Effects of interaural time differences in fine structure and envelope on lateral discrimination in electric hearing[a)]

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Bilateral cochlear implant (CI) listeners currently use stimulation strategies which encode interaural time differences (ITD) in the temporal envelope but which do not transmit ITD in the fine structure, due to the constant phase in the electric pulse train. To determine the utility of encoding ITD in the fine structure, ITD-based lateralization was investigated with four CI listeners and four normal hearing (NH) subjects listening to a simulation of electric stimulation. Lateralization discrimination was tested at different pulse rates for various combinations of independently controlled fine structure ITD and envelope ITD. Results for electric hearing show that the fine structure ITD had the strongest impact on lateralization at lower pulse rates, with significant effects for pulse rates up to 800 pulses per second. At higher pulse rates, lateralization discrimination depended solely on the envelope ITD. The data suggest that bilateral CI listeners benefit from transmitting fine structure ITD at lower pulse rates. However, there were strong interindividual differences: the better performing CI listeners performed comparably to the NH listeners. © *2006 Acoustical Society of America.* [DOI: 10.1121/1.2258390]

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I. INTRODUCTION

An important cue for the localization of sound sources is the interaural time difference (ITD). It is well established that ITD information in unmodulated signals can only be processed up to about 1500 Hz (Zwislocki and Feldman, 1956; for reviews see Blauert, 1997, and Wightman and Kistler, 1997). At higher frequencies a slow modulation of the carrier transmits the ITD information (e.g., Bernstein, 2001). Using modulated signals, like speech, at least two different types of ITD can be defined: ITD in the envelope (ITD ENV) and ITD in the fine structure (ITD FS). Signals with equal ITD ENV and ITD FS can be considered as a special case in that the whole waveform of one channel is delayed relative to the other channel. This case is most often found in natural signals and is referred to as waveform delay (WD).

Several studies have examined ITD perception in cochlear implant (CI) listeners. Lawson *et al.* (1998) showed that lateralization discrimination using ITD only is possible. Using a pulse rate of 480 pulses per second (pps) they obtained a just noticeable difference (JND) of 150 μs. More detailed studies were performed by van Hoesel and Clark (1997), van Hoesel *et al.* (2002), and van Hoesel and Tyler (2003). In general, the performance was much worse than that of normal hearing (NH) listeners and had high intersubject variability. For unmodulated stimuli the JNDs increased for higher pulse rates and could not be determined at a pulse rate of 800 pps. However, when using low-frequency amplitude-modulated stimuli at this pulse rate, JNDs were on the order of JNDs for unmodulated stimuli with carrier pulse rate equal to that of the low-frequency modulation. Unfortunately, they did not separate the relative contribution of ITD ENV and ITD FS, which may be important for amplitude-modulated stimuli like speech. Laback *et al.* (2004) investigated the effects of ITD ENV manipulation (the ITD FS was random and uncontrolled) in electric hearing by presenting acoustic stimuli via unsynchronized speech processors. They showed that JNDs differed between NH subjects (19 μs) and CI listeners (259 and 384 μs, best JNDs for CI listener S2 and S1, respectively) and depended on the type of stimulus (lowest for click trains, highest for speech or noise bursts).

Current cochlear implant systems use a variety of stimulation strategies to transmit the acoustic information; an overview of which is given in Wilson (2004). Almost all strategies were designed for monaural use and do not include any binaural synchronization: the electric stimulation is controlled by two independently running speech processors. As a result, the ITD information is coded in the envelope only. The strategies have one other aspect in common: according to the specification, they use a constant stimulation pulse rate at both ears. Due to the lack of synchronization between the two ears, the stimulation pulses have an interaural delay, which can be regarded as an ITD FS. This depends on the switch-on delay between the processors and has a random value between 0 μs and the interpulse interval (IPI). If CI listeners are sensitive to ITD FS, it will interact with other lateralization cues like ITD ENV or interaural level differences.

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TABLE I. Clinical data of CI listeners.

Subject	Aetiology	Age at implant *L* yr	Age at implant *R* yr	Deafness duration *L*	Deafness duration *R*	Binaural electric stimulation experience
CI1	Meningitis	14	14	5.5 months	1.5 months	6 yr
CI2	Skull trauma	54	48	21 yr	25 yr	4 yr
CI3	Meningitis	21	21	2 months	2 months	1 month
CI8	Osteogenesis imperfekta	41	39	3 yr	12 yr	2 months

Due to the manufacturing tolerances, the time bases deviate between the speech processors at the two ears, resulting in different IPI. Therefore, the pulse rates cannot be assumed to be equal at both ears. This leads to a dynamically changing ITD FS, which varies between 0 and the IPI. The period of this "ITD beat" increases with decreasing deviation in the pulse rates. If subjects are sensitive to ITD FS, the dynamically changing ITD FS will result in a movement of the auditory image.

It was shown in a recent study (Laback *et al.*, 2005) that ITD FS contributes to lateralization discrimination for lower pulse rates. In this case, a controlled ITD FS may support the effect of ITD ENV and improve the lateralization of sound sources. Coding ITD FS information also may be advantageous for speech perception in noise (Licklider, 1948; Hirsh, 1950; Dirks and Wilson, 1969; Bronkhorst and Plomp, 1988; Hawley *et al.*, 1999) or speech segregation (Drennan *et al.*, 2003; Culling *et al.*, 2004). One study, performed with anesthetized cats, indicates that ITD FS in a low-frequency carrier may be a much stronger cue than ITD ENV in an amplitude-modulated high-frequency carrier: Smith and Delgutte (2005) showed that the neuronal tuning curves in the inferior colliculus are sharper for ITD FS in a low-frequency stimulus (tested up to 320 pps) than for ITD ENV in a high-frequency carrier (tested 1000 pps carrier and modulation frequencies up to 160 Hz).

The goal of this study is to systematically investigate the effects of fine structure ITD manipulation on lateralization discrimination in electric stimulation using amplitude-modulated stimuli. It was expected that CI listeners would be sensitive to ITD FS at lower pulse rates. In addition, the same experiments were performed with normal hearing (NH) subjects using a simulation of electric stimulation to compare their performance with that of the CI listeners. The results allow the assessment of the need for the synchronization of speech processors, taking some synchronization methods into account.

II. METHODS

A. Subjects and apparatus

Four NH subjects participated in this study, of whom one (NH3) was female. All subjects were between the ages of 25 and 35 years old and had no indication of hearing abnormalities. Two of them were the authors of this study (NH2, NH4).

Four cochlear implant (CI) listeners were tested. Three of them were implanted bilaterally with the C40+ implant system manufactured by MED-EL Corp. This system provides pulsatile, nonsimultanous biphasic current pulses on up to 12 electrodes with a minimum phase duration of 26.7 μs. One CI listener (CI2) used the C40+ in the left ear and an older implant, the C40, in his right ear. The C40 provides current pulses on up to eight electrodes with a minimum phase duration of 40 μs. Clinical data of CI listeners can be found in Table I. The subjects were selected from a total of seven CI listeners invited for participation in the study. These four listeners fulfilled the selection criterion, as defined by the ability to reproducibly perform left/right discrimination on the basis of waveform ITD in a pulse train with a pulse rate of 100 pps in a reasonable amount of time.

A personal computer system was used to control electric and acoustic stimulation. Each implant was controlled by a Research Interface Box (RIB), manufactured at the University of Technology Innsbruck, Austria. The two RIBs were synchronized, providing an interaural accuracy of stimulation timing better than 2.5 μs. Prior to the experiment, the stimuli were verified using a pair of dummy implants (Detektorbox, MED-EL). The stimuli for acoustic stimulation were output via a 24-bit stereo A/D-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 amplitude-modulated pulse trains which were designed as pulse trains multiplied by a predefined envelope. ITD FS and ITD ENV were introduced by delaying the temporal position of the pulses and of the envelope, respectively, at one ear relative to the other ear. The following ITD conditions were specified: ITD in envelope only (ENV), ITD in fine structure only (FS), no ITD at all, which is the reference condition (REF), and the identical ITD in both the envelope and the fine structure, referred to as waveform delay (WD).

The envelope consisted of four trapezoids with durations of 60 ms, each repeated at a period of 80 ms, resulting in 20 ms gaps between two successive trapezoids and a total stimulus duration of 300 ms (Fig. 1). The trapezoid period of 80 ms yields an amplitude modulation frequency of 12.5 Hz. Since the envelope modulation is trapezoidal, the modulation

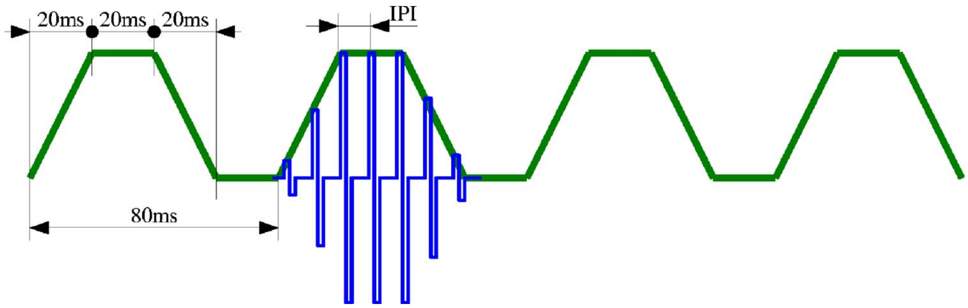

FIG. 1. A schematic representation of the stimulus used in this study. For readability purposes the fine structure characteristics are shown in one trapezoid only. The ramps slope down to the absolute threshold of each subject. Between the trapezoids the amplitude was set to zero. In acoustic stimuli, pulses with positive amplitude were applied.

spectrum contains multiples of the 12.5 Hz as well. There were several reasons for selecting a relatively slow modulation rate. Although sensitivity to ITD increases with growing modulation frequency up to approximately 125 Hz (Henning, 1974; Bernstein, 2001) values in that range interfere with the lower limit of the pulse rates used here (100 pps). Even modulation rates as low as tens of hertz reduce the information available in the fine structure. Furthermore, pulse trains with modulation rates on the order of 12.5 Hz more closely resemble real-world signals than pulse trains modulated with higher rates. In particular, speech has a modulation spectrum peak of approximately 5 Hz (Greenberg *et al.*, 2003). Considering these aspects, these values of modulation frequency lead to signals providing sufficient ITD information in both the fine structure and the envelope. Finally, the rise and release time of each trapezoid was set to 20 ms. This value was chosen to emphasize the onset and the offset effects, which are assumed to enhance sensitivity to ITD ENV. The level of the first and last pulse of each trapezoid was set at the subject's absolute threshold, which was determined in pretests (see Sec. II C). Between the trapezoids, the amplitude was set to zero. The acoustic amplitudes were interpolated logarithmically and the electric currents were interpolated linearly.

Both van Hoesel (2003) and Laback *et al.* (2005) found that subjects differed strongly in their sensitivity to ITD as a function of pulse rate. In the two studies the sensitivity was generally highest at lowest pulse rates tested, which were 50 and 100 pps, respectively. On the other hand, current stimulation strategies use pulse rates up to about 1600 pps (Wilson, 2004), thus, testing these pulse rates is important for real world applications. Consequently, the pulse rates to be tested must be selected individually for each subject: three to four pulse rates between 100 and 1600 pps, corresponding to IPI between 10 ms and 625 μs, were chosen for each subject on the basis of lateralization discrimination pretests described in Sec. II D.

In the case of electric stimulation, the pulse trains were composed of biphasic current pulses. Each phase of a pulse had a duration of 26.7 and 40 μs for the C40+ and the C40 devices, respectively. An interaurally pitch-matched electrode pair, selected in pretests (see Sec. II C), was used for all experiments.

To allow a direct comparison of the results from NH subjects with those from CI subjects, the electric stimulation was simulated in the NH subjects using a method developed by McKay and Carlyon (1999) and further successfully applied by Carlyon *et al.* (2002). Pulse trains were 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 trains were passed through a digital eighth-order Butterworth filter with a geometric center frequency of 4590 Hz and −3 dB bandwidth of 1500 Hz.

Due to the filtering of amplitude-modulated pulse trains, a possible naming clash might have been introduced. In the NH literature, the "fine structure" of the acoustic stimulus refers to the carrier frequency, which is 4590 Hz in our case. Following this definition, every filtered pulse has an "envelope," which is the envelope of the impulse response of the bandpass filter. Furthermore, the envelope of the pulse train appears as a second-order envelope. The carrier frequency arises from the filtering procedure, which is not the object of interest in this study. Thus, the definitions from the CI literature have been adopted to the acoustic signals. In reference to acoustic signals, the term "fine structure" defines the total impulse response of the bandpass filter, not the carrier only, and "envelope" refers to the slow trapezoidal amplitude modulation of the filtered pulse trains. Keeping in mind that the acoustic stimuli represent a simulation of electric stimulation, the same terms can be used to describe electric and acoustic stimulation effects.

Given that the sound pressure level (SPL) depends on the pulse rate, stimulation amplitudes were adjusted to maintain a constant SPL of 59 dB, measured at the headphones, at all rates for all NH subjects. 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 pink noise with a spectrum level of 15.2 dB SPL at 4.6 kHz was continuously played throughout the testing.

Eight ITD FS values were chosen for each pulse rate, which corresponded to values from 0 μs up to seven-eighths of the IPI in steps of eighth IPI. These values covered the range of ITD FS which would occur in a setup of unsynchronized speech processors and included ITDs exceeding the natural head-width delay for lower pulse rates. The investigations on effects of ITD ENV were secondary in this study; thus, only two values were used. The intended values of 400 and 625 μs represent large ITD values with respect to the head size, and correspond to ITD ENV cues as they occur in real-world situations. Unfortunately, in the lateralization pretests the CI listeners showed no sensitivity at 400 μs and very low sensitivity at 625 μs. Thus, intending to produce as much effect as possible, larger ITD ENV values were chosen for the CI listeners: 625 and 800 μs.

C. Pretests

In the experiments with CI users, pretests were performed to determine a binaurally loudness balanced, pitch-matched electrode pair for each listener. The pretests used pulse trains of 300 ms duration with zero ITD, 100 pps pulse rate, no amplitude modulation, and consisted of a manual up/down procedure to estimate each listener's threshold (THR), comfortable level (CL), and maximum comfortable level (MCL); a balancing procedure to iteratively determine levels of binaurally equal loudness for each electrode pair; a monaural pitch estimation procedure to reduce the number of candidates for pitch matching for both ears; and a pitch ranking procedure to determine the pitch discriminability for the pair candidates and finally select one pitch matched pair.

To determine the THR, CL, and MCL for each electrode the perceived loudness was indicated by the subjects by pointing to the appropriate position on a continuous scale, ranging from "not audible" to "just uncomfortably loud." The CL corresponded to the subject's response "comfortable." The same procedure was then applied to determine the binaural CL, i.e., the comfortable level when both ears were stimulated simultaneously. Starting at 80% of the monaural CLs, levels were varied simultaneously in equal steps at the two ears. Subjects were instructed to attend to the overall loudness in the binaural case rather than to "hear out" a left-ear or right-ear contribution. Following the initial adjustment of the binaural CL, centralization of the perceived stimulus was checked and monaural levels were adjusted if necessary. All subjects required a reduction of current levels in the binaural condition relative to the monaural conditions to achieve the same loudness.

A magnitude estimation procedure was applied to obtain an estimate of the perceived pitch across the electrodes at both ears, similar to the procedures applied by Busby *et al.* (1994) and Collins *et al.* (1997). Stimuli were presented randomly between both ears and at each of the electrodes 1–8, using the binaural CLs determined before. Subjects were instructed to assign numbers according to the perceived pitch of each stimulus. No restrictions on the range and type of numbers were given. Each stimulus was presented ten times. The distribution of pitch judgments across the electrodes and the two ears allowed selection of about 16 interaural electrode pairs supposed to elicit similar pitch sensation at the two ears. These pairs were evaluated further in the pitch-ranking task.

An automated procedure was applied to obtain interaurally loudness-balanced levels for each of the electrode pairs used further in the pitch ranking task. The members of each electrode pair were presented in two subsequent intervals. By pressing one of two buttons the subjects adjusted the relative level of the signals between the two ears in steps corresponding to the smallest amplitude changes realizable by the implants to arrive at an interaurally matched loudness. The sum of the two levels within a trial was held constant and corresponded to the sum of the binaural CLs determined for the respective electrodes. The level difference at the beginning of each run was randomly roved. The mean value resulting from four runs was defined as the loudness-balanced levels for the members of the respective electrode pair.

TABLE II. Stimulation levels for each CI listener as parameter of pulse rate. "⋯" shows not tested pulse rates.

	Stimulation current left/right in μA			
Pulse rate in pps	CI1	CI2	CI3	CI8
100	⋯	358/1045	⋯	⋯
150	⋯	355/1045	⋯	⋯
200	478/486	362/1031	⋯	⋯
400	470/401	393/909	478/524	376/586
600	⋯	⋯	⋯	⋯
800	⋯	⋯	440/470	376/586
938	⋯	⋯	⋯	371/532
1600	501/424	⋯	347/370	⋯

In the pitch-ranking procedure the members of each of the electrode pairs were directly compared with respect to the perceived pitch difference, using a two-interval, two-alternative forced-choice (2-AFC) procedure. The pair members were presented randomly either in the first or second observation interval. Subjects were required to indicate which of the two stimuli sounded higher in pitch while concentrating on pitch rather than on other attributes such as timbre or loudness. Electrode pairs with an average discriminability across 25 repetitions within the range of chance (50±18%) were considered as pitch-matched. For subjects with more than one pitch-matched electrode pair, the pair at medial tonotopic position was chosen. The selected electrode pairs were (left/right): 4/1 (CI1), 2/3 (CI2), 4/3 (CI3), and 7/5 (CI8).

Using the automated loudness balancing procedure described earlier, the levels for each pulse rate were determined with the goal of obtaining a binaurally balanced, comfortable loudness level for the selected pitch-matched electrode pair. Table II depicts the subject-dependent stimulation currents for each pulse rate.

D. Procedure

A two-interval, 2-AFC procedure was used in the lateralization discrimination tests. The first interval contained a 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. All stimuli were repeated at least 60 times, in a balanced format with 30 targets on the left and 30 targets on the right. Thus, a subject with no ITD sensitivity could get 50% responses correct by guessing. A score of 100% correct responses would indicate that all stimuli were discriminated, with lateralization corresponding to the ear receiving the leading signal. In contrast, a score of 0% implies perfect discrimination as well, but with lateralization at the ear receiving the delayed signal.[1] To avoid biasing the subjects toward a particular manner of responding, no feedback was

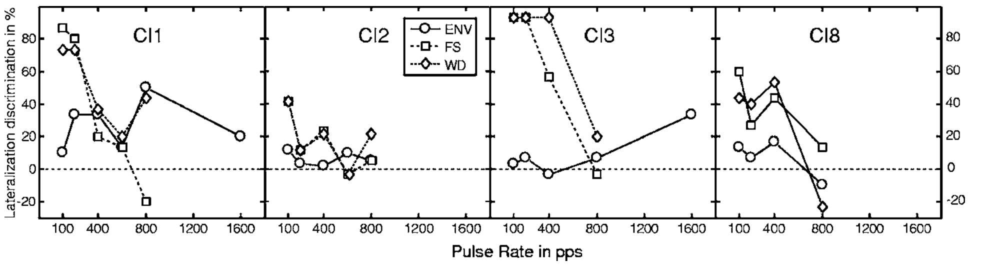

FIG. 2. Pretest results as lateralization discrimination (LD) for different pulse rates and four CI listeners. Conditions: ENV: ITD ENV=625 μs; FS: ITD FS=625 μs; WD: ITD FS=ITD ENV=625 μs.

given. To simplify the interpretation of the results, scores ranging from 0% to 100% were mapped to a range from −100% to +100%, referred to as "lateralization discrimination" (LD). Lateralization discrimination of 0% means that the target could not be discriminated from the reference stimulus with respect to the lateral position and represents 50% correct responses.

Lateralization discrimination pretests were performed to select, for each listener, the pulse rates to be used in the main experiment. Discarding conditions with very low sensitivity to ITD kept the test time as short as possible. In the pretests, one ITD value of 625 μs was presented in three different ITD conditions: ENV, FS, and WD. The results for each CI listener are shown in Fig. 2. Based upon these results and the availability of the subjects three to four pulse rates were chosen for each subject to be tested in main experiments (CI1: 200, 400, 1600 pps; CI2: 100, 150, 200, 400 pps; CI3: 400, 800, 1600 pps; CI8: 400, 800, 938 pps). The NH subjects were tested at 400, 600, 800 and 938 pps.

III. RESULTS

The LD data of the individual CI listeners are shown in Fig. 3 (CI1), Fig. 4 (CI2), Fig. 5 (CI3), and Fig. 6 (CI8). The results of the NH subjects were more homogeneous; as a result, the mean scores of all four NH listeners are provided in Fig. 7. For all listeners there was a common pattern of LD as a function of ITD FS. At the lowest pulse rates (different for each subject) in the conditions ITD ENV=0 μs, LD increased monotonically with ITD FS for ITD FS less than 0.25 IPI with a maximum at about 0.25 IPI. For ITD at approximately 0.5 IPI, LD was at chance (=0%), confirming the ambiguity in the lateralization task using ITD FS only. As ITD FS exceeded 0.5 IPI, the magnitude of LD as a function of ITD FS was similar to that for ITD FS $<$ 0.5 IPI but with the opposite sign. This indicates that LD upon ITD FS is periodic and that stimuli with ITD FS $>$ 0.5 IPI effectively represent stimuli with negative ITD FS. At the highest pulse rates tested (different for each subject) the dependence of LD on ITD FS disappeared. Introducing a nonzero ITD ENV resulted in a lateralization shift toward the ear receiving the stimulus with the leading envelope. This effect seems to increase with increasing pulse rate.

Although most trends were easily distinguishable by visual inspection, a statistical analysis was used to determine the significance of the trends. The statistical method employed was multidimensional contingency table analysis (Lienert, 1978; Agresti, 1984, 1996) implemented in "stats" package of R (R Development Core Team, 2004). This is a useful method for intersubject comparisons of results obtained by a 2-AFC task, for which the variance analysis is not available,[2] although it is an unusual method in psychoacoustics. A general description of this method would exceed the scope of this paper. Thus, only a summary of the tests and models applied in the context of the data analysis is provided.

The significance of the differences between two conditions was tested by obtaining the two-tailed probability p of the Pearson χ^2 statistic for the null hypothesis that the logarithmic odds ratios[3] for both conditions are equivalent (Agresti, 1984). Log-linear models were fitted to determine the interactions between different factors. The goodness-of-fit of a model to the data is described by the G^2, df, and p values. In these cases, the significance of an effect is given by the significance of the corresponding model parameter. In cases of fitted data, the calculation of odds ratios was done using estimated response frequencies, according to Agresti (1984, pp. 47–69). Some conditions were tested with a higher number of repetitions ($>$60) due to differences in the availability of subjects. Thus, the investigations of marginal associations, collapsing[4] the data over the variable tested with different number of repetitions, were done using regularization of the data to the smallest common number of repetitions (=60). To increase the test power, pulse rate and ITD ENV were treated as ordinal factors.

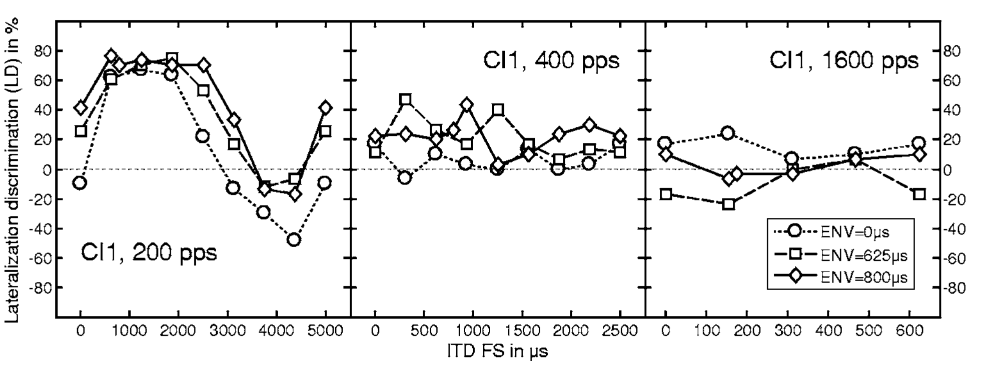

FIG. 3. Lateralization discrimination for CI1 and different pulse rates. To point out the periodicity of the ITD FS the data points for the ITD FS=IPI are copies of the data points for ITD FS =0 μs. Note the different scaling of the X axes.

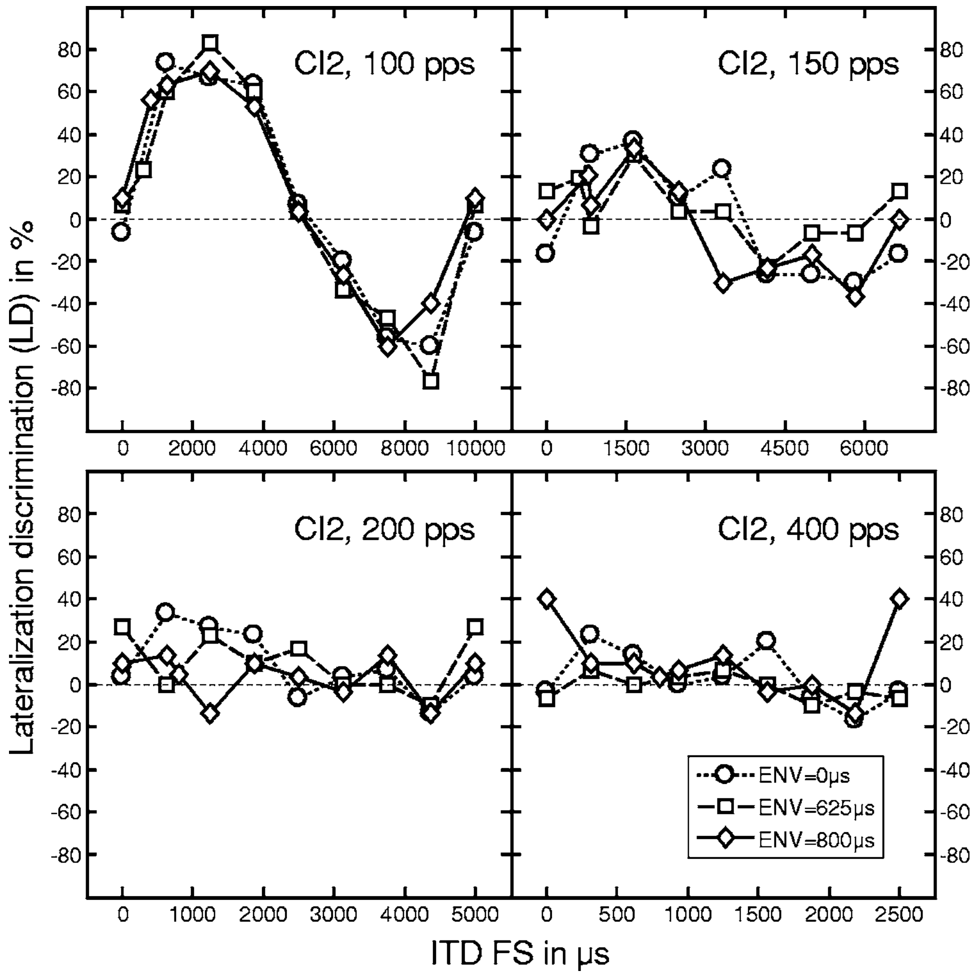

FIG. 4. Lateralization discrimination for CI2 and different pulse rates. To point out the periodicity of the ITD FS the data points for the ITD FS=IPI are copies of the data points for ITD FS $=0\ \mu$s. Note the different scaling of the *X* axes.

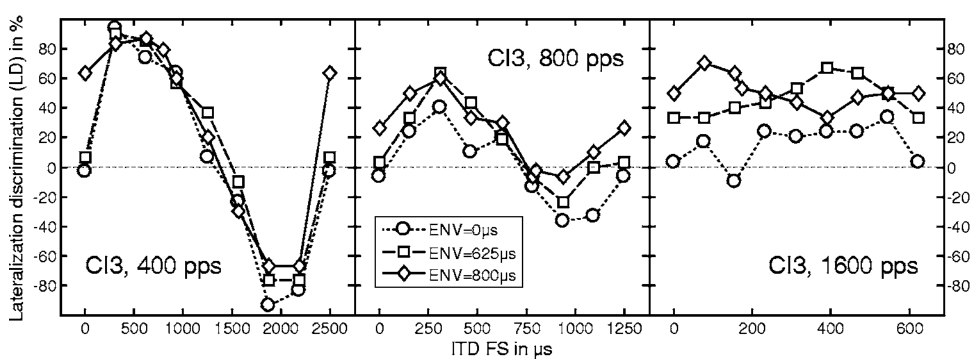

FIG. 5. Lateralization discrimination for CI3 and different pulse rates. All other conventions are as in Fig. 4.

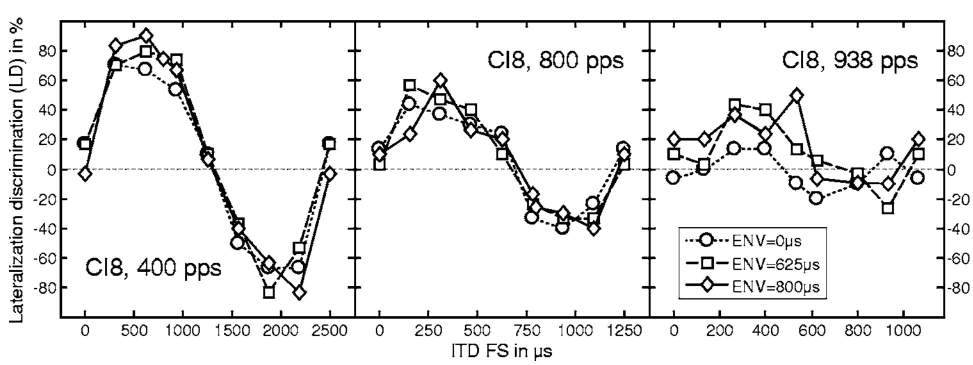

FIG. 6. Lateralization discrimination for CI8 and different pulse rates. All other conventions are as in Fig. 4.

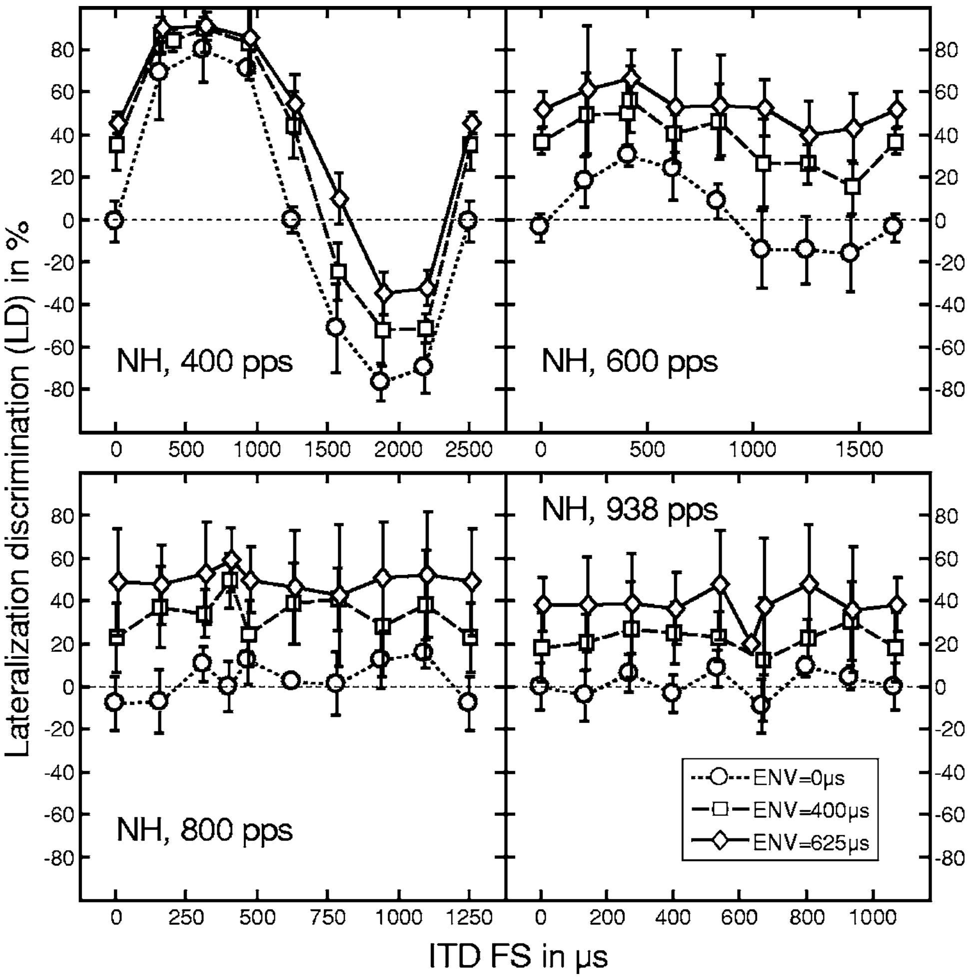

FIG. 7. Average lateralization discrimination for all NH subjects and different pulse rates. To point out the periodicity of the ITD FS the data points for the ITD FS=IPI are copies of the data points for ITD FS=0 μs. The bars shows the standard deviation. Note the different scaling of the *X* axes.

The statistical analysis is structured as follows: in Sec. III A the differences between subjects will be analyzed and a classification will be done to show the homogeneity in the results of the CI listeners and how it compares to the results of the NH listeners. Section III B considers effects of interaural synchronization on lateralization discrimination and shows some improvements which can be achieved by specific coding of the ITD. In Sec. III C the effects of ITD ENV will be analyzed in relation to the factors pulse rate and subject.

A. Groups of subjects

The pulse rate of 400 pps and ITD ENV of 0 and 625 μs were used for the analysis of differences between subjects, since they were the only values available for all subjects. Using these data, the odds ratios for the categorical factor subject were calculated and analyzed. The subjects were clustered according to the type of stimulation and the analysis was performed on each group separately. The results showed that the group of NH subjects was homogeneous ($\chi^2_3=0.07$, $p=0.995$) and the group of CI listeners was heterogeneous ($\chi^2_3=20.0$, $p<0.001$). Therefore, further analyses were performed on the NH listeners as a group and for each CI listener individually. However, the better performing CI listeners (CI3 and CI8) performed sufficiently similar to the NH subjects that they could have been clustered with the NH subjects to form a larger homogeneous group ($\chi^2_5=1.34$, $p=0.93$).

B. Interaural synchronization

To address the question of the need for interaural pulse synchronization, the dependence of LD on ITD FS was investigated. If a subject lateralizes the stimuli for ITD FS <0.5 IPI to one side and for ITD FS >0.5 IPI to the opposite side, that implies that LD depends on ITD FS. Therefore, the data for all conditions fulfilling ITD ENV=0 μs were grouped as follows: the first group contained all LDs for $0<$ ITD FS <0.5 IPI and the second group all LDs for 0.5 IPI $<$ ITD FS $<$ IPI. Results for ITD FS=0 and 0.5 IPI were discarded as there is no lateralization information, and they should be at chance rate. It was hypothesized that if there is a significant difference between the direction of LD for both ITD FS groups, then LD depends on ITD FS, thus indicating the necessity of interaural pulse synchronization.

For the NH listeners the data pool (subject $\times$ ITD FS group $\times$ pulse rate $\times$ response) was collapsed across subjects because of the homogeneity of their performance. A log-linear model was fitted to this data pool with the result that only the saturated model[5] could give an accurate fit, showing a strong interaction between the factors pulse rate and ITD FS group. Thus, the dependency on ITD FS was investigated

TABLE III. Probability of no dependence of LD on ITD FS for ITD ENV=0 μs conditions. Conditions with the highest pulse rate with significant sensitivity on ITD FS are shown bold; df was 1 for all results.

Pulse rate in pps	NH		CI1		CI2		CI3		CI8	
	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p
100	⋯	⋯	⋯		117	<0.001	⋯	⋯	⋯	⋯
150	⋯	⋯	⋯		25.6	<0.001	⋯	⋯	⋯	⋯
200	⋯	⋯	165.1	**<0.001**	7.65	**0.006**	⋯	⋯	⋯	⋯
400	711.9	<0.001	0.1	0.752	1.61	0.21	185.4	<0.001	139.4	<0.001
600	77.89	**<0.001**	⋯	⋯	⋯	⋯	⋯	⋯	⋯	⋯
800	2.186	0.139	⋯	⋯	⋯	⋯	16.48	**<0.001**	42.73	**<0.001**
938	0.1361	0.712	⋯	⋯	⋯	⋯	⋯	⋯	0.571	0.45
1600	⋯	⋯	0.549	0.459	⋯	⋯	2.59	0.108	⋯	⋯

for each pulse rate separately, analyzing the odds ratios in partial contingency tables with fixed pulse rate. For the NH subjects 600 pps was the highest pulse rate with significant sensitivity on ITD FS. For the CI listeners the data were analyzed separately for each subject in the same way as for the NH listeners: odds ratios in partial contingency tables were analyzed for each pulse rate. The better performing CI listeners (CI3, CI8) showed significant sensitivity to ITD FS for pulse rates up to 800 pps, while for the poorer performing CI listeners (CI1, CI2) a significant sensitivity could be found only for pulse rates up to 200 pps. Detailed results of the analysis are shown in Table III.

It was further hypothesized that for conditions showing a dependence of LD on ITD FS, the synchronization of the ITD FS to the ITD ENV would result in a better LD than synchronizing ITD FS to zero. This was evaluated by keeping the ITD constant and comparing the LD between two synchronization conditions: one in which the ITD is carried both by the envelope and the fine structure (WD) or alternatively by the envelope only, keeping ITD FS at zero (ENV). In the statistical analysis, the synchronization conditions were regarded as a factor with two levels (WD, ENV) and the ITD as a factor with two levels, which depended on the subject group (NH: 400 and 625 μs; CI: 625 and 800 μs). The analysis was performed for the NH group and for each CI listener separately. As before, log-linear models were fitted to investigate the interactions. The hypothesis of no interaction between the factors ITD and synchronization condition could not be rejected for CI1 ($G^2=8.3867$, $df=10$, $p=0.591$) or CI8 ($G^2=8.4617$, $df=10$, $p=0.584$). Thus, the data were collapsed over ITD for these subjects. For all other subjects, separate partial tables were used for each ITD value. The probabilities for the hypothesis of equal LDs in both synchronization conditions for each subject and pulse rate showing dependence on ITD FS ($p<0.05$ in Table III), are given in Table IV.

The NH subjects showed an improvement using the WD condition for pulse rates up to 600 pps for an ITD of 400 μs ($p=0.04$). Increasing the ITD to 625 μs, the improvement due to synchronization decreased, and could be found for 400 pps only ($p<0.001$). This revealed an interesting effect of combining ITD FS and ITD ENV: assuming a dependence of LD on ITD FS, it can be expected that increasing the ITD in both the envelope and fine structure (WD) improves LD up to about 0.25 IPI. Above this point, up to ITD=0.5 IPI, LD is expected to decrease because at ITD=0.5 IPI the ITD FS cue provides ambiguous information. Increasing the ITD further, depending on the relative perceptual contribution of ITD ENV, the stimulus may even be lateralized toward the opposite side. This actually happened for CI8 (800 pps, ITD FS=800 μs, see Fig. 6). Thus, the synchronization of the fine structure to the envelope gives an improvement for ITD values smaller than half IPI only.

For the CI listeners, improvements due to synchronization were observed for the following pulse rates: 200 pps

TABLE IV. Probability for equal LD in conditions ENV and WD. Conditions with the highest pulse rate with significantly higher LD for WD than for ENV are shown in bold.

Pulse rate in pps	NH		CI1	CI2		CI3		CI8
	400 μs	625 μs	⋯[a]	625 μs	800 μs	625 μs	800 μs	⋯[a]
100	⋯	⋯	⋯	0.356	**0.007**	⋯	⋯	⋯
150	⋯	⋯	⋯	0.681	0.143	⋯	⋯	⋯
200	⋯	⋯	**<0.001**	0.141	0.729	⋯	⋯	⋯
400	<0.001	<0.001	⋯	⋯	⋯	**<0.001**	0.091	**<0.001**
600	**0.04**	0.696	⋯	⋯	⋯	⋯	⋯	⋯
800	⋯	⋯	⋯	⋯	⋯	0.266	0.043[b]	0.17

[a]ITD was marginalized in these cases.
[b]LD for ENV condition was higher than for WD condition. χ^2 values have been omitted for readability purposes.

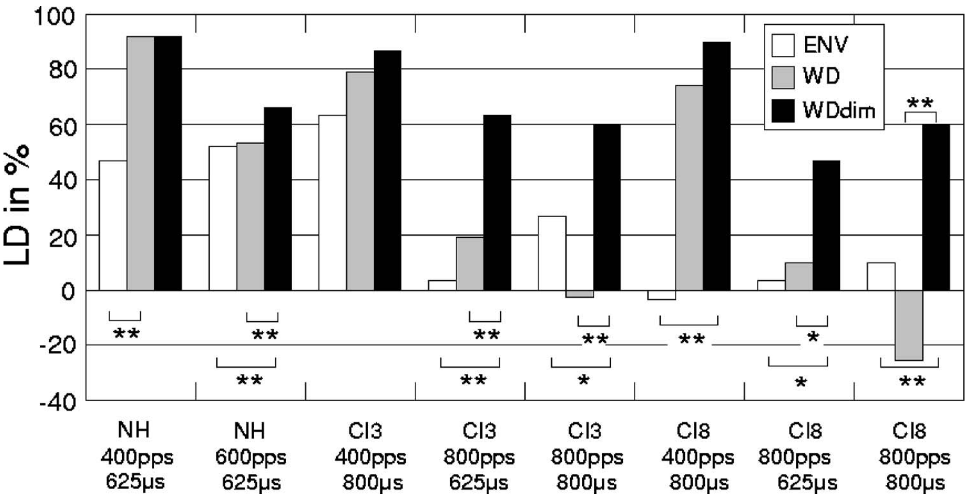

FIG. 8. Comparison of lateralization discrimination for conditions ENV, WD and WD_{DIM}. Significance codes: $^{*}p<0.05$; $^{**}p<0.01$.

(CI1), 100 pps (CI2), and 400 pps (CI3 and CI8). For CI3, at a pulse rate of 800 pps and ITD of 800 μs, there was a significant difference ($p=0.043$), but the LD was higher for ENV than for WD. Since the ITD exceeded 0.5 IPI, this is an example of the effect of combining conflicting ITD FS and ITD ENV, which was also seen in the NH subject' results. This effect seems to reduce the positive effects of synchronizing ITD FS to ITD ENV, but it allows an optimization of coding ITD FS: for ITD values greater than 0.25 IPI the WD condition was modified, diminishing the ITD FS to 0.25 IPI. This condition is termed *diminished waveform delay* (WD_{DIM}) and a new formula for ITD FS coding is proposed:

$$\text{ITD FS} = \min\left(\text{ITD ENV}, \tfrac{1}{4}\text{IPI}\right). \quad (1)$$

To obtain an improvement using WD_{DIM}, the ITD must be greater than 0.25 IPI. To fulfill this requirement for low ITDs the pulse rate must be as high as possible. On the other hand, the effect of ITD FS is weak for higher pulse rates. Thus, the WD_{DIM} optimization is efficient only for medium pulse rates showing sensitivity to ITD FS. Figure 8 compares lateralization discrimination between the conditions ENV, WD, and WD_{DIM}, for each of the ITDs and pulse rates measured and fulfilling the specified requirements. In most cases LD increased using WD_{DIM} optimization; in one case (CI8, 800 pps, 800 μs) even a reversal of lateralization into the correct direction could be achieved.

C. Effects of ITD ENV

To determine the effects of envelope delay, a comparison of the sensitivity to ITD ENV between the subjects was performed for stimuli with 400 pps and ITD ENV values of 0 and 625 μs. For subjects showing no effect of ITD FS at this pulse rate and ITD ENV held constant at either value, all ITD FS values can be averaged to increase the power of the test. Even for subjects showing dependence of ITD FS on LD at this pulse rate, the marginalization of ITD FS is justified, based on the finding of independence between ITD ENV and ITD FS. Thus, log-linear models including the factors subject, response and ITD ENV for results collapsed over ITD FS were fitted to the data. For both CI and NH listeners only the saturated model could be fitted, showing strong intersubject variability ($p<0.001$ for the three-way interaction term). Thus, the NH and CI listener groups were analyzed separately. For the NH listener group the model with the marginalized factor subject fits well ($G^2=3.432$, $df=12$, $p=0.992$), revealing homogeneity of subjects within this group and high sensitivity to ITD ENV ($p<0.001$). For the CI listener group the model including interactions [subject × response] and [ITD ENV × response] gave the best fit ($G^2=6.121$, $df=12$, $p=0.41$) showing a significant overall sensitivity to ITD ENV of the group ($p=0.031$); however, a significant deviation of the performance of listeners CI1 ($p=0.039$) and CI2 ($p=0.032$) from the group of CI subjects could be found. Therefore the ITD ENV sensitivity of the CI listeners was analyzed separately in a contingency table analysis, revealing a significant sensitivity for listener CI1 ($p=0.007$) and no sensitivity for the rest ($p>0.1$ for CI2, CI3, CI8) at 400 pps.

Finally, the effect of ITD ENV (0, 625, 800 μs) on LD was investigated with pulse rate as parameter. The three-way interaction parameters of saturated log-linear models including the factors pulse rate, ITD ENV, and subjects' response for each subject were examined. An interaction between ITD ENV and pulse rate could be found for CI3: increasing the pulse rate within the range of values tested or raising the ITD ENV increased the odds ratio by the factor of 1.129 ($p=0.011$), indicating a greater sensitivity to ITD ENV with increasing pulse rate. For the NH subjects, sensitivity was independent of the pulse rate ($p=0.66$) but strongly associated with ITD ENV (raising the ITD ENV from 0 to 400 μs or from 400 to 625 μs increased the odds ratio by the factor of 1.558, $p<0.001$).

IV. DISCUSSION

The results of this study show that the tested CI listeners are sensitive to ITD in the fine structure for pulse rates up to 800 pps, depending on the individual listener. The NH subjects listening to a simulation of electric stimulation showed sensitivity up to 600 pps for the same conditions. This is qualitatively consistent with the results of Laback *et al.* (2005) who used unmodulated trains with four pulses and found sensitivity to ITD FS up to 800 pps in two out of three CI listeners and up to 400 pps in the NH listeners, depending on the individual listener. Furthermore, in both studies the data of the NH subjects show little intersubject variability, as opposed to the results of the CI listeners, who in this and most other studies show a wide range of performance. Such strong intersubject variability implies that at least one factor influencing sensitivity to fine structure ITD has not been taken into account in this study and furthermore that statistical evaluation of CI listeners as a group may yield misleading conclusions.

Recovery from forward masking (Chatterjee, 1999; Nelson and Donaldson, 2001; Nelson and Donaldson, 2002) could be an explanation for the large subject dependence among CI listeners. Forward masking in CI listeners may imply longer decay in the excitation pattern, which would smear the fine structure resulting in a lower sensitivity to fine structure ITD.

The strong intersubject variability, combined with the small number of subjects, limits the interpretation of the results to case studies. It is interesting that the better performing CI listeners (CI3, CI8) had 1–2 months of bilateral experience, while the worse performers (CI1, CI2) had years of bilateral experience. One may be tempted to hypothesize that CI1 and CI2 lost their ability to utilize fine structure cues because of the longer period of stimulation with signals that are uncorrelated in the fine structure. We had the opportunity to test CI8 one year after the main tests under similar conditions. In contrast to the hypothesis, the performance of CI8 was not significantly different than the previous results, which suggests that either the time constant of the unlearning process is much longer than one year or the origins underlying the individual differences in performance are much more complex. Actually, testing one subject to validate a hypothesis based on evidence derived from two groups of two subjects appears to be very speculative. Thus, more extensive tests with more subjects are required to validate this hypothesis.

There are at least two possible explanations for the higher maximum rate showing significant effects of ITD FS on LD in the better performing CI listeners compared to the NH listeners. First, one of the limiting parameters in acoustic hearing could be the smearing of the temporal information by auditory filtering in the cochlea. Filtering the acoustic signals with a simulation of the auditory filter (center frequency: 4590 Hz) shows that by increasing the pulse rate, the modulation depth of the stimuli decreases, but is still present for pulse rate as high as 938 pps, which was the highest pulse rate used in the experiments with the NH listeners. In electric hearing, the auditory filters are bypassed. Second, in electric hearing, the degree of neural phase locking is known to be stronger than in acoustic hearing due to bypassing the synaptic mechanism at the hair cell (Abbas, 1993). An appropriate characteristic of both effects with respect to the pulse rate might lead to higher ITD FS sensitivity in electric hearing at higher pulse rates, and may account for these results.

ITD FS was varied in the range between zero and IPI, which corresponds to a setup of unsynchronized speech processors, in which ITD FS varies periodically between 0 and IPI. The results obtained for these stimuli show that ITD FS can cause a lateral shift in the perceived position up to a pulse rate of 800 pps (CI listeners) and 600 pps (NH subjects). Therefore, to control the lateral position of the auditory image, the fine structure of the stimulus should be encoded for stimulation pulse rates up to 800 pps.

Comparing the subjects' sensitivity to ITD ENV at 400 pps, three out of four CI listeners showed no sensitivity, as opposed to the results of CI1 and the NH listeners. It appears to be contradictory that CI listeners, who performed comparably to NH listeners with respect to ITD FS, showed much worse sensitivity to ITD ENV. One possible explanation for that is the effect of the amplitude modulation shape. In our study the trapezoidal modulation was a compromise of providing strong envelope and fine structure cues. As an example, the rectangular modulation is expected to provide a stronger ITD ENV cue, but, it allows ITD ENV values in integer multiples of the IPI only and therefore, it is not adequate for this study. On the other hand, it is expected that extending ramps beyond 20 ms results in, besides a higher ITD ENV resolution, an attenuation of the onset effects in each trapezoid. Furthermore, by applying different ramps or changing the duty factor, the amount of information in the fine structure changes, which has an effect on ITD FS sensitivity. A "nice" alternative may be a speech-shaped pulse train, providing information on lateralization discrimination sensitivity to ITD ENV for real-world stimuli.

Considering all pulse rates tested, one subject (CI3) showed a consistent improvement of sensitivity to ITD ENV with increasing pulse rate. The NH listeners showed a positive effect of ITD ENV but no significant effect of pulse rate. This is in agreement with the results of Henning (1974) showing no monotonous effect of rate. In general, the sensitivity to fine structure ITD was higher than to envelope ITD for all subjects in this study.

In the real world, most stimuli carry coherent ITD information in both the fine structure and envelope corresponding to the waveform delay condition (WD) tested in this study. A comparison of the WD and ENV conditions is important with respect to practical applications. These results show that the WD condition results in better LD for pulse rates up to 400 pps (CI listeners) and 600 pps (NH subjects) relative to condition ENV. It was also shown that for the combination of higher pulse rates and higher ITD values, the WD condition leads to a deterioration of LD as a result of ITD FS cues pointing to the wrong side and ITD ENV cues pointing to the correct side. To avoid this negative effect an optimized WD condition called *diminished waveform delay* (WD_{DIM}) was introduced, in which ITD FS was limited to 0.25 IPI. Using WD_{DIM} resulted in an improvement of LD relative to WD for pulse rates up to 800 pps for CI listeners CI3 and CI8. There are practical constraints with regard to implementing the WD_{DIM} rule in bilateral CI systems. Whether to use WD_{DIM} or not should be based on the pulse rate applied in the stimulation strategy: if ITD values greater than 0.25 IPI are expected, WD_{DIM} will improve lateralization discrimination. The efficacy of WD_{DIM} is restricted to pulse rates with sensitivity to ITD FS, i.e., to pulse rates up to 800 pps only. Furthermore, WD_{DIM} requires a bilateral processor with the ability to extract and control ITD cues in the envelope and fine structure, which may be difficult to implement.

There is also another way to provide ITD FS cues to CI listeners: coding the temporal information in the envelope of a very high pulse rate carrier (several thousands of pps) such as "HiRes" (Wilson, 2004). HiRes was investigated in several monaural studies (e.g., Frijns *et al.*, 2002; Filipo *et al.*, 2004; Bosco *et al.*, 2005), showing some improvements, particularly a better speech recognition in noise, compared to pulse rates in the region of 1500 pps. However, it is difficult to interpret these results in the context of bilateral stimulation and effects on fine structure ITD sensitivity.

Improving ITD FS perception requires using lower pulse rates, which may influence the performance with respect to monaural speech perception in quiet. Several studies have compared speech intelligibility performance by varying the pulse rate. For example Fu and Shannan (2000) and van Hoesel (2002) tested different pulse rates, however they did not consider listener accommodation to a new stimulation rate. In contrast, Vandali *et al.* (2000), Holden *et al.* (2002), and Galvin and Fu (2005) tested different pulse rates and did consider listener accommodation. In general these studies provide no contraindication to using pulse rates as low as 250 pps with respect to speech intelligibility in stimulation strategies optimized for ITD FS coding.

One strategy which encodes timing information in fine structure is peak derived timing (PDT) introduced by van Hoesel and Tyler (2003). PDT takes into consideration the fine structure of acoustic signals and provides electric signals similar to the WD condition in this paper. In the PDT strategy, the temporal position of an acoustic peak in a subband is determined and an electric pulse is applied to the corresponding electrode at the corresponding time. As a consequence, the pulse rate varies according to the temporal properties of the acoustic signal at each channel and was limited to a maximum of 1400 pps. Van Hoesel and Tyler could not find any clear difference between the PDT strategy and the standard clinical stimulation strategy with respect to sound localization and speech perception in noise. Unfortunately, the comparison between the two strategies was confounded by differences in the experimental setup such as automatic gain control, dynamic range, and number of electrodes. Hence, more detailed investigations into the efficiency of encoding fine structure timing information with various strategies are required to determine the actual extent of lateralization improvement for CI listeners.

V. CONCLUSIONS

This study shows that CI listeners are able to lateralize stimuli using interaural time differences in the fine structure only, up to pulse rates as high as 800 pps. This may affect the lateralization of sounds using speech processors which do not consider the synchronization of the fine structure. Three different synchronization conditions were introduced and tested with four CI listeners, indicating some possible constraints for future stimulation strategies to take greater advantage of the interaural time difference information in the fine structure and envelope.

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[1]Lateralization to the "wrong" side was possible due to ambiguous ITD information in the fine structure in cases where the ITD exceeded 0.5 IPI.
[2]Note that the lateralization data could not be modeled by means of JNDs since the functions are nonmonotonic.
[3]The odds ratio is the ratio of the probabilities of obtaining a correct response for one condition compared to another condition. An odds ratio of 1 shows that there is no difference in the correct responses between the two conditions. The significance of the difference between the two conditions can be calculated using the logarithmic odds ratios and their corresponding confidence intervals. In multi-factorial design, logarithmic odds ratios directly correspond to the interaction terms in the log-linear models allowing investigation of interactions between factors.
[4]Agresti (1984) uses the term "to collapse" to describe the process of averaging a factor in a data pool. This process is also known as marginalization by a factor.
[5]According to Agresti (1984) a saturated model contains all interactions of all factors. In this model, no factor may be averaged and the data must be analyzed for each level of each factor separately.

Abbas, P. J. (**1993**). "Electrophysiology," in *Cochlear Implants: Audiological Foundations*, edited by R. S. Tyler (Singular, San Diego).

Agresti, A. (**1984**). *Analysis of Ordinal Categorical Data* (Wiley, New York).

Agresti, A. (**1996**). *Introduction to Analysis of Categorical Data* (Wiley-Interscience, New York).

Bernstein, L. R. (**2001**). "Auditory processing of interaural timing information: New Insights," J. Neurosci. Res. **66**, 1035–1046.

Blauert, J. (**1997**). *Spatial Hearing*, 2nd ed., (MIT, Cambridge, MA).

Bosco, E., D'Agosta, L., Mancini, P., Traisci, G., D'Elia, C., and Filipo, R. (**2005**). "Speech perception results in children implanted with Clarion devices: Hi-Resolution and Standard Resolution modes," Acta Oto-Laryngol. **125**, 148–158.

Bronkhorst, A. W., and Plomp, R. (**1988**). "The effect of head-induced interaural time and level differences on speech intelligibility in noise," J. Acoust. Soc. Am. **83**, 1508–1516.

Busby, P. A., Whitford, L. A., Blamey, P. J., Richardson, L. M., and Clark, G. M. (**1994**). "Pitch perception for different modes of stimulation using the cochlear multiple-electrode prosthesis," J. Acoust. Soc. Am. **95**, 2658–2669.

Carlyon, R. P., van Wieringen, A., Long, C. J., Deeks, J. M., and Wouters, J. (**2002**). "Temporal pitch mechanisms in acoustic and electric hearing," J. Acoust. Soc. Am. **112**, 621–633.

Chatterjee, M. (**1999**). "Temporal mechanisms underlying recovery from forward masking in multielectrode-implant listeners," J. Acoust. Soc. Am. **105**, 1853–1863.

Collins, L. M., Zwolan, T. A., and Wakefield, G. H. (**1997**). "Comparison of electrode discrimination, pitch ranking, and pitch scaling data in postlingually deafened adult cochlear implant subjects," J. Acoust. Soc. Am. **101**, 440–455.

Culling, J. F., Hawley, M. L., and Litovsky, R. Y. (**2004**). "The role of head-induced interaural time and level differences in the speech reception threshold for multiple interfering sound sources," J. Acoust. Soc. Am. **116**, 1057–1065.

Dirks, D. D., and Wilson, R. H. (**1969**). "The effect of spatially separated sound sources on speech intelligibility," J. Speech Hear. Res. **12**, 5–38.

Drennan, W. R., Gatehouse, S., and Lever, C. (**2003**). "Perceptual segregation of competing speech sounds: the role of spatial location," J. Acoust. Soc. Am. **114**, 2178–2189.

Filipo, R., Mancini, P., Ballantyne, D., Bosco, E., and D'Elia, C. (**2004**). "Short-term study of the effect of speech coding strategy on the auditory performance of pre- and post-lingually deafened adults implanted with the Clarion CII," Acta Oto-Laryngol. **124**, 368–370.

Frijns, J. H., Briaire, J. J., de Laat, J. A., and Grote, J. J. (**2002**). "Initial evaluation of the Clarion CII cochlear implant: Speech perception and neural response imaging," Ear Hear. **23**, 184–197.

Fu, Q. J., and Shannon, R. V. (**2000**). "Effect of stimulation rate on phoneme recognition by nucleus-22 cochlear implant listeners," J. Acoust. Soc. Am. **107**, 589–597.

Galvin, J., and Fu, Q. J. (**2005**). "Effects of stimulation rate, mode, and level on modulation detection by cochlear implant users," presented at the 28th Midwinter Research Meeting of the Association for Research in Otolaryngology, New Orleans.

Greenberg, S., Carvey, H., Hitchcock, L., and Chang, S. (**2003**). "Temporal properties of spontaneous speech—A syllable-centric perspective," J. Phonetics **31**, 465–485.

Hawley, M. L., Litovsky, R. Y., and Colburn, H. S. (**1999**). "Speech intelligibility and localization in a multi-source environment," J. Acoust. Soc. Am. **105**, 3436–3448.

Henning, G. B. (**1974**). "Detectability of interaural delay in high-frequency complex waveforms," J. Acoust. Soc. Am. **55**, 84–90.

Hirsh, I. J. (**1950**). "The relation between localization and intelligibility," J. Acoust. Soc. Am. **22**, 196–200.

Holden, L. K., Skinner, M. W., Holden, T. A., and Demorest, M. E. (**2002**). "Effects of stimulation rate with the Nucleus 24 ACE speech coding strategy," Ear Hear. **23**, 463–476.

Laback, B., Majdak, P., and Baumgartner, W. (**2005**). "Interaural time differences in temporal fine structure, onset, and offset in bilateral electrical hearing," poster presented at the 28th Midwinter Research Meeting of the Association for Research in Otolaryngology, New Orleans.

Laback, B., Pok, S. M., Baumgartner, W. D., Deutsch, W. A., and Schmid, K. (**2004**). "Sensitivity to interaural level and envelope time differences of two bilateral cochlear implant listeners using clinical sound processors," Ear Hear. **25**, 488–500.

Lawson, D. T., Wilson, B. S., Zerbi, M., van den Honert, C., Finley, C. C., Farmer, J. C., Jr., McElveen, J. T., Jr., and Roush, P. A. (**1998**). "Bilateral cochlear implants controlled by a single speech processor," Aust. Hosp. **19**, 758–761.

Licklider, J. C. R. (**1948**). "The influence of interaural phase relations upon the masking of speech by white noise," J. Acoust. Soc. Am. **20**, 150–159.

Lienert, G. A. (**1978**). *Verteilungsfreie Methoden in der Biostatistik (Non-Parametric Methods in Biostatistics)*, 2nd ed. (Anton Hain, Meisenheim am Glan).

McKay, C. M., and Carlyon, R. P. (**1999**). "Dual temporal pitch percepts from acoustic and electric amplitude-modulated pulse trains," J. Acoust. Soc. Am. **105**, 347–357.

Nelson, D. A., and Donaldson, G. S. (**2001**). "Psychophysical recovery from single-pulse forward masking in electric hearing," J. Acoust. Soc. Am. **109**, 2921–2933.

Nelson, D. A., and Donaldson, G. S. (**2002**). "Psychophysical recovery from pulse-train forward masking in electric hearing," J. Acoust. Soc. Am. **112**, 2932–2947.

R Development Core Team (**2004**). "R: A language and environment for statistical computing," R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, http://www.R-project.org.

Smith, Z. M., and Delgutte, B. (**2005**). "Binaural interactions in the auditory midbrains with bilateral cochlear implants," presented at the 28th Midwinter Research Meeting of the Association for Research in Otolaryngology, New Orleans.

van Hoesel, R. J. M., and Clark, G. M. (**1997**). "Psychophysical studies with two binaural cochlear implant subjects," J. Acoust. Soc. Am. **102**, 495–507.

van Hoesel, R., Ramsden, R., and O'Driscoll, M. (**2002**). "Sound-direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user," Ear Hear. **23**, 137–149.

van Hoesel, R. J. M., and Tyler, R. S. (**2003**). "Speech perception, localization, and lateralization with bilateral cochlear implants," J. Acoust. Soc. Am. **113**, 1617–1630.

Vandali, A. E. (**2000**). "Speech perception as a function of electrical stimulation rate: Using the Nucleus 24 cochlear implant system," Ear Hear. **21**, 608–624.

Wightman, F. L., and Kistler, D. L. (**1997**). "Factors affecting the relative salience of sound localization cues," in *Binaural and Spatial Hearing in Real and Virtual Environments*, edited by R. H. Gilkey and T. R. Anderson (Lawrence Erlbaum Associates, Mahwah, NJ).

Wilson, B. S. (**2004**). "Engineering design of cochlear implants," in *Cochlear Implants*, edited by F. G. Zeng, A. N. Popper, and R. R. Fay (Springer, New York).

Zwislocki, J., and Feldman, R. S. (**1956**). "Just noticeable differences in dichotic phase," J. Acoust. Soc. Am. **28**, 860–864.