Localization cues with bilateral cochlear implants investigated in virtual space – a case study

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1 Introduction

Cochlear implants (CI) stimulate spiral ganglion cells in few, wide areas using discrete, amplitude-quantized pulses. This results in reduced spectral, temporal, and amplitude resolution. Nevertheless, several studies demonstrated outstanding localization ability with selected bilateral cochlear implant subjects, e.g. [4]. To investigate the underlying localization cues a free-field study was conducted previously which showed that interaural time differences (ITD) could not be used for localization with low-frequency carriers [5]. The study also showed that high-pass sounds with little envelope information could be localized. However, envelope cues from the intrinsic modulation in the narrow-band frequency channels of the implant processor could be used by the subject. The relative weighting of interaural temporal (ITD) and level (ILD) cues for localization could be tested by an independent variation of ITD and ILD. Changes in the localized position will reflect the sensitivity to the respective cue [6, 2]. As independent changes of ITDs and ILDs can not be applied in the free-field, virtual sound presentation with synthesized and modified directional cues was used the first time with a CI-subject.

For the virtual sound synthesis ILDs were calculated from recorded test stimuli, which incorporated directional cues and the compressive pre-processing of the CI. ITDs were deduced from directional transfer functions of the speech processors when being placed on a head. The ILD and ITD cues of the test stimuli were then independently modified to represent two different nearby positions.

A localization test using these modified virtual stimuli showed high spacial sensitivity to changes in ILDs, but no or small sensitivity to ITD changes, even for high frequency carriers. It can thus be followed that interaural temporal cues are not used by this subject for localization. In contrast to normal hearing, localization is predominantly based on interaural level cues and monaural spectral cues for our CI subject.

2 Methods

The localization ability was assessed with a light-pointer method. The subject adjusted a horizontally moving light spot on the perceived direction of the sound by turning a trackball [3, 4]. In the free-field experiments the test sounds were played from 11 loudspeakers positioned in a 10°-spacing from −50° left to +50° right at ear level and at a distance of 1.95 m. The speakers were covered by a curtain. Experiments were done in complete darkness. An experiment consisted of 10 blocks containing all 11 directions in random order. The level was roved in 2 dB steps in 61 – 69 dB SPL.

To measure directional transfer functions (DFTs) two Med-El Tempo+ processors were worn by a subject at the behind-the-ear position. The compression was switched off. Using a customized cable the microphone signals were taped-off the processor to a measurement amplifier which fed-in to a measurement system. The DTFs were measured in a 10°-spacing using MLS-sequences played from a loudspeaker. The test stimuli were digitally recorded from the speech processors placed at the ears for the directions −50° to +50° in a 10°-spacing. The compression in the speech processors was set to the everyday level used by the subject, 3/4 left and 1/4 right.

ILDs were computed from the recorded test stimuli. To generate signals with shifts in ILDs the ILD difference between shifted and original position was applied to the recorded stimuli of the original position. ITDs were computed from DFTs of the devices. The ITD differences were applied to recorded stimuli in the same way.

Pulsed wide-band noise (125 Hz – 20 kHz, 5 pulses, pulse duration 30 ms, pause duration 70 ms) was used to provide the entire localization information: ITD and ILD throughout the audible spectrum, monaural spectral cues, and ITD envelope cues. High-pass noise limited to the frequency range of the upper 3 channels of the CI (noise 2644 – 5547 Hz, 164 ms on-duration plus 100 ms Gaussian slopes, "spectral scrambling" [7] 40 dB within CI-channels [2644, 3377, 4360, 5547] Hz) was also presented. Monaural spectral information is suppressed by the random spectral level in each CI-channel. Its evaluation is further hampered by a missing "low frequency anchor". The slow envelope changes make an evaluation of envelope ITD cues difficult.

The playback of virtual stimuli was done over an audio-connection cable for the Tempo+ processor, bypassing the microphone and the compressor. From a D/A-converter the audio-signals passed an attenuator and an isolation transformer before being fed-in the processor. The virtual stimuli levels were set by means of a free-field comparison using the attenuators. Additionally, the interaural level was adjusted to give a centralized image.

Experiments with virtual stimuli constisted of 10 trials for each of the following conditions: directions −50° left to +50° right in a 10°-spacing without cue manipulations, directions ±50° with shifted cue 20° and 40° to the front, ±30° with one cue from ±50°, ±10° and ∓10°, and ±10° with cues originating at ±50°, ±30°, ∓10°, ∓30°. 4 virtual tests were done for both noise stimuli with either

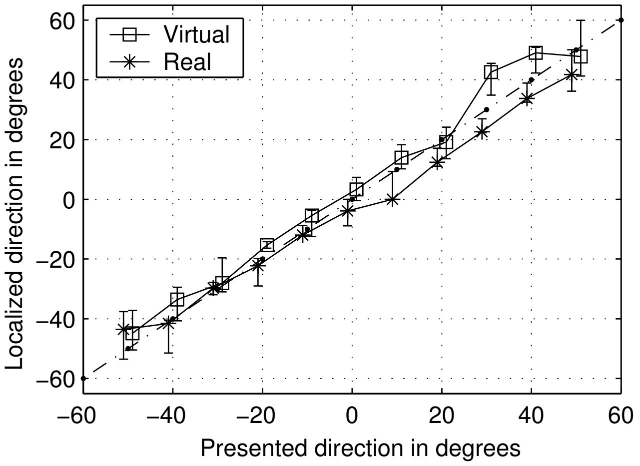

Figure 1: Localization results with bilateral CI for pulsed wide-band noise with virtual or free field sound presentation.

Experiment	Error abs. [°]	Quar-tile [°]	Regression Factor	Regression Const.
Free field	5.2	3.8	0.90	−3.9
Virtual sounds	5.7	4.7	0.99	+4.4

Table 1: Tabelarized localization results of Figure 1.

ITD or ILD shifts. The experiments were completed by an experienced bilateral CI subject (male, 51 years, 1st CI for 4.9 years, 2nd CI for 3.9 years, MED-EL Combi 40+ with TEMPO+ processor on both sides, deafened on Otosclerosis) [4].

3 Results and Discussion

As virtual sound presentation is new to CI studies we first verified the applicability of this technique. A comparison of localization results obtained from the free-field and with virtual acoustics is given in Figure 1 and Table 1. It can be seen that localized directions from real and virtual sound sources coincide well. Localization of virtual stimuli with CIs is possible with small error (5.7°) and quartiles (4.7°). We conclude that virtual sound presentation can be used with bilateral CI to study localization.

The purpose of this study was to assess the relative weighting of ITD and ILD cues for localization by independent, minute changes of these cues starting from natural combinations. Figure 2 shows exemplarly localization results of pulsed wide-band noise at +10° if ILD or ITD cues were shifted to originate from sources ±20° or ±40° away. It can be seen that the localized direction follows partly an introduced shift in ILD, but shifts in ITD lead to no shift in localized direction. This result confirms results of a free-field study with the same bilateral CI subject which suggested that ITDs are not used by him for localization of wide-band sounds [5].

As CI subjects can have a high sensitivity to ITD envelope cues ($25\,\mu$sec [1]) these cues could provide localization information at high carrier frequencies. Seeber et al. [5] found that envelope information is not used for low frequency carriers. Figure 3 displays localization results for high-pass noise with slow envelope changes. As

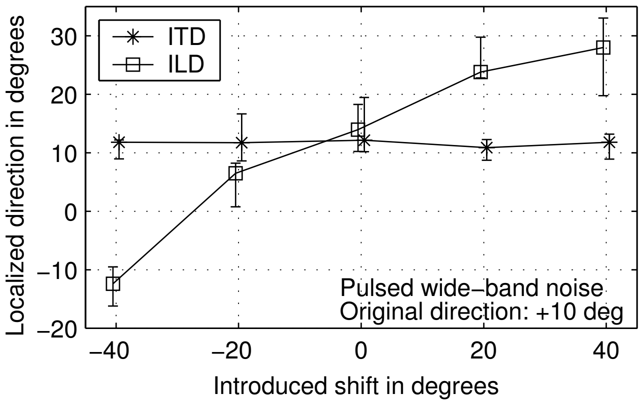

Figure 2: Localization of virtual sources at +10° synthesized with changes in ITD (∗) or ILD (□) towards sources ±20° or ±40° away.

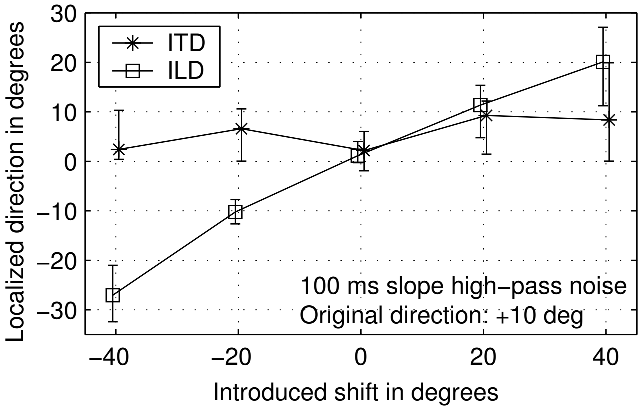

Figure 3: As Figure 2, but for 100 ms slope high-pass noise.

for wide-band noise it can be seen that no sensitivity to changes in ITD information exists. It can be derived that ILD cues are being used for localization of high frequency sounds with slow envelope changes. The intrinsic envelope modulation due to the band-pass filtering of the signal in the speech processor seems not to provide enough temporal cues for localization for our subject.

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