Perception of interaural time differences in electric and acoustic hearing

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Cochlear implant (CI) listeners are sensitive to interaural time differences (ITDs), but their sensitivity is generally lower and more variable across individuals compared to normal hearing (NH) listeners. Previous studies showed sensitivity to ITD in the fine structure, if the pulse rate does not exceed a few hundred pulses per second. Furthermore, introducing binaurally-synchronized jitter was shown to have the potential to overcome this pulse rate limitation. With respect to envelope ITD, basic questions are still open both in normal and electric hearing. In normal hearing, the ITD sensitivity for transposed tones (TTs), a special type of amplitude-modulated high-frequency pure-tones, has been shown to be better than for sinusoidally-amplitude-modulated (SAM) tones. In experiments with nine NH and nine CI listeners we studied which properties of TTs cause the increased ITD sensitivity. We systematically varied the off-time and slope steepness of trapezoidally modulated (27 Hz) carrier signals. The NH listeners showed significant effects of off time and slope. The two effects did not interact and the best performance occurred for the longest off time combined with the steepest slope tested. The CI listeners showed only a significant effect of the off time. The implications with respect to CI coding strategies are discussed.

INTRODUCTION

When a sound source arrives from outside of the median plane, interaural time differences (ITDs) occur at the ears of a listener. ITDs are important cues for the localization of sound sources (Wightman and Kistler, 1992) and for understanding speech in noisy environments (Nie *et al*., 2005). ITDs occur both in the carrier (or fine structure) and in the envelope of a sound. Figure 1 shows fine-structure and envelope ITD for a series of electric pulses (positive phases only) with amplitude modulation. For a corresponding acoustic signal, the carrier signal would consist of a sinusoid.

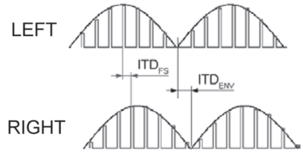

Fig. 1: Illustration of a modulated electric pulse train with ITD in the carrier (fine structure) and in the envelope.

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Most current clinical cochlear implant (CI) systems encode envelope information only and discard fine-structure information (Zeng *et al.*, 2004). A fixed pulse rate is used and in bilateral implantees the processors at the two ears are running independently. It is evident that with such a bilateral CI system fine-structure ITD information is not encoded. Unfortunately, studies have shown that low-frequency fine structure ITD is the dominant cue for judging the sidedness of a sound (Wightman and Kistler, 1992). On the other hand, envelope ITD information is encoded via such a bilateral clinical CI system. Bilateral CI listeners have been shown to be sensitive to some extent to envelope ITD in stimuli presented by clinical processors (Laback *et al.*, 2004, Grantham *et al.*, 2008).

Previous studies have investigated the sensitivity of bilateral CI listeners to ITD in the fine structure of stimuli presented directly to the implant electrodes via a research interface (Majdak *et al.*, 2006; Laback *et al.*, 2007; van Hoesel, 2007). On average, the sensitivity has been found to be lower than in normal-hearing (NH) listeners and to vary largely between listeners. Moreover, the sensitivity decreases for pulse rates exceeding a few hundred pulses per second (pps). This performance decrease with increasing pulse rate has been referred to as "pulse rate limitation". Based on these findings, it appears highly desirable to encode fine-structure ITD information with bilateral CI systems. CI manufacturers have already started to address this approach. However, the problem of the pulse rate limit for ITD perception still remains. Proper sampling of the input signal's envelope requires high pulse rates, at which CI listeners show no or almost no fine-structure ITD sensitivity. Thus, in order to provide CI listeners with usable ITD cues, the pulse rate limit has to be overcome somehow. A potentially useful method for solving this problem is described in study I of this paper.

With respect to envelope ITD perception with direct electrical stimulation, published data show a large range of performance, depending on the specific parameters tested (van Hoesel *et al.*, 2009; Majdak *et al.*, 2006). Overall, the sensitivity to envelope ITD seems to be lower than to fine-structure ITD. In general, several basic questions are still open, both in normal and electric hearing. In particular, it is unclear how two important parameters of a modulated waveform, the off time and the slope steepness, affect the envelope ITD sensitivity. Knowing the perceptual relevance of each of these two parameters may allow to emphasize envelope ITD cues by signal processing strategies in a CI system. To that end, in the second part of this paper, we describe experiments in which the effect of these parameters are studied systematically with NH and CI listeners.

STUDY I: IMPROVING FINE-STRUCTURE ITD SENSITIVITY AT HIGHER PULSE RATES

Hafter and Dye (1983) first described a limitation of NH listeners in perceiving ITD in the ongoing signal for high-frequency filtered pulse trains, if the modulation rate exceeds about 100 pps. This limitation, referred to as binaural adaptation, is reminiscent of the pulse rate limitation for ITD perception in electric hearing. In a subsequent study, Hafter and Buell (1990) showed that introducing short trigger signals in the ongoing signal causes a recovery from binaural adaptation. Effective trigger signals were short tone and noise pulses or gaps and squeezes inserted into the pulse train.

Based on these findings, Laback and Majdak (2008) hypothesized that the pulse rate limitation in CI listeners is related to the binaural adaptation effect. Second, they hypothesized that introducing triggers in the ongoing signal causes a recovery from binaural adaptation. While Hafter and Buell (1990) assumed that the recovery from binaural adaptation is mediated via spectral changes induced by the trigger signals, Laback and Majdak (2008) hypothesized that the effect can be evoked by introducing purely temporal changes in electric stimulation.

Study Design

The basic approach to introduce temporal changes was to jitter the interpulse-interval (IPI), as illustrated in Fig. 2. The upper part shows a periodic pulse train with an ITD indicated by the arrows. The lower part shows a pulse train with jittered (randomized) IPIs. In order to preserve the ITD, the jitter is binaurally synchronized (referred to as binaural jitter). The parameter *k* specifies the amount of periodicity. For *k* = 0, the pulse train is perfectly periodic. For k = 1, the IPI ranges from 0 to twice the nominal IPI. The distribution of IPIs is uniform and the average IPI over the stimulus duration corresponds exactly to the nominal IPI.

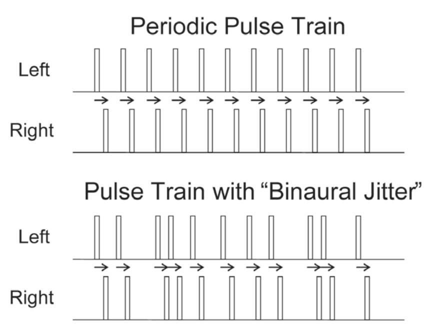

Fig. 2: Pulse trains that are periodic (upper) and that have binaurally-synchronized jitter in the pulse timing (lower). The arrows show the preserved ITD.

Five postlingually deafened bilateral CI listeners, supplied with MED-EL implants, were tested. The stimuli were presented directly to single test electrodes at the two ears via a binaurally synchronized research interface. The pair was selected to elicit interaurally matched place pitch. The stimulation currents were adjusted to obtain a centered auditory image at a comfortable loudness. ITD sensitivity was tested using a left/right discrimination paradigm (2-AFC), where a reference stimulus without ITD is followed by a test stimulus with ITD. The listeners had to judge if the test stimulus was to the left or right of the reference. The stimuli were pulse trains with a slow amplitude modulation (12.5 Hz), as outlined in Fig. 3. The ITD was applied to the entire signal (waveform delay). The independent test variables were the amount of jitter (*k*) and the pulse rate. Psychometric functions for ITD were determined using the constant stimuli method. More details on the methodology can be found in Laback and Majdak (2008).

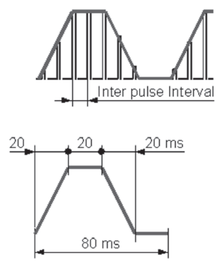

Fig. 3: Temporal envelope of the test stimuli. The modulation rate is 12.5 Hz.

Results and Discussion

Figure 4 shows the left/right discrimination score (*Pc*) as a function of the pulse rate. The parameter is the amount of jitter (*k*). The periodic condition shows rapidly decreasing *Pc* with increasing pulse rate, consistent with the pulse rate limitation described earlier. Conditions were pooled according to smaller amounts of jitter ($k = 0.125, 0.25, 0.5$) and larger amounts of jitter ($k = 0.75, 0.9$). For pulse rates > 400 pps, binaural jitter improves *Pc* and the amount of improvement increases with the amount of jitter. All parameters (*k*, pulse rate, and ITD) have highly significant effects ($p < 0.0001$).

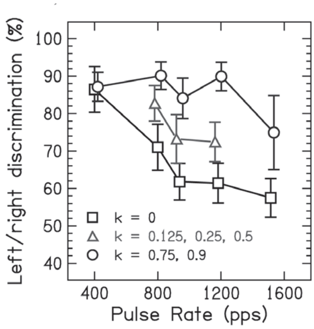

Fig. 4: Left/right discrimination score as a function of pulse rate (Laback and Majdak, 2008).

It has been argued that the effect of jitter could be simply due to the introduction of long IPIs, associated with low instantaneous rates, for which ITD sensitivity is known to be high. However, two lines of evidence argue against this explanation. First, single unit recordings from the inferior colliculus (IC) of bilaterally implanted cats revealed increases of ongoing responses for jittered pulse trains compared to periodic pulse trains for rates > 160 pps (Hancock and Delgutte, 2009; Goupell *et al*., 2010). The response for the 640-pps condition with $k = 0.9$ (longest IPI: 3 ms) was much larger than that for the periodic 320 pps condition (constant IPI: 3 ms). If long IPIs restore ongoing firing to the jittered pulse train at 640 pps, then the neuron should respond strongly to periodic pulses at 320 pps. This was clearly not the case, thus not supporting the long-IPI hypothesis. A second, similar evidence against the long-IPI hypothesis comes from a recent study on the binaural jitter effect in acoustic hearing (Goupell *et al*., 2009). NH listeners, presented with bandpass-filtered pulse trains, showed much larger *Pc* for a 1200 pps pulse train with $k = 1$ (longest IPI: 1.67 ms) than for a periodic 600 pps train (constant IPI: 1.67 ms). The overall pattern of results observed with NH listeners on the binaural jitter effect was very similar to that observed with CI listeners.

Implications for CI signal processing strategies

The practical application of the described effects of binaural jitter might be new stimulation strategies for CI systems to overcome the pulse rate limitation for fine-structure ITD perception described above. Such strategies could explicitly introduce binaural jitter in channels with pulse rates exceeding a few hundred pps. To introduce arbitrary amounts of binaurally-synchronized jitter, such strategies would require strictly coordinated stimulation timing between the two ears. However, it may also be possible that irregularities already present in the temporal structure of an input sound are sufficient to evoke the binaural jitter effect. The signal processing in the CI processors could be designed to emphasize these irregularities. In this case, no synchronization of the two CI systems would be required.

STUDY II: EFFECTS OF SLOPE STEEPNESS AND OFF TIME ON ENVELOPE ITD SENSITIVITY IN ACOUSTIC AND ELECTRIC HEARING

NH listeners have been shown to be more sensitive to ITD in high-frequency "transposed" tones than in sinusoidally-amplitude-modulated (SAM) tones (Bernstein and Trahiotis, 2002). Transposed tones have been designed so that the waveform at the output of peripheral cochlear processing mimics that of low-frequency sinusoids with the corresponding frequency. Figure 5 illustrates that transposed tones have both larger slope steepness and longer off times as compared to SAM tones. Both a steeper slope and a longer off time can be hypothesized to result in improved ITD sensitivity. Furthermore, the larger peak amplitude of transposed tones, required to maintain the same long-term sound pressure level (SPL) as for SAM tones, might contribute to the better ITD sensitivity with transposed tones. To better understand the origins behind the improved ITD sensitivity with transposed tones and to clarify which waveform aspects are important for envelope ITD perception in electric hearing, we conducted experiments with both NH and CI listeners.

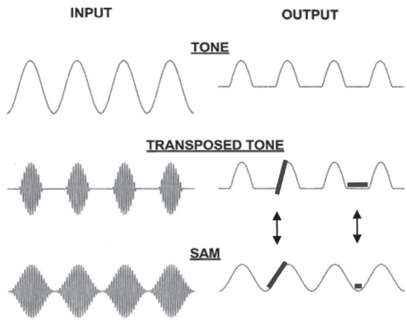

Fig. 5: Waveforms (left side) and envelopes of corresponding outputs from simulated peripheral auditory processing (right side) for sine waves, transposed tones, and SAM tones (from Trahiotis and Bernstein, 2002). The thick lines indicate that transposed tones have steeper envelope slopes and longer off times.

Methods

The basic stimulus to test the above-mentioned hypotheses is outlined in the top panel of Fig. 6. It consists of a 300-ms series of symmetric trapezoids, with a given on time, off time, slopes, and a modulation period. Note that the amplitude axis refers to the logarithmically scaled envelope amplitude, in contrast to the linear amplitude scaling in Fig. 5. The middle panel shows how the steepness of the slopes can be increased (dashed trapezoidsline) without changing the off time. Naturally, this is only possible by increasing the on time. However, using a sufficiently high carrier frequency, the on time can be considered as perceptually irrelevant, since the carrier ITD is not encoded in the neural response. The horizontal dashed line shows the adjusted peak amplitude which is required to keep the sound pressure level (SPL) the same as for the original trapezoid (shown with solid lines). The bottom panel shows how the off time can be decreased without changing the slope. Again the on time has to be increased and again the peak amplitude has to be reduced in order to keep the SPL constant.

In the acoustic experiments, nine NH listeners were tested. The stimuli consisted of a sinusoidal carrier (8727 Hz), modulated with an envelope composed of a series of trapezoids. The horizontal line depicts the estimated absolute threshold of the listeners, at which the off time was defined. The modulation rate was 27 Hz. The stimuli were bandpass-filtered so that the bandwidth corresponds to the ERB of the auditory filter centered at the passband (lower cutoff: 8257 Hz, higher cutoff: 9224 Hz). A continuous low-pass filtered noise (SPL of 40 dB; cutoff: 1500 Hz) was added to mask low-frequency cochlear distortions. The stimuli were presented to the listeners via headphones (Sennheiser, HDA200). The stimuli were presented either at a constant long-term SPL of 76 dB (constant SPL condition) or at a constant peak amplitude, resulting in SPLs in the range from 70.8 to 80.2 dB. The slope of the envelope was defined in dB/ms. In electric hearing requires the slope needs to be defined in a comparable way, i.e. in percent of the dynamic range (DR)

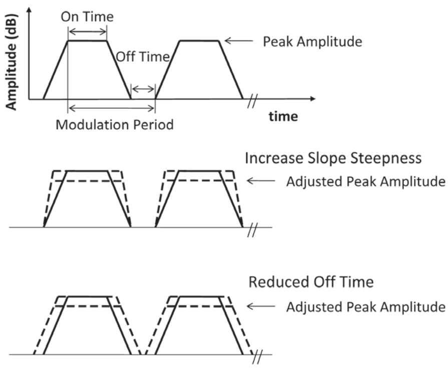

Fig. 6: Top panel: Parameters of trapezoidal temporal envelopes of the test stimuli. Note that the ordinate (amplitude) is scaled logarithmically. Middle panel: Increase of the slope steepness (dashed line). Bottom panel: Reduced off time (dashed line). The horizontal dashed lines in the middle and bottom panels indicate the reduction of the peak amplitude required to keep the long-term SPL constant.

(Zeng and Shannon, 1992; Francart *et al.*, 2008). Therefore, we specified the slope in %DR/ms with DR expressed in amperes. Since the dynamic range in acoustic hearing is approximately 100 dB (Brand and Hohmann, 2002), %DR/ms and dB/ms are considered as approximately equivalent. As already mentioned, the off time was defined as the time during which the amplitude of the trapezoids was equal to or lower than the absolute threshold.

In the electric experiments, nine postlingually deafened, bilaterally implanted (MED-EL devices) listeners were tested. The stimuli consisted of a 1515-pps carrier pulse train which was modulated with the same envelope as in the NH experiments. The stimuli were presented at a single interaural electrode pair in the basal cochlear region. The pair members were selected, based on pre-tests, to elicit the same place pitch. The stimuli were directly presented to the implant electrodes via a binaurally-synchronized research interface. The stimulation levels were adjusted for each condition to obtain a centered auditory image at a comfortable loudness. Note that the condition with constant peak amplitude could not be tested in a meaningful way in electric hearing, since it would result in a non-centered auditory image for many conditions due to the occurrence of interaurally asymmetric loudness functions. If a comfortable loudness could not be reached for some conditions in individual listeners those conditions were discarded. In electric hearing only, we tested two control conditions with an infinite slope steepness. One had an off time of zero and thus represented a 1515 pps constant amplitude pulse train. The other one had an off time of 36 ms and thus represented a 27 pps pulse train.

ITD sensitivity was measured using a left/right discrimination task, as described in study I. The ITD was applied to the envelope only and the fine-structure had a zero ITD. Only for the two control conditions in electric hearing, waveform ITD was used (thus involving fine-structure ITD). In contrast to study I, just noticeable differences (JNDs) could be measured with an adaptive procedure. The 3-down/1-up rule was used, which converges at the 79.4% point on the psychometric function. In the adaptive procedure, the conditions were presented in a trial-by-trial interleaved manner, with a block length of five conditions. Eighteen turnarounds were tested and the JND was defined as the mean of the last 8 reversals. The stepsize was 300 µs at the beginning and was decreased by a factor of 0.7 after each wrong response. The minimal stepsize was 50 or 25 µs, depending on the subject. Usually, 3-6 JNDs were measured, depending on measurement variability. If an adaptive run did not converge, it was discarded and one or more additional runs were performed.

The two main independent test variables off time and slope steepness were varied systematically. For the NH listeners, all the combinations of off time and slope steepness were tested both at a constant long-term SPL and at a constant peak amplitude.

Results

The peak amplitude had a significant effect ($p < 0.001$) on the performance of the NH listeners. The JNDs were found to decrease with increasing peak amplitude. However, the overall pattern of results (in terms of the effects of off time and slope) was similar for the conditions with constant SPL and with constant peak amplitude. For sake of clarity, only the data with constant SPL are presented. Figure 7 shows the average JNDs for the nine NH listeners and 95% confidence intervals. The left panel shows the JNDs as a function of off time with the slope as the parameter. The JNDs decrease monotonously with increasing off time over the whole range tested. The right panel shows the same data, but as a function of the slope with the off time as the parameter. The JNDs clearly decrease from 6 to 8 %DR/ms, but remain constant for steeper slopes. The effect of the slope seems to be independent of the effect of the off time. It seems like the sensitivity depends on the linear combination of the effects of the two parameters. The combination of shallowest slope and shortest off time yields the worst performance and the combination of a steeper slope and a longest off time yields the best performance. A repeated measures (RM) analysis of variance (ANOVA) revealed significant effects of the factors off time ($p < 0.0001$) and slope ($p < 0.0001$), but no interaction ($p = 0.98$). The lack of an interaction confirms the independence of the factors off time and slope.

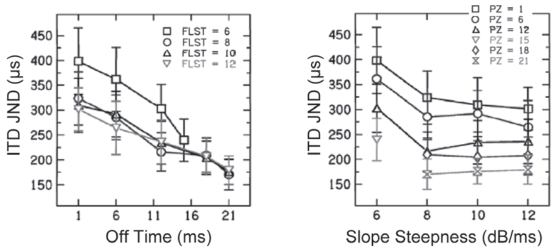

Fig. 7: Mean results for the NH listeners. Left panel: envelope ITD JNDs as a function of the off time. The parameter is the slope steepness (in %DR/ms). The error bars indicate 95% confidence intervals. Right panel: The same data, but as a function of the slope steepness with the off time as the parameter. *FLST* denotes slope steepness and *PZ* denotes off time.

Figure 8 shows the mean JNDs of seven CI listeners. Two listeners were excluded because their ITD sensitivity turned out to be too low to obtain reproducible ITD JNDs lower than 9 ms (one quarter of the modulation period). Data points based on data from less than five listeners are shown with smaller symbols. The JNDs clearly decrease with increasing off time (left panel) for all values of the slope steepness. The infinite-slope conditions (square symbols) with an off time of zero (representing a 1515 pps pulse train) show a performance in the order of that for the trapezoidal envelopes with an off time of zero. In contrast, the infinite-slope conditions with an off time of 36.6 ms (representing a 27 pps pulse train) show better performance than all other conditions. The slope steepness (right panel) seems to have no systematic effect on performance within the range tested. Looking back on the individual data reveals that even the individual listeners mostly show no systematic effect of the slope. The RM ANOVA revealed a highly significant effect of the off time ($p < 0.0001$), no effect of the slope ($p \geq 0.35$), and no interaction ($p = 0.16$). Figure 9 compares the normalized JNDs between the NH and CI listener groups. Normalization was performed for each individual by dividing, for a given slope, the JND for each off time by the JND for the shortest off time. The relative effect of the off time (Fig. 9a) is stronger for the CI listeners. This is mainly due to the larger improvement in performance from 0 to 6 ms in the CI listeners. For off times from 6 to 21 ms, however, the effects are very similar. With respect to the slope steepness (Fig. 9b), the normalized data confirm that there is a marked difference between the two groups. Figure 9c shows the normalized data for the individual CI listeners. Again, no clear picture on the effect of the slope can be derived from these data.

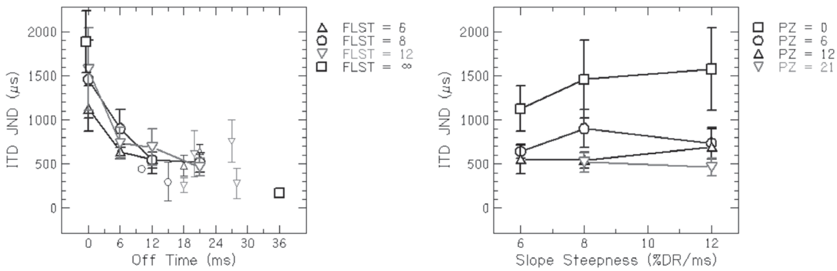

Fig. 8: Mean results for the CI listeners using the same layout as in Fig. 7. The small symbols in the left panel indicate conditions for which data were averaged over less than five listeners.

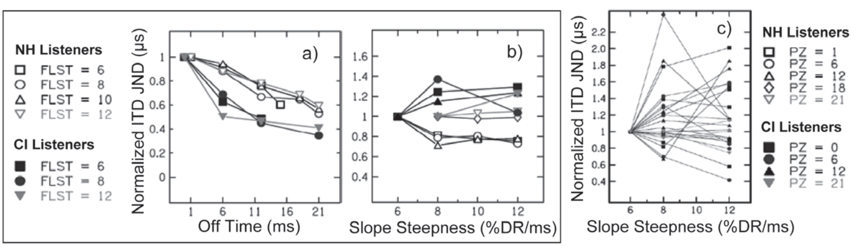

Fig. 9: Comparison of normalized ITD JNDs between NH listeners (empty symbols) and CI listeners (filled symbols). The rightmost panel shows the slope effect for the individual CI listeners.

Discussion

The improvement of envelope ITD sensitivity with increasing off time may be due to the increased synchrony of the neural response following a recovery period. This is consistent with physiological data from Yin *et al.* (1984), who showed that the degree of modulation in the spike count (measured in the IC of cats) improved when the duty cycle of a 250-Hz trapezoidal modulation was reduced. The effect of the slope steepness observed in NH listeners is qualitatively consistent with physiologic data from Heil (1997), who found a systematic increase of spike counts with increasing rate of change of peak pressure at the onset of tones.

A recent study with NH listeners (Ewert *et al.*, in press) investigated the effects of parameters similar to those investigated in the present study. They used a sinusoidal carrier modulated with a raised-cosine envelope. The off time (in their study specified by means of the duty cycle) had an effect only up to 5 ms. However, the relative improvement (in terms of JND ratios) was even larger than the effect we observed in our study over the entire, much larger, range of off time values (up to 21 ms). The difference in outcomes might be due to the different modulation rates (they used 50 Hz) and the different frequency regions (they used 4 kHz). The study by Bernstein and Trahiotis (2002) indicates an effect of the frequency region; the ratio of JNDs for transposed and SAM tones was found to be larger at 4 kHz than at 10 kHz. Note that 10 kHz is close to the frequency region at which we tested.

Figure 10 compares normalized JNDs of the current study with those obtained for transposed tones and SAM tones by Bernstein and Trahiotis (2002). The empty circles (connected with a dotted line) show the normalized JNDs for off times of 1 and 15 ms for the NH listeners of the present study, averaging across all slopes tested. The empty circles (connected with a solid line) show the data for the shallowest slope (at the off time of 1 ms) and for all steeper slopes (at the off time of 15 ms). The filled circles show the data of Bernstein and Trahiotis (2002) for SAM tones (approximated off time: 0 ms) and transposed tones (approximated off time: 16 ms) for a modulation frequency of 32 Hz and a center frequency of 10 kHz, most close to the center frequency of 8727 Hz we used. The finding that the latter two lines have the same slope indicates that the relative increase in sensitivity for transposed tones compared to SAM tones is due to the combined effect of increased off time and increased slope steepness. Interestingly, the data of the CI listeners (triangles) show a similar relative improvement when averaged over all slopes (the slope had no effect). This means that in CI listeners the relative effect of the off time alone is as strong as the combined effect of off time and slope steepness in NH listeners.

The overall envelope ITD sensitivity is about three times worse in CI listeners than in NH listeners. One of several possible reasons may be differences in loudness functions between the two ears of CI listeners, which could disrupt the envelope ITD cue. Such differences in loudness functions may also be a reason why we found no systematic effect of the slope steepness in CI listeners. In order to test this hypothesis, future CI studies may specify the envelopes on a loudness unit scale instead of a current unit scale.

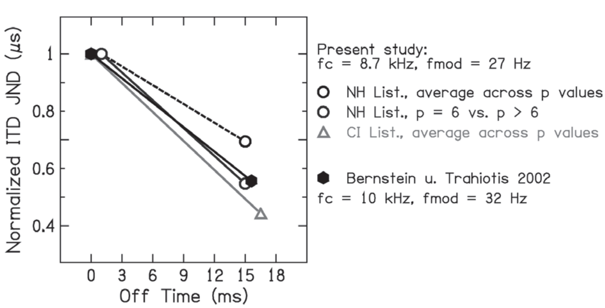

Fig. 10: Normalized JNDs for transposed and SAM tones from Bernstein and Trahiotis (2002) and for trapezoidal stimuli with comparable off times tested with NH and CI listeners in the current study. See text for more details.

Finally, in electric hearing the ITD JNDs observed for trapezoidal stimuli were always larger than those for the 27 pps pulse train (with the exception of listener CI12). Note that increasing the off time and the slope steepness of trapezoidal stimuli further and further finally results in a pulse train with no ongoing envelope modulation. Such a signal can contain the ITD only in the pulse timing (fine structure). The better performance for the pulse train could be due to the much larger pulse amplitude (which was required to obtain a comfortable loudness), the maximally possibly slope steepness, the maximally possible off time, and to the fact that it involved fine-structure ITD. While the observed saturation in the effect of the off time and the lack of an effect of the slope steepness may indicate that these two parameters were not the reason for the better performance for the pulse train, we cannot separate the other two explanations.

Implications for CI signal processing strategies

Given the pronounced effect of the off time observed for the CI listeners, future bilateral CI stimulation strategies systems may emphasize envelope ITD cues in real-life sounds by introducing or enhancing stimulation pauses.

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