Effect of Center Frequency on the Sensitivity to Interaural Time Differences in Filtered Pulse Trains.

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Introduction

Some cochlear implant (CI) listeners are sensitive to interaural time differences (ITD) in the temporal fine structure for pulse rates up to 800 pulses per second (pps) [1,2]. The rate limitation in normal hearing (NH) depends on the type of stimulus. For high-frequency filtered transients, the rate limit is within the range 256 – 600 pps, thus lower than in CI listeners [1,2,3]. For pure tones, the rate limit is about 1500 Hz, thus higher than in CI listeners [4]. This study attempted to verify that the NH listeners' performance using high-frequency filtered pulse-trains in [1,2] was not underestimated by a potentially unfavorable choice of the center frequency (CF) of the stimulus (4.6 kHz) based on the following hypothesis: if the ringing of the auditory filters limits ITD perception at higher pulse rates, the maximum pulse rate showing significant effects of ITD will increase with increasing CF.

ITD sensitivity with SAM stimuli and so-called "transposed tones" has been shown to decrease with increasing CF beyond 4 kHz [3], thus not supporting the hypothesized effect of auditory filters. However, the stimuli in that study had a constant bandwidth in Hz, implying a decreasing bandwidth on the basilar membrane in ERB (equivalent rectangular bandwidth). This could unfairly favor the lower CFs in terms of the number of stimulated neurons. To rule out this confounding variable, we used filtered pulse trains with a constant bandwidth in ERB.

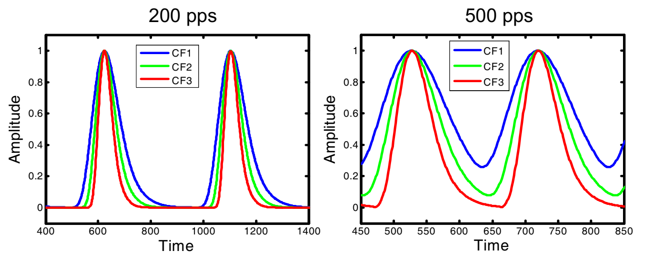

Figure 1: Envelopes of the pulse trains after passing auditory filters at the three CFs at 200 pps (left panel) and 500 pps (right panel). With increasing CF, the amount of modulation increases, in particular at the higher pulse rate.

Methods

Five NH listeners participated in the experiment. Trains of monophasic pulses (pulse duration: 10.4 µs) were bandpass-filtered (digital eighth-order Butterworth filter, 48 dB/octave) in three frequency regions with center frequencies 4589, 6490, and 9178 Hz. The regions are referred to as CF1, CF2, and CF3, respectively. The corresponding bandwidths are 1500, 2121, and 3000 Hz, respectively. Pulse rates from 200 to 588 pps were tested. Pulse trains had a duration of 300 ms and had no onset/offset ramps. Waveform ITD was applied to the ongoing pulses, i.e. all pulses besides the first and last one (see [1]). The sound pressure level was 66 dB SPL. A white background noise (50-20000 Hz) was continuously presented to avoid artifacts like combinations tones from being heard. Fig. 1 shows the envelopes of the pulse trains after passing auditory filters at the three CFs for rates of 200 pps (left panel) and at 500 pps (right panel).

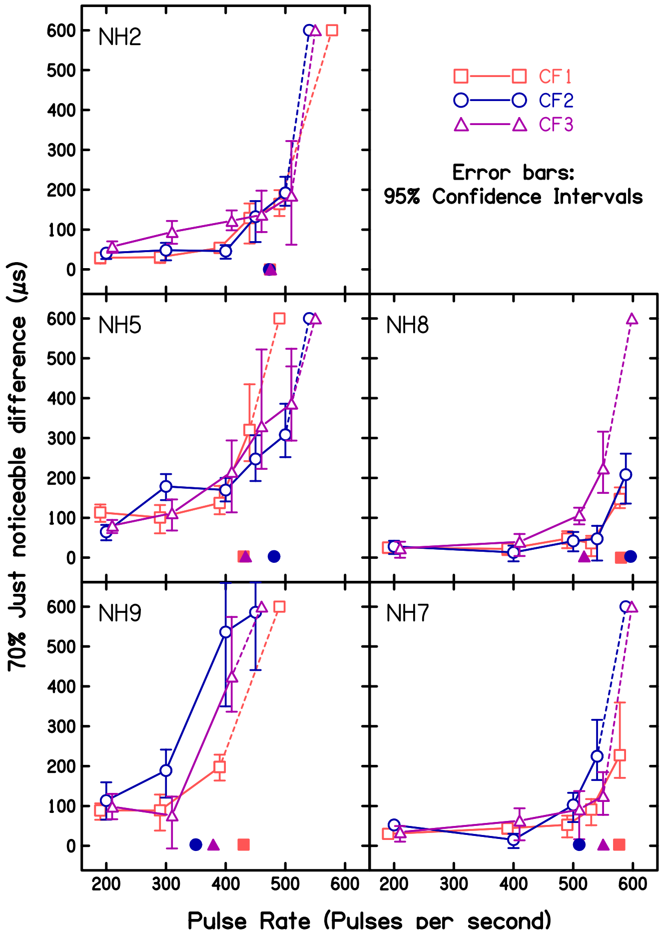

Figure 2: ITD-JNDs as a function of pulse rate in separate panels for each subject. The parameter is the CF. Non-determinable JNDs are arbitrarily plotted at 600 µs. Error bars represent bootstrapping 95% confidence intervals. The filled symbols at the bottom denote the inflection points of the functions JND vs. rate (see text).

Left/right discrimination of a target sound containing ITD was tested in comparison to a preceding reference stimulus with 0-ITD. Visual response feedback was provided after each trial. Each combination of three CFs and up to seven pulse rates was tested in a separate block. Each block contained 70 presentations of four predefined ITD sizes. At least two blocks were completed for each condition. The order of blocks was randomized for each subject. 70% JNDs were determined from the pooled percent correct scores for each condition, thus based on least 560 items.

Results and Discussion

Fig. 2 shows the JNDs for left/right discrimination as a function of pulse rate in separate panels for each subject. The parameter is the CF. Non-determinable JNDs are arbitrarily plotted at 600 µs. Error bars represent bootstrapping 95% confidence intervals. At 200 pps, the performance is not affected by rate limitations, as can be seen by the asymptotic form of most of the JND vs. rate functions towards lower pulse rates. Hence, the JNDs at 200 pps reveal to what extent the CF affects the overall performance. There is no effect of CF at 200 pps (ANOVA: $p = 0.99$). This indicates that all aspects related to the CF, such as the audibility or the number of stimulated neurons, have no influence on performance. The average JND at 200 pps is 58.7 µs (95% confidence interval: ±16.4 µs). This appears to be significantly lower than the JND obtained for transposed tones at a comparable modulation frequency [3].

The data of the individual subjects show only a few significant differences between the CFs, mainly at the higher rates. For listeners NH9 and NH7, CF2 and CF3 has elevated JNDs compared to CF1 at some of the higher rates. For listener NH8, CF3 has elevated JNDs compared to CF1 and CF2. By contrast, for NH5, CF1 has an elevated JND compared to CF2 and CF3 at the highest rate. NH2 shows no effect of CF at all. In summary, there is no consistent effect of CF across the five subjects. This result is supported by an ANOVA on the group data, showing a significant effect of the pulse rate ($p = 0.0001$), but no effect of the CF ($p = 0.11$), and no interaction ($p = 0.73$).

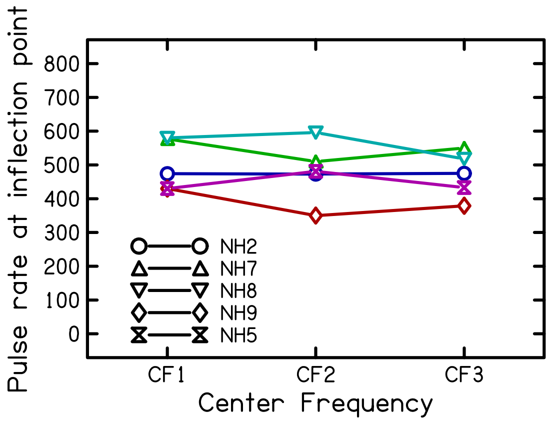

Figure 3: For each subject the pulse rate at the inflection point is shown as a function of the CF.

Because of the larger amount of modulation at the higher CFs, the inflection points of the functions JND vs. rate may shift towards higher pulse rates. At the bottom of each panel in Fig. 2, the inflection points are inserted. They were determined based on the derivative of an exponential least-squares fit to the function JND vs. rate. Fig. 3 shows the pulse rate at the inflection point as a function of the CF for each subject. There is no systematic effect of CF, as supported by an ANOVA ($p = 0.86$)

The results do not support the hypothesis that the ringing of the auditory filters limits ITD perception at higher pulse rates. If this were the case, then the maximum pulse rate revealing ITD sensitivity would be higher for higher CFs. On the other hand, the finding of constant ITD sensitivity as a function of CF differs from a previous study which found decreasing ITD sensitivity with increasing CF [3]. In contrast to our study using a constant bandwidth in ERB that study used transposed tones with a constant bandwidth in Hz. The lack of a decrement in performance at the higher CFs observed in our study could be due to at least two factors. First, the broader bandwidth (exceeding the critical bandwidth) at the higher CFs may cause more neurons to be stimulated. Second, the modulation is better represented for a broader bandwidth. This is shown in Fig. 4, comparing the envelopes of pulse trains (present study) with those of transposed tones [3] at CF1 (left panel) and CF3 (right panel), for a rate of 500 pps.

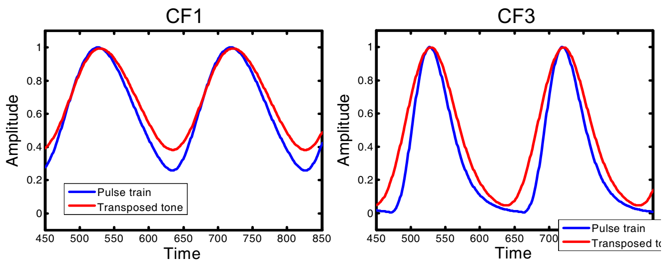

Figure 4: Envelopes of pulse trains (present study) and transposed tones [3] after passing auditory filters at CF1 (left panel) and CF3 (right panel). The pulse rate is 500 pps.

Summary and Conclusions

For pulse trains with a constant bandwidth in the ERB scale, ITD sensitivity is constant as a function of CF in the range from 4589 to 9178 Hz. This is the case both in terms of the overall sensitivity and in terms of the pulse rate limit. Compared to the transposed tones used in [3], pulse trains yield higher ITD sensitivity and a higher rate limit, in particular at higher CFs.

With respect to acoustic simulations of ITD perception of CI listeners [1,2], the results indicate that the performance of the NH listeners in those studies was not limited by cochlear filtering at the CF of the stimuli (4589 Hz).

Literature

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