A model of the auditory nerve for acoustic and electrical excitation

BAI Bio-Inspired Information Processing
Prof. Dr. Werner Hemmert

IMETUM Zentralinstitut für Medizintechnik

Michele Nicoletti and Werner Hemmert

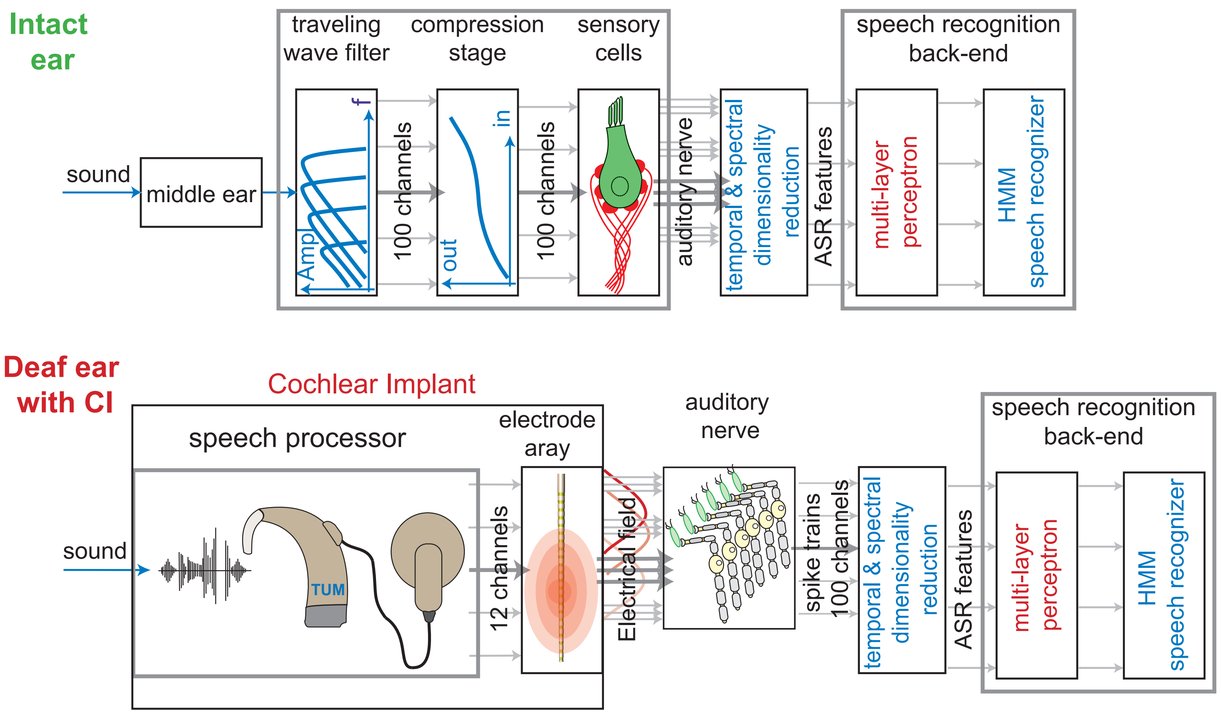
Bernstein Center for Computational Neuroscience Munich

ABSTRACT

For both normal hearing subjects and cochlear implant patients the most drastic step of sound coding for neuronal processing is when the analog signal is converted into discrete nerve-action potentials. As any information lost during this process is no longer available for neural processing, it is important to understand the underlying principles of sound coding. Here we focus on a model of spiral ganglion type I neurons with Hodgkin-Huxley type ion channels, which are also found in cochlear nucleus neurons. Depending on the task, we model the neurons at different levels of detail. We analyze the quality of coding with the methods of information theory.

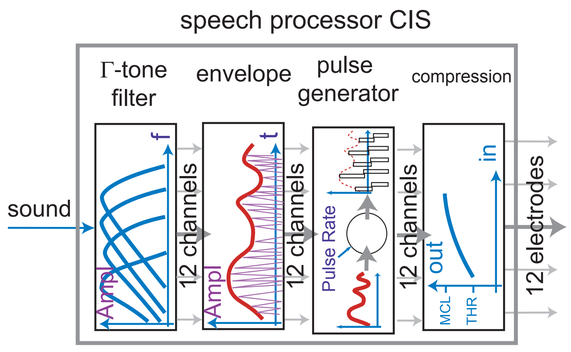
Our results show that for acoustic stimuli, the model provides realistic refractoryness and generates more realistic spike trains compared to an artiffcial spike generator. Not surprisingly, speech discrimination in electrical hearing is lower than in acoustic hearing. On the other hand, the temporal precision of information coding seems to be very high because at levels well above threshold, action potentials are elicited quasi deterministic by the electrical stimuli.We argue that CIS strategies a) waste as much as 50% of this information and b) much of the information coded in the time domain can not be retrieved by the neurons in the cochlear nucleus.

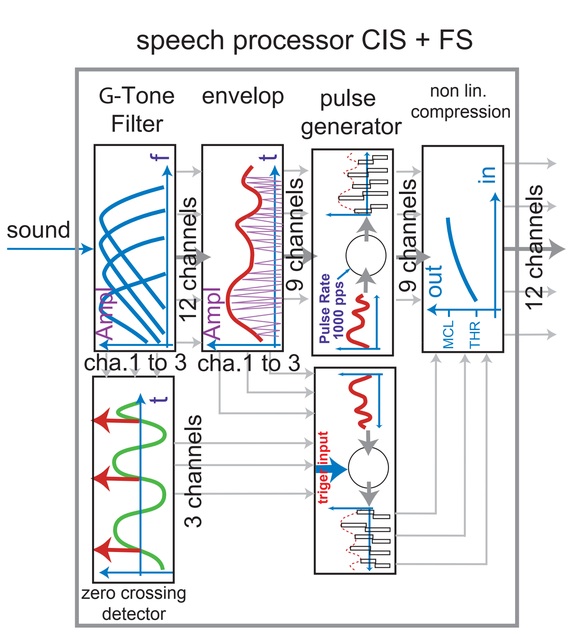
Model of acoustic and electric hearing & interface to ASR



Schematic figure of our models for acoustical (intact inner ear) and electrical (inner ear with CI) stimulation. Our inner ear model separates sound signals into 100 frequency channels. In each channel, a sensory cell converts the band-passed and compressed signal into spike trains of multiple auditory nerve fibers (ANFs). For the implanted ear, auditory nerve fibers are modeled with single- or multi-compartment models with Hodgkin-Huxley like ion channels. Here we focus on a model of spiral ganglion type I neurons with Hodgkin-Huxley type ion channels, which are also found in cochlear nucleus neurons (HPAC, Kht, Klt). Their large time constants might be responsible to explain adaptation to electrical stimulation (Negem 2008). We corrected conductances and time-constants to a body temperature of 38° and solved the differential equations in the time domain with a exponential Euler rule.

The electrode was modeled as an array of 12 current point sources at a distance of 0.5 mm from the spiral ganglion cells. The coupling between electrode and excitation of the neuron is described by the activation function (second derivative of the extracellular potential with respect to the neuron's path). Cannel cross-talk is modeled by a convolution of the activation function with a spread function (symmetric, slope: 1dB/mm).



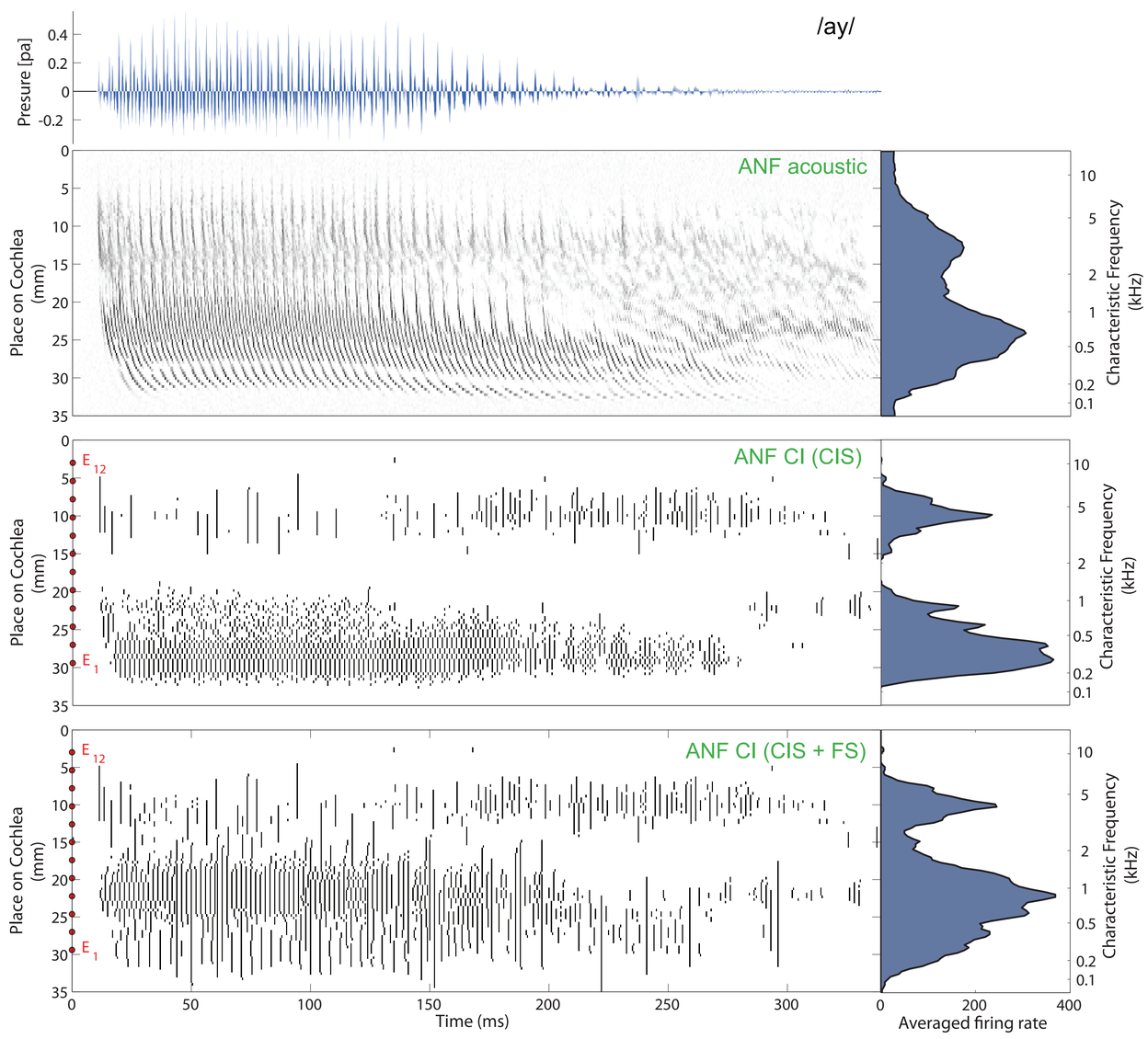


Most of the current CI speech processors use the well-known continuous interleaved sampling (CIS) strategy (Wilson 1999). The CIS strategy was invented to reduce channel interaction using interleaved, non-simultaneous stimuli at a high rate (1000 pps). Sound signals are passed through a digital Gammatone filter bank, then envelopes are extracted and modulated with biphasic current pulses. The biphasic current pulses are compressed and delivered non-simultaneously to the multiple electrodes.

In conversational speech, the acoustic amplitudes may vary over a range of 40 dB. Implant listeners, however, may have a dynamic range as small as 5 dB. Therefore, envelope compression is done by mapping acoustic amplitudes to electrical amplitudes using nonlinear mapping functions (logarithmic compression function).

The fine structure (FS) coding strategy encodes temporal fine structure (TFS) on a few apical channels, while the remaining more basal channels carry CIS stimuli. Temporal information is provided by a zero crossing detector: at each zero crossing in a channel's bandpass filter output, a series of stimulation pulses is elicited.

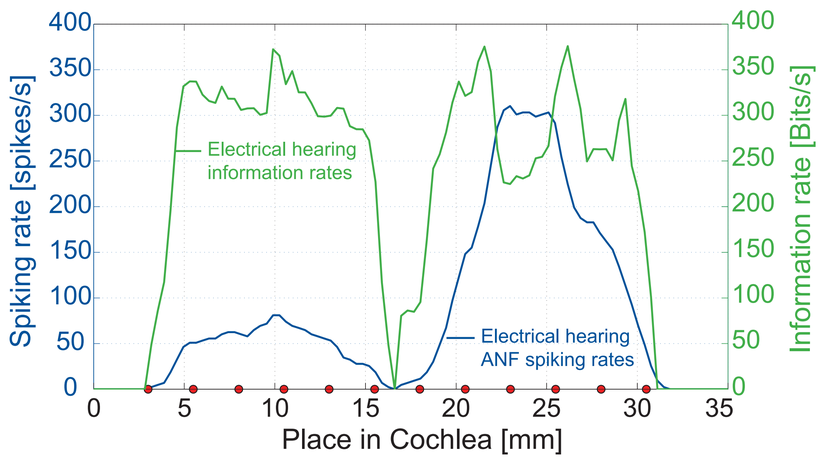
Comparison of Coding Strategies



Response pattern of auditory nerve fibers in response to the spoken utterance /ay/ from the ISOLET database (female speaker fcmc0-A1-t, upper trace, 72.8 dB(A)). Upper panel: acoustic stimulation. Second panel: 60 high-spontaneous-rate ANFs (left) per frequency channel and averaged firing rate (right). Third panel: response of a single ANF for electric stimulation (CIS strategy). Lower panel: ANF response for electric stimulation (CIS + FS strategy). Red circles on the left y-axis represent the positions of the stimulation electrodes in the cochlea. Due to the small dynamic range of electrically excited ANFs and the probably lacking spontaneous activity response patterns exhibit idle areas. Electrical crosstalk (here: 1 dB/mm) limits the resolution of electrical stimulation. Whereas for the CIS strategy, no phase-locking is provided at low frequency channels. The TFS in apical channels provides time and some residual place information (depending on the distribution of electrode center frequencies) for the fundamental frequency (pitch) as well as for the lower harmonics of the sound signal.

Information transmission by neural spike-trains

Information distribution of auditory nerve spike trains along the cochlea. Green lines indicate the information rate (word duration: 10 ms; resolution: 0.25 ms, vowel /ay/ at 72,8 dB(A)). Red circles on the x-axis represent positions of the stimulation electrodes in the cochlea. Electrical hearing aims to replicate spiking rates of the ANF.



The information rate of electrical hearing shows maxima at the formant frequencies of the vowel but degrades with high-level stimulation because the neurons saturate and fire at maximum speed (between 23 and 25 mm location).

Conclusion

- Electric hearing is able to restore rate-place coding with a precision sufficient for speech perception in clean conditions, which however degrades severely in noise.
- Strategies, which code temporal fine structure in low-CF channel seem to provide more natural stimulation of the auditory nerve.
- Model calculations of information transmission (data not shown) for electrical stimulation predict very high values, however, it is unclear if this information can be decoded.

References

• Holmberg, M., Gelbart, D. and Hemmert, W. (2007), Speech Communication, 49(12), pp. 917-932.
• Negm, M. and Bruce, I. (2008). EMBS 2008, pp 5539-5542.
• Shepherd, R. K. & Javel, E. (1997). Hear Res. , 108, pp. 112-144
• Wilson, B. S.; Finley, C. C.; Lawson, D. T.; Wolford, R. D.; Eddington, D. K. & Rabinowitz, W. M. (1999). Nature, Neuroscience Program, 352, pp. 236-238
• Kral, A.; Hartmann, R.; Mortazavi, D. & Klinke, R. (1998). Hearing Research, 121, pp.11-28

This work was funded by a grant from MED-EL Innsbruck and within the Munich Bernstein Center for Computational Neuroscience by the German Federal Ministry of Education and Research (reference number 01GQ0441).