Combining acoustic and electric stimulation to attack the cocktail party problem

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Residual low-frequency acoustic hearing can provide critical temporal fine structure and pitch cues that are not conveyed by current cochlear implants, while electric hearing can provide high-frequency temporal envelope cues that are not effectively delivered by current hearing aids. Therefore combined acoustic and electric stimulation provides complementary information and may have great potential to improve performance on tasks that require good pitch perception, for example speech recognition in noise, music perception, understanding tonal languages, perceiving tone of voice, and talker identification. These tasks are particularly challenging for current cochlear implant users. Acoustic and electric hearing may be combined via electroacoustic stimulation in the same ear (ipsilateral EAS), or via a cochlear implant in one ear and a hearing aid in the other (contralateral EAS). At present, clinical outcomes are encouraging but show large intersubject variability. Theoretical considerations on the underlying mechanisms and optimal fitting are lacking. This paper reviews the difficulties cochlear implant users face on pitch-related tasks, and presents speech recognition results from EAS users and simulation data from normal-hearing controls. In addition, results are presented from a unique subject who has a cochlear implant in one ear, and virtually normal hearing in the other ear; he was implanted due to intractable tinnitus. It is suggested that in some important tasks, the hearing aid and cochlear implant combination may provide a more effective solution than not only each device alone but also than bilateral cochlear implants.

INTRODUCTION

Most cochlear implant users perform very well in quiet situations. However, outside the audiometric booth, it is rare for speech to occur in a quiet environment; there is usually background noise, most commonly competing talkers. Noisy situations are difficult for all hearing-impaired people, especially those using cochlear implants. In addition, cochlear implant users still perform far below normal-hearing listeners in music appreciation, understanding tonal languages, perceiving tone of voice, and identifying different talkers. These are all tasks that rely on good pitch representation, which is lacking in current cochlear implant processing algorithms. This paper illustrates difficult situations for cochlear implant users, and provides EAS data from simulations and cochlear implant users. The use of a contralateral hearing aid in combination with a cochlear implant can provide valuable low-frequency fine structure, which improves results in tasks relying on pitch. It is proposed that the bimodal listening situation may offer advantages over bilateral cochlear implant use in some real-life listening situations.

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LIMITATIONS OF COCHLEAR IMPLANTS

Speech perception with competing talkers

In most real-life situations, speech is not masked by steady-state noise; the background is usually competing talkers. In normal-hearing listeners, better speech recognition occurs when the fundamental frequency, F0, of the target voice differs from that of the masker voice (Brokx and Nooteboom, 1982; Brungart, 2001; Brungart *et al.*, 2001; Drullman and Bronkhorst, 2004). Unfortunately no effect of masker voice pitch is found in cochlear implant users (Stickney *et al.,* 2004) or normal-hearing listeners using a cochlear implant simulation (Qin and Oxenham, 2003). One reason may be that the speech processing method does not encode F0, so this cannot be used for voice segregation.

Figure 1 shows results from unpublished work in our laboratory involving eight high-performing cochlear implant users and seven normal-hearing listeners. They listened to HINT sentences spoken by a male, against a background of either steady-state noise (SSN) or sentences spoken by a female, male, or child talker. The signal to noise ratio at which they scored 50% correct (speech reception threshold, SRT) was measured. A very large difference was seen between the normal-hearing and cochlear implant listeners, especially with a talker masker. The normal-hearing subjects performed better when F0 of the masker was further from that of the target, i.e., they found it easier to separate the male target from a female masker. There was little difference in the results from the cochlear implant users. Clinical testing just using steady-state noise may not reflect the discrepancy between normal-hearing and cochlear implant users in more challenging real-life situations.

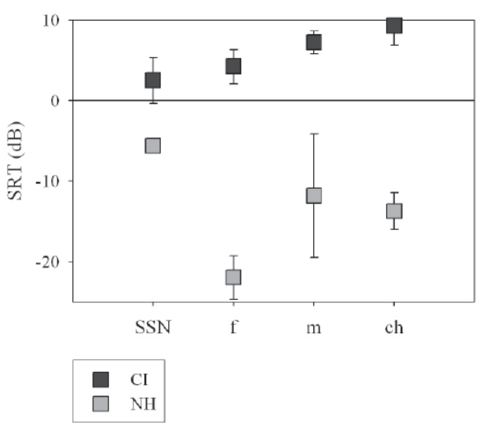

Fig. 1: Speech reception threshold (SRT) for HINT sentences in background noise measured in eight cochlear implant (CI) and seven normal-hearing (NH) listeners. The maskers used were steady-state noise (SSN), female talker (f), male talker (m), and child talker (ch). A lower SRT represents better performance. Error bars represent ± one standard deviation.

Music appreciation

Cochlear implant users perform much worse than normal-hearing people on music perception. Tests used have ranged from simple pitch change or ranking through melody recognition to identification of real musical excerpts. Much work on music appreciation in implant users has been performed by Gfeller *et al*. (2005) in the Iowa group. Recently, 79 adult cochlear implant users were tested on open-set recognition of real musical recordings, and compared with age-matched normal-hearing adults. Results showed that implant users were significantly less accurate than age-matched controls in musical recognition, and the authors concluded that modern cochlear implant systems are not effective in transmitting key structural features of music.

The Montreal Battery of Evaluation of Amusia (MBEA) is a standardized test of music abilities that is used in our laboratory; it is sensitive, normally-distributed, and reliable on test-retest (Peretz *et al.,* 2003). The MBEA has six subtests that examine different aspects of music perception. The subtests mostly rely on a same/different response, thus removing problems of familiarity with melodies. Figure 2 shows results from our laboratory involving five cochlear implant users and 20 age-matched normal-hearing controls. On the first three subtests, where pitch information is tested, the cochlear implant users performed significantly worse than the normal-hearing subjects, in fact just about at chance level. Subtests 4 and 5 show that cochlear implant users perceive rhythm and timing as well as normal-hearing listeners. The final subtest examines music memory, which relies on both pitch and timing information. Again the cochlear implant users are significantly worse than normal-hearing subjects and again perform around chance.

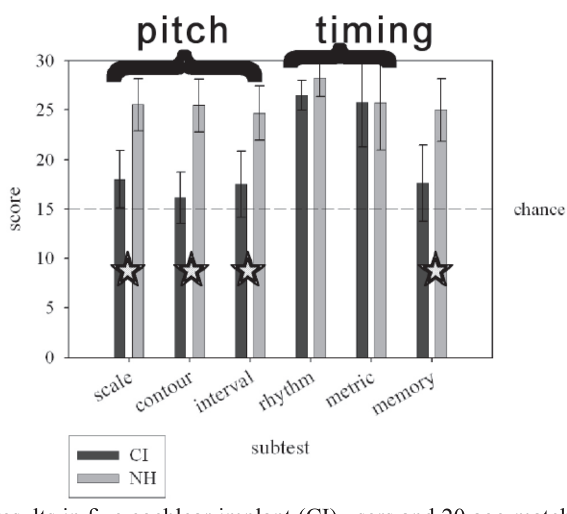

Fig. 2: MBEA results in five cochlear implant (CI) users and 20 age-matched normal-hearing (NH) listeners. Error bars represent ± one standard deviation. The stars indicate a statistically significant difference between cochlear implant and normal-hearing listeners.

Perceiving tone of voice

Prosody refers to the tonal and rhythmic aspects of speech, examples being intonation (tone of voice) and stress. The ability to decode affective information in speech has been found to be associated with relationship satisfaction (Carton *et al.,* 1999) and is crucial to communication. Virtually all the studies examining intonation perception in cochlear implant users have been in Mandarin Chinese speakers. Intonation provides linguistic information in tonal languages; the same word spoken in different ways can convey vastly different meanings. However, in Western languages, intonation communicates the talker's emotional state. A sentence can even have the opposite meaning if the speaker uses a sarcastic tone. Green *et al.* (2005) tested nine cochlear implant users on 30 sentences, where they were required to choose whether the sentence was spoken as a question or statement. The mean score was approximately 68% correct, where chance is 50%.

The Aprosodia Battery is a standardized test for prosody identification which has been used in brain damage studies (Ross *et al.,* 1997). Listeners are required to identify the intonation that is used to speak a sentence (neutral, happy, angry, sad, disinterested, or surprised). Some preliminary results from our laboratory are shown in Fig 3, using five cochlear implant users and 27 age-matched normal-hearing subjects. Cochlear implant users were found to perform significantly worse than normal-hearing listeners on prosody identification. The attitude test assessed whether a sentence was spoken in a sarcastic or genuine tone of voice. There was no significant difference between cochlear implant and normal-hearing listeners on this task. Sarcasm may be more related to timing and stress than pitch cues.

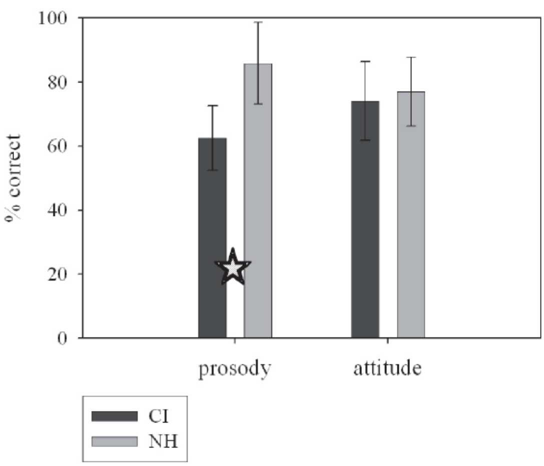

Fig. 3: Intonation perception results using the Aprosodia Battery in five cochlear implant (CI) and 27 age-matched normal-hearing (NH) listeners. Error bars represent ± one standard deviation. The stars indicate a statistically significant difference between cochlear implant and normal-hearing listeners.

Identifying different talkers

Voice gender perception is dependent on accurate pitch information; F0 of female talkers is typically around one octave higher than F0 of male talkers. Despite reduced temporal and spectral information, cochlear implant users typically can perform some degree of voice gender discrimination. Fu *et al.* (2005) found that gender discrimination was good (mean correct score = 94%) when the F0 of male and female voices was very different, suggesting temporal cues could be used for widely disparate F0. But when there was overlap in fundamental frequency between the males and females, the gender discrimination deteriorated to 68% correct, presumably due to reduced spectral resolution.

In addition to the gross male or female categorization, it is also important for listeners to be able to discriminate different voices within the genders. Cleary and Pisoni (2002) found that children with cochlear implants were essentially unable to recognize unfamiliar voices when the linguistic content varied. A further study used manipulated recorded sentences to compare talker discrimination in normal-hearing children and those using a cochlear implant (Cleary *et al.,* 2005). Although the implanted children had high levels of word recognition, they generally performed much worse than the normal-hearing children on talker identification.

Figure 4 shows results from a study by Vongphoe and Zeng (2005) in ten cochlear implant users and six normal-hearing listeners. They were required to identify who spoke vowel tokens from three men, three women, two boys, and two girls. The normal-hearing listeners scored on average 86%, the cochlear implant users scored 23%.

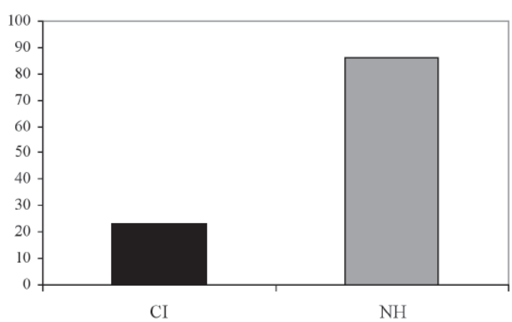

Fig. 4: Talker identification results in ten cochlear implant (CI) users and six normal-hearing (NH) listeners.

IMPROVING COCHLEAR IMPLANT PERFORMANCE

Current cochlear implant systems do not perform well on these tasks requiring good pitch perception. This is due to weaknesses in the speech processing algorithm. All sounds can be considered to consist of envelope and temporal fine structure; these two parts multiplied together produce the original signal. Figure 5 shows a spoken stimulus separated into envelope and temporal fine structure. Current cochlear implant systems extract the amplitude envelope, and present this using a carrier frequency; they discard the temporal fine structure. In quiet situations, the envelope is sufficient for speech recognition (Shannon *et al.*, 1995); however, the fine structure conveys pitch and timbre. Using synthesized stimuli composed of conflicting envelope and fine structure information, Smith *et al.* (2002) elegantly demonstrated that the envelope is most important for speech recognition, and the fine structure is important for pitch perception and sound localization. A cochlear implant attempts to use place coding for pitch, by filtering the incoming signal into several frequency bands, and mapping the signals onto the appropriate electrodes. However, this coding is crude, because the implant typically has less than eight effective channels, and there is almost always a mismatch in the allocation of frequency bands to electrodes.

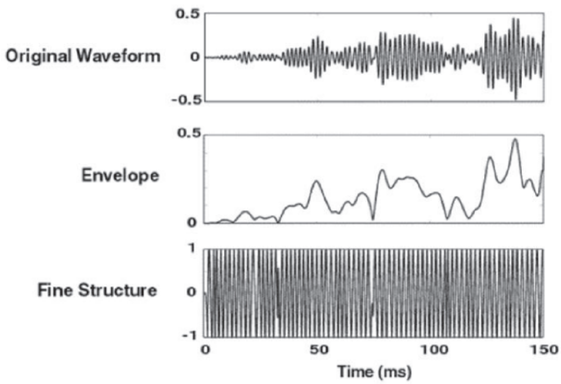

Fig. 5: An example of a speech stimulus separated into envelope and temporal fine structure.

Much research is focused on improving the representation of temporal fine structure to cochlear implant users; one method is by the addition of acoustic hearing. Acoustic hearing can be provided to the ear contralateral to the cochlear implant using a conventional hearing aid; this is termed bimodal hearing. Alternatively, in some patients with near-normal low-frequency hearing thresholds, great success has been achieved by implanting a modified electrode a reduced distance into the cochlea, and using a hearing aid on this same ear (Gantz and Turner, 2004; Gantz *et al.*, 2005; Gantz and Turner, 2003). This is usually described as hybrid stimulation. Acoustic hearing provides the fine structure cue, even just at low frequencies. This paper will focus on bimodal hearing.

Although initially candidates for cochlear implantation had profound or total hearing loss, currently people with severe hearing loss may receive implants. These subjects usually have significant residual hearing in the non-implanted ear that can be amplified with a conventional hearing aid. Many cochlear implant users do not continue to wear a hearing aid on the non-implanted ear, perhaps due to lack of perceived benefit when compared to the tremendous gain they obtain from their implant. In addition, some professionals believe that use of a hearing aid with a cochlear implant can reduce performance achieved with cochlear implant alone (Offeciers *et al.*, 2005) although this has not been robustly demonstrated. The hearing aid is unlikely to provide any speech perception alone, but we suggest that it works cooperatively with the implant to assist in difficult listening situations.

Bimodal hearing provides significant advantages, in terms of listening in noise (Armstrong *et al.*, 1997; Ching *et al.*, 2005a; Ching *et al.*, 2004; Ching *et al.*, 2005b; Dettman *et al.*, 2004; Dunn *et al.*, 2005; Holt *et al.*, 2005; Kiefer *et al.*, 2005; Kong *et al.*, 2005; Tyler *et al.*, 2002) and music perception (Kong *et al.*, 2005). This is believed to be because the acoustic hearing, although almost exclusively low-frequency due to the patient's hearing characteristics, provides pitch information which is not provided by the cochlear implant alone.

BIMODAL HEARING RESULTS

Simulation

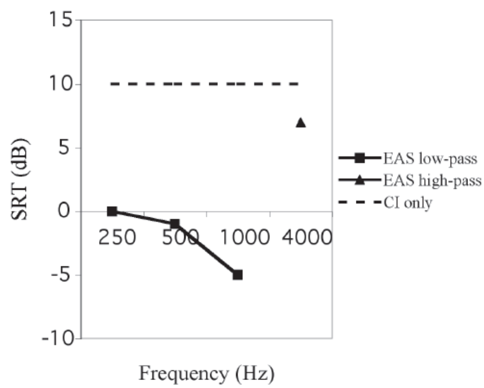

Fig. 6: Speech reception threshold (SRT) for HINT sentences with a female talker masker measured in eight normal-hearing subjects using a cochlear implant simulation. The dotted line represents the SRT with the cochlear implant simulation alone. Varying amounts of filtered acoustic information were added to the simulation, shown by squares for the low-pass conditions, and a triangle for the high-pass condition.

Recent research from our laboratory investigated the effect of adding unintelligible low-frequency sound to a cochlear implant simulation (Chang *et al.*, 2006). Eight normal-hearing listeners used a four-channel sine-carrier cochlear implant simulation. The test material was HINT sentences spoken by a male in the presence of a female talker masker. The SRT was measured; a lower SRT means better performance. The mean SRT was 10 dB with the cochlear implant simulation alone. The original signal was then low-pass filtered at 250, 500, and 1000 Hz, and high-pass filtered at 4000 Hz, producing four new filtered signals. This acoustic information alone produced poor speech intelligibility (0, 10, and 11% for low-pass cut-off 250, 500, and 1000 Hz, respectively). The high-pass information produced 18% sentence intelligibility. However, when this low-pass acoustic information was added to the cochlear implant simulation, it caused vast improvements in SRT. Figure 6 shows the SRT against the filter cut-offs. The squares represent SRT with the low-pass acoustic information. Although information below 250 Hz provided 0% intelligibility alone, when added to the cochlear implant simulation it improved the SRT by 10dB. In contrast, the high-pass information, represented by the triangle, did not provide a significant improvement in SRT, although alone it produced 18% intelligibility.

Cochlear implant subject with normal hearing in one ear

Convincing evidence for bimodal stimulation was obtained from one subject who has an Advanced Bionics HiRes 90k cochlear implant in his right ear, and virtually normal hearing in his left ear. He was implanted due to intractable tinnitus. This subject offers a rare opportunity to directly study the effect of providing natural acoustic information to a cochlear implant user. The subject was tested on HINT sentences spoken by a male, with a female talker masker at a fixed SNR of 0dB. He was tested in the implant ear using direct connection (thus avoiding assistance from the normal-hearing ear). In this condition, he scored only 2% correct words. The original signal was low-pass filtered at 150, 250, 500, and 1000 Hz, and high-pass filtered at 500, 2000, 4000, and 6000 Hz. These signals were presented to the normal-hearing ear using an insert earphone, both alone (acoustic only) and at the same time as the signal was presented to the cochlear implant ear (electroacoustic stimulation, EAS). Figure 7 shows the results. The low-pass acoustic only information presented to the normal-hearing ear (ac only low-pass) provided minimal intelligibility until the cut-off frequency was 500 Hz. However, in the EAS low-pass condition, there was a big improvement in the score. This demonstrates that although the low-pass acoustic information is unintelligible alone, it provides benefit when combined with electric stimulation. The same situation did not apply for the high-pass filtered information; the EAS high-pass and acoustic only high-pass scores were very similar, suggesting that addition of high-frequency fine structure does not improve electric hearing.

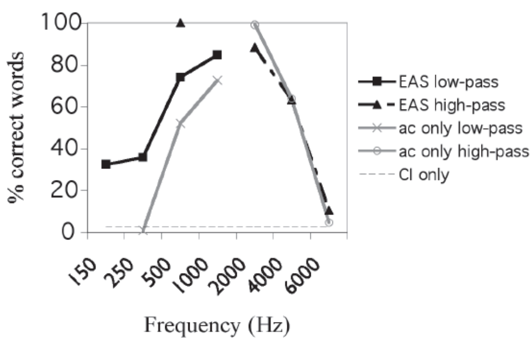

Fig. 7: Word recognition score on HINT sentences with a female talker masker at 0dB SNR measured in a cochlear implant subject with virtually normal hearing in the contralateral ear. The dotted line represents performance with the cochlear implant (CI) only. Varying amounts of filtered acoustic information were added to the normal-hearing ear at the same time as the original signal was heard with the CI ear (EAS). This is shown by squares for the low-pass conditions and triangles for the high-pass conditions. The crosses and the circles represent performance with the filtered low-pass and high-pass acoustic information alone, respectively.

Bimodal implant subjects

Previous work in our laboratory showed that bimodal hearing provided a significant benefit over unilateral cochlear implant use when listening with competing talkers, especially when the competing talker was a different gender from the target (Kong *et al.,* 2005). This is shown in Figure 8. Although the hearing aid alone provided virtually zero intelligibility (represented by the squares), when this was added to the cochlear implant, there was a big improvement in performance (triangles). The same study also examined melody recognition, and found that the subjects scored quite well with their hearing aid alone, and the bimodal condition was not significantly better than hearing aid alone. With cochlear implant alone, the melody recognition scores were poor. Although the hearing aid alone provided no speech intelligibility, it gave significant help with music.

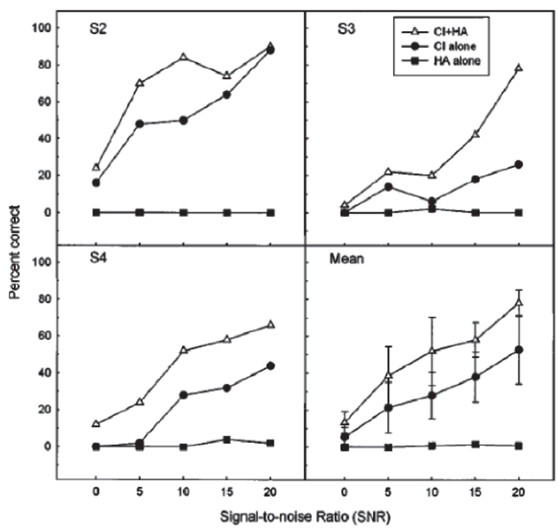

Fig. 8: Word recognition scores on HINT sentences with a female talker masker in three bimodal subjects (fourth panel shows mean). The squares represent performance with hearing aid (HA) alone, the circles are scores with cochlear implant (CI) alone, and the triangles represent bimodal (CI+HA) performance.

COMPARISON WITH BILATERAL COCHLEAR IMPLANTS

Clinicians, researchers, and cochlear implant companies are constantly striving to improve results for their clients. One major development in the past five to ten years has been the provision of a second implant to hundreds of patients: bilateral cochlear implants. Results with bilateral implants have generally shown improved localization and improved hearing in background noise, especially when the sources are spatially separated (Litovsky *et al.,* 2004). However there are some disadvantages of bilateral cochlear implants: the loss of residual hearing, additional surgery, risk of complete loss of vestibular function, and the cost. Residual hearing in both ears can be destroyed during bilateral implantation, thus jeopardizing the patient's chance of benefiting from future improvements in technology, for example hair cell regeneration. Hair cell regeneration has occurred in birds, and is being studied extensively (Bermingham and McDonogh, 2003). Although it may be several decades before this begins to provide a method of treating deafness, a child implanted at the age of one year potentially has many decades of life ahead of them.

Research is ongoing in our laboratory to compare bimodal and bilateral cochlear implant users on listening tasks that rely on pitch, specifically speech recognition with a competing talker, music perception, recognition of tone of voice, and identification of talker. We suggest that the bimodal configuration may provide better results than bilateral cochlear implants on these tasks. Although the hearing aid provides minimal speech intelligibility alone, it does provide complementary information in the form of low-frequency fine structure.

CONCLUSIONS

Bimodal hearing offers real advantages in listening situations that rely on pitch. In a clinical setting, bimodal hearing should always be recommended if there is any residual hearing in the non-implanted ear. Bimodal hearing should be considered the appropriate baseline against which to judge the advantages of bilateral implantation.

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