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Effects of center frequency and rate on the sensitivity to interaural delay in high-frequency click trains

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Abstract

The effects of center frequency and pulse rate on the sensitivity to ongoing envelope interaural time differences (ITDs) were investigated using bandpass-filtered pulse trains. Three center frequencies (4.6, 6.5, and 9.2 kHz) were tested with bandwidths scaled to stimulate an approximately constant range on the basilar membrane. The pulse rate was varied from 200 to 588 pps (pulses per seconds). Five normal-hearing (NH) subjects were tested. Averaged over all rates, the results show a small decrease in sensitivity with increasing center frequency. For all center frequencies, sensitivity decreases with increasing pulse rate, yielding a rate limit of approximately 500 pps. The lack of an interaction between pulse rate and center frequency indicates that auditory filtering was not the rate limiting factor in ITD perception and suggests the existence of other limiting mechanisms, such as phase locking or more central processes. It is concluded that the comparison of the rate limits in ITD perception between cochlear-implant listeners and NH subjects listening to high-frequency bandpass-filtered pulse trains is not confounded by the choice of center frequency of stimulation in NH listeners.

I. INTRODUCTION

Interaural time differences (ITDs) are important for the localization of sound sources (e.g., Macpherson and Middlebrooks, 2002). It is well known that the ITD information in unmodulated signals can only be processed up to about 1500 Hz (Zwislocki and Feldman, 1956; Blauert, 1997). At higher frequencies, ITD information can be processed from the slowly-varying temporal envelope only. This is supported by various psychoacoustic (Henning, 1974; Nuetzel and Hafter, 1976, 1981; Bernstein, 2001; Bernstein and Trahiotis, 2002) and physiologic studies (Yin *et al.*, 1984; Skottun *et al.*, 2001; Shackleton *et al.*, 2003). The ability to transmit envelope and carrier information in separate paths seems to be a general property of the auditory system (Liang *et al.*, 2002) and was also found in other sensory modalities like visual and electrosensory systems (Middleton *et al.*, 2006).

There is strong evidence that envelope ITD sensitivity depends on the temporal properties of the fast-varying carrier signal. This was shown for sinusoidally amplitude-modulated (SAM) tones (Henning, 1974; Stellmack *et al.*, 2005; Nuetzel and Hafter, 1976), two-tone complexes (Mc-Fadden and Pasanen, 1976; Bernstein and Trahiotis, 1994), transposed tones (Bernstein and Trahiotis, 2002), and bandpass-filtered click trains (Hafter and De Maio, 1975; Hafter and Dye, 1983). All these studies found that envelope ITD sensitivity is limited with respect to the rate of the envelope fluctuations. However, ITD sensitivity depends not only on the rate of envelope fluctuations. For example, Bernstein and Trahiotis (2002) found

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that transposed tones, which have sharper[1] envelopes than SAM tones, yield higher performance for comparable rates. On the physiological basis, it was shown that, under certain conditions,[2] the neural response to transposed tones can even be comparable with the response to low-frequency pure tones (Griffin *et al.*, 2005; Dreyer and Delgutte, 2006).

In cochlear-implant (CI) listeners, Majdak *et al.* (2006) and Laback *et al.* (2007) investigated the sensitivity to ongoing ITD presented at one binaural electrode pair. At least one CI listener tested showed sensitivity up to 800 pps (pulses per second).[3] Further, they compared sensitivity to ongoing *envelope* ITD of normal-hearing (NH) subjects. In NH experiments, they used bandpass-filtered pulse trains to simulate pulsatile stimulation with CIs, similar to McKay and Carlyon (1999). The best NH listeners showed sensitivity up to 600 pps (Majdak *et al.*, 2006) and 400 pps (Laback *et al.*, 2007). Thus, compared to the best performance in electric stimulation, the rate limit of the best NH listeners was lower. Even though only two of five CI listeners showed a higher rate limit than NH listeners, this finding is rather surprising. It has been concluded that the comparison between these two groups may be affected by different properties of electric and acoustic stimulations. In acoustic stimulation the bandpass-filtered pulse train passes through the basilar membrane, where the envelope sharpness can be reduced depending on the stimulation place. This filtering process is bypassed in electric stimulation. Thus, assuming that a sharp envelope is required for ITD sensitivity (Stellmack *et al.*, 2005), the rate limit of the NH listeners may have been affected by auditory filtering in the cochlea. The investigation of a possible limitation in the comparison between NH and CI listeners' results was the main motivation for this study.

If auditory filtering limits ITD perception, then the increase in the stimulus center frequency (CF) should improve performance. This is because the auditory filter bandwidth increases with the CF, causing relatively less reduction in the envelope sharpness (e.g., Patterson *et al.*, 1992), especially at high modulation rates. However, the inversion of that argument is not valid: if performance does not improve with CF, it does not mean that auditory filtering has no effect because auditory filtering may be counteracted by other effects associated with the stimulation of different tonotopic places. Those are (1) changing hearing thresholds, which may result in a change of ITD sensitivity (Nuetzel and Hafter, 1976); (2) stimulating different amounts of peripheral neurons when constant bandwidth stimuli are applied (Buell and Hafter, 1991); and (3) differences in the higher processing stages (e.g., changing number of responding cells in the central nervous system as indicated in Bernstein and Trahiotis, 1994, or differences in the tonotopic specialization of the coincidence detectors as shown in chicks by Kuba *et al.*, 2005). Thus, the ITD sensitivity as a function of CF alone is a misleading indicator for a possible effect of auditory filtering.

However, the question of auditory filtering can be addressed by investigating the effect of CF on the *rate limit*. This is because both increase in rate and decrease in CF can reduce envelope sharpness . Thus, if auditory filtering affects ITD sensitivity, the rate limit should significantly increase with CF. In other words, a significant interaction between CF and rate could indicate that the reduction in the envelope sharpness depends on the tonotopic position and, thus, auditory filtering limits ITD sensitivity. If the interaction is not significant then the rate limit is not affected by the choice of CF and, thus, this limit is probably a result of some more central limitations.

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[1]Besides the rate, various other aspects of the temporal envelope may be important for envelope ITD perception, namely, modulation depth, duty-cycle, and slope steepness. We use the term "sharpness" to refer to all these aspects.

[2]The required condition is between stimulus levels near thresholds with modulation frequencies below 250 Hz and low spontaneous discharge rate.

[3]The five CI listeners from both studies showed rate limits of 100, 100, 400, 800, and 800 pps, respectively.

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In NH listeners, Hafter and Dye (1983) investigated the detection of ITD in bandpass-filtered click trains as a function of the inter-pulse interval (IPI) and the number of clicks. Although they did not collect data for different CFs, their results indicate that the envelope sharpness reduction due to auditory filtering does not explain the decrease in performance for increasing pulse rate. However, additional data on ITD sensitivity at different CFs are required to substantiate their conclusions.

For other types of stimuli, there are indications that auditory filtering is not the limiting factor in ITD perception, as supported by the results of two studies: Bernstein and Trahiotis (1994) and Bernstein and Trahiotis (2002). For 100% SAM tones and two-tone complexes, Bernstein and Trahiotis (1994) found a general decrease in ITD sensitivity when the CF was increased. They varied the modulation rate as well, showing that the sensitivity to ITD decreased as the rate of envelope fluctuation increased. The comparison of the modulation rate effect between different CFs led to the conclusion that the change in ITD sensitivity is unlikely affected by auditory filtering. For transposed tones, Bernstein and Trahiotis (2002) investigated ongoing ITD sensitivity and compared their results to those obtained with SAM and pure tones. For the lower modulation frequencies (<256 Hz), listeners showed even higher ITD sensitivity to transposed tones than to pure tones with comparable frequency. However, using higher modulation frequencies, JNDs could not be determined for transposed tones. Furthermore, increasing the center frequency of the transposed tones resulted in lower sensitivity as well. From their results, Bernstein and Trahiotis (2002) concluded that for SAM and transposed tones, ITD perception is not primarily limited by the effects of auditory filtering.

Nevertheless, Bernstein and Trahiotis (2002) found large differences in ITD sensitivity between the SAM and transposed tones. Those findings indicate that the relative decrease in ITD sensitivity usually observed for high-frequency stimuli (compared to low-frequency stimuli) is associated with the type of stimuli used, as specified by the center frequency, rate, and sharpness of envelope fluctuation. Hence, conclusions derived for SAM and transposed tones do not automatically apply to other types of stimuli like bandpass-filtered click trains. All these stimuli have different envelope sharpness even for the same CF and rate. Thus the impact of auditory filtering on ITD perception may be different and requires a separate investigation for click trains.

Majdak *et al*. (2006) and Laback *et al*. (2007) used bandpass-filtered click trains because these stimuli appear to be a good approximation of the electric stimulation in CIs when investigating temporal effects (McKay and Carlyon, 1999; Carlyon *et al*., 2002) in NH listeners. Electric pulse trains presented at one electrode in the cochlea have a very steep onset, which may be best approximated by bandpass-filtered click trains in acoustic stimulation. Of course, when compared to electric pulse trains, the response of an auditory filter to bandpass-filtered click trains results in temporal fluctuations with a clearly reduced envelope sharpness. However, the resulting envelope is still sharper than for SAM or transposed tones. Dreyer and Delgutte (2006) showed that phase locking to transposed tones is better than to SAM tones and for transposed tones, it even reaches levels comparable to pure tones under certain restrictions.[2] Transposed tones clearly have sharper envelopes than SAM tones. Thus, stimuli with even sharper envelopes like bandpass-filtered pulse trains offer the possibility of further improvements in the phase locking effects.

An additional advantage of bandpass-filtered click trains is that the onset slopes do not change with the pulse rate as it is the case for SAM and transposed tones. The amplitude spectrum of a click train is a harmonic series, which can be limited in frequency by applying a bandpass filter. Thus, the bandwidth and the CF are independent, making it possible to systematically stimulate different amounts of neurons at different tonotopic places. In

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contrast, for both SAM and transposed tones the bandwidth is directly related to the modulation rate and is constant for all CFs. Thus, assuming an approximately logarithmic scaling of the frequency-to-place mapping (Greenwood, 1961), fewer neurons may be stimulated at higher CFs than at lower CFs when SAM and transposed tones are used. Even though the effect of bandwidth on the sensitivity to envelope ITD is still unclear, there are some indications that increasing bandwidth leads to improved envelope ITD perception (Buell and Trahiotis, 1993). Using stimuli with a logarithmically-scaled bandwidth may compensate for the decrease in performance found in the literature for SAM and transposed tones at higher CFs. Thus, for lower rates, co-varying the bandwidth with the CF could lead to high performance across all CFs, which is important in our study in order to limit potential floor effects when switching from lower to higher rates. Notice, that in the present study we varied the bandwidth with the CF, however, we do not treat it as an independent variable and its effects are not investigated.

The main focus of this study is to reconsider the comparison between CI and NH listeners performed in Majdak *et al.* (2006) and Laback *et al.* (2007) under the hypothesis that the NH performance was not underestimated because of auditory filtering. The effect of auditory filtering was investigated by systematically varying CF and the pulse rate of bandpass-filtered pulse trains and testing the sensitivity to ongoing envelope ITD in NH listeners. The main hypothesis is tested by comparing the rate limit between three different CFs. This is performed by a statistical analysis of the interaction between CF and pulse rate. Additionally, the results are discussed in the context of the general effects of CF and pulse rate on ITD perception in NH and CI listeners.

II. METHODS

A. Subjects and apparatus

Five NH subjects participated in this study. All subjects were aged between 25 and 35 years and had no indication of hearing abnormalities. One of them (NH2) was an author of this study.

A personal computer system was used to control the experimental task. The stimuli were output via a 24-bit stereo D/A converter (ADDA 2402, Digital Audio Denmark) using a sampling rate of 96 kHz per channel. The analog signals were sent through a headphone amplifier (HB6, TDT) and an attenuator (PA4, TDT), and presented to the subjects via a circumaural headphone (K501, AKG). Calibration of the headphone signals was performed using a sound level meter (2260, Brüel & Kjær) connected to an artificial ear (4153, Brüel & Kjær).

B. Stimuli

The stimuli were 300-ms pulse trains composed of monophasic pulses with a duration of 10.4 μs, corresponding to one sampling interval at a sampling rate of 96 kHz. The pulse rate was varied from 200 to 588 pps. The smallest IPI was 1700 μs. Both of the studies with click trains discussed above, Majdak *et al.* (2006) and Laback *et al.* (2007), showed that for pulse rates above 600 pps ongoing ITD sensitivity degrades to chance rate. Hence, higher pulse rates were not tested.

The ITD was introduced by delaying the temporal position of the pulses at one ear relative to the other ear. To restrict the ITD to the ongoing part of the stimulus only, the position of the first pulse pair (onset) and the last pulse pair (offset) was fixed to a zero ITD (Laback *et al.*, 2007). To minimize the monaural perception of irregularities, half of the ITD was applied to the leading ear and the other half to the lagging ear. Laback *et al.* (2007) showed that these irregularities are not perceptible. The ITD values varied[4] from 20 to 400 μs. The

ITD was adapted to account for the subject's sensitivity. According to Majdak *et al.* (2006), ITDs higher than 0.25 IPI can lead to lower performance compared to ITDs lower than 0.25 IPI. This is an effect of the ambiguity in ongoing ITD information provided by the stimulus for ITD=0.5 IPI and results in a nonmonotonic psychometric function. Thus, combinations of ITD and pulse rate resulting in ITD values higher than 0.25 IPI were not tested in this study.

The pulse trains were passed through a digital eighth-order Butterworth filter. Three different CFs were tested: 4589 (CF4.6), 6490 (CF6.5), and 9178 Hz (CF9.2). The lowest CF, CF4.6, was chosen to be identical with the CF used in Carlyon *et al.* (2002); Majdak *et al.* (2006); and Laback *et al.* (2007). The highest CF, CF9.2, is double the frequency of CF4.6 and corresponds to the CF used in Carlyon and Deeks (2002). CF6.5 is the geometrical average of CF4.6 and CF9.2. Using CFs higher than 10 kHz would lead to even shorter impulse responses of auditory filtering. However, we did not test CFs above 10 kHz since Bernstein and Trahiotis (1994) showed that it is hard to retrieve valid data for very high CFs. Also, in electric hearing, the most-basally implanted electrode usually corresponds to frequencies below 10 kHz.

The bandwidth of the stimuli was co-varied with the CF with the aim to obtain an approximately constant stimulation range on the basilar membrane. The bandwidth for CF4.6 is 1500 Hz, which is identical to the bandwidth in previous studies. It corresponds to the ERB-rate of 2.53 (according to Moore and Glasberg, 1983) and a stimulation range of 2.28 mm on the basilar membrane (according to Greenwood, 1990). For CF9.2, the bandwidth is double the bandwidth for CF4.6, which results in 3000 Hz. It roughly corresponds to the ERB-rate of 2.11 and a stimulation range of 2.32 mm on the basilar membrane.[5] Further details about the filter configurations can be found in Table I. By doubling the bandwidth from CF4.6 to CF9.2 and using the geometrical average for CF6.5, we hoped to achieve a similar ITD sensitivity for the three CFs at lower rates. With these bandwidths, the signals clearly stimulate regions outside the critical bandwidth. By doing that we hoped to achieve a good ITD sensitivity at lower rates, which was required to avoid potential floor effects because the performance was expected to decrease with increasing rate.

Given that the sound pressure level (SPL) depends on the pulse rate, the amplitudes of the stimuli were adjusted to maintain a constant A-weighted SPL of 66 dB (with reference to 20 μPa), measured at the headphones, for all rates and CFs. We did not compensate for differences in hearing thresholds at different CFs. Despite the filtering of the pulse trains, some artifacts like harmonic distortions or intermodulation at the basilar membrane can cause stimulation outside the desired frequency band. To prevent these artifacts from being heard, a binaurally uncorrelated background noise was continuously played throughout the testing. We used Gaussian white noise ranging from 50 Hz to 20 kHz with the overall A-weighted SPL of 52.2 dB. This corresponds to a sound pressure spectrum level of 9.2 dB (with reference to 20 μPa in a 1-Hz band), which is approximately 28 dB below the maximum level of the tonal components in the filtered pulse train. According to Goldstein (1967), with this background noise level the intermodulation components and difference tones, which may potentially transmit ITD information outside the desired frequency band, were masked by either the background noise or the stimulus itself.[6]

[4]The actual values for the ITDs were integer multiples of the sampling interval of 10.4 μs. Thus, the lowest ITD value tested was 20.8 μs, and the highest ITD value tested was 395.8 μs.

[5]Notice that, according to Moore and Glasberg (1983), the formula for ERB-rate calculation is based on data collected up to 6.5 kHz only.

[6]More recent study (Wiegrebe and Patterson, 1999) suggests that the level of quadratic distortion products may be higher than the levels of combination tones as suggested by Goldstein (1967).

C. Procedure

A two-interval, two-alternative forced-choice procedure was used in a lateralization discrimination test. The first interval contained the reference stimulus with zero ITD evoking a centralized auditory image. 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. The chance rate was 50%. A score of 100% correct (P_c) responses indicates that all stimuli were discriminated, with lateralization corresponding to the ear receiving the leading signal.

The tests were performed in blocks. Each block contained 70 presentations of four different ITD values[7] for a combination of CF and pulse rate. The ITD values were presented in a randomized order with 35 targets leading to the left and 35 targets leading to the right. The rate and ITD values were varied from block to block with the goal to obtain a good estimation of the 70%-threshold. Thus, in cases where the performance was at chance, blocks with lower ITD values or higher rates were not tested. In cases where the performance was at ceiling, higher ITDs or lower rates were not tested. The initial four ITD values were estimated on the basis of the training results. At least two blocks were completed for a tested condition and the order of blocks was randomized for each subject. Visual response feedback was provided after each trial.

Stimuli with the pulse rate of 200 pps and ITD of 600 μs at CF4.6 were used to train subjects before the main test started. The subjects were trained until they showed a stable performance which was achieved within a few hours.

III. RESULTS

Figure 1 shows the percent correct (P_c) scores as function of the ITD with the pulse rate as parameter. Each panel shows data for one subject and one CF. The dashed horizontal lines show the 70%-threshold used for the JND estimation.

The comparison of the data between the three CFs (columns) suggests a difference in performance. Especially comparing CF9.2 and CF4.6 for subjects NH2, NH7, NH8, and NH9, performance appears to decrease at higher CFs. The effect of the pulse rate seems to be more salient: performance decreases with increasing pulse rate, independent of subject, CF, and ITD.

In Fig. 2, data from Fig. 1 for the ITD of 200 μs were replotted to directly show the effect of the CF. The data are shown as a function of CF and the parameter is rate. Each panel shows data for one listener. It appears that with increasing pulse rate the differences between the CFs become larger, particularly for subject NH8. However, for NH5, the performance appears to be constant for all CFs. Generally, for the highest rate, the performance is in the range of chance, and for the lowest rates, the performance is at ceiling.

The data for all ITD values were statistically analyzed by calculating a multiway repeated-measures analysis of variance (RM ANOVA) with the factors CF, pulse rate, and ITD. The RM ANOVA was chosen because it considers the individual tendencies of each subject in the analysis. To not violate the assumption of homogeneity of variance required for ANOVA, the P_c scores were transformed using the rationalized arcsine transform (Sherbecoe and Studebaker, 2004). The results show that the main effect of CF is highly significant ($p<0.0001$) with decreasing performance for increasing CF. The main effect of the pulse rate is highly significant ($p<0.0001$); performance decreases with increasing pulse

[7]For one subject, NH9, only three ITDs were tested.

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rate. As expected, the effect of ITD is highly significant ($p < 0.0001$) showing increasing performance for increasing ITD values.

Due to the individual performance of the subjects, for some subjects and conditions there are more extreme P_c scores like 100% or 50% than for others. These extreme values, which represent the tails of the psychometric functions, have an impact on the analysis producing ceiling or floor effects. For example, the Tukey–Kramer *post-hoc* test revealed that the results for the pulse rates of 200, 300, and 400 pps are not significantly different ($p > 0.05$), which indicates a possible ceiling effect for pulse rates lower than 400 pps. To reduce this problem, the RM ANOVA was performed again. However, this time we excluded all combinations of ITD×CF×rate×subject for which the P_c was below 60% and above or equal to 90%. The exclusion of these data resulted in a well populated condition matrix and the interactions could be included in the analysis. The main factors were CF, ITD, and pulse rate and the interactions were CF×ITD and CF×pulse rate. The interactions of pulse rate×ITD and pulse rate×ITD×CF were not included.

The results for the main effects did not change ($p = 0.002$ for CF; $p < 0.0001$ for the effects of ITD and pulse rate). Neither interaction was significant ($p = 0.1188$ for CF×ITD; $p = 0.4247$ for CF×pulse rate) showing the independence of the effects of CF, ITD, and pulse rate. The significance of the factor CF is an effect of a decreasing performance with increasing CF as indicated by the P_c averaged over ITD, rate, and subjects for the three CFs (72.7%, 71.5%, and 69.2% for CF4.6, CF6.5, and CF9.2, respectively). For each of the rates from 200 to 541 pps, the Tukey–Kramer *post-hoc* tests revealed a significant decrease in performance between CF4.6 and CF9.2 ($p < 0.05$). At the rate of 200 pps, which is least affected by rate limitation effects, the P_c averaged over ITD and subjects are 82.1% (CF4.6), 78.7% (CF6.5), and 79.1% (CF9.2). At 588 pps, there was a non-significant effect of CF ($p > 0.05$; with an *increase* in performance of 0.98% between CF4.6 and CF9.2). For this rate the data represent results from three subjects only. Notice that the presented average P_c scores are averages over subjects while the statistical analysis takes into account the between-subject variability. These averaged P_c scores are only used to determine the direction of the CF effect. In all cases, the performance decreases with increasing CF.

This comparison may be confounded by the fact that not always the same combination of ITD and rate was tested at different CFs. To strengthen the previous findings, we performed an additional statistical comparison for one ITD only, namely, for the ITD of 200 μs. For this ITD, the results (see Fig. 2) show a good balance between ceiling and floor effects, and the data are available for most combinations of rate×CF×subject.[8] Thus, the condition matrix was almost full in this case. An RM ANOVA was performed with factors CF and rate and included the interaction between CF and rate. All main effects were significant ($p < 0.0001$) and the interaction was, as in the previous analysis, not significant ($p = 0.415$). This supports the previous finding that the rate limit does not change with CF. As in the previous comparison, the effect of CF is due to performance decrease with increasing CF as indicated by the P_c averaged over subjects and rate (85.7%, 80.1%, and 75.9% for CF4.6, CF6.5, and CF9.2, respectively). The Tukey–Kramer *post-hoc* tests revealed a significant decrease in performance between CF4.6 and CF9.2 ($p < 0.05$) for 400 pps only. For this rate, the P_c averaged over ITD and subjects are 93.8% (CF4.6), 88.1% (CF6.5), and 82.7% (CF9.2). For all other rates, the P_c averaged over ITD and subjects decreases (not always monotonic) with increasing CF; however, the changes are not statistically significant.

[8]Three exceptions are given for NH9: (1) for 541 pps, he was tested at CF4.6 only because his performance was at chance already for 500 pps at higher CFs; (2) for 400 pps, we have data for CF4.6 and CF6.5 only; and (3) for 450 pps, we have data for CF6.5 and CF9.2 only.

To compare the results to the literature the ITD-JNDs were calculated. Psychometric functions were estimated from maximum-likelihood cumulative Gaussian fits to the raw data (Wichmann and Hill, 2001b).[9] The ITD value yielding 70% of the P_c score along the psychometric function was defined as JND. The estimated JNDs are shown as functions of the pulse rate in Fig. 3, one panel per subject. The parameter is CF. In some cases, mostly for the higher pulse rates, the psychometric functions did not reach 70% and the JNDs could not be determined. These not determinable (ND) JNDs are plotted at "ND." The vertical bars show the 95% confidence intervals of the JNDs and were determined applying a bootstrapping method (Wichmann and Hill, 2001a).

The JNDs for 200 pps, averaged over subjects (±1 standard deviation) are 57.3±48.9 μs (CF4.6), 59.9±32.9 μs (CF6.5), and 58.7±31.1 μs (CF9.2). By increasing the pulse rate, larger differences in JNDs as a function of CF can be found, especially for subjects NH7, NH8, and NH9. However, no general trend can be revealed just by visual inspection. Many JNDs could not be determined for the higher pulse rates and the consequences of this problem for the statistical analysis are discussed in the Appendix. Thus, the estimated JNDs are only used to further facilitate the interpretation of results and for a comparison to the literature in Sec. IV.

IV. DISCUSSION

In this study, the effect of auditory filtering on ongoing envelope ITD-based perception was tested by varying the CF and the pulse rate of bandpass-filtered pulse trains. The bandwidth of the stimuli was co-varied with the CF to obtain an approximately constant stimulation range on the basilar membrane. In this section, we first generally compare our data to previous studies, and then discuss the effects of CF, rate, and auditory filtering on ITD sensitivity.

A. General comparison

A recent study, which describes effects of subject's variability and training patterns, is Zhang and Wright (2007). They studied ITD sensitivity in eight subjects listening to SAM tones (4-kHz carrier and 300-Hz modulator). After training, the subjects achieved an average JND (±1 standard deviation) of approximately 220±50 μs, with 50 μs for the best and 320 μs for the worst subject. Their condition corresponds best to our condition of CF4.6 with the rate of 200 pps, for which the average JND is 57.3±48.9 μs, with 22 μs for the best and 89 μs for the worst subject. Their data can also be compared to our condition CF4.6 with the rate of 300 pps, for which the average JND is 56.3±35.8 μs, with 23.8 μs for the best and 100.8 μs for the worst subject. Thus, the variability of our subjects is similar to that shown in Zhang and Wright, 2007. However, the absolute JND values in our study are much lower, which may result from the different types of stimuli used in both studies. Bernstein *et al.* (1998) tested 19 subjects and showed a JND of 377±191 μs for narrow-band noise stimuli (CF of 4 kHz, bandwidth of 400 Hz). Their variability is much higher than the variability across our subjects. We conclude that the performance variability of our subjects is within a reasonable range and that the conclusions of this study are not likely to be confounded by an accidentally bad sampling of the population.

Bernstein and Trahiotis (2002) studied the sensitivity to ongoing ITD using transposed tones under conditions similar to ours. For 4 kHz and modulation rates of 128 and 256 Hz, they found JNDs of 79 and 100 μs, respectively. These conditions correspond best to our

[9]Using PSIGNIFIT version 2.5.41 (see http://bootstrap-software.org/psignifit/), a software package for fitting psychometric functions to psychophysical data (Wichmann and Hill, 2001b).

condition CF4.6 and 200 pps, where we found a lower JND of 57 μs. Considering an information integration across frequencies, the larger bandwidth of our bandpass-filtered pulse trains provides a potential explanation for the performance differences. Additionally, our bandpass-filtered click trains, after passing the auditory filters, provide sharper envelopes than SAM or transposed tones. These aspects may explain why bandpass-filtered pulse trains show a higher sensitivity to ITD than transposed tones at the similar rate.

For bandpass-filtered pulse trains at CF4.6 and 200 pps, Laback *et al.* (2007) found a performance, which roughly corresponds to a JND[10] of 200 μs. This JND is much higher than ours. However, they used four-pulse stimuli, which results in a stimulus duration of 20 ms. The temporal integration effect of the ITD information for our much longer stimuli is the most likely reason for such a large difference. This is supported by findings of Hafter and Dye (1983), who showed that for 200 pps, appending more pulses to a short stimulus improves ITD sensitivity.

B. Effect of the CF

Our results show a significant decrease in ongoing envelope ITD sensitivity as the CF increases. In the following, we try to estimate the size of the sensitivity decrease. The average decrease in P_c scores averaged over subjects, rate, and ITD is 3% when changing from CF4.6 to CF9.2. This difference increases to 10%, when only data for the ITD of 200 μs are considered. However, in both cases, the data contain conditions with rates near the rate limit, which may confound this estimation. Thus, we consider a lower rate, for which there is no evidence for a strong rate limitation due to auditory filtering, namely, a rate of 200 pps. For this particular rate, P_c scores averaged over subjects and ITD show a significant decrease by approximately 3% when CF is increased from CF4.6 to CF9.2. For 200 pps and ITD of 200 μs, for which the condition matrix is well-populated, analysis of the data revealed a non-significant effect of CF. Further, for 200 pps, the estimation of JNDs also shows approximately constant sensitivity for all CFs, with an average JND of about 59 μs. Thus, even though the quantitative comparison of the sensitivity between different CFs depends on the way of analyzing the data, the decrease in ITD sensitivity for increasing CF appears to be small.

Both the statistical analysis and JNDs show results which are contrary to the outcome of Bernstein and Trahiotis (2002). They found a considerable decrease in ITD sensitivity as CF increased for transposed tones; for the modulation rate of 128 Hz, the JNDs increased from 79 to 170 μs when CF was increased from 4 to 10 kHz. Their results for 128-Hz SAM tones showed an even larger effect of CF: the JNDs increased from approximately 150 μs (for 4 kHz) to 350 μs (for 10 kHz). Bernstein and Triahiotis (2002) concluded that the decrease in performance with increasing CF may result from a frequency dependence of central binaural mechanisms which process ITD.

However, the larger CF effect for SAM and transposed tones can also be explained by comparing the envelopes of the auditory filter response to stimuli with the same rate: by increasing the CF, the envelope of SAM or transposed tone response has only a slight increase in the envelope sharpness because of the constant bandwidth. In contrast, for the envelope of our bandpass-filtered click train response, the relative increase in sharpness with increasing CF is even stronger because the bandwidth was increased too. This probably leads to a more compact period histogram of neural discharges (i.e., more neural synchrony), which may contribute to the higher ITD sensitivity. Actually, our stimuli were designed to yield a constant stimulation range on the basilar membrane. By doing this we hoped to

[10]They calculated 65%-JNDs, while we calculated 70%-JNDs.

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stimulate approximately constant amounts of neurons for different CFs. Our results indicate that stimuli with such a bandwidth *almost* compensate for the CF effect observed with SAM and transposed tones. Nevertheless, this is not necessarily at odds with Bernstein and Trahiotis' (2002) conjecture of a frequency dependency in central processing stages. It still may be the case that the sharper envelopes associated with a roughly constant ERB-rate of our stimuli simply compensate for the hypothesized sensitivity decrease in higher ITD processing stages. It is also worth mentioning that the slightly better ITD sensitivity at CF4.6 may be just because the subjects were trained exactly at this CF.

In electric hearing, the place (electrode) has no systematic effect on the width of excitation patterns (Cohen *et al.*, 2003) and therefore, a constant stimulation range is assumed along the tonotopy. With respect to ITD sensitivity, van Hoesel *et al.* (2002) tested in one CI listener at two different tonotopic places and they did not find any difference in JNDs. However, Litovsky *et al.* (2005) showed an effect of place on ITD sensitivity in electric stimulation, although it was not consistent across all subjects and the most plausible explanation may be the place-dependent survival of neurons (dead regions). Hence, the frequency dependencies in higher processing stages postulated for acoustic hearing could not be shown yet in electric hearing.

Carlyon and Deeks (2002) tested the detectability of dynamic ITDs using bandpass-filtered pulse trains at different CFs. Two of their CFs correspond to our CF4.6 and CF9.2 and for these CFs, they used exactly the same bandwidths as we did. They tested with a 300-Hz *alternating* phase complex, which corresponds to our pulse rate of 600 pps. From the point of view of the monaural stimulus configuration, this is the best-comparable study. However, Carlyon and Deeks (2002) tested a different task: at one ear, they presented signals with a fixed rate and, at the contralateral ear, they presented signals with a fixed but different rate. In such a stimulus, the rate difference creates a dynamic ITD, which periodically bounces between the positive and the negative IPI. In that study, the duration and the rate differences were fixed in such a way that the ITD varied from 0 to at least 413 μs (in terms of increase and decrease) depending on the rate difference. This yields a kind of moving, blurred, or diffuse binaural image, depending on the bouncing rate relative to the limit of binaural sluggishness (Blauert, 1972). In particular, such detection of dynamic ITD corresponds to an incoherence detection task, for which the performance is found to be based on the size of interaural fluctuations (Goupell and Hartmann, 2006). An interesting aspect of Carlyon and Deeks (2002) with respect to our study is that they used exactly the same bandwidth as we do, but they obtained a higher performance then we did. For CF4.6, in their study, all four subjects showed sensitivity to ITD ($d' \geq 1$), while in our study for 588 pps, all subjects performed primarily at chance. For CF9.2, in their study, one of three subjects still showed sensitivity to ITD, whereas, in our study, for 588 pps, none of the five subjects performed consistently above the chance. However, their better ITD sensitivity may result from the fact that in general, listeners are extremely sensitive to changes from coherent signals to slightly-incoherent signals (Gabriel and Colburn, 1981), which may have been the main cue in their task. Nevertheless, their outcome validates our finding of a high ITD sensitivity even at CFs as high as 9.6 kHz and supports our further findings about auditory filtering (see Sec. IV D).

C. Effect of the pulse rate

The results show a strong effect of pulse rate. The median rate limit, which is the highest rate yielding a valid JND, is 500 pps. For transposed tones, Bernstein and Trahiotis (2002) found a rate limit of 256 Hz at 4 kHz, which decreased to 128 Hz at 10 kHz. The lower rate limit at 10 kHz may result from floor effects in the performance because their JNDs for 10 kHz were generally higher than the JNDs for lower CFs even at the lowest rate (32 Hz). For CF4.6, Laback *et al.* (2007) found a limit of 200 pps, which is, again, lower than ours. This is probably an effect of overall lower performance resulting from using much shorter stimuli. Majdak *et al.* (2006) tested NH subjects for pulse rates of 400, 600, 800, and 938 pps using stimuli of 300 ms duration, which is the same as in our study. From their Fig. 7, JNDs can be estimated by applying a 70%-threshold to their P_C-data. This way, the JND can be determinated for the rate of 400 pps only. For the next higher rate tested, 600 pps, the JND is not determinable. Thus, their rate limit is higher than 400 pps and lower than 600 pps, which is in agreement with the results of the present study.

In CI listeners, according to Majdak *et al.* (2006), the rate limitation varied between 100 and 800 pps, depending on the subject. Laback *et al.* (2007) found similar rate limits in CI listeners, again varying between 100 and 800 pps across the subjects. In van Hoesel and Tyler (2003) and van Hoesel (2007), ITD sensitivity of eight CI listeners in total was tested under several conditions. Their rate limit ranges from 100 to 600 pps.

Generally, it appears that CI listeners show sometimes a lower and sometimes a higher rate limit than NH listeners. However, both van Hoesel (2007) and we found individual rate limits, which are equal or higher than those in NH listeners. It appears that the average rate limit (over the subject group tested) is similar for both groups, with the difference that the CI listeners' data show much higher variability. The origin for the strong subject dependence found in the CI-studies is still unclear. However, the existence of CI listeners who show higher rate limits than NH listeners indicates that the lower rate limit found in other CI listeners is not a general property of electric stimulation. On the contrary, the sometimes higher rate limits in CI listeners suggest the existence of different limiting mechanisms in the two listener groups, for example, a lower degree of phase locking in acoustic hearing (Abbas, 1993).

D. Rate limit: Effect of auditory filtering?

Let us return now to the main question posited in this study: does auditory filtering affect the rate limit in ITD perception? Considering CF as the only parameter, an increase in ITD sensitivity with increasing CF would argue for an effect of auditory filtering. However, this can be overshadowed by the effects of changing bandwidths, changing absolute thresholds, or even differences in neural processing when CF of the stimulus changes. Thus, a decreasing performance with increasing CF does not rule out a possible effect of auditory filtering. The impact of auditory filtering can be revealed by also varying the pulse rate: with increasing pulse rate, auditory filtering smears the timing information more and more and reduces the envelope sharpness. Thus, if auditory filtering is responsible for the rate limit, this limit should increase with CF. In the statistical analysis of our data, a significant interaction between pulse rate and CF would support such an effect. In fact, two different statistical analyses showed no such interaction ($p>0.415$) between pulse rate and CF, suggesting no effect of auditory filtering. Thus, our data provide no evidence that the choice of the CF affects the rate limit in ITD perception.

This conclusion is in agreement with the study of Carlyon and Deeks (2002), who compared rate discrimination between monaural and binaural conditions at the rate corresponding to our 600 pps (see Sec. IV B.). They concluded that, even for such a high rate, there is sufficient temporal information in the auditory periphery, which can be used by the binaural system. This implies that auditory filtering is not the rate limiting factor in ITD perception.

However, such a general conclusion is limited by the methods we used. It could still be the case that the power of our statistics was too small to reveal an effect. The across-channel integration may have concealed some differences in performance, preventing us from finding an effect. We tested only five subjects, thus, there is a chance that auditory filtering affects the rate limit in a subpopulation which was not tested in this study. Furthermore, a

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possible CF dependency in the more central processing stages of the brain may compensate for the effect we are looking for.

An alternative explanation for the rate limit could be a consequence of a limitation in higher stages of auditory processing. It may be explained by neural effects in terms of a binaural adaptation mechanism, which seems to affect ITD sensitivity at higher pulse rates when periodic pulse trains are used (Hafter and Dye, 1983). This topic still requires more investigation. For example, as shown in Laback and Majdak (2008) for CI listeners and in Goupell *et al.* (2008) for NH listeners, the temporal structure of stimuli plays an important role in the rate limitation mechanism in ITD perception at higher rates.

Finally, one of our aims was to validate the comparisons between the electric and acoustic rate limits in Majdak *et al.* (2006) and Laback *et al.* (2007). Based on our results, we conclude that those comparisons were not affected by the particular choice of the CF in the acoustic CI simulation.

V. SUMMARY AND CONCLUSIONS

This study investigated the effects of rate and center frequency on ongoing *envelope* ITD sensitivity. With increasing center frequency, the bandwidth of our stimuli was co-varied, aiming at an almost constant stimulation range on the basilar membrane. The results show a decrease in sensitivity when the CF is increased from 4.6 to 9.2 kHz. Compared to studies with a constant bandwidth, our stimuli yielded a relatively *small* effect of CF on ITD sensitivity. Further, ITD sensitivity decreased with increasing rate, showing a median limit at 500 pps. No interaction between the effects of rate and CF could be found. This suggests that the rate limitation is not caused by the ringing of auditory filters. Thus, there is no indication that the comparison of rate limits between electric stimulation and acoustic CI simulation is affected by auditory filtering. It is conjectured that in both acoustic and electric hearing, different mechanisms such as phase locking or some higher stages in the binaural processing are responsible for the upper rate limit in ITD perception.

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APPENDIX

In some cases, mostly for the higher pulse rates, the psychometric functions did not reach 70% for all tested ITD values and the JNDs could not be determined. This appendix shows the problem of including conditions with ND JNDs in an RM ANOVA.

The RM ANOVA is usually performed on all data. However, conditions with ND JNDs cannot be included in the analysis. In the ANOVA model, those conditions are treated as "no information given," leading to a condition matrix not of full rank. This results in a lower test power of the ANOVA. To compensate for this problem, the ND JND conditions can be replaced by a hypothetical JND value, forcing the ANOVA to treat these conditions as if they were measured, even though no sensitivity was found. Thus, the ND JND replacement should be of a sufficiently high magnitude.

We analyzed the JND data using the RM ANOVA under different conditions. The different conditions correspond to the results presented in Table II. In the first ANOVA we excluded

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the ND JND conditions, taking into account having a condition matrix not of full rank (condition *excluded* in Table II). In the following ANOVAs, we included the ND JND conditions and each ANOVA was performed with a different ND JND replacement. In the second ANOVA, the ND JNDs were set to 630 μs (condition 630 μs), which corresponds to the natural ITD for lateral sounds for an average subject (Blauert, 1997). In the third ANOVA, the ND JNDs were set to ¼ IPI (condition ¼ IPI), assuming that this yields maximal sensitivity for the ongoing ITD cue (Majdak *et al.*, 2006). In the fourth ANOVA, the ND JNDs were set to the highest JND derived for each subject and CF [condition max (JND)]. These values ranged from 125 to 585 μs. In the fifth and last ANOVA, the ND JNDs were set to 10 ms (an approximation of infinity, which could not be used due to technical limitations). This was the condition 10 ms. All ANOVA results are presented in Table II. The effect of CF is just significant and not significant ($0.0373 \leq p \leq 0.2327$), depending on the choice for the ND JND replacement. The main effect of the pulse rate is always significant ($p<0.0001$) and the interaction between CF and pulse rate is not significant for all analyses ($p>0.2776$). The comparison of different ND JND replacements clearly shows that inclusion of the ND JND conditions in the ANOVA is problematic and the results depend strongly on the choice of the ND JND replacement.

A straight forward solution is to exclude ND JND conditions from the analysis. However, this leads to a low test power for at least two reasons. First, for the higher pulse rates, only a small amount of data is available for all subjects. Unfortunately, this is the range of pulse rates where we expect an effect of CF and which needs to be well represented by the data. Second, at lower pulse rates, although the data are available for all subjects, the test power of the ANOVA is reduced using the concept of the JND. Performing the ANOVA on JNDs implies comparing only one sample of data per condition and subject. This reduces the test power compared to the analysis based on P_c scores: they are represented by three to five samples per condition and subject.

Furthermore, the concept of the sigmoidal psychometric function is questionable in our study. This model requires a stimulus variable which, under certain conditions, can always be detected (a small observer lapse is allowed; Wichmann and Hill, 2001b). Said another way, the function range should be between 50% and 100% in our discrimination task. This is not always the case: performance in the ND JND conditions never reached 70%. Furthermore, for conditions with determinable JNDs, it cannot be ensured that increasing ITD would lead to P_c=100% (e.g., NH8, CF4.6, 588 pps). For example, Majdak *et al.* (2006) showed more general results for ongoing ITD, which were above 70%-threshold but never reached 100% (their Fig. 7, left upper panel). These results show that sigmoidal psychometric functions are not an appropriate model for the statistical analysis of such an effect. Thus, given the absence of an adequate model for our ITD data, only the statistical analyses of the P_c data are appropriate. Nevertheless, the estimated JNDs remain important to facilitate the interpretation of the results and for a comparison to the literature.

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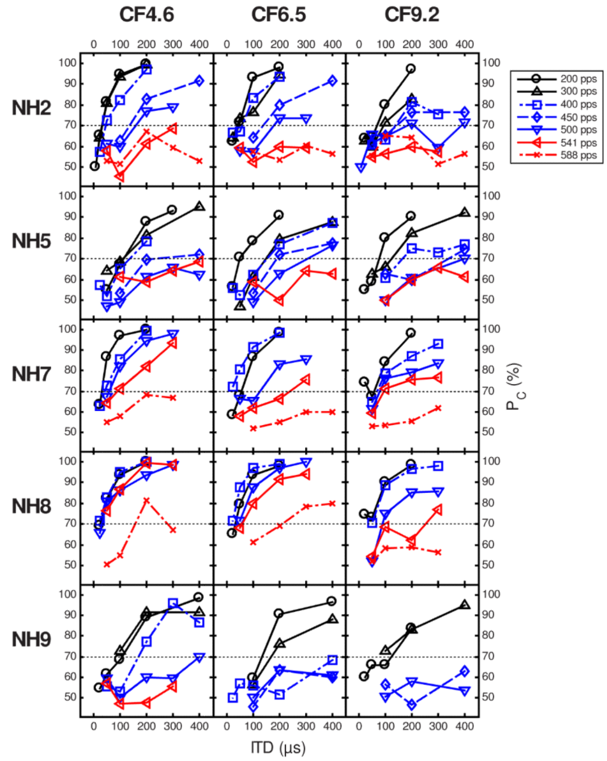

FIG. 1.
(Color online) Performance in percent correct (P_C) as a function of the ITD. The parameter is the pulse rate in pps. Each column shows one CF and each row shows results for one subject. The dashed lines show the threshold used for the JND estimation.

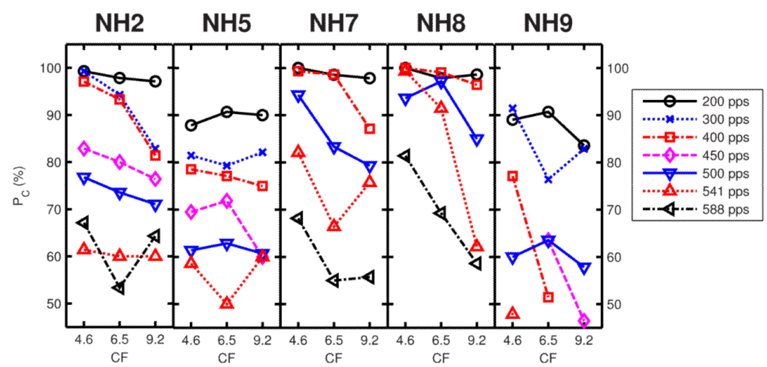

FIG. 2.

(Color online) Percent correct (P_C) data from Fig. 1 for ITD of 200 μs as a function of CF. The parameter is the pulse rate. Each panel shows results for one subject.

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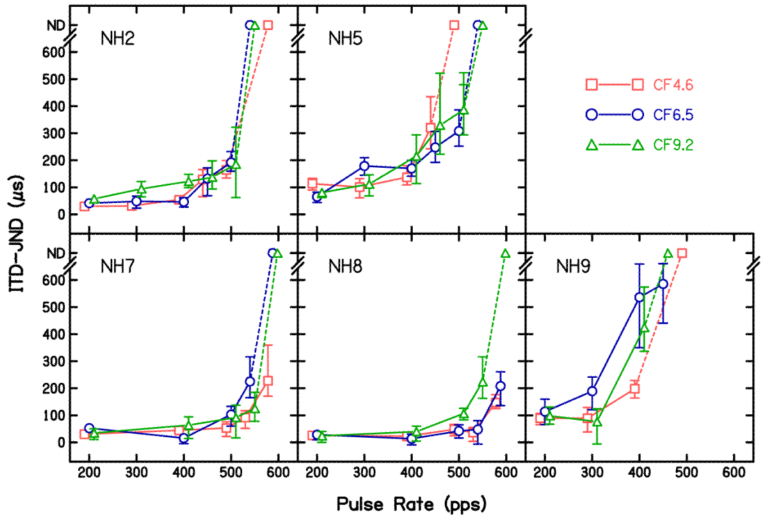

FIG. 3.

(Color online) ITD-JNDs as a function of the pulse rate in pps. The parameter is the CF. The vertical bars indicate the 95% confidence intervals. The non-determinable JNDs are drawn at “ND” and are connected with dashed lines.

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TABLE I

Filter configuration for the conditions CF4.6, CF6.5, and CF9.2. The CF (Hz) is the geometrical CF resulting from the lower and upper edges. The bandwidth (ERB-rate units) is according to Moore and Glasberg (1983). The distance on the basilar membrane (BM) is according to Greenwood (1990).

Code	Center frequency (Hz)	Lower edge (Hz)	Upper edge (Hz)	Bandwidth (Hz)	Bandwidth (ERB-rate units)	Distance on BM (mm)
CF4.6	4589	3900	5400	1500	2.53	2.28
CF6.5	6490	5515	7637	2121	2.35	2.30
CF9.2	9178	7800	10800	3000	2.11	2.32

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TABLE II

Results from separate ANOVAs applying different assumptions for ND JND replacements. Significant effects (p<0.05) are shown in bold. "ND JND" describes the replacement for a non-determinable JND (see Appendix).

ND JND	*p* (CF)	*p* (pulse rate)	*p* (CF×pulse rate)
Excluded	0.0859	<**0.0001**	0.9826
630 μs	**0.0414**	<**0.0001**	0.5045
¼ IPI	**0.0373**	<**0.0001**	0.8050
max(JND)	0.0545	<**0.0001**	0.9722
10 ms	0.2327	<**0.0001**	0.2776