. Although there was inter-subject variability in the subjects' spectral profile resolution (5.1 dB - 16.5 dB) in the combined-EAS condition, speech-recognition performance was highly uniform among the eight cochlear-implant subjects, ranging from 80 to 94% % for CNC words in quiet and from 72% to 98% for AzBio sentences in noise. The lack of a significant correlation between spectral profile resolution and speech recognition is likely due to a ceiling effect of speech-recognition performance.

Conclusions

(1) The overall results of spectral profile detection suggest that the spectral profile resolution of residual acoustic hearing is not as good as normal but is better than that of electric hearing. It appears that the speech-perception benefits observed in listeners with combined contralateral EAS are attributable to the better spectral resolution of residual acoustic hearing.

(2) A significant correlation between spectral profile resolution and sentence recognition in noise in the electric-stimulation condition suggests that the spectral profile resolution accounts for a substantial portion of the variance of speech-

recognition performance, and is a strong predictor of speech perception in cochlear-implant listeners.

Chapter 5. Summary of Results from Three Experiments.

The primary goals of the experiments detailed in Chapters 2 through 4 are (i) to investigate the benefits of low-frequency acoustic information to the speech-perception abilities of individuals with combined contralateral EAS (Experiment 1), and (ii) to relate their speech-recognition performance to their underlying psychophysical abilities in the region of both acoustic hearing and electric hearing (Experiment 2 and 3).

In Experiment 1, it was hypothesized that the differences in the minimum amount of low-frequency acoustic information from the nonimplanted ear available to cochlear-implant listeners would affect the speech-perception benefits both in quiet and in noise from combined contralateral EAS. Speech-recognition performance of CNC words in quiet and AzBio sentences in a competing babble noise at +10 dB SNR were measured in three listening conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. The acoustic stimuli presented to the nonimplanted ear were wide band or low-pass filtered at 125 Hz, 250 Hz, 500 Hz, and 750 Hz. The electric stimuli presented to the implanted ear were wide band or low-pass/high-pass filtered at 250 Hz, 500 Hz, and 750 Hz. The results showed that adding low-frequency acoustic information from the nonimplanted ear to electric hearing led to an overall improvement in speech-recognition performance for both CNC words in quiet and AzBio sentences in noise at +10 dB SNR. This improvement was observed even when the acoustic input was low-pass filtered at 125 Hz, suggesting that the speech-perception benefits are primarily attributed to the voice-

pitch information (even one harmonic) from the acoustic input. A further improvement in speech-recognition performance for sentences in noise was observed when the low-pass cutoff frequency increased from 250 Hz to 750 Hz, suggesting that part of the speech-perception benefits are likely due to the improved spectral representation of the first formant. The limited low-frequency acoustic hearing in the nonimplanted ear functions as an additional "independent" channel, providing acoustic cues for speech perception distributing over time mostly in the time and amplitude domains of the speech signal, which include envelope cues, periodicity cues and temporal-fine-structure cues. Envelope cues and periodicity cues are available for residual hearing down to 125 Hz, providing information about word- and phoneme-size units, "manner" and "voicing" of consonant articulation, and $F0$, which leads to a substantial improvement in speech-recognition performance for both CNC words in quiet and AzBio sentences in noise. Additional temporal-fine-structure cues are also available for residual hearing up to 500- and 750-Hz, providing information about the first formant, which leads to a further improvement in speech-recognition performance for sentences in noise. A mechanism that is common to improvement both in quiet and in noise is proposed: The information in the acoustic signal aids in the recognition of consonant voicing and manner which leads to a large reduction of word candidates in the lexicon. Results from Experiment 1 suggest the importance of preserving the residual acoustic hearing in the nonimplanted/implanted ear in cochlear-implant listeners.

As a minor issue, it was also hypothesized in Experiment 1 that reducing the overlap in frequency representation in the input filters of the cochlear implant and in

acoustic hearing would be beneficial to speech recognition for listeners with combined contralateral EAS. Speech-recognition performance of CNC words in quiet and AzBio sentences in a competing babble noise at +10 dB SNR was evaluated in three listening conditions: acoustic stimulation alone, electric stimulation alone, and combined contralateral EAS. The acoustic stimuli presented to the nonimplanted ear were wide band or low-pass filtered at 250 Hz, 500 Hz, or 750 Hz. The electric stimuli presented to the implanted ear were wide band or high-pass filtered at 250 Hz, 500 Hz, or 750 Hz. The results suggest that a reduced frequency overlap between acoustic and electric stimulation is not beneficial for patients who use an implant in one ear and who have low-frequency hearing in the other ear, due to a speech-recognition advantage for the full frequency range over the reduced frequency range of the electric signal.

Given the outcomes of significant speech-perception benefits from the limited acoustic input (<125 Hz) and no significant speech-perception benefits in the reduced frequency overlap between acoustic and electric stimulation in Experiment 1, clinicians should always aid the ear contralateral to an implant and use a standard cochlear implant programming for patients who have residual hearing on the ear contralateral to the implant.

In Experiments 2 and 3, it was hypothesized that the temporal and/or spectral resolution of low-frequency acoustic hearing in the nonimplanted ear would be better than that of electric hearing, which may account for the speech-perception benefits in listeners with combined contralateral EAS. Psychophysical estimates of TMTFs and SMTFs were conducted and compared among the acoustic-stimulation, electric-

stimulation, and combined-contralateral-EAS conditions. In addition, the temporal resolution and the spectral resolution of cochlear-implant subjects were also compared to those of normal-hearing subjects. Furthermore, the correlation of temporal/spectral modulation sensitivity and speech recognition was assessed separately in three stimulation conditions. The overall results suggest that (i) the temporal resolution of acoustic hearing, electric hearing, and combined electric and acoustic hearing is essentially normal in subjects with combined contralateral EAS; (ii) the spectral profile resolution of residual acoustic hearing is not as good as normal but is better than that of electric hearing; and (iii) it appears that the speech-perception benefits observed in listeners with combined contralateral EAS are attributable to the normal temporal resolution and the better spectral resolution of residual acoustic hearing. The lack of any significant correlations between temporal modulation sensitivity and speech recognition in all three stimulation conditions suggests that the normal temporal/amplitude resolution of acoustic, electric and combined EAS is sufficient to perceive substantial acoustic features of speech linked to temporal envelope variations and, therefore, is not a strong predictor of speech perception in cochlear-implant listeners. A significant correlation between spectral resolution and sentence recognition in noise in the electric-stimulation condition suggests that the spectral resolution of electric hearing accounts for a substantial portion of the variance of speech-recognition performance, and is a strong predictor of speech perception in cochlear-implant listeners.

The present dissertation research provided important information about the benefits of low-frequency acoustic input added to electric hearing in cochlear-implant

listeners with some residual hearing. The overall results reinforced the importance of preserving residual acoustic hearing in cochlear-implant listeners.

Future Directions

The outcomes of Experiment 1 suggest that the low-frequency acoustic information from the contralateral ear can provide significant speech-perception benefits both in quiet and in noise when that information is from an extremely limited frequency range (<125 Hz) and when auditory thresholds in that limited frequency range are elevated. Future studies are needed to investigate whether the speech-perception benefits could be achieved in patients who have less amount of residual acoustic hearing, in other words; what are the minimum thresholds at the limited frequency range (<125 Hz) necessary for achieving an EAS effect in listeners with combined EAS?

The outcomes of Experiment 3 suggest that the measurement of SMTF by using a broad-band noise carrier is a meaningful way to characterize the spectral profile perception for both acoustic and electric hearing. Further research into the measurement of SMTF by using a narrow-band noise carrier in cochlear-implant listeners is necessary to specify the effective frequency regions associated with a higher specificity of neural populations activated in electrical stimulation. This may have a potential clinical application in terms of specifying the "functional channels" and improving the clinical programming of the cochlear implant speech processor. In addition, further research is required to investigate the potential clinical applications of the adaptive spectral profile resolution test. The measurement of SMTF may

provide a time-efficient and non-linguistic measure which may contribute to the prediction of performance in both adult and child cochlear-implant listeners by improving the predictive power of models which use variables, such as duration of deafness and preoperative sentence scores, to describe the variance in cochlear-implant speech recognition, via the inclusion of the spectral profile resolution threshold as an additional factor.

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