

Localization cues with bilateral cochlear implants

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Selected subjects with bilateral cochlear implants (CIs) showed excellent horizontal localization of wide-band sounds in previous studies. The current study investigated localization cues used by two bilateral CI subjects with outstanding localization ability. The first experiment studied localization for sounds of different spectral and temporal composition in the free field. Localization of wide-band noise was unaffected by envelope pulsation, suggesting that envelope-interaural time difference (ITD) cues contributed little. Low-pass noise was not localizable for one subject and localization depended on the cutoff frequency for the other which suggests that ITDs played only a limited role. High-pass noise with slow envelope changes could be localized, in line with contribution of interaural level differences (ILDs). In experiment 2, processors of one subject were raised above the head to void the head shadow. If they were spaced at ear distance, ITDs allowed discrimination of left from right for a pulsed wide-band noise. Good localization was observed with a head-sized cardboard inserted between processors, showing the reliance on ILDs. Experiment 3 investigated localization in virtual space with manipulated ILDs and ITDs. Localization shifted predominantly for offsets in ILDs, even for pulsed high-pass noise. This confirms that envelope ITDs contributed little and that localization with bilateral CIs was dominated by ILDs.

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I. INTRODUCTION

Localization of sounds is one of the most important tasks for the auditory system as it not only helps orientation in space but it is also crucial for the segregation of multiple sounds in the auditory scene. Normal hearing subjects show an outstanding ability to localize sounds and directional changes of 1° can be detected in the front (Mills, 1958; Blauert, 1997). Several recent studies demonstrated that cochlear implant (CI) subjects can regain the ability to localize sounds after bilateral implantation (Tyler *et al.*, 2002; van Hoesel *et al.*, 2002; Grantham *et al.*, 2003; van Hoesel and Tyler, 2003; Laszig *et al.*, 2004; Nopp *et al.*, 2004; Schoen *et al.*, 2005). One subject in a study by van Hoesel (2004) made no errors discriminating between the two frontal loudspeakers at $\pm 13^\circ$ in an array spanning 180° using a clinical stimulation strategy and a pink noise stimulus. However, root mean square-error increased for non-frontal directions to $10\text{--}35^\circ$. Seeber *et al.* (2004) studied localization of bilateral CI subjects as well as of subjects with hearing aid and cochlear implant using a high-resolution pointing technique. All four bilateral CI subjects were able to localize but one subject showed excellent localization ability with quartiles of only 4.4° and a regression slope of 1.15. This localization ability is close to one of normal hearing subjects who showed quartiles of 1.7° and a slope of 0.95 in the same task (Seeber, 2002). The purpose of the present article is thus to explain this surprisingly good localization ability by studying the localization cues used by this and another subject.

Several recent studies investigated the sensitivity of CI subjects to binaural cues. All studies correspondingly showed high sensitivity to interaural level differences (ILDs). Lawson *et al.* (1998), (2000), and van Hoesel and Tyler (2003) found sensitivities as small as one current step. Sensitivity rarely exceeded a few current steps across several subjects and electrodes. Despite the dynamic range compression in CI processors this translates into high sensitivity to ILDs at the acoustical input. Van Hoesel (2004) measured just-noticeable differences (JNDs) for ILDs at the input of a research processor. Both of his subjects showed ILD-JNDs smaller than 1 dB. Likewise, Laback *et al.* (2004) measured ILD-JNDs of two subjects at the direct input of clinical processors with disabled automatic gain controls (AGCs). They found ILD-JNDs of 1.4–2.7 dB (S1) and 1–5.2 dB (S2) for various stimuli which were about 1 dB larger than for normal hearing subjects.

A larger range of sensitivities was found for interaural time differences (ITDs) in several recent studies. Several subjects demonstrated JNDs beyond 1 ms for ITDs in the carrier, which is outside the naturally occurring range (van Hoesel *et al.*, 1993; van Hoesel and Clark, 1997; Lawson *et al.*, 2000; van Hoesel, 2004). Selected subjects achieved higher sensitivities at certain electrode combinations. Lawson *et al.* (1998) found ITD-JNDs of $150\ \mu\text{s}$ in one subject with synchronized processors for pulses at a rate of 480 pulses per second (pps). Van Hoesel and Tyler (2003) showed JNDs of 90, 150, and $250\ \mu\text{s}$ each for two subjects for carrier ITDs in pulses at 50 pps. The subjects studied by Lawson *et al.* (2000) showed mixed results, but several subjects demonstrated ITD-JNDs of $50\text{--}150\ \mu\text{s}$ on at least one electrode combination. The bilateral CI-subject BW, who

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demonstrated excellent localization ability in our previous study (Seeber *et al.*, 2004), participated in their study (ME5) and showed ITD-JNDs of 50 μ s on one and 150 μ s on two electrode combinations. One subject in the study by Lawson *et al.* (2000) (ME8) showed ITD-JNDs of 50 μ s on 5 electrode combinations and JNDs of 150 μ s on 16 other tested combinations which were by far the best and most consistent results of any subject in the test. Because of his high sensitivity to ITDs this subject was selected to participate in the current study (DF).

While previous studies investigated localization with bilateral CIs, the sensitivity to binaural cues, or lateralization with isolated binaural cues the present article focuses on the combination of binaural cues for *localization*. If available, the auditory system utilizes information from multiple cues, but cue weighting depends on the spectral content and the temporal structure of the sound. ITDs are present in the envelope and the carrier of the sound while ILDs are physically larger only at higher frequencies. Normal hearing subjects can evaluate ITDs in the carrier up to 1500 Hz and the threshold for ITDs can be as low as 10 μ s (Klumpp and Eady, 1956; Buell and Hafter, 1991). At higher frequencies ITDs can be well detected in the envelope and thresholds of a few 10 μ s were reported. (Henning, 1974; van de Par and Kohlrausch, 1997). ILD detection is relatively independent of frequency and thresholds can be as low as 0.5 dB in normal hearing (Yost, 1981). However, the contribution of ILDs to localization is limited to their range of natural occurrence. Physical ILDs do not exceed 5 dB below 1 kHz, but they can be as large as 30 dB at high frequencies (Shaw, 1974). Strutt (Lord Rayleigh) (1907) postulated in the “Duplex Theory” that ITDs dominate ILDs below about 1500 Hz while ILDs provide the information for localization at higher frequencies. This general trend has been confirmed, e.g., in trading experiments for tones (Hafter and Jeffress, 1968). The perceived direction of wide-band sounds is mostly determined from ITDs at low frequencies, i.e., carrier ITDs (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002), while the contribution of envelope ITDs seems to be limited to sound onsets (Hafter, 1996; Freyman and Zurek, 1997; Hartmann *et al.*, 2005). Envelope ITDs might also help resolve ambiguities (Buell and Hafter, 1991). However, the dominance of carrier ITDs for localization can be broken if ILDs are consistent with envelope ITDs (Smith *et al.*, 2002; Zeng *et al.*, 2004). This is important for localization with CIs since current processors do not encode ITDs in the carrier, but they do transmit ILDs and envelope ITDs. The role of envelope ITDs in CI listening might therefore be much higher than in normal hearing. Some CI subjects were shown to be highly sensitive to envelope ITDs and thresholds down to 25 μ s have been reported (Lawson *et al.*, 2001), while other reports showed thresholds of about 290 μ s (van Hoesel and Tyler, 2003) or 260–380 μ s (Laback *et al.*, 2004). Complete lateralization with envelope ITDs of 600–700 μ s has been reported for selected subjects (Schoen *et al.*, 2005). It is therefore conceivable that localization of CI subjects is governed by ILDs and envelope ITDs.

The purpose of the present study was to investigate localization cues of two selected CI subjects with three different approaches. Unlike previous studies, this study evaluated the contribution of binaural cues to *localization* rather than pure sensitivity to binaural cues. Both subjects were selected for their outstanding localization ability and subject DF was chosen for his high sensitivity to ITDs. In experiment 1, localization cues of both subjects were studied through a localization test in which several sounds of different spectral content and temporal envelope structure were presented. Experiment 2 assessed how subject DF utilized cues for localization by modifying the placement of the CI processors away from their normal position on the ears. By placing the processors above the head, ITDs and ILDs could be physically altered as no head shadow was effective. In experiment 3, ITDs and ILDs were manipulated in virtual acoustical space. Head-related transfer functions (HRTFs) of the CI processors were altered to slightly offset ITDs or ILDs from their natural combination. A shift in localization correlated to the offset would indicate sensitivity to the altered cue (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002). Obviously, this test can be administered only to subjects with good localization ability, as previously demonstrated by subject BW (Seeber *et al.*, 2004). Localization was tested with an accurate, continuous method which requires subjects to point to the perceived azimuth of the sound with an adjustable light pointer (Seeber, 2002).

II. METHODS

A. Subjects

Two bilateral cochlear implant subjects participated in the experiments. Subject BW was singled out because of his extraordinary localization ability in a previous study (Seeber *et al.*, 2004). Subject BW was 50 years old and he received his first implant on the right ear 4.2 years and his second implant 3.2 years before the study. Both implants were Med-El Combi 40+ (C40+) controlled by Med-El Tempo+ speech processors. Both processors were set up with a logarithmic map in 300–5547 Hz for 12 channels. BW deafened on Otosclerosis 1.1 years before he received his first implant. Travel costs were reimbursed at government mileage rates.

Subject DF was 54 years old and he received his first implant 7.8 years and his second implant 3.1 years before the tests. He deafened on Meningitis and Endolymphatic Hydropress. The first implant on the left side was a Med-El Combi 40 (C40) while the right side received a Med-El C40+ later, both controlled by Med-EL Tempo+ speech processors. All 8 channels of the C40 (left) were mapped logarithmically to cover an extended range of 200–8500 Hz. Channel 12 was not assigned on the C40+ (right). The remaining 11 channels were set to cover the same frequency range as the implant on the left ear according to logarithmic spacing. This implies that individual channels analyzed different frequency ranges on both ears. The subject preferred this map as it allowed him better music perception. DF was reimbursed for his travel, and hotel accommodation was arranged for him. BW and DF did not receive payment for the experiments.

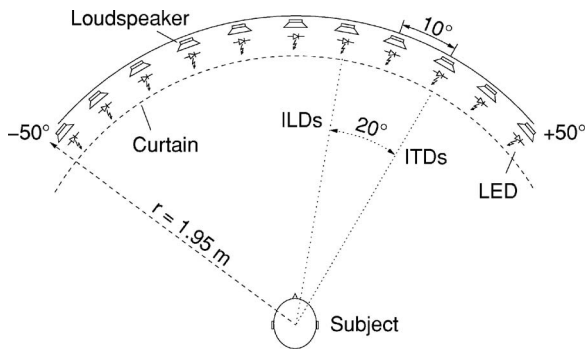


FIG. 1. Sketch of the apparatus for localization studies and exemplification of binaural cue manipulation in experiment 3. In experiments 1 and 2 sounds were played via loudspeakers while in experiment 3 spatialized stimuli were fed directly into the CI processors. The figure shows an example for binaural cue trading used in experiment 3: While the prerecorded stimulus from, e.g., $+10^\circ$, was played to the subject it was run through an all-pass filter that incorporated the ITD changes necessary to represent ITDs from $+30^\circ$. A shift in localization to the ITD direction would suggest a dominance of ITDs whereas a localized direction halfway between the ITD and ILD direction shows equal weighting of both cues. Likewise, conditions with manipulated ILDs were run.

B. Cochlear implants

The Combi 40+ implant by MedEl GmbH consists of an intracochlear array of 12 active electrodes in 2.4 mm spacing while the Combi 40 implant uses 8 active electrodes in 2.8 mm spacing. The stimulation occurred in monopolar mode against an extracochlear reference electrode placed on the skull beneath M. Temporalis. The Tempo+ speech processor delivered a continuous interleaved sampling strategy at a rate of 1515 pps on each of the 12 channels for subject BW. DF used a rate of 1456 pps on the C40 (left) and 1583 pps on the C40+ (right). Behind-the-ear (BTE) type speech processors were used in the standard everyday configuration for the subjects.

C. Localization test

The experiments were done in a darkened anechoic chamber which hosted an apparatus of 11 identical closed-cabinet loudspeakers (Fig. 1). The loudspeakers were placed at ear level of the subject on a horizontal arc with a radius of 1.95 m. They spanned an angle of -50° left to $+50^\circ$ right with a spacing of 10° . Loudspeakers were individually equalized to be frequency independent within 125 Hz–20 kHz to ± 2.5 dB at the subject's head position. A detailed description of the apparatus can be found in Seeber (2002).

Localization was tested with a light pointer method according to which the subject adjusts a movable light spot to the perceived direction of the sound with a trackball (Seeber, 2002). The light spot was projected on a cylindrical, acoustically transparent curtain that covered the loudspeakers from view. The projection was done by deflecting a laser beam with a computer-controlled two-mirror system. The subject could move the light spot on a horizontal arc by turning on a trackball within -70° left to $+70^\circ$ right with an accuracy of 0.2° . Unlike source identification methods, this technique allows for a continuous display of the localized direction. The method shows very small variance (quartiles 1.7° for normal

hearing subjects), which permits an accuracy closed to the minimum audible angle obtained in detection tasks (Mills, 1958; Seeber, 2002). The high accuracy comes in part from the fact that no part of the body directly displays the perceived sound direction like in head or hand pointing. The method is thus called the Proprioception Decoupled Pointer.

III. EXPERIMENT 1

A. Stimuli and procedures

The aim of experiment 1 was to investigate the relative contribution of binaural cues by studying localization of specific sounds played via loudspeakers in the free field. Each sound could be localized on the basis of a particular set of cues. Sound characteristics and localization cues are listed in Table I. Low-pass noise (LPN) restricts the availability of ILDs which are physically small at low frequencies. It could be localized predominantly on the basis of carrier or envelope ITDs. High pass noise (HPN) could be localized using ILDs which are large at high frequencies (Fig. 9). Envelope ITDs introduced either by envelope modulation of the signal or by the bandpass filtering in the CI processor could also contribute to localization. For HPN of larger bandwidth spectral cues might be utilized. Access to spectral cues can be limited by scrambling the spectrum of the signal such that the level in each frequency channel is randomly chosen and thus stands in no relation to sound direction (Wightman and Kistler, 1997). Spectral cues could be particularly useful by comparing the direction dependent levels in a high-frequency channel with the relatively constant level in a low-frequency channel. This low-frequency anchor is restrained with high-pass sounds. Pulsation of the noise with steep slopes emphasizes envelope ITDs, and slow envelope changes in the order of 200 ms evoke the opposite. Test sounds were individualized according to the channel mapping of the subject.

Prior to all experiments the sensitivities of the speech processors were adjusted to give a centered image for speech coming from the front. After a short training session for accommodation with the method, localization was tested in separate runs for each test sound. Localization with bilateral CIs was studied for all sounds and each single CI was tested with pulsed wide-band noise (WBN). A localization experiment for a single sound consisted of ten trials for each of the 11 sound directions (110 trials total) which took approximately 11 min to complete. Presentation was divided into ten blocks, with the eleven directions presented in random order within each block. Sound level was roved in random order in 2 dB steps in 61–69 dB sound pressure (SPL) with each of the five level steps administered twice in the ten trials per sound direction. Ten separate frozen noise tokens were generated and used for the ten trials. No feedback was provided during the experiment, but the training session consisting of 1–3 presentations of each test direction included feedback.

In a single localization trial the test sound was played followed by a pause of 500 ms after which the light spot appeared at 0° in front of the subject. The subject then moved the light spot to the remembered direction of the sound and confirmed this direction by pressing a button at the trackball. The light spot ceased and after a pause of

TABLE I. Overview of stimuli.

Stimulus ^a	Bandwidth ^b [Hz]	Envelope ^b	Spectrum	Duration ^b [ms]	Available cues ^c			
					ILDs	Carrier-ITDs	Envelope-ITDs	Spectrum
WBN, pulsed	125-20000	5 pulses of 30 ms, 70 ms pause, 3 ms slopes,	Gaussian noise	500	++	++	++	++
WBN-CI, 200 ms env	BW: 300–5547; DF: 200–8500	200 ms slopes	Gaussian noise	500	++	++	o	++
LPN, 200 ms env.	BW: 300–486; DF: 200–525	200 ms slopes	Gaussian noise	500	o	++	–	–
LPN, pulsed	BW: 300–486; DF: 200–525	10 pulses of 10 ms, 40 ms pause, 1 ms slopes	Scrambled by up to 40 dB in: BW: [300, 381, 486], DF: [200, 328, 525] Hz	500	o	++	++	--
HPN, scrambled	BW: 2644–5547; DF: 3103–8500	200 ms slopes	Scrambled by up to 40 dB in: BW: [2644, 3377, 4360, 5547], DF: [3103, 4362, 6134, 8500] Hz	500	++	--	o	--
LPN 400 Hz Additionally in experiment 3 (BW only):	DF only: 200–400	200 ms slopes	Gaussian noise	500	–	++	–	--
HPN, 100 ms env.	2644–5547	100 ms slopes	Scrambled by up to 40 dB in [2644, 3377, 4360, 5547] Hz	164	++	--	–	--
HPN, pulsed	2644–5547	10 pulses of 10 ms, 40 ms pause, 0.5 ms slopes	Scrambled by up to 40 dB in [2644, 3377, 4360, 5547] Hz	500	++	--	++	--

^aWBN: Wide-band noise; WBN-CI: Wide-band noise limited to frequencies processed by the CI; LPN: Low-pass noise; HPN: High-pass noise.

^bCorner frequencies of noises in Hz. All slopes had Gaussian shape. Signal durations computed at 67.5% points.

^cEstimate of availability of physical localization cues, coded in five steps as -- (unavailable), o (medium), ++ (strong presence). Carrier ITDs are reported to be available as in the duplex theory.

500 ms the next trial started with sound being played from another direction. At the beginning of the experiment and between each of the 10 blocks a light spot appeared for 5 s in front of the subject followed by a pause of 500 ms. This allowed the subject to take a short break and to align the head to the front. The head was fixed by leaning it against a headrest. The experimenter verified through an infrared camera system that the head was not moved during sound presentation parts of the experiment.

B. Results

Localization results for all stimuli of experiment 1 are given in Figs. 2 and 3 for subjects BW and DF, respectively. Median results are plotted along with error bars which depict quartile ranges. Summary statistics of the results are listed in Tables II and III.

BW was able to discriminate the side of sound origin using either the first or the second implanted ear (panel A of Fig. 2) while subject DF could do so only with his first CI (Fig. 3(A)). Subject BW localized sounds coming from the contralateral side of the CI towards that side whereas sounds from the ipsilateral side were localized in the front, independent of their true direction. Despite the strong variance in the results, discrimination of left from right is significant in a test which compared the pooled responses for -50° and -40° to responses for $+50^\circ$ and $+40^\circ$ (Wilcoxon rank sum test, last column in Table II). As BW has no residual hearing on either implanted ear the ability to discriminate left from right has to rely on the evaluation of monaural spectral cues. Despite the

overall level rove, timbral cues can be picked up and used for localization as the spectrum of the white noise pulses is predictable. It is interesting to note that BW was not able to discriminate left from right with the second CI at the time of our first test 1.3 years before the current study (Seeber *et al.*, 2004). Although he wore both implants continuously throughout that time he learned the information needed for the task with a single CI.

Localization results of wide-band noise (WBN) with pulsed and with slowly changing envelope using both CIs are shown in panel B of Figs. 2 and 3. These data confirm what we previously showed for pulsed WBN that subject BW has excellent localization ability (Seeber *et al.*, 2004). Compared to his previous data the slope of the regression line is slightly shallower (0.82 vs 1.15) in the current data set, but average quartiles are also smaller (3.3° vs 4.4°). The ratio of quartiles to slope could be seen as a measure of internal sensitivity to localization cues. Since it did not change (4.0 vs 3.8) it can be assumed that localization ability did not change in the 1.3 years between both tests. Based on a similar consideration it is interesting to see that localization ability did not change if envelopes were changed slowly instead of being pulsed. Localization results for WBN with slow envelope changes show a perfect regression slope of 0.97 paired with an offset of 3.5° and very small quartiles of 3.9° ; however, with the increase in slope quartiles increased similarly compared to the pulsed WBN. Apparently, envelope ITDs seem not to contribute to localization of wide-band stimuli beyond that due

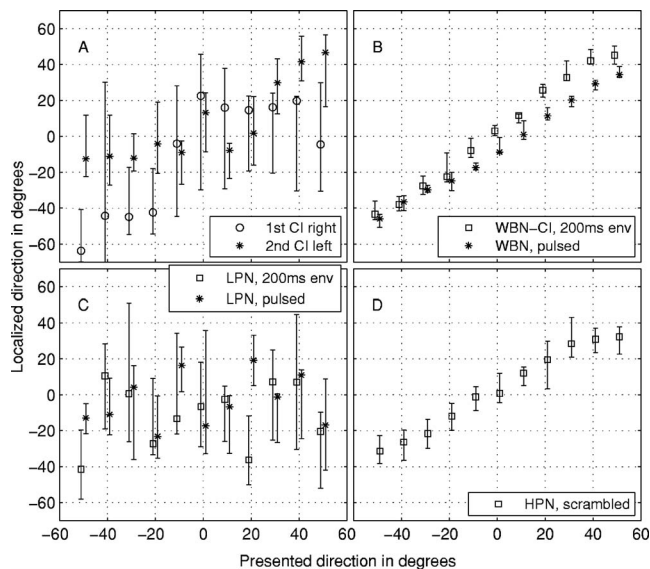


FIG. 2. Free-field localization results of subject BW in experiment 1. Results are presented as medians and quartiles. Panel A shows results for each single CI for pulsed WBN, whereas panels B-D show results for various stimuli with bilateral CIs (see inlets and Table I).

to other binaural cues. The reduced slope with pulsed WBN might stem from the compression in the CI processor which is assumed to be larger with the pulsed stimulus because of its larger maximum amplitude.

Subject DF shows nearly a similar level of localization performance as both WBN-stimuli can be localized well (Fig. 3(B)). Localization was best for WBN with slow envelope changes. Despite an offset of the regression line (8.5°) the good localization ability is supported by the near perfect slope (0.86) combined with small quartiles (4.5°), which yields high, significant correlation of presented direction to localized direction (0.97). Interestingly, localization ability seems slightly poorer for the pulsed WBN as quartiles increase to 8.0° , although this stimulus provides more binaural information. The increase in variance might be attributable to temporal effects of compression in the CI processor as ILDs might change during the first pulses.

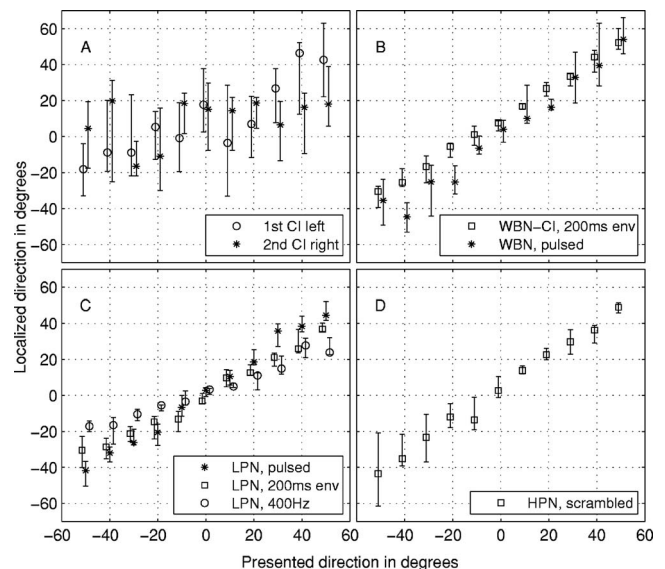


FIG. 3. Free-field localization results of subject DF in experiment 1. Panel C shows additional results for LPN limited to 400 Hz. Results are plotted as in Fig. 2, stimuli are described in Table I.

Localization tests with low-pass noise (LPN) were done to investigate the contribution of ITDs at low frequencies at which ILDs are small. Despite his excellent localization ability of wide-band sounds, subject BW showed no localization ability for LPN (Fig. 2(C)). Neither the LPN with slow envelope changes nor the pulsed noise could be localized. The slope of the regression line is zero and quartiles are large (22.4° and 14.3° , respectively). This confirms that ITDs at low frequencies could not be evaluated by BW. Moreover, ITDs in the envelope of this low-frequency carrier also did not contribute to localization, indicating that neither ITDs in the phase at low frequencies nor in the envelope contributed to localization. The results thus suggest that localization of subject BW is exclusively based on the evaluation of ILDs which will be tested in experiment 3.

Localization results of DF for low-pass sounds differed from the results of BW. DF was able to localize the LPN

TABLE II. Summary statistics to free-field localization results of subject BW in experiment 1 for different stimulus conditions, cf. Fig. 2.

Condition	Error ($^\circ$) ^c		Quartile ($^\circ$)	Correlation coefficient ^d	Regression line		Side diff ^e
	Absolute ^a	Arithmetic ^b			Slope	Offset	
1 st CI right	30.0	-17.3	25.7	0.36**	0.48	-8.6	+
2 nd CI left	17.7	5.2	15.2	0.50**	0.46	6.0	**
Both CIs							
WBN, pulsed	8.5	-7.8	3.2	0.97**	0.82	-6.5	**
WBN-CI 200 ms env	4.5	2.1	3.9	0.97**	0.97	3.5	**
LPN, 200 ms env	31.1	-9.7	22.4	0.03	0.03	-7.0	
LPN, pulsed	30.8	-3.6	14.3	0.05	0.05	-3.6	
HPN, scrambled	9.9	1.4	7.6	0.91**	0.71	2.3	**

^aAbsolute error: Mean absolute deviation of single localization results from presented direction.

^bRelative, arithmetical error: Mean deviation of single localization results from presented direction.

^cAverage value of single quartiles.

^dSignificance of correlation coefficient: **0.001, *0.01, +0.05.

^eDifferentiation of side of sound origin: Wilcoxon rank sum test on identity of the results at -50° and -40° (pooled) vs $+40^\circ$ and $+50^\circ$ (pooled). Results for both sides are significantly different at **0.001, *0.01, +0.05.

TABLE III. Summary statistics for localization results of subject DF in free-field experiments 1 and 2, cf. Figs. 3 and 4. Statistics as in Table II.

Condition	Error (°)		Quartile (°)	Correlation coefficient	Regression line		Side diff
	Absolute	Arithmetic			Slope	Offset	
1 st CI left	23.7	9.9	16.3	0.46**	0.45	10.4	**
2 nd CI right	23.1	4.8	13.8	0.16	0.13	7.5	
Both CIs							
WBN, pulsed	8.1	1.8	8.0	0.91**	0.98	3.2	**
WBN-CI 200 ms env	8.0	7.8	4.5	0.97**	0.86	8.5	**
LPN, 200 ms env	8.1	-1.8	4.2	0.95**	0.71	-0.3	**
LPN, pulsed	5.1	2.4	4.6	0.97**	0.92	2.2	**
HPN, scrambled	6.1	2.4	4.8	0.93**	0.90	3.0	**
LPN, 400 Hz	14.5	2.0	3.1	0.92**	0.48	2.5	**
Elevated CIs, Experiment 2							
Together	24.2	0.9	9.8	0.16	0.08	3.2	
Distanced	19.2	3.6	8.2	0.55**	0.39	6.2	**
Plate	10.2	-4.3	7.6	0.87**	0.83	-2.5	**

with slow envelope changes relatively well (Fig. 3, panel C). His responses were compressed towards the front which is indicated by a reduced regression slope of 0.71. Variance was small (quartiles 4.2°). Localization improved considerably if the LPN was pulsed. This is indicated by the ideal regression slope of 0.97 combined with small quartiles of 4.6° and a small offset of 2.2°. The results seem to confirm that localization with CIs can be based on the evaluation of ITDs through the phase or the envelope. The emphasis of envelope ITDs also leads to an improvement of localization, which again suggests a contribution of ITDs to localization, even though this is opposite to that with WBN above. However, an alternate explanation would be that ILDs still contributed enough information at 500 Hz and that the pulsation improved localization because of increased spectral splatter. The combination of pulsation and the relatively shallow upper slope of the noise might result in sufficient energy at high frequencies to be useful for evaluating ILDs.

To address this question DF was tested again using noise with a lower cut-off frequency and slow envelope changes. The lower cut off at 400 Hz still provides considerable energy in the second implant channel while the information in phase and envelope ITDs remains nearly unchanged. Results are given in Fig. 3(C). Localization ability appears considerably reduced compared to the similar stimulus with slightly wider spectrum. The slope of the regression line for “LPN 400 Hz” is only 0.48, but quartiles remain small (3.1°). The fact that localization ability was reduced for this stimulus suggests that ILDs clearly contributed to localization of the other two LPNs. However, it cannot be ruled out that ITDs also contributed, which will be tested further in experiment 2.

Both subjects were able to localize high-pass noise (HPN) with scrambled spectrum (Figs. 2 and 3, panel D). Localization ability deteriorated only slightly compared to WBN (BW: correlation for HPN 0.92 cf. 0.97 for WBN; DF: 0.93 cf. 0.97). This is surprising since the HPN was limited to spectrally cover only the three highest channels in the CI. Further, monaural spectral cues were not available due to spectral scrambling between channels and the absence of en-

ergy in low-frequency channels which could otherwise facilitate level comparison to high-frequency channels. As carrier ITDs are not encoded in the CIs and the results with LPN suggest that they were not used, localization of the HPN must have relied on ILDs or envelope ITDs. A discrimination between both is not possible with the standard CI configuration in the free field. Experiments 2 and 3 were designed to yield a more definitive answer by going beyond the limitations of the free-field approach of experiment 1.

IV. EXPERIMENT 2

A. Stimuli and procedures

In experiment 1 ILDs and ITDs co-varied in natural fashion which limits the possible testing to manipulations of spectral content and temporal shape of the stimuli. In experiment 2 CI processors were raised 18 cm above the ears in order to minimize the acoustical effects of the head. Processors were mounted on thin rods which were fixed on a stiff plastic head band taken from a protective helmet. There were three possible configurations. In session “Together,” processors were brought together in the center of the head, but 18 cm above ear level. This arrangement minimizes ILDs and ITDs. For the setting “Distanced,” processors were placed exactly above the ears. In this setting processors were about one head diameter apart which roughly preserved natural ITDs but gave nearly no ILDs. In the “Plate” setting, processors were placed next to each other but separated by a carton board. The board had about the size of the cross section of the head (10*13 cm). The purpose of the board was to evoke ILDs, while ITDs were nearly absent due to the small distance between the processors. Localization procedures were identical to experiment 1 and a pulsed wide-band noise was used in all three sessions with subject DF (WBN, pulsed, Table I).

B. Results

Localization results of subject DF can be seen in Fig. 4 for three different processor placement conditions. Summary

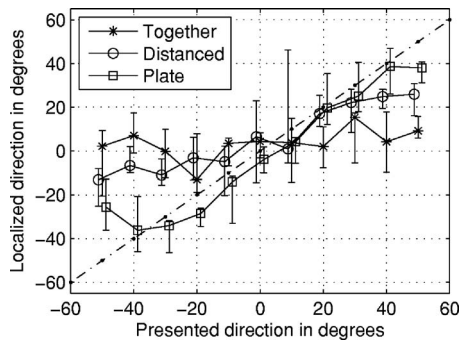


FIG. 4. Free-field localization results of experiment 2 of subject DF with elevated CI processors for pulsed wide-band noise (Table I). In the condition “Together” (*), processors were placed above the head next to each other, whereas in condition “Plate” (□) a cardboard was placed between the two processors that were still next to each other. The elevated processors were spaced at ear distance in the condition “Distanced” (o), but there was no plate between them. Medians are connected by lines and error bars show quartiles.

statistics are given in the lower part of Table III. In the first condition, “Together,” processors were placed next to each other above the head. This placement minimizes ITDs and ILDs and, as expected, the pulsed wide-band noise stimulus could not be localized. The slope of the regression line shows independence of the presented direction (0.08) and quartiles are large (9.8°).

In condition “Distanced,” processors were placed at ear distance above the ears which mainly introduces ITD cues. Differentiation of left from right became possible. The regression slope is shallow (0.39) and variance is high (quartiles 8.2°) which does not indicate that multiple directions could be localized. This suggests that ITDs contributed to localization but they provide only limited information.

A board separated both processors in condition “Plate”, which introduced mainly ILD cues while ITDs were kept small. Localization improved considerably in this condition. While quartiles remained large (7.6°) localization covered a much broader azimuthal range and the regression slope reached 0.83. Although localization was nearly perfect within ±40°, responses for ±50° were compressed to the center. This indicates that ILD cues did not increase beyond ±40°. The pronounced increase of localization performance in the plate condition suggests that ILDs are the main localization cue, while the ability to discriminate left from right in the distanced condition indicates a small contribution of ITD cues. Since ITDs and ILDs were very inconsistent, for example, with ILDs being present while ITDs were near zero, it is also conceivable that the weighting of both localization cues differed strongly from the natural state. Experiment 3 was designed to investigate cue weighting particularly for HPN for which envelope ITDs and ILDs could be cues.

V. EXPERIMENT 3

A. Overview

Experiment 3 took a different approach than the previous experiments in two ways: (1) Localization of subject BW was investigated in virtual auditory space with direct input to the CI processors instead of playing sounds in the free field,

and (2) Binaural cue weighting was studied by slightly off-setting binaural cues from their natural combination as this technique is thought to provide a better look at the normal cue weighting in the auditory system. In the present study, binaural stimuli prerecorded at one location were played directly into the processors while one binaural cue was filtered to originate from a different nearby location. A shift in localization towards the new location of the manipulated cue would indicate its contribution to directional perception.

B. Virtual acoustics with CIs

Head-related transfer functions (HRTFs) of Tempo+ processors, the type used by subject BW, were measured at the standard BTE positions on a human subject. The processor provides an output of the signal of the built-in microphone after the analog amplification and compression stage. The signal from the processor was routed via isolation transformers and measurement amplifiers to a measurement system or a digital recording system. Two measurements were done prior to the experiments:

- (1) The device HRTFs were measured with maximum-length sequences (MLS) using audio measurement equipment (Audio Precision System One Dual Domain) inside an anechoic chamber. While the head was fixed by a headrest the subject was turned on a swivel chair and measurements were taken in 10° steps relative to the front. MLS sequences were played from a high-quality studio monitor (Klein & Hummel O98). Measured impulse responses were shortened to 512 taps at 44.1 kHz. Both processors were set to minimum amplification which is the least compressive setting. The remaining level offset between left and right HRTF was normalized according to the offset at frontal sound incidence.
- (2) The test stimuli for experiment 3 (see below) were recorded directly off the processors with the amplification and compression settings commonly used by subject BW. The stimuli were played sequentially from the loudspeakers of the localization apparatus and the subject was seated at the standard position. The recorded stimuli contain all the directional information, ILDs and ITDs, that is forwarded to the later stages in the processor, and they include the alterations that stem from the compression stage of the processor. Since attack and release times of the compressors affect ILDs differently for each stimulus all test stimuli were recorded off the processor.

In experiment 3 the relative salience of ITD and ILD cues was tested by bringing both cues into opposition. However, according to the plausibility hypothesis the relative weighting of both cues will change if they are inconsistent (Hartmann, 1996; Wightman and Kistler, 1996). Thus, the natural weighting can only be studied for small cue discrepancies. Figure 1 outlines the approach taken here. ITDs and ILDs were brought into a small disparity of 20° or 40° by filtering the prerecorded stimulus with an ILD- or ITD-only filter (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002). The filter contained only the difference in ITDs or ILDs between the new target location and the origi-

nal location while the recorded stimulus contained ITDs and ILDs belonging to the original location. The filtered signal can be thought of containing ILDs of one location and ITDs of the other. For linear, time-invariant systems this would be perfectly true, but here the situation was complicated by compression. The processing was done differently for ITD and ILD filters.

The ITD filter was computed from the fast Fourier transform (FFT)-phase spectra of the measured CI-HRTFs. The difference between the phase spectrum of the new and the old location was computed separately for the left and the right ear HRTF which preserves the difference in ITDs between both locations; 512-taps all-pass finite impulse response (FIR) filters were generated for both ears by the inverse FFT of the difference phase spectrum. If this pair of filters is applied to a signal that is already filtered with HRTFs of the original location, ITDs will exactly point to the new location while ILDs and the monaural spectrum still correspond to the original location. The procedure was verified by informal listening. It should be noted that the ITDs had to be computed from the measured CI-HRTFs since exact phase relationships could not be maintained between recordings of the stimuli. The computation could be done from HRTFs since the effect of compression on ITDs is small.

The situation is different for ILDs since they are severely affected by compression. The difference in ILDs between two directions was computed from the prerecorded test stimuli as a temporal average over the total duration of the recorded stimulus. This average ILD difference was incorporated into 512-point FIR filters with linear phase and equal delay for both ears. If a binaural stimulus is filtered this way ITDs remain at the original location while ILDs shift to the average ILD of the new location. It is worth pointing out again that compression affects the ILDs as a function of the stimulus and of time. As the computation was done separately for each stimulus, part of the variance between stimuli was captured by the procedure, however, the temporal dependence of ILDs on the stimulus could not be reproduced exactly. This might be especially important for transient stimuli as the compression takes time to react.

Prerecorded stimuli were played into the direct input of the CI processor that bypasses the compression stage. This way compression is applied only once to the signal. The stimuli were played from a PC-type computer via a digital soundcard, an external digital-to-analog converter and an amplification stage. The amplified signal was routed via analog attenuators with 0.1 dB resolution and isolation transformers to the direct input of the CI.

C. Stimuli and procedures

The weighting of ILDs and ITDs was studied with a special focus on envelope ITDs at high frequencies. Besides the pulsed wide-band noise of experiment 1 high-pass noise with pulsed or slowly changing envelope was used. The pulsation enhances the availability of envelope ITDs. Stimuli are described in Table I.

The procedures in experiment 3 were similar to experiment 1 but subject BW localized virtual stimuli that were fed

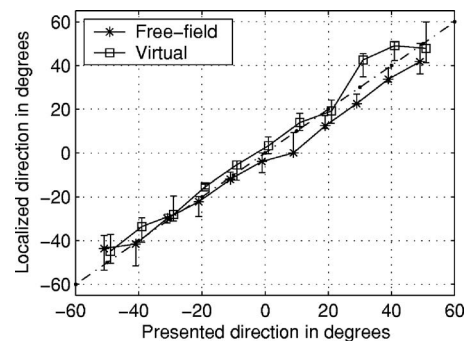


FIG. 5. Comparison of free-field localization (*) and virtual localization (□) of subject BW (experiment 3). The stimulus was pulsed wide-band noise (Table I).

directly into the speech processor instead of stimuli played via loudspeakers. At the beginning of the session the loudness of the directly fed prerecorded stimulus (WBN, pulsed) was adjusted to the loudness that the same stimulus evoked when played from the frontal loudspeaker at 69 dB SPL. The attenuation of the direct signal was changed recursively by the experimenter to minimize the loudness difference between free field and virtual presentation. The attenuation was also adjusted to yield a centered image for the stimulus played from the virtual front.

Localization was tested for the three stimuli each for ILD and ITD shifts. The following conditions with disparity were run (original/cue shifted location): -50° paired with -30° , -10° ; -30° paired with -50° , -10° , 10° ; -10° paired with -50° , -30° , $+10^\circ$, $+30^\circ$, as well as their symmetrical counterparts on the right hand side. The conditions with disparity were interleaved in random order with conditions without disparity for the azimuths -50° , -40° , ..., $+50^\circ$. Level was roved in 2 dB steps in 61–69 dB SPL. Ten trials were taken per condition which gave a total of 290 trials for each test sound. Similar to experiment 1 a light emitting diode lit up in the front for 5 s between blocks of 11 trials, but here trials were presented in completely randomized order. A break was introduced after 145 trials (13 min). Eleven trials without directional disparity were presented with feedback before the data collection began to help the subject get used to the virtual sound presentation.

Experiment 3 was run with subject BW 8 months after experiment 1. On the same day a single localization session identical to experiment 1 was administered to gather comparison data to free-field localization for the pulsed wide-band noise stimulus.

D. Results

Figure 5 shows localization results of subject BW taken in the free field and in virtual space without cue discrepancies for comparison and for verification of the technique. Table IV lists summary statistics. The free-field results, taken anew on the day of testing with virtual stimuli, confirm the outstanding localization performance for pulsed WBN (cf. Fig. 2). Surprisingly, the virtual stimulus presentation leads to a similar level of excellent localization performance, indicated by the ideal slope of the regression line of 0.97 and

TABLE IV. Summary statistics for localization results of subject BW in experiment 3, cf. Figs. 5 and 6: localization in the free field of pulsed wide-band noise and of virtual stimuli with consistent binaural cues. Virtual localization results were combined from trials without disparities from a session with ILD and one with ITD disparities. Statistics as in Table II.

Condition	Error (°)		Quartile (°)	Correlation coefficient	Regression line		Side diff
	Absolute	Arithmetic			Slope	Offset	
Free field							
WBN, pulsed ^a	5.2	-2.7	3.8	0.98**	0.90	-3.9	**
WBN, pulsed ^b	8.5	-7.8	3.2	0.97**	0.82	-6.5	**
Virtual presentation							
WBN, pulsed	6.3	4.3	4.4	0.99**	0.97	4.7	**
HPN, 100 ms env.	7.6	-3.6	5.4	0.99**	0.86	-3.7	**
HPN, pulsed	6.8	3.2	6.0	0.99**	0.95	4.2	**

^aTaken on day of testing with virtual stimuli.

^bFrom experiment 1 eight months earlier (cf. Table II).

very small quartiles of 4.4°. Quartiles increase with the transition from free field to virtual presentation by only 0.6°, while the regression slope increases as well and approaches 1. This suggests that virtual presentation captures all binaural information that is needed for horizontal localization by subject BW. The good level of performance with the pre-recorded virtual stimuli is surprising given the fact that compression settings in the recording are likely to differ somewhat from the settings used by the subject on the day of testing, that recoding processors were only of the same type, but not identical to the processors used by the subject, and that a long signal transduction chain was used for recording and playback of virtual stimuli that is likely to alter the signals somewhat, e.g., in the isolation transducers. This is to our knowledge the first report of a successful application of virtual auditory space techniques with CI subjects.

Figure 6 shows base line localization results without cue manipulation for all stimuli in virtual space and Table IV lists associated statistics. Results for pulsed WBN were replotted from Fig. 5 for reference. Both high-pass noises (HPNs) could be localized very well; however, at first sight localization of the HPN with slow envelope changes seems slightly worse than localization of the pulsed HPN. This is evidenced in a slightly lower regression slope (0.86 for slow vs 0.95 for pulsed envelope) which is based on deviating responses for +20°, +30°, and +50°. However, the increase in quartiles with pulsation (5.4° to 6.0°) and the equally high correlation coefficient of 0.99 for both HPNs rather suggest

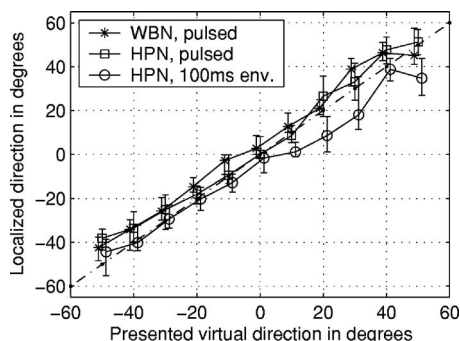


FIG. 6. Localization results of subject BW with virtual sound presentation without binaural cue disparities for different stimuli (Inset and Table I).

that localization ability was stable, independent of envelope modulation. Thus, these results extend in virtual space the previous results of the free-field experiment 1 by adding that envelope ITDs seem not to contribute to localization of high-pass sounds while experiment 1 showed this for wide-band sounds only. This distinction is important since ITDs in the envelope of high-frequency stimuli can be detected very well in normal hearing as well as with CIs.

Even though envelope-ITDs might not be the dominant localization cue, their redundancy to other cues might cover their contribution to localization. If ITDs contribute, small offsets in ITDs should affect localization responses. An example of localization results for stimuli with cue discrepancies is in Fig. 7. The WBN from +10° was localized at about +10° if binaural cues were not manipulated, i.e., no offset was introduced. If ILDs were set to correspond to a position with an offset of +20° to the right, i.e., to +30°, localization responses shifted by about 12° rightwards. The introduced offset was not followed completely, but a strong sensitivity to ILDs was apparent. On the contrary, localization was unaffected by offsets in ITDs, which shows that ITDs did not contribute to localization in this condition.

Figure 8 presents summary results across all directions and disparity conditions for all stimuli. Localization of pulsed WBN follows an ILD offset by about 50% while offsets in ITDs are not followed by more than 10% at 20° offset

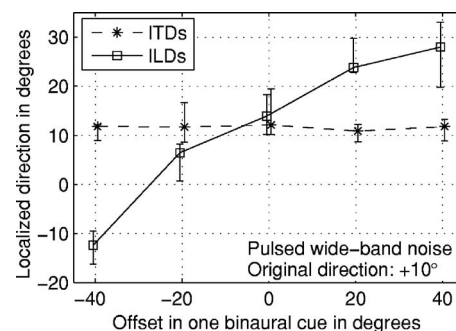


FIG. 7. Localization results of experiment 3 with binaural cue disparity (subject BW). A binaural recording of pulsed wide-band noise taken at +10° was manipulated so that one binaural cue (ILDs or ITDs) stemmed from a different direction ±20/40° away from +10°. Localization followed this offset only for ILDs.

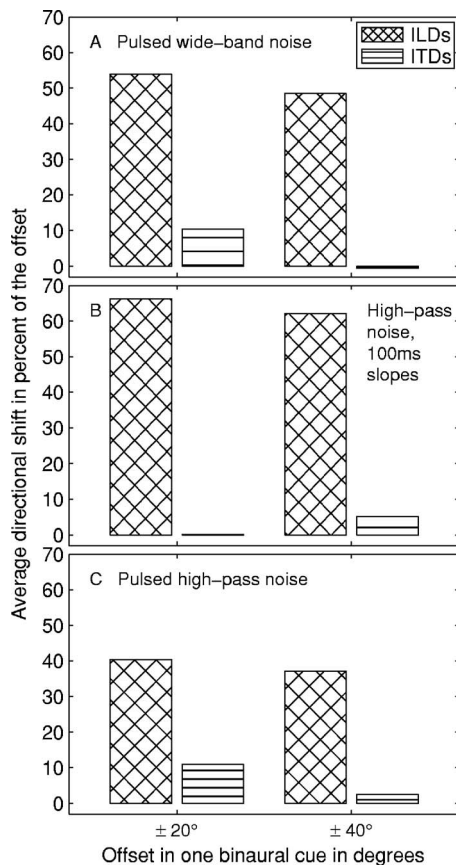


FIG. 8. Average directional shift observed in experiment 3 with subject BW for different disparities between ILD and ITD cues. Panels A–C give results for pulsed wide-band noise, high-pass noise with slow slopes and pulsed high-pass noise, respectively (cf. Table I). Data are averages over several originating directions.

(panel A). This confirms that ILDs provided the predominant information for localization of wide-band sounds for subject BW while the relative contribution of ITD cues is small despite the pulsation. For HPN with slow envelope changes ILD-weight seems to increase and ITD-influence appears absent (Panel B). The dominance of ILDs did not change even for pulsed HPN (panel C). The pulsation emphasized envelope ITDs and their weight increased, but it still remained low. For small discrepancies ILDs evoked directional shifts of about 40% while ITDs shifted directions by 10%. It should be noted that the directional shift of 2° corresponding to 10% ITD influence is well below the localization variance (quartiles of 6.0°). Interestingly, there might be a small trend for pulsed stimuli to yield a slightly higher ITD weighting at 20° compared to 40° offsets (panels A+C). This trend is consistent with the idea that cue weighting changes with cue discrepancy.

It is apparent from Fig. 8 that ILD-based shifts did not exceed 67% of the introduced offset despite the low contribution of ITDs. One reason for the apparently limited contribution of ILDs is that the cue weighting is computed relative to the introduced physical cue discordance, not relative to the change in localized direction. This has the advantage that localization errors in the base line without cue discordance have no effect on computed cue weighting, however, a base line localization slope smaller than one results in cue

weighting below 100%. Given that most slopes are close to one (Table IV) we found that the resulting reduction in weight would be acceptable as the maximal error should be in the order of the observed variance. Another reason for the reduced contribution of ILDs can be found in the way ILD filters were generated. ILDs were computed by integration over the total duration of the recorded stimulus which included compression. While integration over pauses in pulsed stimuli should not offset the ILD-estimation per se, the effect of compression could. ILDs are larger at the beginning of the pulses before compression starts. The averaged ILDs incorporated in the filters were thus smaller than ILDs at sound onsets. This will lead to compression of localization responses towards the front if the subject would evaluate ILDs mostly from sound onsets.

It can be concluded from experiment 3 that ILDs were the dominant cue for localization of subject BW for wide-band and for high-pass stimuli and that ITDs played only a minor role even if stimuli were envelope modulated.

VI. OVERALL DISCUSSION

The relative weighting of binaural cues with bilateral CIs was tested in a localization task with three different methods, in both free field and virtual space. In experiment 1, two subjects localized sounds differing in spectral and temporal composition in the free field. Both subjects showed the ability to discriminate the side of sound origin for wide-band noise (WBN) with a single CI, indicating the evaluation of monaural spectral cues. Using two CIs, both subjects were able to localize WBN with pulsed or slowly changing envelope with similar, high accuracy, suggesting that envelope ITDs played only a minor role. Low-pass noise (LPN) could not be localized by subject BW, while performance for subject DF was good for a cut-off frequency at 525 Hz, but deteriorated clearly when the cut off was reduced to 400 Hz. This indicates a strong contribution of remaining ILDs as ITD evaluation should not be affected by the reduction in bandwidth. Both subjects localized high-pass noise (HPN) with scrambled spectrum nearly as well as WBN which indicates the use of interaural cues. Experiments 2 and 3 were designed to clarify the contribution of ITDs by artificially dissociating ITDs from ILDs.

In experiment 2, localization of subject DF was studied with physically manipulated binaural cues in the free field. It was meant to elucidate the contribution of ITDs in light of his inconclusive results with LPN. CI processors were placed above the head and localization of WBN was best if a cardboard was placed between processors, while mere processor spacing by ear distance that gave mainly rise to ITDs elicited only discrimination of left from right. Experiment 2 shows that ILDs were the more efficient localization cue for subject DF while ITDs contributed somewhat, consistent with the results of experiment 1.

Experiment 3 was designed to clarify the contribution of envelope ITDs to localization of HPN by subject BW which could not be answered by experiment 1. The introduction of a discordance between ITD and ILD cues in virtual acoustical space provided a clean way to assess their relative importance. Virtual localization of subject BW was shown to be

similar to the free field. When binaural cues were brought in conflict to each other, localization of WBN or HPN followed the introduced offset more for ILD shifts while ITDs contributed slightly only when the envelope was pulsed. In agreement with the results of experiment 1 the data from virtual space show a clear ILD dominance for subject BW. Experiment 3 adds that ILDs dominate even when the evaluation of ITDs was emphasized by pulsation.

A. Interaural time differences

The preprocessing and the pulsatile stimulation in CIs alter monaural and binaural cues available to the subject. Signal processing for CIS-type processors, as used by the subjects of this study, consists of compression, bandpass filtering, envelope extraction and pulse forming parts. The log-transformed value of the envelope is used to determine the current of the stimulation pulses while their temporal position is independent of the signal and pulses follow a fixed rate (Zierhofer *et al.*, 1995). This leads to a dissociation of fine-structure and envelope information. The fine structure does not carry information about the signal and hence the best strategy for the auditory system would be to ignore it. In support of this view CIs use stimulation rates too high to be followed directly by the auditory nerve. As pulses are not placed temporally with respect to the signal phase ITDs are not encoded directly and hence ITDs cannot be detected through the phase at low frequencies. The problem is enhanced by the fact that processors are not synchronized between the ears. The lack of synchronization introduces arbitrary ITDs that change from day to day or drift during the day. Subject DF used different stimulation rates on both ears which lead to varying carrier ITDs. A good strategy for the auditory system would be to ignore unreliable, changing carrier ITDs.

Even though the envelope is sampled at a rate that is too low for a good direct representation of ITDs it seems that the auditory system can nevertheless extract ITDs fairly well from the *envelope*. Envelope-ITD thresholds with CIs can be close to thresholds seen in normal hearing and values of 25 μ s have been reported in two subjects (Lawson *et al.*, 2001). In comparison, only a few subjects show thresholds for carrier ITDs down to 50 μ s on selected electrodes; the same subjects show higher thresholds on most other electrode pairs. Thresholds often range from 100 to 300 μ s while some subjects cannot detect carrier ITDs of 1 ms (van Hoesel and Clark, 1997; Lawson *et al.*, 1998; Lawson *et al.*, 2000; van Hoesel *et al.*, 2002; Long *et al.*, 2003; van Hoesel and Tyler, 2003). An exception is subject DF who showed very low ITD thresholds across many electrode combinations, the reason for which he was chosen for the current study. Lawson *et al.* (2000) identified five electrode combinations for him (coded as ME8) with ITD thresholds lower than 50 μ s and 16 other combinations with thresholds lower than 150 μ s. In the same study, subject BW (ME5) showed an ITD threshold below 50 μ s on one electrode combination, below 150 μ s on another two electrode combinations, while four combinations showed thresholds of 1–2 ms. Despite the good sensitivity of DF to ITDs in the carrier the results of the current study indicate that his localization was not dominated

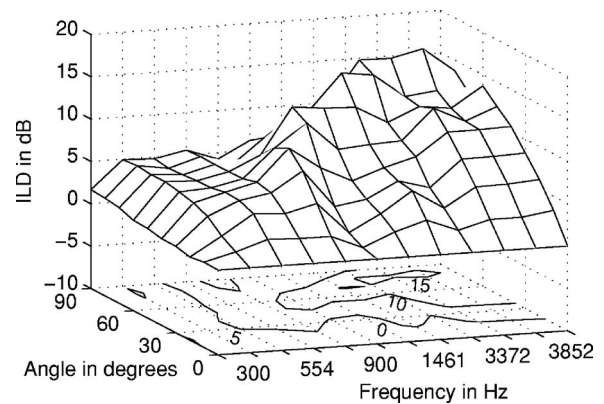


FIG. 9. ILDs computed from HRTFs measured on Med-El Combi 40+ processors. ILDs were derived from the level of HRTF-filtered narrow-band noise signals. The frequencies and the bandwidth of the noise corresponded to the log-spaced channel mapping in 300–5547 Hz used by subject BW. Tickmarks on the frequency axis correspond to CI channels. Levels were normalized to be zero for frontal sound incidence to correct for amplification offsets in both CI processors. ILDs were averaged for sound from the right and the left side.

by ITDs. This finding can be explained at least partly by the fact that the CIS strategy does not encode ITDs in the carrier pulses. But the question remains why both subjects, DF as well as BW, weighted ITDs low which *are* transmitted in the envelope and which *are* detectable, but relied on ILDs for localization instead.

B. Interaural level differences

One possible reason why the contribution of ITDs is small is because sensitivity to ILD changes is far better than to ITDs for most subjects. ILD thresholds were often as low as the minimum possible current step (van Hoesel *et al.*, 1993; Lawson *et al.*, 1998; Lawson *et al.*, 2000; van Hoesel and Tyler, 2003). This could be as low as 16 μ A at 1.1 mA current, which is equivalent to a change of 0.125 dB at a dynamic range of 9.5 dB (Lawson *et al.*, 1998). Given this high sensitivity, we assessed the physically occurring ILDs at the input of the speech processors. Figure 9 shows ILDs in the measured HRTFs of the speech processors computed in channel bands for the common logarithmic map in 300–5547 Hz as used by subject BW. For frontal sound incidence and for low-frequency channels ILDs are small (<5 dB). They are unlikely to serve as a good localization cue, but they might provide some information in $\pm 30^\circ$ where a monotonic increase with angle can be observed in channels 2–4. For frequencies beyond 800 Hz (channel 5) ILDs change over a larger angular range and ILDs up to 15 dB can be observed. A strong monotonic increase of ILDs with angle can be seen for the upper 3 CI channels between 0° and 60° . Beyond 60° ILDs do not increase further, but a channel specific pattern of peaks and troughs could be evaluated by the auditory system. In general, the pattern of ILDs measured at the CI-speech processors is consistent with ILDs measured in the ear canal but some fine detail is lost due to the averaging in CI channels. The occurrence of ILDs up to 5 dB in low-frequency channels 2–4 might seem surprising at first. However, HRTFs measured in the ear canal have similar ILDs in the corresponding frequency range of 500–1000 Hz. ILDs of

5 dB may be sufficient to allow for localization of frontal directions. Subject DF showed coarse localization of 400 Hz low-pass noise and good localization of 500 Hz LPN and pulsed LPN in experiment 2. We analyzed the low-pass stimuli of experiment 2 for their spectral content. The -20 dB points of the averaged spectrum were found at 710 Hz both for the pulsed noise and for the 500 Hz LPN. One would assume that pulsation leads to spectral widening. However, due to the 40 dB spectral scrambling applied to the pulsed LPN the -20 dB bandwidth turns out to be wider in only 50% of the sequences, whereas it is smaller in the other 50%. Both sounds led to about the same localization performance, which is in support of an ILD-based localization process since the underlying bandwidth was identical. For the 400 Hz LPN the -20 dB point lies at 592 Hz. Given the electrode mapping of subject DF the 400 Hz LPN covers only 2/3 electrodes at the left and right ear, respectively, whereas the 500 Hz LPN provides energy over 3/4 electrodes. Localization performance was considerably worse with the 400 Hz LPN which is consistent with the limitation in spectral range for ILD evaluation. If the localization process was based on ITDs this slight limitation in spectral extent should not reduce the envelope-ITD information considerably.

Further support for an ILD-dominated localization process with CIs stems from lateralization studies. [Van Hoesel and Tyler \(2003\)](#) showed lateral position of 50 pps pulse sequences to be more dependent on ILDs than ITDs in 5 out of 5 tested subjects when electrodes were stimulated directly through a research interface. The stronger dependency of lateralized position on ILDs is also in line with results by [Long et al. \(2003\)](#) and [Schoen et al. \(2005\)](#).

C. Plausibility of localization cues

According to the plausibility hypothesis less weight is given to localization cues that are in conflict across the spectrum or against other localization cues ([Hartmann, 1996](#); [Wightman and Kistler, 1996](#)). This applies to ITDs with CIs. ITDs in the carrier pulses are random with unsynchronized devices while envelope ITDs transmit useful information, albeit quantized. Assuming that the binaural system derives ITDs from the carrier in low-frequency regions and from the envelope at high frequencies inconsistent ITDs will be computed across the spectrum and the binaural system should thus ignore ITDs altogether according to the plausibility hypothesis. Subject DF uses different stimulation rates on both ears which potentially introduces varying ITDs. Although recent studies suggest that it is unlikely that the auditory system extracts carrier ITDs at stimulation rates above 1400 pps ([Majdak et al., 2006](#); [van Hoesel, 2007](#)), the variable carrier ITD would contrast with the envelope ITD. According to the plausibility hypothesis this could reduce DF's reliance on ITDs. Also, ITD sensitivity varies largely across electrodes, whereas ILD detection is consistently good on most electrodes. This high sensitivity for ILDs across many electrodes is more likely to provide the binaural system with a reliable, consistent localization cue.

D. Consistency with other studies

The dominant influence of ILDs on localization is utilized in the loudness balancing procedure at the beginning of the localization tests. By changing the amplification in the devices the auditory image can be centered which relies on the dominant influence of ILDs for lateralization. Localization offsets for frontal sounds simply depend on the relative amplification in both devices—a setting that is changed often throughout the day. Thus, offsets do not characterize the localization *ability* of the subject. The localization method must be able to distinguish between offsets, localization slope, and variance since only the latter two characterize the auditory system in the case of CIs ([Seeber, 2002](#)). The localization method used here provides this information.

In the present as well as in several other studies with bilateral CIs sound sources from the sides were localized more towards the center ([van Hoesel et al., 2002](#); [van Hoesel and Tyler, 2003](#); [Nopp et al., 2004](#); [Schoen et al., 2005](#)). In the discussion to Fig. 9 this was related to a compression of ILDs in the HRTFs for azimuths from 60° to 90° . Alternatively, azimuth compression might also occur for overly compressive settings of the mapping law. A too compressive map will reduce the stimulation current at high levels more than necessary and thus compress effective ILDs. Likewise, the automatic gain control (AGC) employed in most processors compresses ILDs in a similar way. As compression does not severely affect envelope ITDs the observation of a compressed azimuthal range suggests an ILD-dominated localization process.

VII. CONCLUSIONS

The relative dominance of binaural cues was studied with three different approaches in two bilateral CI subjects with excellent localization ability. Although both subjects did not participate in all experiments the results show consistently that both subjects predominantly relied on ILDs for localization of all tested types of sounds while ITDs contributed only a small amount of information. ITD influence seemed strongest when their evaluation was emphasized by modulating the sound envelope, but it still remained far below the contribution of ILDs. In contrast, in normal hearing ITDs dominate localization for most wide-band sounds and ILDs play a role only for some high-frequency sounds. CI subjects thus show reversed dominance of localization cues compared to normal hearing. As ITDs play only a minor role, CI subjects lose the redundancy to rely on either localization cue. As long as subjects face situations in which the single localization cue provides enough information, no shortcomings in localization might occur. However, this might be different for situations with multiple sounds in which one cue might prove unreliable and the redundancy of cues would be needed to resolve ambiguities. We predict that localization of CI subjects would suffer considerably in those situations similar to the strong deterioration of speech understanding in background noise ([Qin and Oxenham, 2003](#); [Firszt et al., 2004](#)).

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