Binaural jitter improves ITD sensitivity of cochlear implantees and normal hearing listeners

Bernhard Laback, Piotr Majdak, and Matthew Goupell

[1] *Acoustics Research Institute, Austrian Academy of Sciences, 1040 Wien, Austria*
email: Bernhard.Laback@oeaw.ac.at

Introduction

Interaural time differences (ITD) in the fine structure of a sound are an important cue for localization in the left/right dimension [1]. Cochlear implant (CI) listeners have been shown to be sensitive to fine-structure ITD but their sensitivity is limited to a few hundred pulses per second [2,3]. This poses a problem for speech coding where higher pulse rates are required. This rate limitation in CI listeners is reminiscent of the decreasing ITD sensitivity of normal hearing (NH) listeners with increasing modulation rate of a high-frequency carrier signal, a phenomenon referred to as binaural adaptation [4].

In this study it was hypothesized that the rate limitation in CI listeners can be overcome by introducing temporal changes into the pulse timing. This was inspired by the finding of [5] that introducing a change (trigger) in a pulse train causes a recovery from binaural adaptation in NH listeners.

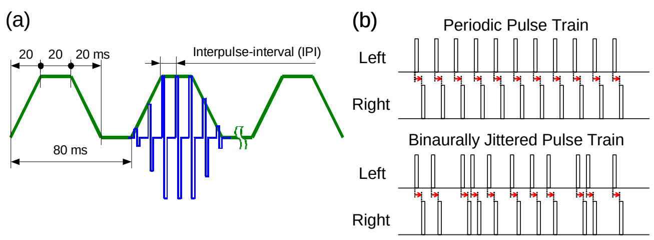

Fig. 1: a) Schematic illustration of the experimental stimuli. b) periodic condition (upper panel) and condition with binaural jitter (lower panel).

Study 1 reports the effect of binaural jitter, a means of ongoing temporal change, on the ITD sensitivity of CI listeners using pulse trains. Study 2 reports the effects in NH listeners of the same manipulation on acoustic pulse trains. The neural response to the acoustic pulse trains was analyzed using an established model of peripheral auditory processing.

Study 1: Effect of jitter in CI listeners

Five postlingually deafened CI listeners (*C40+*, *MED-EL*) were tested on a single interaural electrode pair, which elicited the same place pitch. The stimuli were transmitted directly via an interaurally synchronized research interface. The current levels of the stimuli, 300-ms trains of biphasic pulses, where adjusted at each tested rate to obtain a centralized image at a comfortable loudness. The pulse trains were amplitude modulated at 12.5 Hz, as shown in Figure 1a). Both the carrier and the envelope contained the ITD. The task of the subjects was to left/right discriminate a target stimulus with ITD presented after a reference stimulus with zero-ITD. Figure 1b) shows the two types of pulse trains tested. Periodic pulse trains have a constant interpulse interval (IPI). Jittered pulse trains have random IPIs which are synchronized between the two ears. Thus, the ITD between pulses remains constant. The jitter followed a uniform distribution with the parameter k determining the amount of jitter. For $k = 0$ the pulse train is periodic and for $k = 1$ the largest possible IPI is twice the nominal IPI and the smallest IPI is 0. Pulse rates from 400 up to 1515 pps were tested at ITD values 100, 200, 400, and 600 µs. More details of the experiment are provided in [6].

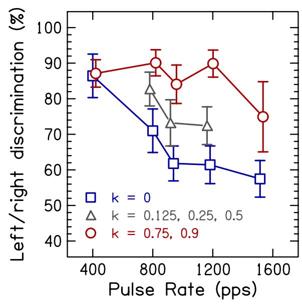

Fig. 2: *Pc* as a function of pulse rate, averaged over five CI listeners and the ITD values 200, 400, and 600 µs. The parameter is the amount of jitter (k).

Figure 2 shows the left/right discrimination score (*Pc*) as a function of pulse rate, averaged over the five subjects and the three larger ITD values. At 400 pps, *Pc* is high and there is no difference between the periodic and the jittered conditions. At rates greater than 400 pps, *Pc* decreases sharply with increasing pulse rate ($p < 0.0001$) for the periodic condition. For the jittered conditions, there are large improvements ($p < 0.0001$), which are larger for larger k values (0.75, 0.9) compared to lower k values (0.125, 0.25 and 0.5). The improvements are significant even at 1515 pps ($p < 0.0003$). Plotting the data at higher pulse rates (where large effects of jitter were found) as a function of ITD (not shown) reveals almost flat functions for the periodic condition and monotonicly increasing functions for the jittered conditions. Interestingly, jitter improves *Pc* significantly even for ITDs exceeding ¼ IPI, which have been shown to provide ambiguous cues [3] (e.g. ITD = 600 µs at 1182 pps)

Study 2: Effect of jitter in NH listeners

Six normal hearing listeners were tested listening to bandpass-filtered acoustic pulse trains (center frequency: 4.6 kHz, bandwidth: 1500 Hz). The stimuli were presented via headphones.

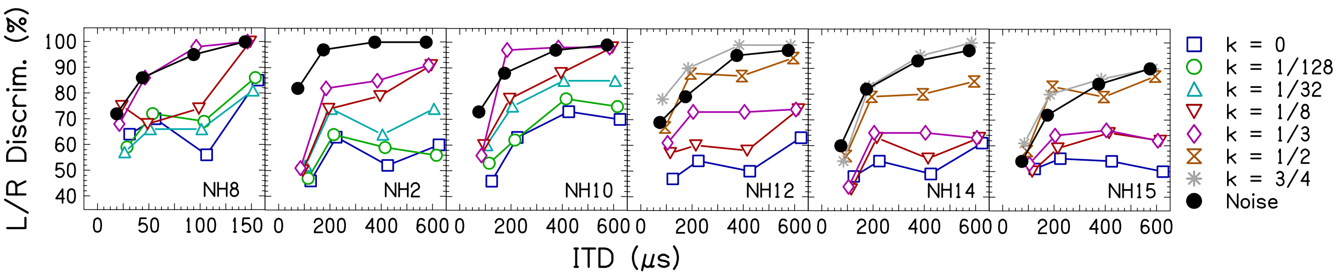

Fig. 3: *Pc* as a function of ITD for six NH listeners. The parameter is the amount of jitter (*k*). Gaussian noise data are indicated by filled circles.

The pulse trains had no AM but 150-ms linear ramps. The pulse rate was 600 pps and *k*-values were selected individually to sample a wide range of performance. The level of the stimuli was 61.3 dB SPL. A continuous masking noise (low-pass filtered at 3500 Hz) was presented to mask any low-frequency ITD cues. Other aspects of the experiment were the same as in the "electric" study with the exception of one especially sensitive listener who required lower ITD values (25, 50, 100, 150 µs). As a special condition, bandpass-filtered Gaussian noise was tested using the same filter settings as for the pulse trains.

Figure 3 shows *Pc* vs. ITD for the individual listeners. The data show that adding jitter increases ITD sensitivity which was supported by statistical analysis ($p < 0.0001$). The amount of improvement increased with increasing *k*. Note that different subjects required different *k*-values to obtain a certain degree of improvement. The performance seems to be limited by the data taken for the Gaussian noise.

Modeling of neural response in normal hearing

To better understand the effect of jitter, the response of neurons in the auditory nerve and cochlear nucleus (CN) was simulated [7]. Figure 4 shows the post-stimulus time histogram (PSTH) of an array of 200 CN neurons over a 20 ms window for a 600-pps pulse train with k = 0, ¼, ¾, and for Gaussian noise, generated from 100 repetitions of the model. For k = 0, each pulse evokes a small peak in the PSTH. For $k > 0$, there are less but higher peaks. Thus, jitter causes a redistribution of spikes, leading to more synchrony at certain time instances. Interestingly, the response to filtered noise is similar to that for the pulse train with k = ¾.

General Discussion

Binaural jitter considerably improved fine-structure ITD sensitivity of CI listeners at high pulse rates, even up to 1515 pps. This is advantageous for encoding speech, where such high rates are required. Thus, binaural jitter may be used in future CI systems to improve sound localization and speech perception in noise. The mechanisms leading to the improvements of the CI listeners are unclear so far. They could be understood in terms of a recovery from binaural adaptation due to the ongoing *temporal* changes. Note that Hafter and Buell [4] interpreted the recovery from binaural adaptation resulting from insertion of a gap in an acoustic pulse train by means of the induced *spectral* changes. The improvements by jitter could also be understood in terms of the explanation provided for the NH listeners, namely the increased temporal synchrony of responses at the CN.

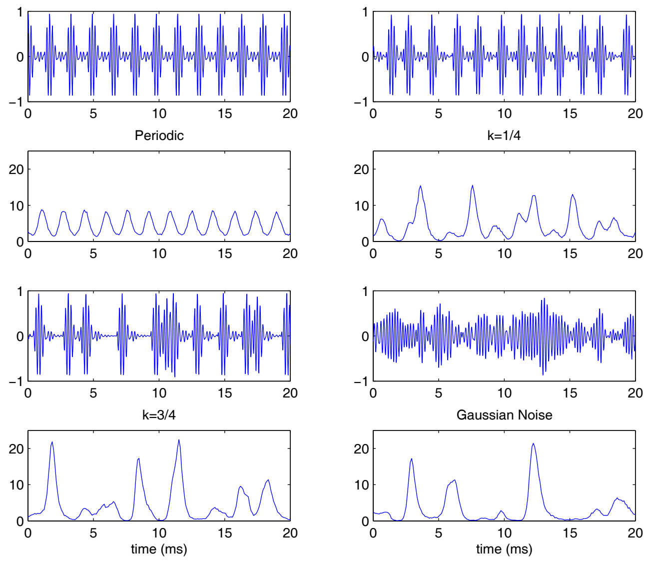

Fig. 4: Simulated post-stimulus time histogram of an array of 200 CN neurons for 600 pps pulse trains with k = 0, ¼, and ¾ and for Gaussian noise, based on 100 model repetitions.

References

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