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Speech recognition in noise for cochlear implant listeners: Benefits of residual acoustic hearing

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The purpose of this study was to explore the potential advantages, both theoretical and applied, of preserving low-frequency acoustic hearing in cochlear implant patients. Several hypotheses are presented that predict that residual low-frequency acoustic hearing along with electric stimulation for high frequencies will provide an advantage over traditional long-electrode cochlear implants for the recognition of speech in competing backgrounds. A simulation experiment in normal-hearing subjects demonstrated a clear advantage for preserving low-frequency residual acoustic hearing for speech recognition in a background of other talkers, but not in steady noise. Three subjects with an implanted ''short-electrode'' cochlear implant and preserved low-frequency acoustic hearing were also tested on speech recognition in the same competing backgrounds and compared to a larger group of traditional cochlear implant users. Each of the three short-electrode subjects performed better than any of the traditional long-electrode implant subjects for speech recognition in a background of other talkers, but not in steady noise, in general agreement with the simulation studies. When compared to a subgroup of traditional implant users matched according to speech recognition ability in quiet, the short-electrode patients showed a 9-dB advantage in the multitalker background. These experiments provide strong preliminary support for retaining residual low-frequency acoustic hearing in cochlear implant patients. The results are consistent with the idea that better perception of voice pitch, which can aid in separating voices in a background of other talkers, was responsible for this advantage.
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I. INTRODUCTION

For many people with severe and profound hearing losses, cochlear implants have restored speech understanding to remarkable performance levels that acoustic amplification via hearing aids was unable to provide. However, the decision to undergo implantation surgery involves some tradeoffs, as the patients' residual acoustic hearing is no longer usable, and only electric stimulation is available. For example, many users of cochlear implants report that the perception of sound becomes ''mechanical'' or ''raspy'' when compared to their memories of acoustic hearing, and that many of the aesthetic qualities of sound are diminished. This loss of aesthetic quality of sound is most likely related to a decrease in the ability to perceive the pitches of sounds (Gfeller *et al.*, 2002). The loss of pitch perception is primarily a consequence of the limited spectral resolution of current cochlear implants, which does not appear to be a limitation for understanding speech in quiet for the most successful implant users (Fishman *et al.*, 1998). However, understanding speech in background noise requires spectral resolution even finer than that required to understand speech in quiet (Fu *et al.*, 1998). Even the most successful implant users only realize perhaps 6–8 channels of distinct ''place–frequency'' information across the entire spectral range, and this deficit in spectral resolution has a direct negative consequence on the implant patients' ability to understand speech in background noise (Friesen *et al.*, 2001).

A recent development in cochlear implants has been to implant an electrode only partially into the cochlea, in order to preserve the residual acoustic hearing that many patients still have for low frequencies (Von Ilberg *et al.*, 1999; Gantz and Turner, 2003). In these patients, usable acoustic hearing is usually present up to frequencies of 500 or 750 Hz, and the electrical stimulation provides the patient with high-frequency speech information. Thus, these patients perceive sound via a "combined acoustic and electric" (A+E) mode. In addition to the possibility that preserving residual acoustic hearing may have for the aesthetic qualities of sound, it is also possible that preserving residual hearing may contribute to better speech recognition in background noise.

There are several mechanisms by which the preserved residual low-frequency hearing might improve speech understanding in noise as compared to the traditional full-length (long) cochlear implant. The low-frequency residual acoustic hearing presumably has better spectral resolution than the low-frequency portion of a traditional cochlear implant. Henry and Turner (2003a) showed that normal-hearing listeners could resolve spectral ripples nearly an order of magnitude more closely spaced in frequency than cochlear implant users. Although the presence of sensorineural hearing loss typically might decrease spectral resolution compared to normal hearing, patients with sensorineural hearing loss still had better spectral resolution than that provided by a typical long-electrode cochlear implant (Henry and Turner, 2003b). This advantage in spectral resolution might provide a relative benefit in perceiving the spectral features of speech sounds, particularly when presented in noise. On the other hand, many of the features of speech that depend upon spectral resolution (i.e., place of articulation) are located in the higher frequency regions of the spectrum, and low-frequency residual hearing therefore may not be of much assistance.

Another way in which residual acoustic hearing might be helpful to the implant listener would be when speech recognition is tested in a background of multiple talkers. Whereas most normal-hearing listeners can often perform as well or better when listening in fluctuating backgrounds of other talkers as compared to steady noises, implant users usually perform more poorly under these circumstances. Nelson *et al.* (2003) found that cochlear implant users have considerable difficulty in recognizing speech in modulated-noise maskers. Their study also demonstrated, by presenting spectrally limited speech to normal-hearing listeners (to simulate cochlear implant processing), that the reduced spectral resolution was responsible for the problems that implant users experience in fluctuating backgrounds. Qin and Oxenham (2003) demonstrated that even with 24 channels of frequency resolution provided to normal-hearing listeners in a simulation of cochlear implant speech, performance was poorer than for unprocessed speech in a background of a competing talker. Stickney *et al.* (2003) reported that traditional cochlear implant users showed no advantage in recognizing speech presented with a competing talker as compared to steady noise. These studies attribute their findings to the fact that the cochlear implant listeners could not gain an advantage (as normal-hearing listeners did) by perceiving the different pitches of the talkers. Dorman *et al.* (1996) as well as Gfeller *et al.* (2002) have shown that cochlear implant users have great difficulty in distinguishing the pitches of tones, with frequency difference limens for low-frequency tones approaching 100 Hz in some cases. Thus, preserving low-frequency acoustic hearing for cochlear implant patients might, in such cases, lead to an advantage in speech understanding in a background of other talkers, as compared to traditional cochlear implants. Some support for this concept has been demonstrated by Kong *et al.* (2003), who found that cochlear implant users showed improved speech recognition in a competing-talker background when they were allowed to use their low-frequency acoustic hearing in the contralateral ear, even though the contralateral ear by itself was not capable of any speech recognition.

If the improved pitch perception of residual low-frequency hearing could be used by the listener to "separate" various voices via fundamental frequency, then the patient may experience improved speech understanding in multi-talker backgrounds. Different fundamental frequencies assist the listener to "group" the various upper-frequency components of speech and therefore improve recognition of the target voice (Assmann, 1999). Brokx and Nooteboom (1982), Assmann and Summerfield (1990), Culling and Darwin, (1993) and Bird and Darwin (1999) have shown the importance of the fundamental frequency cue for the separation of simultaneous voices in normal-hearing listeners. However, several studies have indicated that traditional cochlear implant users have difficulty in perceiving the fundamental frequency of signals for frequencies greater than 200 Hz. This is due to the fact that place–frequency cues for the fundamental are generally poor (due to poor spectral resolution), and envelope (temporal) cues for the fundamental are only salient at the lower frequencies (Geurts and Wouters, 2001; Green *et al.*, 2002).

The present experiments investigate the possibility that residual low-frequency acoustic hearing can provide benefits for speech understanding in background noises. Two different background conditions were employed, speech-shaped steady noise and competing talkers, in order to distinguish between the several hypothesized advantages of preserving residual hearing. A simple improvement due to increased spectral resolution of speech features should occur equally in both noise and competing-talker backgrounds, whereas an improvement that is due specifically to an advantage in the perception of the voice pitch would be expected to appear most strongly in the multiple-talker background. The first experiment employs simulations of cochlear implant processing (both traditional or long-electrode, and the "combined acoustic and electric" or A+E approach). The second experiment uses the same measures of speech understanding in backgrounds for two groups of actual patients using either traditional long-electrode cochlear implants or the combined acoustic plus electric implants (i.e., A+E).

II. EXPERIMENT 1: SIMULATIONS IN NORMAL-HEARING LISTENERS

A. Subjects

15 young-adult listeners participated in this experiment. All had hearing within 20 dB of the normal standards at octave audiometric frequencies (0.25–8.0 kHz) and were native speakers of American English.

B. Stimuli and procedures

The task for the listeners was to identify a spondee (two-syllable) word spoken by a female talker in the presence of a background sound. The 12 spondee items were homogeneous in difficulty and were digitized from a commercial recording (Harris, 1991). The fundamental frequency of the spondee items ranged from 212–250 Hz. The spondees ranged in duration from 1.12 to 1.63 s. For each presentation, the spondee was chosen randomly from the set of 12. Following each presentation, the listener responded on a touch screen with the spondee that they thought had been presented. The listeners were required to respond on each trial, and instructed to guess if they were not sure of the correct answer. The nontest ear was plugged during the testing.

Two different backgrounds were employed. The competing-talker condition consisted of two simultaneously presented sentences originally recorded as items on the SPIN test (Bilger, 1984). One background talker was a male (fundamental frequency range (81–106 Hz) and the other a female (fundamental frequency range 149–277 Hz). This female talker was not the same talker who produced the spondee. The two background voices were mixed together at equal rms amplitudes. The same mixed-sentence background was presented on each trial. The other background condition was a steady-state white noise that had been low-pass filtered at −12 dB/octave above 400 Hz, to generally simulate the long-term speech spectrum. The same sample of noise background was presented on each trial. The spectra of the competing-talker background and the steady noise were not matched; the competing-talker spectrum contained considerably more spectral peaks and valleys than the steady noise. The competing background signal durations (both sentences and noise) were 2.5 s, and the onset of the target spondee was 500 ms following the onset of the background signal.

The spondees and the backgrounds were presented in three conditions. The first was an unprocessed condition which consisted of the unprocessed speech spondee and the unprocessed background. The second condition was a simulation of a 16-channel cochlear implant, implemented by using the temporal speech envelope within each frequency channel to modulate a corresponding narrow frequency band of noise. Both the target spondees and the background noises were processed. This general technique has been used to simulate cochlear implant speech in numerous studies (i.e., Shannon *et al.*, 1995) and has been shown to provide a good approximation of the theoretical maximum performance of cochlear implant patients for a given degree of frequency resolution (Fishman *et al.*, 1998). The current procedure was implemented using routines written in MATLAB, and the specifics for this 16-channel simulation are described in detail in Henry and Turner (2003a). The third condition was designed to simulate the short-electrode "acoustic plus electric" (A+E) situation. The unprocessed spondees and backgrounds were each low-pass filtered at 500 Hz using a −24-dB/octave digital filtering algorithm. The 16-channel simulations of the spondees and backgrounds were high-pass filtered at 500 Hz, using a similar digital filtering algorithm at −24 dB/octave. These low-pass unprocessed and corresponding high-pass implant simulations were then combined to yield the A+E condition, which had the same relative balance between the low- and high-frequency portions of the spectrum as the unprocessed speech. These A+E stimuli therefore consisted of the entire upper 13 channels (and part of the 14th channel) of the electric simulation mixed with the acoustic signal below 500 Hz. The background signals (noise and competing talker) were processed separately from the spondees, and were then combined following the appropriate attenuation values to obtain the desired signal-to-noise (S/N) ratio, expressed in the rms average value of the spondee and the background.

Prior to any speech in noise testing, each subject participated in one or more practice runs to familiarize them with the spondees and the responses. In this practice run, the spondees were presented without any background noise. All subjects were able to recognize the spondees at 100% accuracy following these practice sessions.

All signals were presented via a loudspeaker in sound field, and the spondees were presented at an average level of 68 dB SPL. Both target spondees and backgrounds were stored on a Macintosh G4 computer and output through separate channels of a DigiDesign 16-bit digital-to-analog converter. The level of the background was controlled by a TDT programmable attenuator. An adaptive procedure was then used to determine the 50%-correct point (in terms of S/N ratio) for recognition of the spondees in noise (SRT). The spondees were initially presented at a signal-to-noise ratio of either +10 or +20 dB (depending upon the condition); this allowed the listener to easily identify the target voice and recognize the spondees of the first few trials. For each correct response the S/N ratio was decreased by 2 dB and for each incorrect response the S/N ratio was increased by 2 dB. For a single run this procedure continued until 14 reversals had occurred and the final value for that run was taken as the average of the final ten reversals. Each subject completed four runs in each condition, and their final data for that condition were taken as the average of the last three runs. Each subject completed all four runs of a condition before progressing to another condition. The order of conditions was randomized across subjects.

C. Results and discussion

Figure 1 displays the results averaged across subjects of experiment 1. The SRT in noise (in dB S/N ratio) is plotted as a function of the three processing conditions. It is clear that there are large differences between three processing conditions when the background is composed of competing talkers, whereas the differences between processing conditions are smaller or nonexistent for the noise background. The general finding of improved speech recognition in a background of voices for unprocessed speech over spectrally limited speech is in agreement with past results (Qin and Oxenham, 2003). The present results differ slightly from that of Qin and Oxenham (2003) for the case of a steady noise background. In their study, unprocessed speech yielded SRTs that were 5.5 dB better than 24-channel processed speech, whereas in our study the improvement for unprocessed speech over 16-channel speech was 2.2 dB (which was not significant). Perhaps differences in the specific speech materials and maskers account for this discrepancy.

The comparison of particular interest for this study was to determine if supplementing the cochlear implant speech

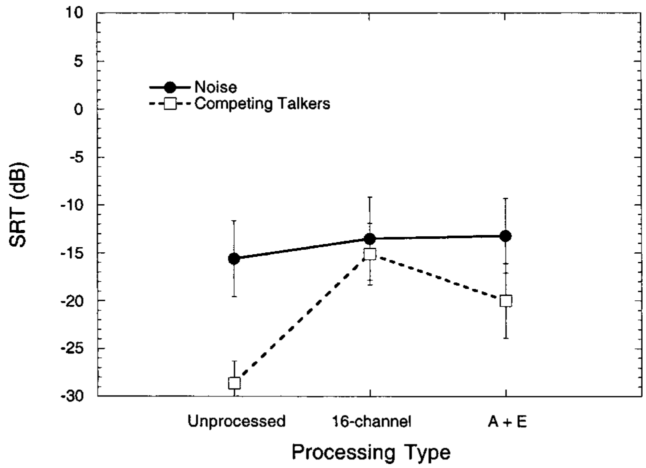

FIG. 1. Group mean SRT values for the acoustic simulations presented to normal-hearing listeners in the two types of background stimuli. The error bars represent the standard deviations across subjects for each condition.

with natural low-frequency acoustic hearing (A+E) could be used to improve some of the advantage in competing talkers that is lost to traditional cochlear implant users. The SRT in competing talkers for unprocessed speech was −28.6. dB, as compared to −15.1 dB for the 16-channel simulation; this was a 13.5-dB disadvantage for the simulated implant speech. The addition of low-frequency unprocessed speech to the simulation reduced this disadvantage to 8.6 dB. In steady noise, the differences between processing conditions were less than 2.5 dB for all comparisons. A two-way ANOVA was performed on the data for the A+E and 16-channel conditions for both noise and competing-talker backgrounds. Both main effects were significant (condition; $F=5.40$, df=1,56; $p=0.0024$; background, $F=17.75$, df =1,56, $p=0.0001$). Of interest is the significant interaction between the two main effects ($F=6.58$, df=1,56 $p=0.013$), which indicates that an advantage was seen in competing talkers over noise for the A+E condition as compared to the 16-channel condition, but not for the noise background condition. The lack of advantage for maintaining low-frequency acoustic hearing in noise suggests that presumably improved spectral resolution for acoustic low frequencies (as compared to 16-channel processed speech) does not result in an improvement in speech recognition in general, consistent with the idea that low-frequency speech cues are not particularly dependent upon fine spectral resolution. One possibility is that the improved spectral resolution in the low frequencies presumably leads to the ability to use pitch information to separate talkers in a multiple speaker situation. Thus, the simulation experiments provide evidence that residual low-frequency acoustic hearing can provide an advantage for speech recognition in a background of other talkers.

III. EXPERIMENT 2

A. Subjects

The subjects for experiment 2 were adult users of cochlear implants. The traditional "long-electrode" group consisted of 20 patients, each using the Nucleus 24 cochlear implant and its associated speech processor. They were tested using their own speech-processor maps and strategies (12 used the ACE strategy, 3 used the CIS strategy, and 5 used the SPEAK strategy). Each had been using an implant for at least 24 months.

The A+E group consisted of three patients implanted with the Iowa/Nucleus Hybrid 10-mm short-electrode device (Gantz and Turner, 2003). These patients were the first three patients to receive the 10-mm electrode and each had been wearing the device for at least 12 months prior to the data collection, and their data for speech recognition in quiet and in noise were no longer improving over time. Two of these three A+E subjects wore hearing aids in their test ear that were fit to amplify the low-frequency portion of the spectrum (unaided thresholds of the two subjects with hearing aids for frequencies of 500 Hz and below were 60–65-dB HL and their aided thresholds were 40-dB HL or better). The third A+E subject did not require a hearing aid to amplify low-frequency hearing (pure-tone thresholds of 20–25-dB HL for 500 Hz and below). The short-electrode cochlear implant stimulated 6 channels in the basal end of the cochlea, using a CIS processing strategy. The cochlear implant frequency maps that these patients found most beneficial in everyday life were also used in this study. For two of the subjects (the ones who used hearing aids) the frequency range assigned to these electrodes was 1062–7937 Hz. For the third subject, the frequencies assigned to the implant were 687–5187 Hz. The hybrid system improved consonant recognition for this group approximately 40% over the hearing-aid-only condition (Gantz and Turner, 2003).

B. Stimuli and procedures

The stimuli for experiment 2 were the same natural (unprocessed) spondees and backgrounds as used in one of the conditions in experiment 1. The nonimplant ear for all subjects was plugged during testing. Cochlear implant users listened to the spondees presented in background signals through their everyday speech processor. The A+E subjects listened to the stimuli using their cochlear implant speech processor and their acoustic hearing (which for two of them included the use of an in-the-ear hearing aid in the test ear). The spondees were presented at 68 dB SPL. During the practice sessions the subjects were allowed to adjust the output levels of their devices. The practice sessions revealed that all implant users, except for the two poorest-performing traditional electrode subjects, could identify 100% of the spondees in quiet. The two poorest-performing long-electrode implant users could only identify approximately 80% of the spondees in quiet. All implant users completed at least four runs of the adaptive SRT procedure in each of the two background conditions, and data were collected until at least three runs showed no improvement over time. The final result was taken as the average of the final three runs.

C. Results and discussion

The mean data for the two groups (long-electrode vs A +E) across the two background conditions are displayed in Fig. 2. The most obvious difference between both types of

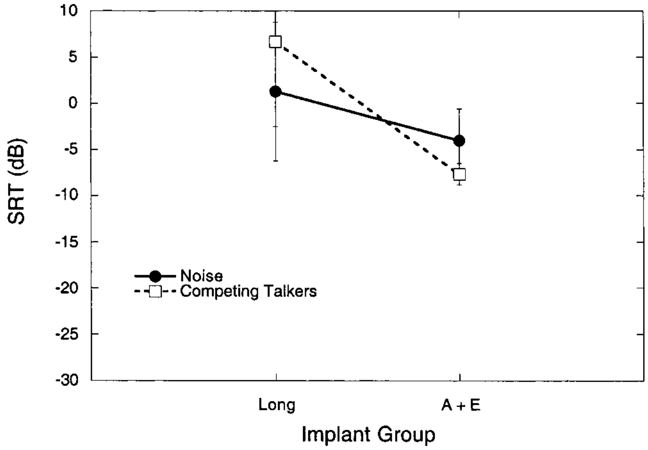

FIG. 2. Group mean SRT values for the two groups of cochlear implant listeners in the two types of background stimuli. The long-electrode group consists of all 20 long-electrode subjects. The error bars represent the standard deviations across subjects for each condition.

cochlear implant users of Fig. 2 and the normal-hearing listeners of Fig. 1 (listening to the same unprocessed stimuli) is that the implant users perform much more poorly than the normals. In steady noise, normal-hearing subjects' SRT's are approximately -15 dB SNR, whereas the implant users are approximately 15 dB poorer. In the competing-talker background, the difference is more striking, with normal-hearing listeners outperforming the traditional implant users by more than 30 dB, and the A+E users by 20 dB for unprocessed stimuli. Even the 16-channel cochlear implant simulation group mean data from the normal-hearing subjects (Fig. 1) are approximately 15 dB better than those of the actual implant users for both steady noise and competing-talker backgrounds.

There are at least several factors contributing to this deficit. First is the general inability of implant users to perform well in noise backgrounds, as shown by Fu *et al.* (1998) and Friesen *et al.* (2001). Typical cochlear implant users do not possess the spectral resolution required to accurately identify speech in noise, and even the 16-channel simulation condition in the present experiment overestimates the spectral resolution of probably all cochlear implant users. A second reason is the particular disadvantage that cochlear implant users show in understanding speech in a competing-talker background, as shown by Nelson *et al.* (2003) and Stickney *et al.* (2003). A third reason is that implant patients typically do not have a full population of surviving auditory nerves, and this can result in a general disadvantage in speech recognition (even in quiet) for electric stimulation as compared to normal-hearing listeners (Fishman *et al.*, 1998).

The A+E patients also showed a deficit compared to the normal-hearing subjects of experiment 1, and several additional factors most likely contributed to this difference. The A+E subjects received only 6 channels of electrical stimulation for the high frequencies, whereas the normal-hearing subjects had much better spectral resolution (even in the simulation which had 13–14 channels). An additional factor may be that the electric stimulation for the A+E patients is directed to a position in the cochlea that is considerably more basal than normal, due to the 10-mm insertion depth of the electrode array. This frequency–place mismatch has been shown to negatively affect speech recognition in combined acoustic and electric hearing (Gantz and Turner, 2003; Brill *et al.*, 2001)

A question of considerable clinical utility is whether the A+E approach offers an advantage over the traditional implant, as suggested by the simulation study of experiment 1. As seen in Fig. 2, the mean SRTs for the A+E subjects were lower than that of the traditional implant user, for both noise and competing-talker backgrounds. Statistical analysis of these data using a mixed-mode ANOVA, with background as a within-subjects factor and implant type as a between-subjects factor, showed a significant interaction between type of implant and background condition ($F=18.85$, df$=1,21$; $p<0.001$). Follow-up *t*-tests indicated that the differences between groups occurred only for the competing-talker condition [$t(21)=2.63, p<0.01$] and not for the steady noise [$t(21)=1.18; p>0.10$]. These results were in agreement with the outcome of the simulation experiment. The variability across subjects is displayed in detail in Figs. 4 and 5 and discussed below.

The group of 20 long-implant users included a wide range of speech recognition abilities, as is typical for a cochlear implant subject pool. Recognition scores on a test of consonant /aCa/ materials presented in quiet (Turner *et al.*, 1995, Fu *et al.*, 1998) ranged from 13% to 74%, with a group mean of 47%. The three A+E subjects had a mean score on this same consonant test of 63% correct (range 53%–71%). It therefore appears that the long-electrode cochlear implant patients in the previous comparison were not only poorer than the A+E patients for speech in background noises, but also poorer for speech recognition in general. This discrepancy could confound the across-subjects comparisons of Fig. 2, if one is looking for real-patient evidence to support the theoretical concept that preserving residual low-frequency acoustic hearing is advantageous. Therefore, the long-implant patients were subdivided to form a smaller subgroup of subjects that had, on average, the same speech scores in quiet as the A+E subjects. Beginning with the top-performing long-implant user on the /aCa/ test and moving downward in ability, additional subjects were added to form a "matched subgroup" until the mean value for the long-implant group was within 1 percentage point of the mean for the A+E group (63%). This matched group contained 10 of the original 20 subjects. The group mean results of this comparison are shown in Fig. 3. As in Fig. 2, the mean values for the A+E group are better than the "matched" long-implant group for the competing-talker condition (9-dB advantage). This group comparison was in the same pattern as the previous all-subjects comparison. Using a mixed-mode ANOVA, with background as a within-subjects factor and implant type as a between-subjects factor, a significant interaction between type of implant and background condition was observed ($F=20.76$, df$=1,11$, $p=0.001$). Follow-up *t*-tests indicated that the two groups were not different for steady noise [$t(11)=0.89; p>0.5$], but were different for the competing-talker background [$t(11)=1.84; p<0.05$]. Thus, even when differences in speech recognition in quiet are accounted for, the A+E approach appears to offer a significant

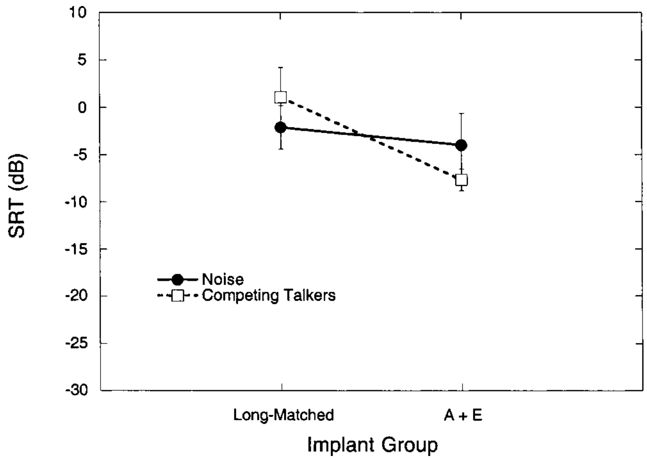

FIG. 3. Group mean SRT values for the two groups of cochlear implant listeners in the two types of background stimuli. The long-electrode group consists of the ten long-electrode subjects matched to the short-electrode subjects in terms of consonant recognition in quiet abilities. The error bars represent the standard deviations across subjects for each condition.

advantage over the long-electrode cochlear implant in a multitalker background.

Figures 4 and 5 display in histogram format the individual data for the traditional implant users and the A+E subjects for the noise and competing-talker backgrounds, respectively. The A+E subjects are indicated by the dark solid bars, the members of the matched group of long-electrode implant users by the hatched bars, and the remaining long-electrode implant users by the open bars. In Fig. 4, the SRT scores in the steady noise are shown. The A+E subjects' data are at the upper end of the entire distribution; however, when compared only to the matched group, their scores are not distinguished. In Fig. 5, the data for speech in the competing-talker background are plotted. In this case, not only are the A+E scores at the upper end of the entire distribution, they are also better than any of the matched group's scores. These raw data also provide strong preliminary support to the idea that preserving acoustic hearing in cochlear implant patients can provide an advantage for understanding speech in a background of other talkers, but not in steady noise.

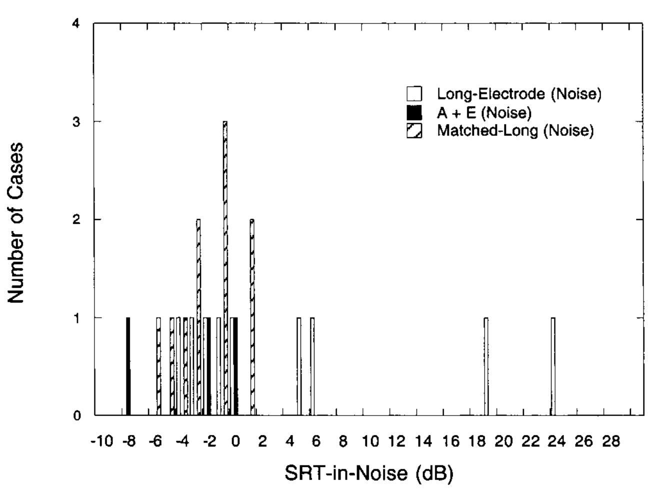

FIG. 4. Individual cochlear implant listeners' SRT values for the condition where the background was steady noise.

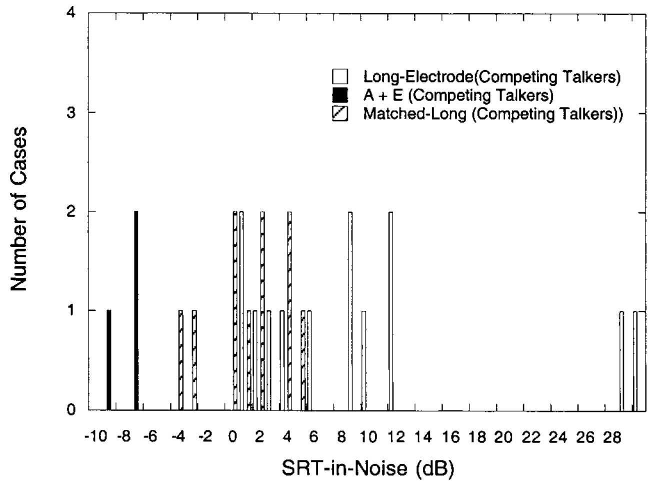

FIG. 5. Individual cochlear implant listener' SRT values for the condition where the background was competing talkers.

IV. GENERAL DISCUSSION

Theoretical advantages of preserving low-frequency acoustic hearing in cochlear implant patients for understanding speech in background noises were presented. A simulation experiment using normal-hearing subjects provided clear evidence that providing unprocessed low-frequency acoustic speech information yielded an advantage for the condition that the background is composed of competing speech. For the present speech and masking stimuli, only a small and nonsignificant advantage was observed for steady noise. These results are in agreement with the idea that the low-frequency acoustic hearing allows the listener to perceive the fundamental frequencies of the talkers and assists in separating the target speech from a background of other talkers. The same task was employed in a group of traditional long-electrode cochlear implant users, as well as three subjects using the acoustic plus electric approach that employs a "short-electrode" cochlear implant, which preserves low-frequency acoustic hearing. The acoustic plus electric approach shows significant advantages over the long-electrode cochlear implant for the recognition of speech in multitalker backgrounds, but not in steady noise, similar to the simulation study. While the recognition of speech presented in a background of competing talkers for both groups of cochlear implant patients was certainly poorer than that observed for normal-hearing listeners, the preservation of low-frequency acoustic hearing using the acoustic plus electric device can reduce at least some of the deficit seen for traditional long-electrode cochlear implant users.

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