Coding of interaural phase differences in BiCI users

STEFAN ZIRN*, SUSAN ARNDT, AND THOMAS WESARG

Department of Oto-Rhino-Laryngology of the Medical Center, University of Freiburg, Germany

The ability to detect a signal masked by noise is improved in normal-hearing (NH) listeners when interaural phase differences (IPD) between the ear signals exist either in the masker or the signal. We determined the impact of different coding strategies in bilaterally implanted cochlear implant (BiCI) users with and without fine-structure coding (FSC) on masking level differences. First, binaural intelligibility level differences (BILD) were determined in NH listeners and BiCI users using their clinical speech processors. NH subjects (n=8) showed a significant mean BILD of 7.5 dB. In contrast, BiCI users (n=9) without FSC as well as with FSC revealed a barely significant mean BILD (0.4 dB respectively 0.6 dB). Second, IPD thresholds were measured in BiCI users using either their speech processors with FS4 or direct stimulation with FSC. With the latter approach, synchronized stimulation providing an interaural accuracy of stimulation timing of 1.67 μs was realized on pitch matched electrode pairs. The resulting individual IPD threshold was lower in most of the subjects with direct stimulation than with their speech processors. These outcomes indicate that some BiCI users can benefit from increased temporal precision of interaural FSC and adjusted interaural frequency-place mapping presumably resulting in improved BILD.

INTRODUCTION

Interaural timing cues are important for normal-hearing (NH) listeners for sound source localization and for binaural unmasking of speech in the presence of spatially separated interfering sounds (e.g., Moore 2012; Colburn *et al.*, 2006).

In bilaterally implanted cochlear implant (BiCI) users sound source localization as well as binaural unmasking of speech are impaired compared to NH listeners. The main limitation may arise from limited availability of interaural timing cues when using their clinical devices, whereas interaural level differences can be perceived with a considerably higher precision (Kerber *et al.*, 2012; Seeber *et al.*, 2008; van Hoesel *et al.*, 2008).

On the other hand, BiCI users show considerable sensitivity to interaural time differences (ITD) in bilaterally synchronized electric pulse trains with and without on-/offset differences. Especially Laback *et al.* (2007) showed that even ongoing ITDs are perceivable to selected BiCI users at low pulse rates.

*Corresponding author: stefan.zirn@uniklinik-freiburg.de

Proceedings of ISAAR 2015: Individual Hearing Loss – Characterization, Modelling, Compensation Strategies. 5th symposium on Auditory and Audiological Research. August 2015, Nyborg, Denmark. Edited by S. Santurette, T. Dau, J. C. Dalsgaard, L. Tranebjærg, and T. Andersen. ISBN: 978-87-990013-5-4. The Danavox Jubilee Foundation, 2015.

Furthermore, Goupell *et al.* (2015) measured binaural masking level differences (BMLDs) in constant high-rate pulse trains. They found average BMLDs up to 11 dB.

These outcomes on single electrode pairs are promising for real-life benefits with multi-electrode stimulation. However, if and how single electrode experiments in this context translate to multi-electrode scenarios is unknown. With the fine-structure coding strategy 'FS4' from MED-EL, a coding strategy that processes interaural phase differences (IPDs) is clinically available.

Aim of this work

With this work we investigated if the fine-structure coding strategy FS4 enables binaural unmasking of speech in terms of measurable binaural intelligibility level differences (BILD). As a reference BILD was evaluated in the same BiCI users programmed with HDCIS and in NH listeners.

Furthermore, IPD thresholds with signals processed by the clinical CI processors programmed with FS4 or HDCIS were compared with the same signals processed with synchronized bilateral direct stimulation obtained with a research platform.

METHODS

Stimuli

For measuring the influence of IPD in broad-band signals, the binaural intelligibility level difference (BILD) has been measured similar to the approach first described by Licklider (1948). Speech material was taken from the German Oldenburger Sentence Test (OLSA, 2011). The masker was OLnoise, a steady-state noise with a speech shaped spectrum. The BILD was determined as the difference in speech reception threshold (SRT) between two listening conditions. First, a diotic condition (speech in noise on both ears, no difference between ear signals) and a dichotic condition (speech in noise on both ears, the phase of the speech signal was inverted on one ear).

With speech in noise two interaural cues are available to the listeners: interaural envelope differences and interaural fine-structure differences. To examine the effect of interaural fine-structure differences exclusively, IPD sensitivity was measured using narrow-band signals. For this purpose, a 150 Hz pure tone was ramped up and down with hann windows. On the right ear, the pure tone was presented without any phase variations (Eq. 1).

$$y(t) = A_c \sin(\omega_c t) \quad (1)$$

The phase of the left pure tone, however, was modulated according to Eq. 2.

$$y(t) = A_c \sin(\omega_c t + m(t) + \varphi_c) \quad (2)$$

where $\omega_c = 2*\pi*f_c$, f_c is the carrier frequency (150 Hz), m(t) is the sinusoidal modulation signal, and $\varphi_c = 0°$.

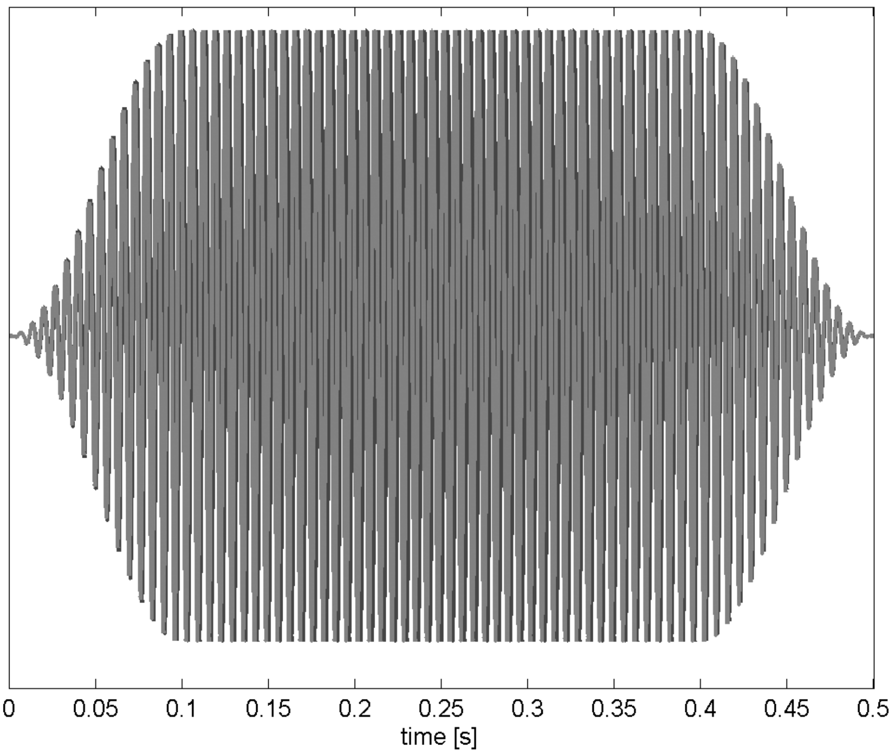

Fig. 1: IPD stimuli – two 150 Hz sinusoidal tones. The left ear signal (dark grey) was phase modulated which then lags behind the right ear signal (light grey). Note that no envelope differences between the ear signals exist.

150 Hz corresponds to the center frequency of CI channel 1 in the typical FS4 map with all 12 CI channels activated.

Procedure

For the IPD test, a 3-alternative forced-choice paradigm for masked threshold determination was implemented. For every two correct answers one after one other, the IPD was lowered, one false response lead to an increase of the IPD (2-down 1-up procedure).

For the BILD effect speech understanding of 5 word OLSA sentences was investigated with an adaptive procedure as well. For every sentence with more than two words correct, the signal-to-noise ratio was lowered. For every response with two or less than two words correct, the signal-to-noise ratio was increased. The procedure was similar to that described in the OLSA documentation (OLSA, 2011). In contrast to the BILD procedure described in this documentation, the signals were not presented in free field, but using the auxiliary inputs of the speech processors in BiCI users and headphones in NH listeners.

The BILD was defined similarly to Licklider (1948) and to Goverts and Houtgast (2010): the difference between the speech-reception threshold in noise in diotic presentation mode (SRT N_0S_0) and in dichotic presentation mode with antiphasic speech (SRT N_0S_π).

Participants, cochlear implants, and stimulation hardware

Nine BiCI users and eight NH listeners participated in the broad-band BILD experiment. Six BiCI users and three NH listeners participated in the narrow-band IPD experiment. All BiCI users had two cochlear implants from MED-EL types PULSAR, SONATA, CONCERTO, or SYNCHRONY with electrode arrays of either 31.5 or 28 mm length. All of them used two OPUS 2 processors.

Acoustic stimuli were generated using a PC, MATLAB, and soundcard type RME Fireface UC with 44.1 kHz sampling frequency and 16 bit quantization depth. The stimuli were presented to the BiCI users using a y-audio cable and the auxiliary inputs of the OPUS 2 processors.

Electric stimuli (biphasic current pulse trains) were generated using the RIB2 direct stimulation platform manufactured at the University of Innsbruck, Austria with custom made MATLAB code. The coding strategy implemented for direct stimulation with the RIB2 was orientated at the FS4 strategy. The major difference was that stimulation was synchronized across ears, which is possible with the RIB2. Furthermore, an increased sampling frequency relative to the 6000-12000 Hz applied with FS4 was implemented. With direct stimulation we used 1 MHz. This led to a higher temporal precision of zero-crossing determination. It was then limited by the RIB2 with a temporal precision of 1.67 µs. In the following we call this coding strategy “Fine HighPrecision”.

RESULTS

BILD

The BILD results of NH listeners and BiCI users are shown in Fig. 2.

The SRT of NH listeners in the diotic condition was −7.1 ± 0.8 dB SNR (mean ± standard deviation), in the dichotic condition −14.6 ± 1.6 dB SNR. The BILD was considered as the difference of these SRTs. In this group of NH listeners, the mean BILD was 7.5 dB. Statistical analysis with the Wilcoxon signed-rank test revealed that this BILD was significant (p=0.008).

In BiCI users programmed with FS4, the SRT in the diotic condition was −2.1 ± 1.8 dB SNR, in the dichotic condition −2.6 ± 1.9 dB SNR. In this group of BiCI users, the mean BILD was 0.5 dB with FS4. This BILD was statistically significant (p=0.05).

The same BiCI users programmed with HDCIS reached an SRT in the diotic condition of −1.4 ± 1.9 dB SNR, in the dichotic condition −2.0 ± 2.0 dB SNR. The resulting mean BILD was 0.6 dB with HDCIS. This BILD was also statistically significant (p=0.02).

No significant difference between the SRTs using either HDCIS or FS4 occurred. This held for the diotic and the dichotic condition.

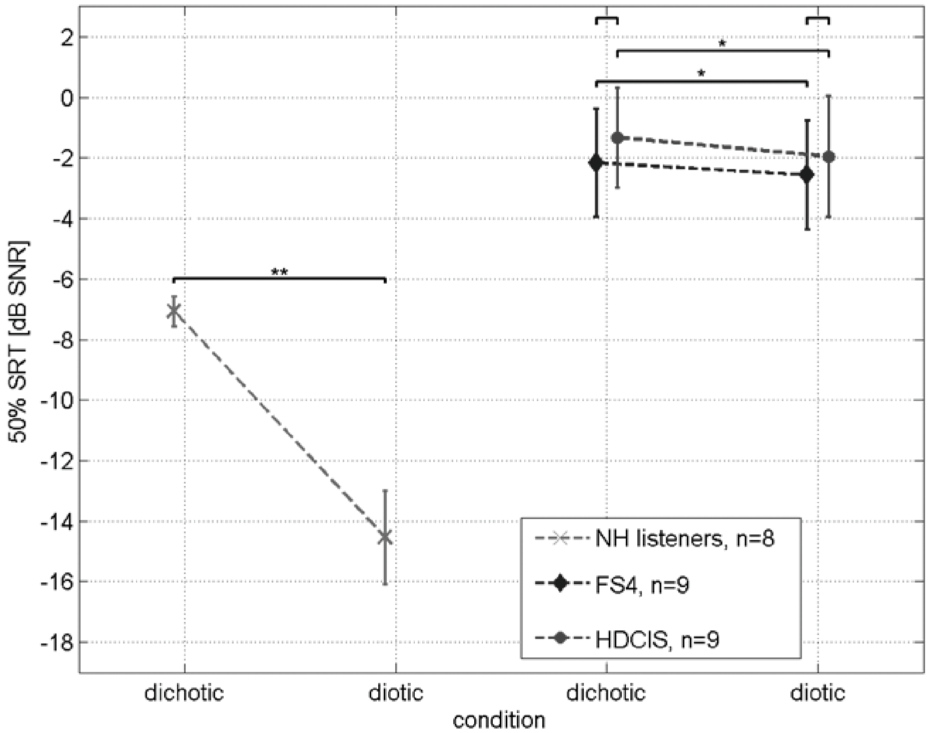

Fig. 2: Results of the BILD experiment. The data of NH listeners is shown on the left. The results of BiCI users tested with two different coding strategies (HDCIS and FS4) are shown on the right. An adaptation phase of three months was applied in each BiCI user to familiarize to changes in the coding strategy.

IPD threshold measurements

Figure 3 shows the IPD thresholds obtained in NH listeners and BiCI users.

The three NH listeners reached a mean IPD threshold of 25° which corresponds to 0.46 ms.

The results of the 6 BiCI users included in this experiment were very inhomogeneous and dependent on the coding strategy. The constant rate coding strategy HDCIS led to the worst IPD threshold of 180° or 3.3 ms, which was defined as the upper limit of the test. The same BiCI users programmed with FS4 reached lower IPD thresholds except two. The lowest IPD thresholds were achieved with the Fine HighPrecision coding strategy in every BiCI user.

Two out of the six BiCI users (CI1 and CI6) reached IPD thresholds close to those of NH listeners.

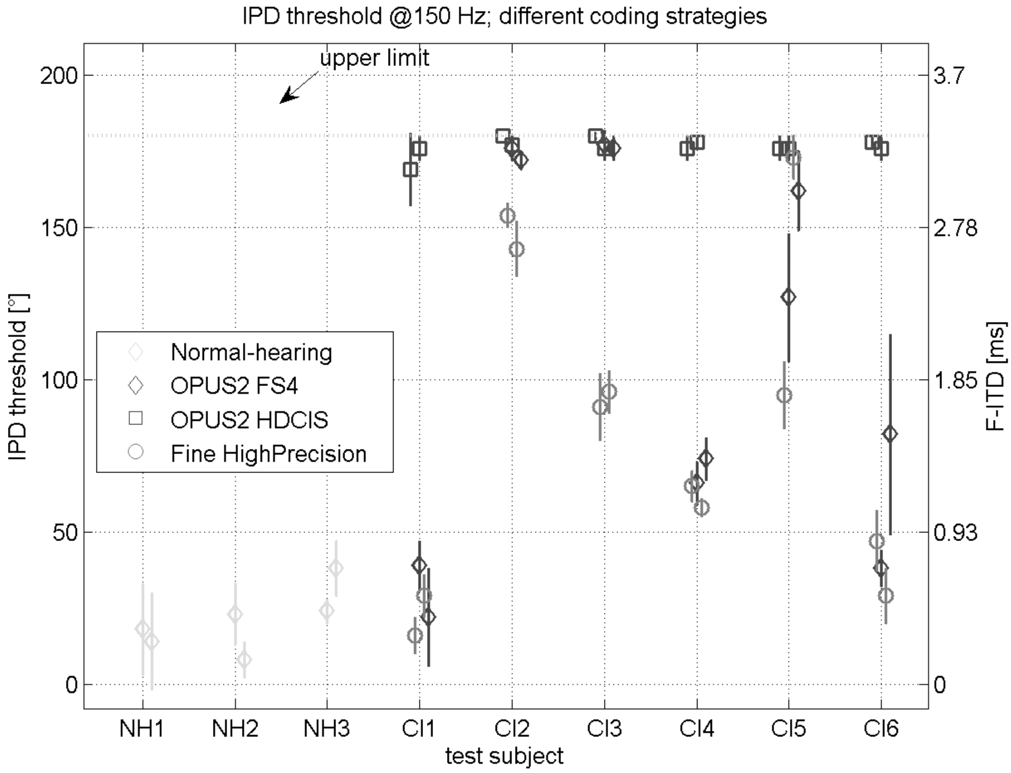

Fig. 3: Results of the phase modulation experiment. The data of NH listeners are shown on the left. The results of BiCI users are shown on the right.

DISCUSSION

The broad-band experiment showed that SRTs as well as BILD were not dependent on the coding strategy in our group of BiCI users. With both FS4 and HDCIS, the included BiCI users reached significantly lower SRTs in the dichotic condition, i.e., with interaural phase differences. Thus, envelope and fine-structure information coded with FS4 was as effective as coding of the envelope only in this group of BiCI users. An explanation might be that with HDCIS the representation of the envelope is more precise than with FS4 in the apical CI channels.

The narrow-band experiments were designed in a way that no interaural envelope differences occurred. According to this, the IPD thresholds with HDCIS were at the upper limit of the test (180° corresponding to 3.3 ms). Thus 0% of the BiCI users showed IPD sensitivity with HDCIS. With FS4, four out of six BiCI users (66%) reached better IPD thresholds than with HDCIS, whereas all six BiCI users (100%) showed better IPD sensitivity with Fine HighPrecision.

Consequently, some BiCI users can benefit from increased temporal precision of interaural fine-structure coding and adjusted interaural frequency-place mapping. With such a high precision fine-structure coding strategy an improved BILD might be achieved provided that the effect is still present in a multi-channel stimulation strategy.

However, the ideal way of interaural frequency-place mapping is still a topic of discussion. Hu and Dietz (2015) pointed out recently that the optimal interaural electrode pairing method might not be pitch matching as done in this work. They compared three such methods namely pitch matching, ITD sensitivity, and/or binaural interaction potentials (BIC). Another study by Kan *et al.* (2013) supports this approach. They showed that lateralization in BiCI users was still possible with up to 3 mm of interaural mismatch determined by pitch matching. But they also pointed out that mismatched inputs might not be ideal since it leads to a distorted auditory spatial map. On the other hand, the auditory system is adaptive. Therefore, it is still a topic of discussion how to optimize the frequency-place mapping for bilateral CI stimulation in order to achieve an optimized binaural multi-electrode stimulation strategy.

ACKNOWLEDGEMENTS

This work was supported by MED-EL Elektromedizinische Geraete Gesellschaft m.b.H., Innsbruck, Austria.

REFERENCES

Goupell, M.J. and Litovsky, R.Y. (**2015**). “Sensitivity to interaural envelope correlation changes in bilateral cochlear-implant users,” J. Acoust. Soc. Am., **137**, 335-349.

Goverts, S.T. and Houtgast, T. (**2010**). “The binaural intelligibility level difference in hearing-impaired listeners: the role of supra-threshold deficits,” J. Acoust. Soc. Am., **127**, 3073-3084.

Hu, H. and Dietz, M. (**2015**). “Comparison of interaural electrode pairing methods: Pitch matching, ITD sensitivity and binaural interaction component,” Conference on Implantable Auditory Prostheses, Lake Tahoe, California.

Kan, A., Stoelb, C., Litovsky, R.Y., and Goupell, M.J. (**2013**). “Effect of mis-matched place-of-stimulation on binaural fusion and lateralization in bilateral cochlear-implant users,” J. Acoust. Soc. Am., **134**, 2923-2936.

Kerber, S. and Seeber, B.U. (**2012**). “Sound localization in noise by normal-hearing listeners and cochlear implant users,” Ear Hearing, **33**, 445-457.

Laback, B., Majdak, P., and Baumgartner, W.D. (**2007**). “Lateralization discrimination of interaural time delays in four-pulse sequences in electric and acoustic hearing,” J. Acoust. Soc. Am., **121**, 2182-2191.

Licklider, J. (**1948**). “The influence of interaural phase relations upon the masking speech by white noise,” J. Acoust. Soc. Am., **20**, 150-159.

Moore, B.C.J. (**2012**). *An Introduction to the Psychology of Hearing.* 6th Ed., Brill.

OLSA (**2011**). *Oldenburger Satztest. Bedienungsanleitung für den manuellen Test auf Audio-CD.* http://www.hoertech.de/web/dateien/HT.OLSA_Handbuch_Rev01.0_mitUmschlag.pdf

Seeber, B.U. and Fastl, H. (**2008**). “Localization cues with bilateral cochlear implants,” J. Acoust. Soc. Am., **123**, 1030-1042.

Colburn, H.S., Shinn-Cunningham, B., Kidd, G., Jr., and Durlach. N. (**2006**). “The perceptual consequences of binaural hearing,” Int. J. Audiol. Suppl., **45**, S34-44.

van Hoesel, R., Bohm, M., Pesch, J., Vandali, A., Battmer, R.D., and Lenarz, T. (**2008**). “Binaural speech unmasking and localization in noise with bilateral cochlear implants using envelope and fine-timing based strategies,” J. Acoust. Soc. Am., **123**, 2249-2263.