Innovative methods and technologies for spatial listening and speech intelligibility using hearing implants

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The proportion of the population with acquired hearing loss is increasing worldwide. Specific types of hearing loss require the treatment with hearing implants. Cochlear implants and bone conduction hearing implants are two examples. The present contribution is a prospect of the underlying project in its early stadium. The project addresses new methods and technologies that improve spatial hearing with such implants. The methods are adjusted specifically for both types of hearing implants. For cochlear implants bio-inspired signal processing methods are applied. For bone conduction implants new working principles for mechanical stimulation based on piezoelectric transducers are investigated. To evaluate the developments perceptional experiments are conducted, which investigate spatial hearing and speech intelligibility with normal-hearing and hearing-impaired persons. For this purpose a virtual listening environment is applied to synthesize different room acoustics, source positions, audio signals, and acoustic scenes with different complexity. Cochlear implants and a custom-made bone conduction device are used as playback systems. The bone conduction device generates the mechanical input and transmits mechanical oscillations via the temporal bone to the cochlea. Listening tests assess speech intelligibility with spatially distributed background noise and localization abilities.

INTRODUCTION AND MOTIVATION

Due to extensive research in the field of cochlear implants (CI) and bone conduction hearing implants (BCI), significant improvements have been achieved for hearing-impaired patients in the last decades. The range of indications for these implants is constantly extending because of diverse continuance of system developments. However, as hearing cannot be fully restored by such implants, hearing implant users are faced several challenges in everyday situations. For example, a reduced or missing capability to localize sound objects leads to reduced speech intelligibility in noisy situations.

We aim to contribute to the development of novel technologies for hearing implants and new methods for improved spatial hearing. The methods are evaluated, validated

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and in particular adjusted for the two types of hearing implants, CI and BCI. In case of CI research, we work on improvements of a biologically inspired speech processing strategy, which will be evaluated in tests with bilaterally implanted CI users. In the field of BCI, our aim is to investigate piezoelectric transducers for mechanical stimulation. For listening tests with normal-hearing persons a custom-made device for bilateral percutaneous bone conduction will be used. Furthermore, a virtual listening environment is created to synthesize different room acoustics, source positions, audio signals, and acoustic scenes with different complexity. Cochlear implants and the head-mounted bone conduction hearing device are used as playback systems.

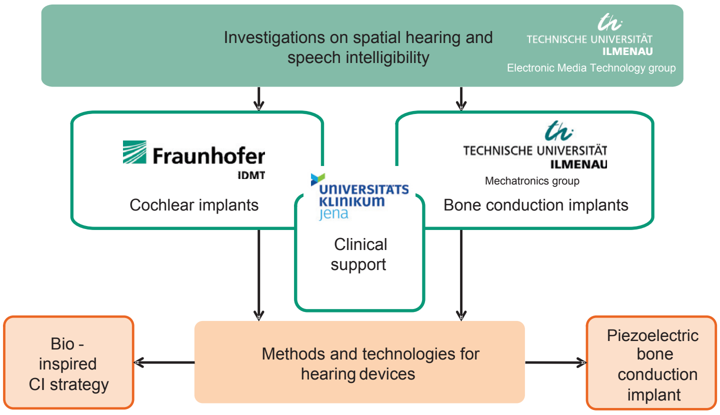

Fig. 1: Composition of the research group: The four upper boxes show the expertise of each institution. The three boxes at the bottom stand for the three main goals of the project.

A schematic overview of our research group and our aims is given in Fig. 1. In a first step, methods and technologies for both CI and BCI are developed. Secondly, investigations on spatial hearing and speech intelligibility are performed for both types of hearing implants under the supervision of clinicians. Finally, the analysis of listening tests data is the base for further improvements of the two hearing device technologies.

COCHLEAR IMPLANT STRATEGIES

One factor influencing performance of CI users is the signal processing algorithm (also called CI strategy), which translates acoustic signals into electrical stimuli. Common CI strategies usually rely on linear filter banks and therefore mimic the processes of normal hearing only to a limited extent. As a result, CI users usually reach good speech intelligibility in quiet, but have deficits in noisy environments and music perception. Moreover, various studies show that spatial hearing is very limited, due to inadequate transmission of temporal fine structure in current CI strategies (Ching *et al.*, 2017; Wilson *et al.*, 2003).

To improve CI user performance, we developed a novel bio-inspired CI strategy called Stimulation based on Auditory Modeling (SAM, Harczos *et al.*, 2013a). It is based on a model of the human peripheral auditory system. By closer mimicking the normal human cochlea, a more natural hearing impression should be achieved. A pilot study demonstrated the potential of SAM for improvements in hearing perception (Harczos *et al.*, 2013b). Furthermore, simulations showed possible advantages of SAM regarding sound source localization (Harczos *et al.*, 2011).

For further enhancements of the new bio-inspired strategy, SAM will be adapted for bilateral usage. The aim is to investigate main characteristics of the SAM strategy for spatial hearing and speech intelligibility to optimize signal processing in respect to computational effort and perceived quality. For this purpose, the processing stages of SAM (shown in Fig. 2) will be modified and preprocessing algorithms for improved spatial hearing will be included into the strategy.

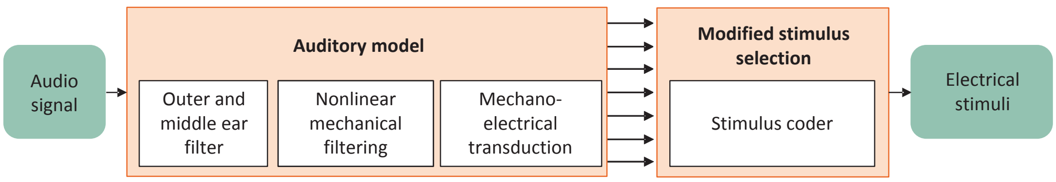

Fig. 2: Processing stages of the novel bio-inspired CI strategy SAM (Stimulation based on Auditory Modeling).

BONE CONDUCTION TECHNOLOGY

In today's bone conduction (BC) hearing devices, like BAHA® or BONEBRIDGE™, electromagnetic transducers are commonly used for exciting bone vibrations. Due to the bandpass characteristic of their electro-magneto-mechanical impedance between output force and input voltage current devices are limited to BC-excitation frequencies less than 7 kHz. This restricts the intelligibility of fricatives and spatial hearing. Moreover, the functional principle leads to an electromechanical resonance in the auditory frequency range, which requires electronic compensation. An idea to avoid such disadvantages is the use of piezoelectric transducers. The principle of operation is based on a clamping mechanism instead of using the principle of inertia. Electromechanical resonances in the auditory frequency range can thus be avoided. The proposed concept is illustrated in Fig. 3. The long-term objective is to investigate possibilities and limitations of the use of piezoelectric transducers as implantable actuators. These should be embedded in the mastoid completely under the skin.

We will study the transmission characteristic of piezoelectric transducers and compare it with data of their electromagnetic counterparts. Since there are no subjects with implanted piezoelectric actuators, listening tests are carried out with normal hearing listeners using a custom-made device for bilateral percutaneous bone conduction.

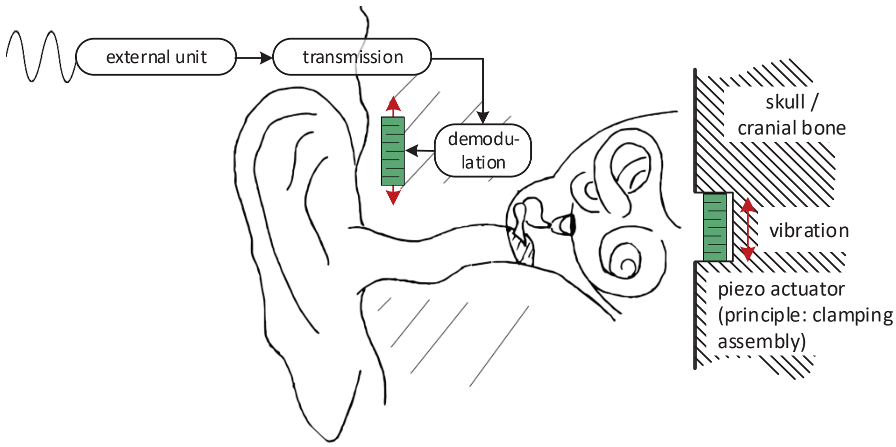

Fig. 3: Basic principle of implanted piezoelectric transducers for bone conduction.

We designed and built the device to produce comparable and reproducible listening test results. It has options to adjust the contact pressure and contact position of the piezoelectric transducer to the skin, see Fig. 4.

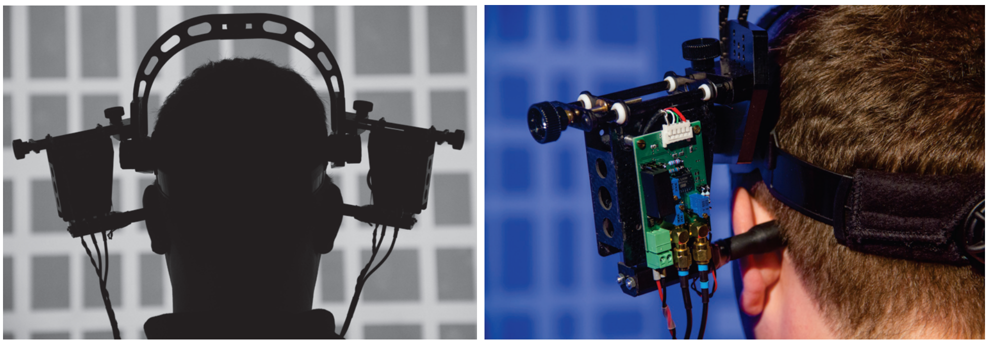

Fig. 4: Custom-made device for bilateral percutaneous bone conduction using piezoelectric transducers.

Only a few studies exist investigating spatial hearing via bone conduction. Regardless of the transducer principle, there are some restrictions on spatial listening. One reason for that is binaural cross-talk, which interferes with the interpretation of naturally occurring interaural level and time differences (ILD and ITD). Compared to air conduction, larger ILDs and ITDs are necessary for bone conduction to realize the same sound sources lateralization (Stenfelt and Zeitooni, 2013). This fact is probably the reason for the results of Barde *et al.*, 2016, who report elevated levels for the minimum discernible angular difference when using bone conduction and binaural synthesis. Another difficulty is the equalization of bone conduction devices, because the speed of sound depends on frequency and position. Beside of studies on localization, no other publications investigating other parameters of spatial hearing, such as distance or externality, could be found. Therefore, we aim to evaluate a wider range of spatial auditory parameters.

BINAURAL SYNTHESIS

Perceptional investigations and experiments for spatial hearing with CI and BC are realized using a binaural synthesis system. Binaural room impulse responses (BRIRs) have been recorded in real rooms using a head and torso simulator (KEMAR) (Klein *et al.*, 2017). BRIRs for several source-to-receiver positions for three different rooms are available. This allows to create numerous combinations of different room acoustics, source positions, audio signals, and acoustic scenes with different complexity for the planned listening tests. The technical and perceptional principles of binaural synthesis using airborne sound and playback via headphones are well understood (Lindau, 2014; Werner *et al.*, 2016). The challenges within the project lie in the measurement of system characteristics and development of adequate signal processing approaches for CI and BCI. The addressed characteristics for bone conduction are the estimation of transfer functions of the custom-made device for bilateral percutaneous bone conduction using equal loudness level contours. Furthermore, the binaural cross-talk is estimated in an indirect way using localization tests varying magnitudes of the used interaural cues of the binaural synthesis system.

LISTENING TESTS

Listening tests with bilateral cochlear implant users

In order to evaluate the novel CI strategy SAM, twenty adult patients with bilaterally implanted CIs, who have no apparent neurological or psychiatric disorders, will be invited to several listening tests. All tests described in the section below will be conducted as a comparison between SAM and a commercial strategy. Furthermore, the tests are performed iteratively in order to accompany the enhancements of SAM. Before each test, the CI users complete a habituation procedure to the coding strategy used subsequently.

Listening tests with the bone conduction device

To evaluate the novel bilateral piezoelectric bone conduction device (Fig. 4) a total number of 40 adult listeners (age between 18 and 25 years) with normal hearing and no apparent neurologic or psychiatric disorder will be tested. Participants wear the bone conduction device and in-ear hearing protectors whenever required, to minimize hearing of airborne sound. To calibrate the new device, curves of equal loudness will be measured for both airborne sound and bone conduction. The participants will perform the tests A to C, as described below, to investigate the properties of spatial hearing with the new device. To ensure equal loudness levels for all participants, the contact pressure of the piezoelectric actuators is adjusted accordingly.

Description of tests

In **Test A** the Oldenburg Sentence Test (OLSA, Wagener *et al.*, 1999) is conducted with spatially distributed sound sources. Speech recognition thresholds (SRT) are assessed in noise and in quiet. **Test B** describes a localization tests with varying spatial positions (see right side of Fig. 5) on the horizontal plane around the head of the subject. We measure the accuracy as the angular difference and as number of missed trials (no direction perceivable). Speech signals are used as test signals. **Test C** is a relative distance perception test at four directions. The two stimuli of each trial vary in distance to the listeners, who must tell in a 2-alternative-forced-choice task (2-AFC with response options for "first stimulus" or "second stimulus") which of the two stimuli is perceived as being closer. As additional experimental factors, the reverberation of the synthesized listening room is either dry or reverberant. The left side of Fig. 5 visualizes this test procedure. Speech signals are used as test stimuli.

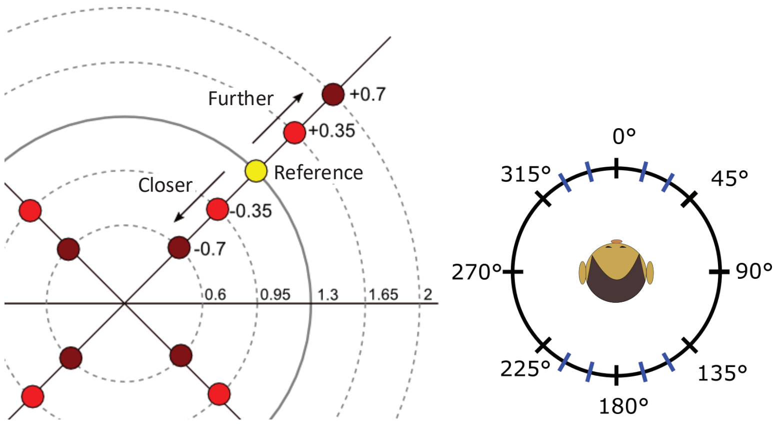

Fig. 5: Visualization of the direction and distances used for the spatial hearing listening tests.

Test D is designed to determine the just noticeable difference in the perception of pitch, direction, and distance. The 3-AFC 1-up-2-down method (Levitt, 1971) will be used. The listener has to determine which of the three stimuli is perceived as "different", or "odd". **Test E** aims to mimic a cocktail party situation. This competing talker test, measures the 50% SRT with OLSA sentences material. This time, however, the noise is replaced by two concurrent additional talkers. Possible combinations of positions are shown in Fig. 6. **Test F** is a test on prosody perception (Kuhnke *et al.*, 2015). The participants must discriminate in a 2-AFC procedure if a sentence is spoken with the intonation of a question or a declaration.

CONCLUSION

While the presented research plans promise great advantages for future users of the two types of hearing implants (CI and BCI), there are many open issues. Listening test evaluating new methods and technologies for hearing implants are difficult: For an

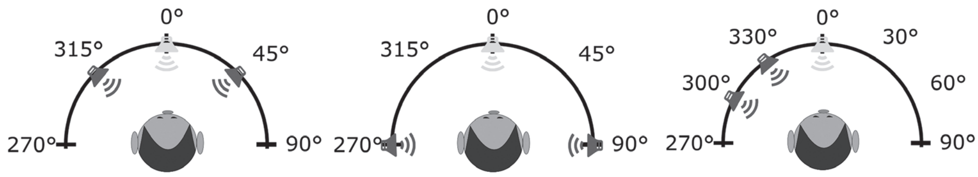

Fig. 6: Different sound source combinations for the cocktail party test. The target speech is marked light grey and the concurrent speakers dark grey.

objective comparison of different CI strategies adaptation processes have to be taken into account. The habituation of a CI patient to an new strategy is usually a long-term process and can not be covered within the short test periods. In case of BCI, the new technology can currently only be evaluated with normal hearing listeners. Thus the comparability with currently used bone conduction implants is limited. For implantation of the new technology there are still many challenges to overcome.

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