Cochlear Implants

Work supported by a grant from the W.M.Keck Foundation

OSP Numbers: 65405

Donald K. Eddington, Academic and Research Staff
Joseph Tierney, Academic and Research Staff
Victor Noel, Academic and Research Staff
Maggie Whearty, Massachusetts Eye and Ear Infirmary

Keywords: cochlear implants, neural prostheses, sensory aids, binaural hearing, signal processing

Introduction

Cochlear implants are devices designed to restore a measure of hearing to the deaf by electrically stimulating the remaining auditory-nerve fibers. Typically, an external sound processor transforms the output of a microphone into six to twenty spectrally distinct analysis channels. The output of each channel is encoded and transmitted to an implanted receiver/stimulator that delivers each of the output waveforms to a separate metal contact of an electrode array implanted near auditory nerve fibers in the patient's inner ear.

Figure 1 is an example of an early sound-processing strategy used for cochlear implants (Eddington 1980). After an automatic gain control (AGC), the microphone signal is presented to a set of band-pass filters that separate the sound spectrum into four processing channels. The current sources translate the voltage waveforms at the filters' outputs to the current waveforms delivered to the implanted electrodes. Output channels are connected to electrodes such that the higher the center frequency of a channel's band-pass filter, the more basal its electrode's position.

The dynamic range associated with electric hearing ranges from 3 to 24 dB (Eddington, Dobelle et al. 1978). This means that the 120-dB dynamic range of acoustic hearing must be compressed by the AGC. This system's name, Compressed Analog (CA), stems from the analog nature of the stimulus waveforms and the front-end compression.

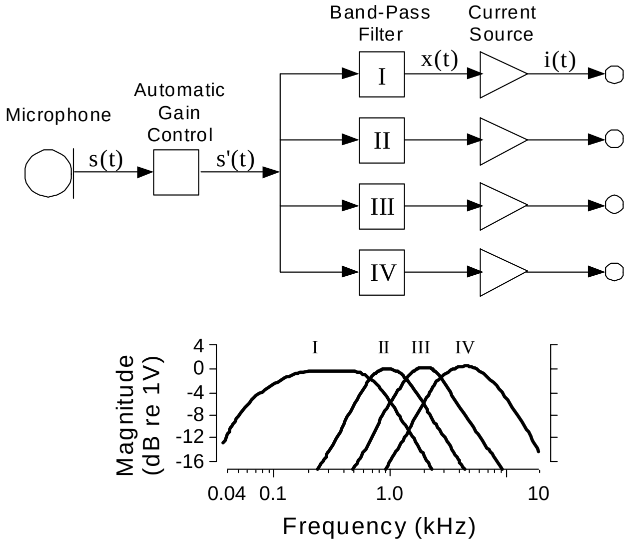

Figure 1. Top: block diagram of an early, four-channel sound processing system. Bottom: magnitude of the band-pass filters' transfer functions.

One problem with the CA strategy is illustrated in Figure 2 where the output waveforms in response to the vowel /a/ are plotted. Note that the stimulus produced by channel III is relatively strong, indicating significant energy in the input signal within the bandwidth of that channel. The vertical line of this figure marks a time when the output of channel III reaches a peak and channel II is delivering a negative signal. Because the distance between the electrodes of these neighboring channels is less than 4mm, their potential distributions will overlap and the responses of a significant number of nerve fibers will be influenced by the stimuli of both channels. At this time, the stimuli from these two channels are out of phase and will tend to cancel. This kind of interaction between the stimuli of two or more electrodes represents a distortion that can adversely affect speech reception.

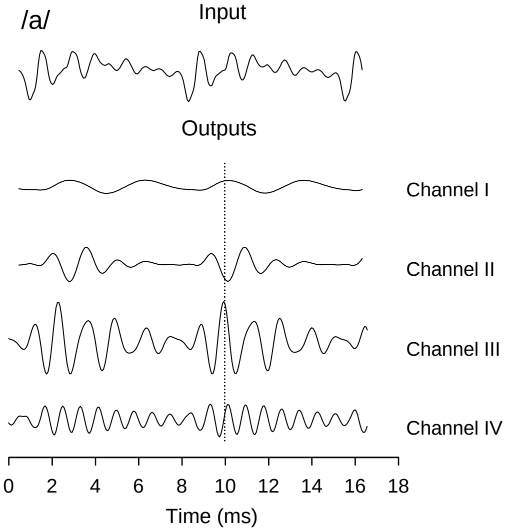

Figure 2. Stimulus waveforms produced by a four-channel CA processor in response to the vowel /a/. The top waveform is the input signal and the four bottom waveforms are the output sugnals of channels I through IV (see Figure 1).

In last year's report, we presented results showing that a patient's ability to receive speech information is negatively correlated with the degree to which a subthreshold masking stimulus delivered to the masker electrode influences the threshold measured using a standard test stimulus delivered to a neighboring test electrode. We defined an interaction index (II) that varies between 0 (no interaction) to 1 (threshold shifted the same amount as when the masker and test stimuli are both delivered to the test electrode). These data from 11 local subjects are shown here as Figure 3. Except for two subjects, the ability to recognize single-syllable words shows a strong negative correlation with the II.

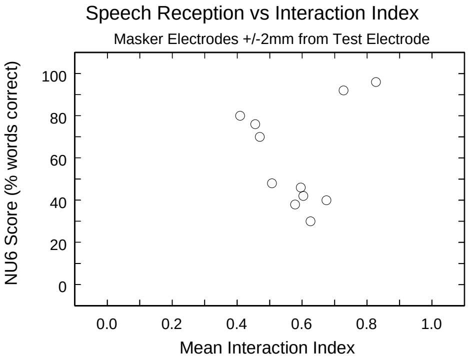

Figure 3. Scatter plot of single-syllable word recognition as a function of the mean Interaction Index for 11 subjects.

One approach that can reduce interaction is to use a processing strategy that temporally interleaves stimuli across electrodes (Eddington, Dobelle et al. 1978; Wilson, Finley et al. 1991). Two channels of such a processing strategy are shown in Figure 4. Like the

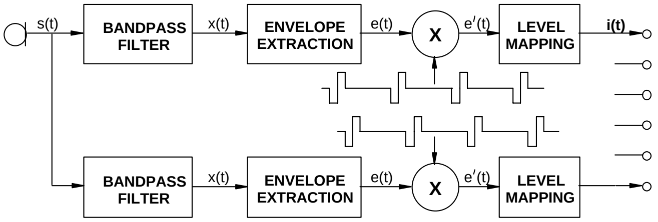

Figure 4. Block diagram of a processing strategy that interleaves stimuli across stimulating electrodes.

CA processor of Figure 2, this processor uses a set of band-pass filters to separate the spectrum into a number of channels. Each channel then extracts the filtered signal's envelope and uses it to amplitude modulate a biphasic pulse train. After compression by a level-mapping function, this modulated pulse train is delivered as a current waveform to the electrode. The pulsatile nature of the stimulus makes it possible to adjust the relative timing of the pulse trains across channels so that only one electrode receives non-zero stimulation current at any one time. This style of signal processing is called a Continuous Interleaved Sampling (CIS) processing strategy.

Figure 6 shows the effect on speech reception of switching from a CA to a CIS strategy in 14 local subjects . Different lists of the recorded CUNY sentences (Boothroyd, Hanin et al. 1985) were used (without speechreading) to evaluate performance of the subjects at the three times described in the caption. These test materials are relatively easy because the internal predictability of each sentence (e.g., "Take your baseball glove to the game.") enables one to piece together the unrecognized segments from the scattered segments that are recognized.

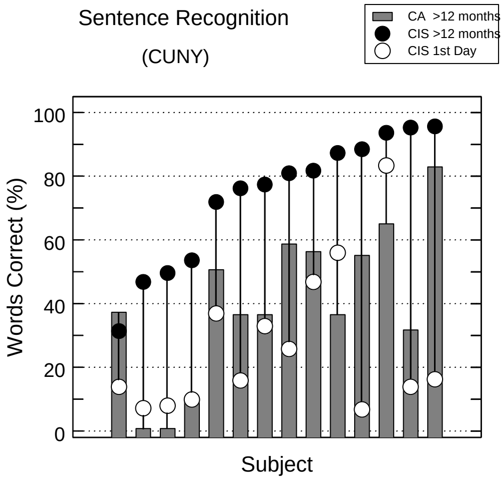

Figure 5. Percentage of words identified correctly when lists of the CUNY sentences are presented without speech reading to 14 profoundly impaired users of the Ineraid cochlear implant system. Each subject was tested at three times: (1) after 12 months experience using a CA style sound processor (bars), (2) the same day they switched from the CA processsor to a CIS processor (open cirlcles), and (3) after 12 months experience with the CIS processor (filled circles).

The bars of Figure 6 represent the word scores of the 14 subjects tested using their CA strategy. At the time of the test, they had worn that system for at least 12 months. The scores for this case range from 0 to 82%. The open circles represent the scores measured using the CIS system on the day subjects switched to this new processing strategy. Note that in some cases performance increased immediately but in others it decreased substantially. After using the CIS strategy for more than 12 months, performance was measured again (filled circles).

It is clear that the CIS system resulted in better speech reception for most of these subjects.

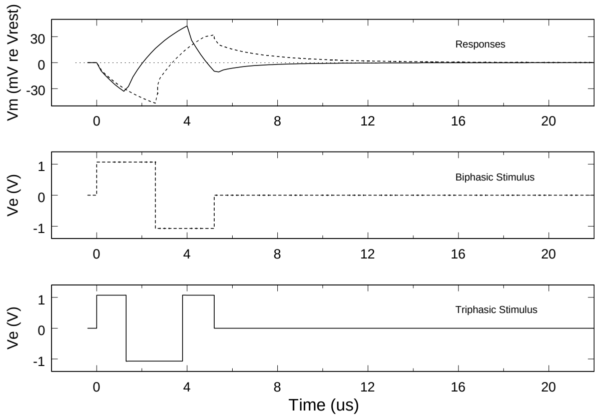

Figure 6. The top panel plots the membrane voltage (Vm) at a single node of a single-fiber model in response to the two electric stimuli shown in the bottom two panels. Ve represents the voltage at the same node.

Because this improvement is likely due to a reduction in the interaction between stimuli delivered by separate electrodes, other techniques for minimizing interaction may also prove beneficial. One method we are currently investigating is optimizing the stimulus waveform. This is motivated by data like those shown in Figure 6 where the model (Frijns 1995) nerve-fiber response to the two stimuli diagrammed in the bottom panels are plotted in the top panel. Note that in the case of the triphasic stimulus, the membrane potential (Vm) is substantially closer to the resting value at the end of the stimulus waveform than in the case of the biphasic waveform. This means that the response to a second stimulus directly following the first is more likely to be influenced by the biphasic than the triphasic waveform.

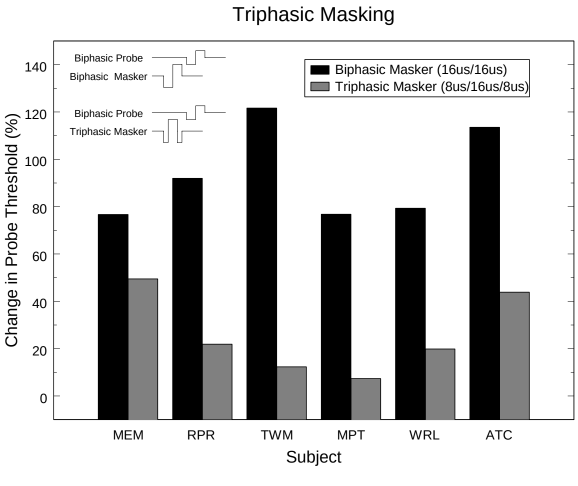

Figure 7. The time waveforms in the upper left show the relationship of the biphasic and triphasic maskers to the biphasic probe waveform. The bars represent the percentage change in the probe threshold when measured in the presence of each masker for six subjects.

The results in Figure 7 show the degree to which the behavioral threshold of a biphasic pulse (16 μsec/phase) delivered to one electrode (the probe stimulus) is influenced by a suprathreshold, masker stimulus delivered to an adjacent electrode (4 mm electrode separation) for triphasic and biphasic maskers. Note the substantial reduction in the masker's effect for triphasic vs. biphasic masker waveforms. We are currently designing sound processing strategies that employ triphasic waveforms to determine whether the reduced interaction will result in better speech reception.

References

Boothroyd, A., L. Hanin, et al. (1985). A Sentence Test of Speech Perception: Reliability, Set Equivalence, and Short Term Learning. New York, NY, City University of New York.

Eddington, D. K. (1980). "Speech discrimination in deaf subjects with cochlear implants." J Acoust Soc Am **68**(3): 885-91.

Eddington, D. K., W. H. Dobelle, et al. (1978). "Auditory prosthesis research with multiple channel intracochlear stimulation in man." Ann Otol Rhinol Laryngol Suppl **87**(6 Pt 2): 1-39.

Frijns, J. H. M. (1995). Cochlear implants: a modelling approach. Faculteit der Godgeleerdheid. Eindhoven, Rijksuniversiteit te Leiden: 184.

Wilson, B. S., C. C. Finley, et al. (1991). "Better speech recognition with cochlear implants." Nature **352**(6332): 236-8.

Publications

Litvak, L., B. Delgutte, et al. (2001). "Auditory nerve fiber responses to electric stimulation: modulated and unmodulated pulse trains." J Acoust Soc Am **110**: 368-379.

Nadol, J. B., J. Y. Shiao, et al. (2001). "Histopathology of Cochlear Implants in the Human." Ann Otol Rhinol and Laryngol **110**: 883-891.

Manuscripts Submitted

Litvak, L., B. Delgutte, et al. (2002 (submitted)). "Responses of auditory-nerve fibers to sustained, high-frequency electric stimulation. I. Unmodulated pulse trains." J Ascoust Soc Am.

Litvak, L., B. Delgutte, et al. (2002 (submitted)). "Responses of auditory-nerve fibers to sustained, high-frequency electric stimulation. II. sinusoidal modulators." J Ascoust Soc Am.

Litvak, L., B. Delgutte, et al. (2002 (submitted)). "Responses of auditory-nerve fibers to sustained, high-frequency electric stimulation. III. Vowel modulators." J Ascoust Soc Am.

Theses

Long, C. J. (2000). Bilateral cochlear implants: basic psychophysics. Harvard-MIT Division of Health Sciences and Technology. Cambridge, Massachusetts Institute of Technology**:** 175.