Effects of interaural time differences in fine structure and envelope on lateral discrimination in bilateral electrical hearing

Piotr Majdak[1], Bernhard Laback[1], Wolf-Dieter Baumgartner[2]

[1] *Acoustics Research Institute, Austrian Academy of Sciences, 1010 Wien, Austria, Email: piotr@majdak.com*

[2] *HNO-Abteilung, Allgemeines Krankenhaus, 1090 Wien, Austria*

Introduction

Localization of sound sources is partly based on interaural time differences (ITDs) [1]. For lower frequencies, the neural stimulation pattern is synchronized to the phase of the carrier signal [2]. Interaural difference of the phase, so called fine structure ITD (ITD FS), is important for determining the lateral position of the sound source. Bilateral cochlear implant (CI) listeners currently use stimulation strategies which encode ITD in the temporal envelope but which do not transmit ITD in the fine structure due to the constant phase in the electrical pulse train [3].

To determine the necessity for encoding ITD FS, ITD-based lateralization discrimination was investigated with CI listeners and normal hearing (NH) subjects at different pulse rates for various combinations of independently controlled ITD ENV and ITD FS. Results show that ITD FS had the strongest impact on lateralization discrimination at lower pulse rates, with significant effects for pulse rates up to 800 pulses per second (pps). At higher pulse rates, lateralization discrimination depended on envelope ITD (ITD ENV) only. It is concluded that bilateral CI listeners benefit from transmitting fine structure ITD at lower pulse rates.

Methods

Four CI listeners were tested. Three of them were implanted bilaterally with the C40+ implant system manufactured by MED-EL Corp. One CI listener (CI2) used the C40+ in the left ear and an older implant, the C40, in his right ear. Four NH subjects participated in this study and they had no indication of hearing abnormalities. To allow a direct comparison to CI subjects, NH subjects were tested listening an acoustical simulation of electrical stimulation [4].

The stimuli were amplitude modulated pulse trains. ITD FS and ITD ENV were introduced by delaying the temporal position of the pulses and of the envelope, respectively, at one ear relative to the other ear. The envelope consisted of 4 trapezoids with durations of 60ms, each repeated at a period of 80ms, resulting in 20ms gaps between two successive trapezoids and a total stimulus duration of 300ms (Figure 1).

The electrical pulse trains were composed of biphasic current pulses. An interaurally pitch matched electrode pair was used for all experiments. The levels were binaurally balanced at a comfortable loudness. The pulse rates to be tested were 200, 400, 1600pps (CI1); 100, 200, 400pps (CI2); 400, 800, 1600pps (CI3); and 400, 800, 938pps (CI8). These parameters were selected individually for each subject in pretests [5].

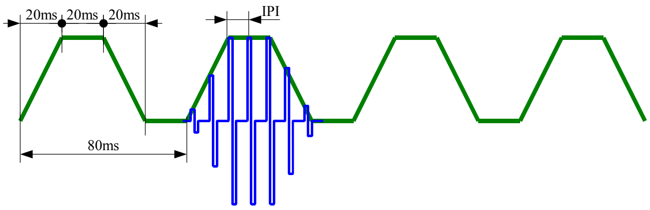

Figure 1: A symbolic representation of the stimulus used in this study. For readability purposes the fine structure characteristics is shown in one trapezoid only.

Eight ITD FS values were chosen for each pulse rate, which corresponded to values from 0µs up to seven-eighth of the interpulse interval (IPI) in steps of eighth IPI. These values corresponded to ITD FS which would occur in a setup of unsynchronized speech processors. Two ITD ENV values were chosen per listener group: 400µs, 625µs for NH listeners and 625µs and 800µs for CI listeners.

A two-interval, two-alternative forced-choice procedure was used in the lateralization discrimination tests. The first interval contained a reference stimulus with zero ITD. The second interval contained the target stimulus with the ITD tested. The subjects were requested to indicate whether the second stimulus was perceived to the left or to the right of the first one by pressing an appropriate button. Each stimulus was repeated at least 60 times, in a balanced format with 30 targets on the left and 30 targets on the right. Thus, a subject with no ITD sensitivity could get 50% responses correct by guessing. To simplify the interpretation of the results, scores ranging from 0% to 100% were mapped to a range from -100% to +100%, referred to as “lateralization discrimination” (LD).

Results

The lateralization discrimination (LD) data of the individual CI listeners and NH subjects as average are shown in Figure 2. For all listeners there was a common pattern of LD as a function of ITD FS. At the lowest pulse rates (different for each subject) in the conditions ITD ENV = 0µs LD increased monotonically with ITD FS for ITD FS <= 0.25 IPI with a maximum at about 0.25 IPI. For ITD ~ 0.5 IPI, LD was at chance (=0%), confirming the ambiguity in the lateralization task using ITD FS only. As ITD FS exceeded 0.5 IPI, the magnitude of LD as a function of ITD FS was similar to that for ITD FS < 0.5 IPI but with the opposite sign. This indicates that LD upon ITD FS is periodic and that stimuli with ITD FS > 0.5 IPI effectively represent stimuli with negative ITD FS. At the highest pulse rates tested (different for each subject) the dependence of LD on ITD FS disappeared. Introducing a non-zero ITD ENV resulted in a lateralization shift towards the ear receiving the stimulus with the leading envelope. This effect seems to increase with increasing pulse rate.

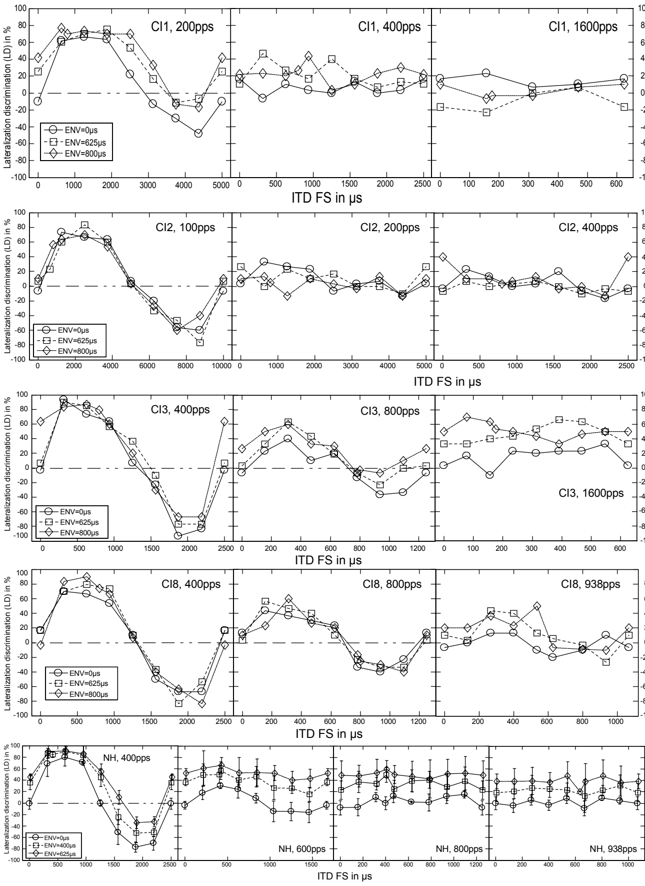

Figure 2: Lateralization discrimination for CI and NH listeners and different pulse rates. To point out the periodicity of ITD FS the data points for ITD FS = IPI are copies of the data points for ITD FS = 0µs. Note the different scaling of the X axes.

Although most trends were easily distinguishable, a multidimensional contingency table analysis [6] was used to determine the significance of the trends. To address the question of the need for interaural pulse synchronization the dependence of LD on ITD FS was investigated, revealing that the better performing CI listeners (CI3, CI8) showed significant sensitivity to ITD FS for pulse rates up to 800pps, while for the poorer performing CI listeners (CI1, CI2) a significant sensitivity could be found only for pulse rates up to 200pps.

It was further hypothesized that for conditions showing a dependence of LD on ITD FS, the synchronization of ITD FS to ITD ENV (WD) would result in a higher LD than synchronizing ITD FS to zero (ENV). For the CI listeners, improvements due to this synchronization were observed for the following pulse rates: 200pps (CI1), 100pps (CI2), and 400pps (CI3 and CI8). The NH subjects showed an improvement using the WD condition for pulse rates up to 600pps for an ITD of 400µs ($p=0.04$) and up to 400pps for an ITD of 625µs ($p<0.001$). This revealed an interesting effect of combining ITD FS and ITD ENV: assuming a dependence of LD on ITD FS, it can be expected that increasing the ITD in both the envelope and fine structure (WD) improves LD up to about 0.25 IPI. Above this point, up to ITD = 0.5 IPI, LD is expected to decrease because at ITD = 0.5 IPI the ITD FS cue provides ambiguous information. Increasing the ITD further, depending on the relative perceptual contribution of ITD ENV, the stimulus may even be lateralized towards the opposite side. This actually happened for CI8 (800pps, ITD FS=800µs). Thus, the synchronization of the fine structure to the envelope gives an improvement for ITD values smaller than half IPI only. To avoid this problem a condition termed *diminished waveform delay* (WD_{DIM}) and a new formula for ITD FS coding are proposed:

$$ITD\,FS = min\left(ITD\,ENV\,, \frac{1}{4}\,IPI\right) \qquad (1)$$

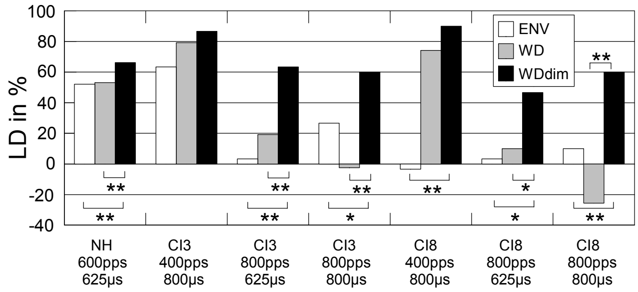

Figure 3: Comparison of lateralization discrimination for conditions ENV, WD and WD_{DIM}. Significance codes: * $p<0.05$; ** $p<0.01$

Figure 3 compares lateralization discrimination between the conditions ENV, WD, and WD_{DIM}. In most cases LD increased using WD_{DIM} optimization; in one case (CI8, 800pps, 800µs) even a reversal of lateralization into the correct direction could be achieved.

References

[1] Factors Affecting the Relative Salience of Sound Localization Cues. *Binaural and Spatial Hearing in Real and Virtual Environments*, Lawrence Erlbaum Associates, Mahwah, New Jersey, 1997

[2] Auditory Processing of Interaural Timing Information: New Insights. J Neurosci Res **66** (2001), 1035–1046

[3] Sensitivity to interaural level and envelope time differences of two bilateral cochlear implant listeners using clinical sound processors. Ear & Hearing **25** (2004), 488-500

[4] Dual temporal pitch percepts from acoustic and electric amplitude-modulated pulse trains. J Acoust Soc Am **105** (1999), 347-357

[5] Interaural Time Differences in Temporal Fine Structure, Onset, and Offset in Bilateral Electrical Hearing. 28th Midwinter Research Meeting of the Association for Research in Otolaryngology, New Orleans, 2005

[6] Analysis of Ordinal Categorical Data. John Viley & Sons, Inc., New York, 1984