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Advancing Binaural Cochlear Implant Technology

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Abstract

This special issue contains a collection of 13 papers highlighting the collaborative research and engineering project entitled Advancing Binaural Cochlear Implant Technology—ABCIT—as well as research spin-offs from the project. In this introductory editorial, a brief history of the project is provided, alongside an overview of the studies.

Keywords

cochlear implant, bilateral, binaural

Compared with normal-hearing individuals, users of cochlear implants (CIs) are at a distinct disadvantage when facing everyday listening situations. Even in the presence of only moderate levels of background noise, many implant users struggle to follow a conversation or locate the source of a sound with any accuracy (should they even detect it). A major factor in normal-hearing listeners performing these tasks well is their use of binaural, or two-eared, hearing. Compared with listening through one ear alone, binaural hearing not only underpins the localization of sound sources, but it also offers considerable advantages in cocktail-party listening, rendering signals more detectable (and intelligible) by many decibels. The clear benefits of binaural hearing have spurred the advent of bilateral cochlear implantation; the potential for implant users to achieve at least some of the benefits of binaural hearing has become a de facto argument for the increased cost of fitting and maintaining implants in both ears. Nevertheless, even when a patient receives two implants, they remain independent devices, incapable of exploiting many of the important differences in sounds at the two ears that render cocktail-party listening possible. Currently, only one CI manufacturer produces devices that have the capability of delivering synchronized pulse timing to the two ears, using one processor serving both cochleae. Even so, the great potential of such technology has not yet been fully realized, so that it can be argued that no current clinical device provides truly binaural hearing, as opposed to two monaural devices (bilateral hearing). Thus, the promise of exploiting specific binaural processing strategies that make use of the brain's remarkable ability to compare small timing differences in sounds at the two ears to hear out speech in noisy conditions remains unfulfilled.

To this end, in 2012 a consortium of researchers and commercial partners in the United Kingdom, France, and Germany secured funding from the European Union's "Seventh Framework Programme for Research and Technological Development" to develop a research program aimed at moving bilateral cochlear implantation toward true binaural performance. The aim of this program, Advancing Binaural Cochlear Implant Technology (ABCIT), was to develop a framework in which binaural hearing was central to the function of CI technology, thereby enhancing the lives of the profoundly deaf through the development of a binaural CI that exploits the spatial information available in the sound input to improve the listening experience of CI patients. At the time the project was funded, the original commercial partner within the consortium (Neurelec, now Oticon Medical) offered a unique therapeutic intervention—the closest of all available CI designs to being capable of true binaural processing. Initially aimed at being cost effective, Oticon Medical's CI device processes the left and right microphone signals on a single processor, allowing the interaural cues essential for spatial hearing to be extracted and manipulated through the

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delivery of interaurally synchronized electrical pulses to both cochleae. The design of this implant, with its galvanic connection across both sides of the brain, is going to offer the unique opportunity to record neurally evoked responses from the auditory brainstem (EABRs) with the CI device itself, without the requirement of additional electrodes attached to the skin. In contrast to electrically evoked compound action potentials (ECAPs), EABRs are informative as to the activity of the binaural nuclei and can therefore be employed to ensure objective measures are used in establishing and enhancing binaural fitting procedures.

Working closely in a formal, but dynamic, relationship, the four ABCIT partners, Neurelec/Oticon Medical, the Ear Institute at University College London, UK, the Germany-based audio technology company HörTech, and the Medical Physics group from the University of Oldenburg, Germany undertook a series of Work Packages, each designed to advance bilateral implantation toward true binaural benefits. Over the 36 months of the project, which ended in August 2015, scientists and engineers across the partner institutions developed new *tools* for CI engineers and researchers, explored novel pre-processing and stimulation strategies designed to enhance the transmission of information at the device-brain interface, developed new objective measures of binaural function to enhance fitting procedures and explore brain responses to bilateral implantation, undertook a range of psychoacoustic studies in spatial listening in normal, hearing-impaired and CI listeners, and developed a collection of hardware demonstrations that, together, provide the means of building a truly binaural CI device. The success of the ABCIT project lies not only in the generation of published and publishable articles and presentations but also in its development of new technologies (five patents were jointly filed across the partners) as well as the host of research collaborations it has spawned.

This special issue contains a collection of 13 studies from the ABCIT project and research spin-offs from the project. The issue is structured in a similar manner to the organization of the Work Packages in the project itself, following the processing chain of a sound wave through the CI and, from there, through neural or perceptual elements of the auditory pathway.

The first article (Backus, Adiloglu, & Herzke, 2015) outlines the development of a binaural research-platform environment that enables online processing of both acoustic signals and electric pulse trains. Its back end provides highly synchronized output to left and right CI. Next come four studies reporting and assessing potential algorithms to enhance spatial listening, with a special focus on binaural pre-processing of the acoustic signals reaching the processor microphones (Adiloglu et al., 2015; Baumgärtel, Hu, et al., 2015; Baumgärtel, Krawczyk-Becker, et al., 2015; Völker, Warzybok, & Ernst, 2015). The last three represent a series of studies testing both new and existing algorithms in normal-hearing listeners, as well as users of hearing aids (Völker et al., 2015), bilateral CI listeners (Baumgärtel, Krawczyk-Becker, et al., 2015), and in silico modeling (Baumgärtel, Hu, et al., 2015). All three studies were performed with the same algorithms, identical signal-processing chains, the same virtual environment, and the same signals. A summary of these three studies is illustrated in Figure 1, which reveals similarities but also large systematic deviations, across the different groups of listener. The fourth study in this group (Adiloglu et al., 2015) presents a new binaural algorithm for moving talkers (or a moving listener) by combining a robust direction-of-arrival estimator with a binaural beamformer.

The next stage along the chain is the transformation of the acoustic signal to electrical pulses. Within this category, the study by Hu Lutman et al. (2015) assesses the sparse conversion of acoustic signals to electrical pulse patterns, while Ballestero et al. (2015) report the influence of a novel stimulation strategy (a modified pulse shape) on the activation of auditory neurons and the influence this strategy might have on the spread of electrical current within the implanted cochlea.

Closely related to optimizing the transformation to electric pulses is CI fitting, that is, finding patient-specific parameters such as stimulation currents. In the case of bilaterally implanted patients, the ideal fitting involves optimizing the individual interactions of the two devices. Hu and Dietz (2015) present a study on binaural fitting methods, suggesting how corresponding left–right electrode pairs might be matched for optimal binaural performance. Interaural pitch matching, left–right discriminability, and more objective auditory brainstem responses were measured in the same bilateral CI subjects. In a related study, Haywood, Undurraga, Marquardt, and McAlpine (2015) compare two binaurally evoked response measures and their potential for use in CI fitting in a study with normal-hearing subjects.

Monaghan, Bleeck, and McAlpine (2015) investigated the upper frequency limits for envelope interaural time differences in normal-hearing listeners. This topic is highly relevant for CI listeners, as these are typically the only interaural time difference cues available with their clinical processors. Differences between the two subject groups have previously been found to be minor for these envelope cues.

One study that encompasses multiple stages of CI processing—from sound propagation, through signal processing, to the electrode-nerve interface and binaural integration—is the modeling study by Kelvasa and Dietz (2015), predicting the sound localization performance of bilateral CI subjects and investigating the origin

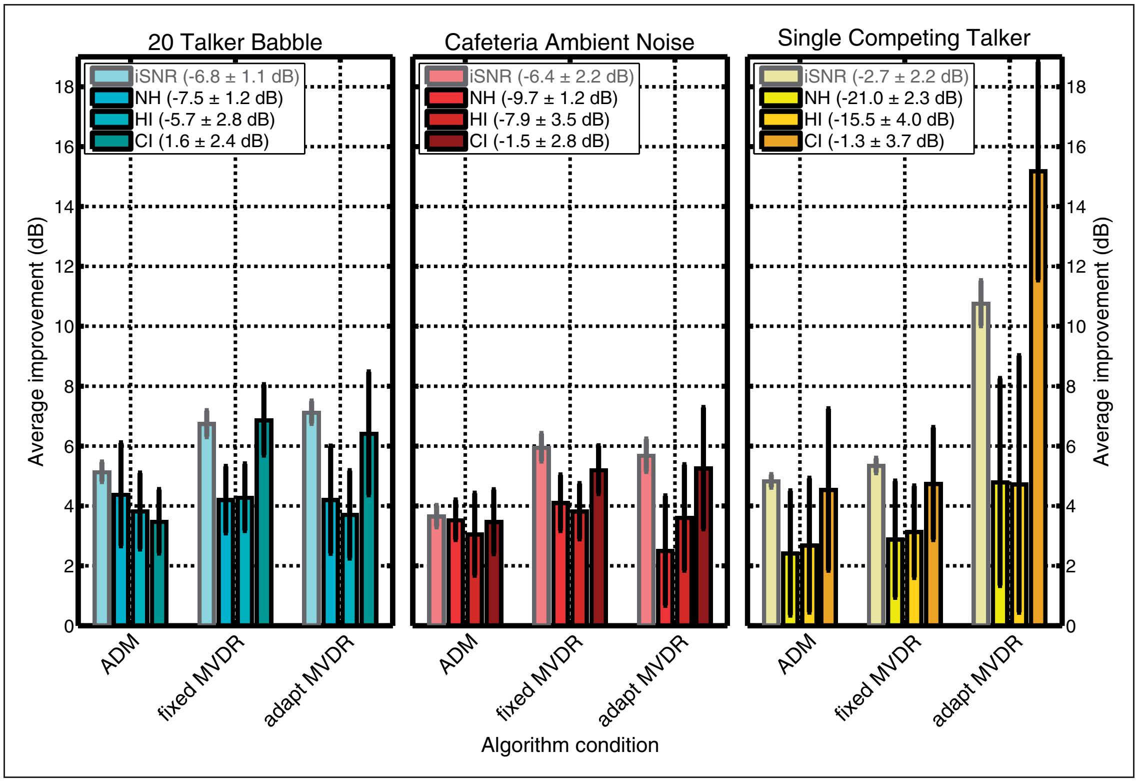

Figure 1. Comparison of speech reception threshold (SRT) improvements. This overview figure contains sample data from three articles published in this issue. iSNR improvement (Baumgärtel, Hu, et al., 2015), SRT improvements of normal-hearing listeners and hearing-aid users (Völker et al., 2015), and SRT improvements of CI listeners (Baumgärtel, Krawczyk-Becker, et al., 2015). Data are shown for three of the eight algorithms tested: ADMs without a binaural link are currently available in most hearing aids and CI devices, and serve as a reference. Two minimum-variance, distortionless binaural beamformers (fixed MVDR and adaptive MVDR) provide a larger SRT increase, particularly for the CI subjects. Tests were performed in three different noise environments (see title of each respective panel). For details please refer to the respective studies. iSNR = Intelligibility weighted signal-to-noise ratio; NH = normal hearing; HI = hearing impaired; CI = cochlear implants; ADM = adaptive differential microphone; MVDR = minimum variance distortionless response.

of its limitations. A similar multistage perspective appears in a study of binaural speech intelligibility by Williges, Dietz, Hohmann, and Jürgens (2015). This study includes psychoacoustic assessments of speech intelligibility in normal-hearing listeners under a range of different simulated listening conditions, from CIs or hearing aids in the left ear, the right ear, or both, and the contribution of head shadow, binaural summation, and binaural squelch to binaural benefit. Finally, the study by Bizley, Elliott, Wood, and Vickers (2015) completes this issue, introducing a new test procedure for simultaneous measurement of speech intelligibility and localization performance specific to bilateral CI users.

These studies cover the range of topics explored during the ABCIT project, but they are by no means exhaustive. Earlier published work from the project assessed factors such as stimulus artifact reduction in objective measures of brain activity in CI (Hu, Ewert, Campbell, Kollmeier, & Dietz, 2014; Hu Kollmeier Dietz et al., 2015), as well as the lateralization of stimuli with different envelope shapes (Dietz, Klein-Hennig, & Hohmann, 2015). Studies from the final period of the project that were not ready for transmission by the timeline imposed by this issue were presented at the Conference on Implantable Auditory Prostheses, Lake Tahoe, CA, July 2015, and include auditory steady-state response measures with binaural CI stimulation, a binaural algorithm specific for the needs and constraints of bilaterally implanted CI subjects, and a psychoacoustic study on the different temporal weighting of interaural time differences between CI listeners and normal-hearing listeners.

Altogether, the ABCIT project spawned a wide range of research projects and interactions, the outcomes of which will likely find their way into new research platforms, diagnostic tools, and therapeutic interventions. The project as a whole also offers a new way of working across university, commercial, and third-sector boundaries to advance scientific discovery in pursuit of clinical benefit.

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