Hearing4all
The Future of Hearing

www.hearing4all.de
Affecting more than 15 million people in Germany alone, hearing impairment is a common condition around the world. Most cases are due to either noise-induced hearing loss or hearing loss in old age. As German society ages, the number of people affected is increasing. Being able to hear well and understand what’s going on in the world is very important. Hearing, our most active sensory system, is crucial for communication, orientation, and safety. However, hearing is often regarded as a second-class sense. Only when our hearing deteriorates do we notice the supporting role it plays in everyday communication. People with untreated hearing loss often feel isolated and are more likely to suffer from depression and insomnia. In addition to unquantifiable losses in the quality of life, economic losses can result, for example, by being forced to go on disability support or to retire early.

Hearing impairment: an oft underestimated challenge

Hearing impairment can affect any or all aspects of our hearing, including sound processing in the brain. Each case is unique. Depending on the type and extent of hearing loss, there are various ways to compensate for it. For moderate hearing loss, hearing aids are usually used. In severe cases, including total deafness, solutions such as cochlear implants are another possible option. For people who no longer have a functioning auditory nerve (as may happen after tumors are removed), brain-stem implants and even midbrain implants may work. Finding the optimal solution requires scientifically well-founded diagnostics.

Although work on technologies to assist or solve hearing loss has been going on for almost a century, many problems have yet to be resolved. In particular, hearing in the presence of background noise, and identifying the direction of sounds remain major challenges. Through technological advances and because of changes in user requirements for communication, the demand for individualized hearing solutions has risen sharply. However, the real benefits of the new technologies for many (potential) users remain limited, because they have not been specifically adapted to individual needs nor to particular acoustically challenging environments.

The Hearing4all Cluster of Excellence has set itself the goal of improving hearing for people with all types and degrees of hearing loss. The first part of this task is to develop a better understanding of hearing and hearing disorders. It’s not enough to limit ourselves to the ear itself. The ear is only the first station of a very complex auditory pathway that enters via the auditory nerve into various auditory centers in the brain up to the cortex, i.e., the area responsible for conscious perception. To ensure optimal care for all, researchers at the Cluster of Excellence are working on solutions to the following three fundamental problems:

1. Conventional diagnostic methods often cannot determine the exact cause and pathophysiology of a patient’s hearing loss. To gain a better understanding of an individual’s hearing, the Cluster of Excellence is developing theoretically sound diagnostics based on a unified, functional auditory model. Based on human and animal experiments and both invasive and non-invasive methods, new diagnostic methods are being established to improve the individual treatment of those affected.

2. One major deficit in today’s hearing aids is the intelligent suppression of background noise in almost any acoustic scenario. To create truly customized hearing systems for the future, the Cluster of Excellence is working on developing innovative signal processing algorithms and stimulation methods (acoustic, mechanical, neuronal, and optical) that actually reduce the information lost because of the hearing impairment. Models that predict the hearing performance of patients with different hearing aids will further aid in the selection of treatment options. New fitting concepts and the ability of the user to further adapt the functionality of the hearing system increase the individual benefits of the chosen solution.

3. In order to make “Hearing 4 all” a reality, that part of the population that has age-related progressive hearing loss but has not yet been diagnosed (the “subclinical” population) must also be considered. By incorporating technology originally developed in the field of technical hearing aids into conventional consumer electronics (mobile phones, video conferencing systems, televisions), the Cluster of Excellence is developing solutions that will help to identify cases of hearing loss at an early stage. This will provide many of treatment to the subclinical portion of the population before peripheral hearing disorders result in damage to the central hearing processing system.

Hearing 4 the future: progress is being made

The goal of the interdisciplinary Hearing4all Cluster of Excellence is evident in its name: making it possible for everyone to hear and for each individual to better communicate. Over the last five years, by improving individual hearing diagnostics and personalizing the prescription of hearing aids, our researchers have achieved great success. Since 2006, the universities and research institutions that have joined the Audiology Initiative of Lower Saxony (AIN) and the Auditory Valley have continued to grow together through intense collaboration in the Cluster of Excellence. Important structures have been established, including permanent new professorships and the setting up of a joint research academy to encourage young talent in this field. Thanks to Cluster funding, each site has extensive new equipment and laboratories (such as a 3-D virtual reality lab) that are proving to be crucial for the research being conducted.

The translational idea is inherent in the Cluster of Excellence: research questions have their origins in unsolved clinical and practical problems. Close and productive cooperation with industry has also grown over the past five years. This close cooperation is manifest in the annual, international Hearing4all symposium, which brings representatives from industry together with top scientists from all over the world.

In this brochure, we present twelve of the more than 100 individual current projects that have decisively advanced hearing research and thus our ability to communicate with one another.

Thinking ahead: Hearing4all 2.0

Our successful in research is enabled by thinking through successful concepts, using established structures, and developing ideas for the future. In the current Cluster of Excellence, we have developed important building blocks for better diagnostics, for hearing systems, and also assistive technologies. We now want to build on these to create tailor-made solutions for all forms of hearing loss. We are thus moving from an empirical, subjective approach to modern, data-driven scientific research and high-standard precision medicine. This will bring us one more step closer to the goal of Hearing4all.
Understand hearing
Models for the hearing systems of the future

Scientific models are an indispensable tool for gaining new insights. Their primary function is to explain and predict phenomena. The medium to long-term goal of the Hearing4All Cluster of Excellence is to integrate newly-formed models into intelligent, situational, and customizable hearing solutions based on the “model-in-the-loop” principle. For each listening situation, the hearing aid will aim to predict what the user will need next. For such hearing systems of the near future, the hearing models and hearing diagnostic systems being developed and validated in the Excellence Cluster are an absolutely indispensable prerequisite.

Dr. Go Ashida’s model, for example, examines the cellular properties and mechanisms that are responsible for ensuring that our brain has sufficient spatial resolution to distinguish the direction from which sounds emanate. Describing neuronal representations of acoustic signals is essential for encoding and customizing implantable hearing systems such as the cochlear implant. The task force run by Junior Professor Dr. Waldo Nogueira is developing optimal stimulation patterns for cochlear implants. Direct electrical stimulation of the auditory nerve is intended to produce the most realistic possible impression in what is heard by CI users.

By contrast, effective models of auditory signal processing describe how the sense of hearing works. A biological representation of background noise is suppressed, and how the target sound can be deliberately reinforced, thus achieving better speech intelligibility. This effective model is particularly well-suited for later integration into an intelligent hearing aid or hearing implant as a solution to the “cocktail party effect” that continues to plague many users of hearing aids.

The “Framework for Auditory Discrimination Experiments” (FADE) model was developed by Professor Marc René Schädler and combines elements from psychoacoustics, speech perception research, and automatic speech recognition with machine learning. This model will describe a whole range of hearing functions with astonishingly high accuracy on the basis of only a very few, generally accepted listening principles. The inner-ear hearing loss of each patient can thus be divided into several components, each of which has a specific influence on the hearing and requires different rehabilitation strategies. With the FADE model, the Excellence Cluster is in the verge of providing a universal and accurate predictive system for clinical hearing diagnostics.

How exact can diagnoses of individual aspects of hearing loss be? To answer this question, the Excellence Cluster is evaluating not only new clinical diagnostic procedures such as the Oldenburg sentence test (DLSA) against background noise, but also binaural (bilateral) loudness scaling combined with a series of other clinical auditory measurement methods and assessing their potential value as diagnostic models.

For example, doctoral students Meike Thaden and Anja Gieseler are identifying the key aspects of hearing loss that are most variable among a large clinical sample of patients. These will be recorded as efficiently as possible, being the most important aspects of a future, more goal-oriented, hearing diagnostic procedure.

Using a similar approach, the working group of Professor Andreas Bülchmer has, in a project of Dr. Sabine Haumann, even been able to predict the success of cochlear implant surgery and subsequent rehabilitation in adults using less, but audiological tests. It is both easy to understand and useful for making diagnoses and giving recommendations for treatment. This computer-assisted method is designed to help doctors in diagnosis and treatment. In another application, the path can also be reversed and can show which audiological tests are best suited for differentiating between certain diagnoses.

In order to create an “audiological precision medicine” with exact, individualized diagnostics and to combine incomplete audiological data from different clinics in a “big data” concept over the long term, doctoral student Mareike Buhl (of the Kollmeier and Lücke working group) is pursuing the new concept of common audiological functional parameters (CAPPAS). This uses a few meaningful, intermediate variables to create a universal, compact representation of audiological findings from a variety of data sets. It is intended to serve as the basis for targeted hearing diagnostics, for making recommendations, and for predicting the success of specific treatment methods (such as the prescription of a hearing aid). Figure 1 shows how the model forms a compact representation of hearing loss based on data from available audiological tests. It is both easy to understand and useful for making diagnoses and giving recommendations for treatment. This computer-assisted method is designed to help doctors in diagnosis and treatment. In another application, the path can also be reversed and can show which audiological tests are best suited for differentiating between certain diagnoses.

Key Publications

Of Gerbil and Men

PET imaging as a diagnostic tool

Dositron emission tomography (PET) is a modern medical imaging process allowing visualization of human brain activity that was triggered by stimuli. With minimal amounts of radioactive biomarkers, it is possible to use messenger substances to visualize the activity in nerve tissues or to see signals as they are transmitted across the brain. The biomarkers used in PET include a positron emitter that can be detected by emission tomography as it spreads across the brain. In clinical hearing research, a radioactively labeled sugar molecule (18F-fluorodeoxyglucose) and water labeled with short-lived oxygen (15O) are often used. The PET method is mainly used with patients with hearing implants, since they cannot be examined with functional radio-magnetic resonance imaging (fMRI), due to the special risks posed by the magnetic fields used in that technology.

With the development of new detector materials and measurement electronics, the sensitivity of PET has been increased ten-fold over the last twenty years. Another technical breakthrough has come thanks to the miniaturization of the detectors and their spatial resolution capabilities. With a resolution in the millimeter range, these devices can now specifically measure activity in individual regions of the brain’s hearing system, not just in humans, but even in the experimental animals used in hearing research, such as gerbils. Molecular structures and messenger substances for the transmission of signals between nerve cells can also be quantitatively and regionally measured with PET. For hearing research, changes in inhibitory-ac
ting signal transmission systems such as the GABAergic system; GABA = gamma-aminobutyric acid) in old age or as a result of plastic changes after the placement of a hearing implant, are of particular importance.

The working group led by Prof. Georg Berding (Hannover Medical School) aims to improve understanding of the pathophysiology of hearing disorders and the restoration of hearing by implants. For this purpose, PET is used to take objective measurements of activation in regions of the hearing system and functionally connected brain areas before and after implant placement. A study of patients with different types of hearing implants (cochlear, brainstem, and midbrain implants) showed a correlation between speech comprehension and activation in the upper temporal lobe (Fig. 1, Berding et al. 2015).

PET measurements of the activation of the hearing system and of the extent of GABAergic signal processing are also possible in small rodents such as rats and gerbils. These animals have sensitive hearing systems in a frequency range similar to that of humans and are therefore good animal models for translational hearing research. Together with the working group of Prof. Georg Klump (University of Oldenburg), PET and behavioral experiments are being used to study the changes in hearing processing during age-related hearing loss. The PET measurements in preclinical molecular imaging at Hannover Medical School show clear activation patterns in the midbrain (inferior colliculus), and this can be used to represent hearing processing in the central nervous system (Fig. 2). As in humans, animal hearing perception can be investigated with psychoacoustic experiments (e.g. Tolnai et al. 2017) and, in combination with the PET measurements, can be used to establish the relationship between age-related perceptual performance and the underlying activation patterns in the brain.

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Key Publications

The cochlear implant (CI) is an implantable inner ear prosthesis that enables people with hearing impairments to hear sounds and understand speech. A voice processor carried behind the ear picks up, digitizes, processes, and wirelessly transmits signals to the implant. The CI then takes over the function of the inner ear by directly stimulating the auditory nerve electrically.

Many people who require a cochlear implant suffer from high-grade hearing loss in the upper frequency range, but still have sufficient residual hearing at low frequencies. For these patients, a relatively new implant-delivery strategy is the combination of electrical stimulation via the cochlear implant and acoustic stimulation of residual hearing via a hearing aid (electro-acoustic stimulation, EAS). It can be expected that this patient group will benefit from the simultaneous stimulation by acoustic and electrical means.

The aim of this project is to develop a better understanding of this phenomenon, in order to develop stimulation algorithms for future use that will allow electrical and acoustic stimulation to be combined with significantly better results. To achieve this, the nature of the masking effects needs to be precisely defined, for which measurement methods are being developed and studied at Hannover Medical School.

Psychoacoustic experiments investigate the subjects’ perception of simultaneous stimulation by acoustic and electrical stimuli. Is there, on the other hand, an increase in the acoustic thresholds when electrical stimuli are simultaneously presented (electrical masking)? On the other hand, the effect of acoustic stimuli on electrical stimulation is also being examined (acoustic masking).

The position of the individual electrode contacts in the cochlea can also be detected using digital volume tomography. The Greenwood equation can be used to determine the perceived pitch for each electrode contact. With electric masking, acoustic tones of known frequency are presented one-by-one. For each frequency, sound perceptions are generated by electrical means via individual electrode contacts and the stimulus strength required (hearing threshold) to match the acoustically generated sound is measured.

One would expect that the closer the electrically generated frequency sensation was to the frequency of the acoustic sound, the higher would be the threshold for the perception of the acoustic stimulus. The left panel of figure 2 shows that this is indeed the case and that the audible threshold for the acoustically generated signal decreases to practically zero over 1- to 2-octave differences to the electrically generated masking signal.

The counterpart, using electrical stimulation and acoustic masking is interesting. The right panel of figure 2 shows that the masking effect of the acoustic signal remains nearly constant over the entire frequency spectrum of approximately 6 octaves. However, the threshold is raised less than during acoustic stimulation with electrical masking.

Key Publications

B. Krüger, A. Büchner, W. Nogueira (2017), Simultaneous Masking between Electric and Acoustic Stimulation in Cochlear Implant Users with Low Frequency Hearing, Hearing Research, https://doi.org/10.1016/j.heares.2017.06.014

M. Imrie, B. Krüger, A. Büchner, T. Lenarz, W. Nogueira, Electric-acoustic forward masking in Cochlear Implant users with ipsilateral residual hearing, Hearing Research, (Submitted October 2017)

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Fig. 1: A) Sketch of an EAS implant. B) Typical audiogram of a patient eligible for this strategy. High-grade hearing loss in the upper frequency range and residual hearing in the low frequency range.

Fig. 2: Perceptual thresholds for electrical- and acoustic masking. The results show that there is an asymmetry between electrical and acoustic masking. This could be an indication of the origin of the fundamental psychoacoustic phenomenon of masking, both for CI users and for the normal hearing system.
Hearing aids nowadays are high-performance computers in the smallest of spaces. To compensate for the hearing loss, their integrated signal processing algorithms reduce background noise, recognize the acoustic situation the wearer is currently experiencing, and enhance what the conversational partner is saying. For individual setting of the amplification values in a hearing aid, calculation rules based on the patient’s hearing threshold are used as a starting point. The hearing threshold corresponds to the level at which sounds are just perceptible. The purpose of the fitting concepts is to compensate for hearing loss and improve speech intelligibility and thus improve communication in hearing-aid wearers. Despite continuous development of fitting concepts, however, the perception of loud signals with hearing aids is still rated as worse than the situation without a hearing aid: about 20% of users are dissatisfied with their level of comfort when listening to loud signals (“That’s too loud for me!”).

A research project in the Hearing4all Cluster of Excellence has shown that one major reason for this is that based on established, but, as it turns out, not quite correct models for volume perception, the amplification values were set too high for many hearing aid wearers. It has been demonstrated that sinusoidal tones, which have become established as standard signals for measuring the threshold of hearing, are not suitable for predicting loudness perception for broadband signals such as speech. Especially when listening with both ears, patients with very similar hearing thresholds will show significant differences in their perception of volume.

Fig. 1 shows unaided volume measurements both for people with normal hearing and those with hearing impairments. For lower-level signals, it can be seen that the signals are perceived as quieter by those with hearing impairments than those without. For high-level signals, the picture is not uniform. For some people with hearing impairments, the signals are perceived as quieter, whereas for other hearing impaired, the signal was rated as louder and thus „too loud“. This increased perception of volume is due to an increased binaural loudness summation for wideband signals that only becomes visible if one measures both ears simultaneously. In this case, it must be individually determined whether the hearing aid should amplify the signals or even weaken them, so that a normal sense of volume is restored. Based on binaural broadband loudness measurements that better map these natural signals, a new loudness-based fitting concept called „trueLOUDNESS“ has been developed that takes these individual differences into account and applies the values that are appropriate for that individual. Patients whose simulated hearing aids have been adjusted with trueLOUDNESS will regain a natural sense of loudness. The amplification values determined by trueLOUDNESS are very different from established fitting concepts. For some subjects, negative amplification was necessary to achieve a natural sense of loudness. Other subjects needed amplification values well above the established fitting concepts, to obtain the same result.

Currently, this information on binaural broadband loudness, which is important for fitting hearing aids, is not being measured by audiology practices nor can it be deduced from existing diagnostic measurements such as the audiogram. This is why the trueLOUDNESS fitting concept is being developed as part of research projects that aim to further develop the special fitting procedure so that it is available as a medical device for audiologists. This creates the opportunity for every hearing-impaired person to have the chance to be provided with the latest research-based fitting methods. The goal with trueLOUDNESS is to set an amplification value than was previously possible with hearing threshold-based fitting concepts. The developed fitting method not only improves hearing aid fitting in the approx. 22% hearing aid users who are sensitive to noise, but also offers conventional adaptations for hearing aid wearers with insensitive hearing (about 17%).

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Fig.1: Shown are loudness evaluations of natural signals by a group of normal hearing (N=11, green) and a group of hearing impaired subjects (N = 18). The unaided (u) measurements of the hearing impaired are shown in blue and the aided (v) measurements with a loudness-based fitting according to the trueLOUDNESS concept are shown in red.

When listening with both ears, the loudness differences are greater than expected.
It gets under your skin
Epidural leads for fine-tuning cochlear implants

At present, people with cochlear implants (CI) have few options for adapting their CI to the current hearing situation. Depending on the manufacturer, they may able to use adjust various settings, such as volume and microphone sensitivity, or select specific pre-processing algorithms, e.g., for music or speech, with or without a remote control. However, this is very impractical for short-term adjustments, for example, for group conversations where the CI user wants to listen first to one person, then another. Normal hearing can select and amplify the desired speaker and blend out any other speakers to whom they do not wish to pay attention.

Some automatic adjustments are already available in cochlear implants, such as directional microphones that amplify the speaker in whose direction users turn their heads. In everyday practice, however, these systems also have their weaknesses. For example, users might not turn immediately to the next speaker or they might want to listen to a soft-spoken person while the implant’s automatic recognition algorithm has chosen to focus on someone else based on their volume.

Researchers from the Hearin4all, Cluster of Excellence have now set themselves the goal of developing a technology with which implants or hearing aids can be quickly adjusted to the respective situation by users’ power of thought. For this purpose, an auditory control circuit will be realized via a brain-computer interface (BCI). By measuring the electrical activity of the brain, the interface will determine to which interlocutor users wish to listen and automatically adjust the CI or hearing aid accordingly. The working group around Prof. Debener in the Cluster of Excellence uses an inconspicuous, C-shaped multisensor array placed behind users’ ears to control hearing aids.

Even more convenient and practical would be electrodes that are placed under the skin or even under the bone (epidural), avoiding the need to wear anything behind the ear. Much better signal quality can also be expected from this placement than with a device mounted exterior to the body. An internal variant is particularly suitable for CI users, since an operation is already required to make the implant. The measuring electrodes can thus be directly implanted during the same procedure. They could even be integrated directly into the CI. A first step, however, requires testing to see whether the approach works as well as hoped.

The project is the world’s first feasibility study in which three individual electrodes are placed on the cerebral membrane along with the CI. The exact positions of the three electrodes are determined on the day before the operation with an MRI, the results of which are used to navigate the surgeon’s hands during placement. The three cables are then passed through the skin.

In the days after the operation, measurements are carried out in which the CI is stimulated with acoustic stimuli and the corresponding electrical brain activity is measured via the epidural measuring electrodes. For comparison, the same measurements are taken with the standard clinical setup, i.e., using electrodes attached to the skin on the forehead and behind the ears. After several days, the measuring electrodes can be removed without renewed anesthesia, since they are completely smooth. For the patient, this feels much like pulling a drainage tube after an appendectomy.

So far, the study has been performed on nine patients. Compared to the standard clinical setup, the epidural electrodes showed a significantly better signal quality, with less interference in all nine patients. The expected responses were clearer in all patients and could be detected at even lower stimulation intensities.

In the next step, the optimal positions for the electrodes to be implanted will be determined using different acoustic stimuli. In the future, measuring electrodes could be connected directly to the CI, with the aim of obtaining a fully integrated, closed auditory control loop.

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Key Publications

Binaural noise and reverberation suppression for hearing aids

In many applications for spoken communication, such as hearing aids, voice-controlled systems, and hands-free telephony, the microphones are typically located a long distance from the speaker. As a result, the recorded microphone signals contain not only the desired speech but also ambient sounds and reverberation. Noise and reverberation result in reduced speech quality and intelligibility, both for people with and without hearing impairments. Even with automatic voice recognition, background noise and “reverb” can affect the performance.

Prof. Dr. Simon Doclo and his team in the Cluster of Excellence have developed various speech enhancement algorithms to address these issues. There have been major leaps in recent years, especially in the area of binaural noise and reverberation suppression for hearing aids.

Wearing hearing aids in both ears provides an important advantage in signal processing, since microphone signals from both hearing aids can be used for spatial perception, allowing the auditory system to exploit binaural information. Although many existing algorithms for binaural speech enhancement are okay at suppressing noise and reverberation, they often do not receive the binaural features of all sound sources in an acoustic scene,” explains Doclo. This is clearly undesirable, since the auditory impression of the acoustic scene is then distorted, which in some situations (such as in traffic) can even be dangerous. Recently, researchers have succeeded in developing algorithms for binaural noise cancelation that preserve the binaural features of both the target speaker and other environmental sounds. The parameters of these algorithms have been optimized on the basis of psychoacoustic criteria, and perceptual experiments showed that the algorithms developed improve both speech intelligibility and the spatial hearing impression. Current research aims to integrate computer-aided acoustic scene analysis into these algorithms, further improving performance for complex and highly time-variant acoustic scenes. Professor Doclo and his team are researching the integration of external microphones on a desk, for example, in addition to the microphones of the hearing aid. Initial results in terms of noise reduction and the preservation of binaural features are promising.

In addition to background noise, reverberation is another important factor that influences the quality of voice communication from a distance. It is caused by acoustic reflections, e.g., off the walls of a room. The goal of reverberation suppression algorithms is to estimate the speech signal “blindly” from the reverberant microphone recordings. Since obviously neither the pure speech signal nor the reverberation is known in practice, reverberation was, until a few years ago, considered a very difficult problem yet to be addressed in acoustic signal processing,” said Doclo. The reverberation suppression algorithms have shown that the algorithms developed improve both speech intelligibility and the spatial hearing impression. Current research aims to integrate computer-aided acoustic scene analysis into these algorithms, further improving performance for complex and highly time-variant acoustic scenes. Professor Doclo and his team are researching the integration of external microphones on a desk, for example, in addition to the microphones of the hearing aid. Initial results in terms of noise reduction and the preservation of binaural features are promising.

Since last year, these algorithms were tested in a new acoustics laboratory with variable reverberation times in the NESSY building in Oldenburg. With rotatable panels with absorbent material on one side and reflective material on the other side, the reverberation can be quickly adjusted from 0.2 seconds to 1.2 seconds. “There are only a few laboratories worldwide where the reverberation time can be changed so quickly over such a wide range,” explains Doclo. “That’s why this lab is very important for the further development and validation of our algorithms.”

This algorithm received the best ratings in the international “REVERB challenge” in terms of overall language quality; a result with which we were extremely satisfied. We also developed an approach to suppressing reverberation in recording spoken voices, by using multiple microphones based on multi-channel linear prediction, exploiting the sparse nature of speech signals in the time-frequency domain. Using this approach, we can estimate the reverberation components and subtract them from the reverberant microphone signals, which delivers impressive results.

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Key Publications
Continuous research and new technological developments are making signal processors for digital hearing systems increasingly more powerful and energy-efficient. This facilitates the use of novel, computationally intensive algorithms for effective signal processing. The hearing aid of the future will become more intelligent, for example, by recognizing and filtering out relevant speakers from complex acoustic environments, to further improve the user’s individual hearing ability. In order for such a hearing-aid system to provide the required computing power under such limiting factors as low battery life and the necessary small form factor of such devices, the Hearing4all Cluster of Excellence has explored the design and optimization of the processor architecture of a hearing-aid system using algorithms.

The KAVUAKA hearing aid processor developed in this project is a so-called application-specific, instruction-set processor (ASIP). The generic base processor architecture has been adapted and optimized based on the algorithms developed in the Cluster. The adaptation was achieved by inserting complex, adapted instructions into the basic instruction set. Noteworthy enhancements include a multiplication-addition unit that can handle both real and complex numbers, architectures designed to counter losses in power when listening to different registers, and a low-latency audio interface. During the development phase of the KAVUAKA, many design-space studies were carried out with the help of simulations, in an effort to apply various algorithms to optimize the processing power and reduce power loss. It was shown that KAVUAKA calculates more efficiently than comparable hearing aid processors. Since the computing power, power loss, and chip size can be optimized in different ways, depending on the priorities set, this project developed a system-on-chip (SoC). A block diagram of this SoC can be seen in Fig. 1.

The SoC offers four different optimizations of the KAVUAKA processor. These can be activated separately or simultaneously, in order to increase the computing power or minimize loss in performance. To avoid flaws in the architecture, the SoC was tested under real conditions using the Cluster’s algorithms by connecting the SoC to dummy hearing aids and simulating typical listening situations (Fig. 2).

In this case, the entire SoC was emulated using a rapid prototyping system and coupled with the Cluster’s in-house hearing-aid development platform in order to test the overall functionality. To prepare the SoC as a chip, it can be tested with the development platform and dummy hearing aids in battery mode. The development platform offers a Bluetooth interface for wireless communication with the hearing aid via smartphone or tablet, allowing the algorithms to be remotely controlled. There is also the possibility of calculating the processor’s current power consumption during operation.

In the final phase of the project, the SoC with the four KAVUAKA processors will be manufactured as a chip. The chip technology used has been designed for low power dissipation and has a structure size of 40 nm. The chip has an area of about 3.5 mm². The power consumption will be just a few thousandths of a watt. The research carried out in this project and their future usefulness for hearing aid processors can be seen in the chip as a finished product.

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CI research taking a new turn

Hydrogel electrode: a new approach to realizing atraumatic electrode placement

Cochlear implants are able to treat people with severe inner ear-related hearing loss by creating an artificial sense of hearing through electrical stimulation in the inner ear. Usually, after appropriate familiarization and targeted training, an acceptable level of speech comprehension can be achieved.

Although human hearing has more than 3,500 different frequency channels, the frequency resolution when stimulated via a cochlear implant is much more modest. Even if implants contain up to 22 stimulating electrodes, the number of simultaneously active channels is capped at 8. The limitation to perceiving different pitches is therefore not due to the low number of electrical contacts. Rather, the frequency resolution is limited by the superposition of the electric fields of the individual electrode contacts. The removal of the electrode contacts to the spiral ganglion of the auditory nerve, which runs along the central cochlear axis (modiolus), plays a major role here.

Although optimized to minimize stiffness, conventional CI electrode arrays resist flexion when implanted and nestle against the outer wall of the bony scala tympani of the inner ear. As a result, the distance from the electrodes to the auditory nerve is greater than if the electrode were nestled against the inner side of scala tympani. There is also a risk that the user may have sensitive biological structures at various points along the cochlea, often causing the loss of any remaining residual hearing. Further manufacturer developments of the implants have been particularly focused on the mechanical action of the insertion into the cochlea and attempts to construct the electrode shaft so that the risk of injury is reduced (so-called ‘atraumatic electrodes’). Modern electrode shafts therefore have a certain amount of pre-bending and are introduced via a guidance stylet. However, the electrode shaft clings to the modiolus only at some points. To date, there is no electrode available that can cling to the modiolus over its entire length.

Our current approach is to make targeted use of a hydrogel, which swells when it comes into contact with water, to cause the electrode shaft to curve. We have succeeded in incorporating a hydrogel compartment into a silicone-based CI shaft, and positioned near the outer edge. When introduced into scala tympani, the hydrogel swells in response to the surrounding perilymph fluid and shows the expected bending effect. It can be thought of as a bimetallic strip, in which a curvature is caused by heating, such as is often used in electrical equipment as a heat-controlled switch.

Because a self-contained hydrogel compartment was considered not to be sufficiently durable, i.e. unable to continue functioning for the life of the patient, a procedure was developed that allows the hydrogel to be incorporated into the outer part of the silicone sheath during fabrication. In this way, the hydrogel can be firmly anchored in the silicone so that it does not peel off over time. However, a hydrophobic material such as silicone cannot be mixed with a hydrophilic material like the hydrogel. The problem was solved by introducing the hydrogel into the silicone prepolymer in the form of a dry powder. Advanced milling techniques have allowed us to obtain microparticle fractions of hydrogel powders that control both water uptake and the homogeneity of the curvature.

The behavior of our hydrogel electrode shafts is so promising that we made contact with a manufacturer of CI electrodes. Together with Advanced Bionics, we have integrated our actuation mechanism into a conventional manufacturing process. Together, it was possible to prove that conventional CIs with platinum plates and wires can be caused to attain the required curvature.

Of course, such translation phases of biomedical device development come with additional issues. With the recent appointment of the group to the Hannover Fraunhofer Institute’s ITEM, the researchers are now working together on the aspects of biocompatibility resulting from the mixing of different materials, the long-term stability, the still missing curvature of the electrode tip, and the future possibility of automated fabrication of self-curving CI stems based on individual patient anatomy.

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Key Publications

Patients with a neurofibromatosis 2 (NF2) tumor usually develop tumors on the two auditory nerves that make up the nerve connection between the ears and the brain. Even if the tumors are removed from the auditory nerves, new ones can form again, eventually affecting the entire auditory nerves and requiring their removal to prevent further spreading. This, however, cuts the connection between the cochlea and the brain, leaving the patients without hearing.

A cochlear implant, which is inserted into the cochlea to stimulate the auditory nerve electrically, is obviously not a solution for these patients, since they no longer have the auditory nerve to transmit the signals. Instead, this group of patients is usually treated with an auditory brainstem implant (ABI). This is placed on the surface of the brainstem, but it is difficult to position and the electrode may subsequently slip. Also, the tissue can be scarred by the tumor removal, which makes positioning and stimulation even more difficult. As a rule, only a rudimentary impression of sounds is achieved, allowing some orientation in the environment (e.g., the ability to hear road traffic). A satisfactory understanding of speech without relying on the support of lip reading is the exception, especially for NF2 patients.

For this reason, the auditory midbrain implant (AMI) was developed. It is not placed on the brainstem, but a level higher in the auditory pathway, in the colliculus inferior of the midbrain. As a rule, tumors do not form here, the location is easier for the surgeon to visualize, and long-term stability can be ensured.

A first generation of AMIs [monolateral electrode carriers] was successfully implanted in five patients between 2006 and 2008. One of these patients has been able to achieve a better understanding of speech than almost all of the 38 adult patients who were previously treated with ABI at the MHH.

However, the first generation of the AMI has also shown that optimal placement of the electrode carriers during the procedure is quite difficult. In addition, refractory effects were observed in subsequent studies, so that the neurons could only be stimulated at reduced rates. This results in reduced signal quality and, in conjunction with non-optimal placement, is believed to be responsible for the limited ability to comprehend speech. These findings led to the further development of the AMI, which now has two electrode legs and is being tested on five patients as part of a Phase 1 safety study at Hannover Medical School. Not only has the implant itself been improved, but also the image-based navigation technique, which allows precise placement on the colliculus inferior. So far, one patient has been treated with a two-legged AMI. The results of the first audiological measurements are very promising.

The safety study is funded by the National Institutes of Health (NIH), the premier US biomedical research-funding agency.

The stimulation algorithm of the electrodes is undergoing continuous refinement, based on the research findings of the Cluster of Excellence. The EEG-based diagnostic studies of AMI patients performed by the Cluster also provided important insights into the processing of auditory signals in brain centers. If the AMI delivers clearly better speech comprehension than the results of the ABI implants, AMI may become the treatment of choice for NF2 patients who have lost their auditory nerve due to tumor removal.

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Key Publications
Eye glasses are intended to compensate for vision defects and at the same time provide the impression of complete optical transparency without distortions. This apparent contradiction between correction by sensory assistance and simultaneous falsification of the resulting sensory impression has largely been resolved with modern visual aids, but still has not with modern hearing aids! The aim of the Hearing4all Cluster of Excellence is to make it possible for people with low- to medium-level hearing impairments to access “hi-fi hearing systems”, which will maximize the accuracy of the sound impression while simultaneously correcting the hearing damage. In other words, users should not be consciously aware of the assistance offered by the hearing aid!

The researchers of the Hearing4all Cluster of Excellence have come a lot closer to achieving this goal: With the acoustically transparent earmold, developed by the „Individualized Hearing Acoustics“ research group and the Kollmeier, Hohmann, and Doclo working groups, we are coming a step closer to the hearing technology of the future (Fig. 1). In addition to three microphones and two hearing-aid receivers, as well as a large vent between the inside and outside, this patent-pending development is based on Florian Denk’s dissertation. The device is primarily actuated through the associated signal processing: In order to compensate for the acoustic effect of the earmold as a sound barrier, incoming sound is automatically processed and reproduced with the aid of an in-ear microphone located in the auditory canal, so that the hearing impression with the hearing aid is the same as without a hearing aid, albeit at a volume that the user can change at will. This adjustment in the way the hearing aid transmits the sound to the individual circumstances of the outer ear and ear canal allows for a very natural, transparent sound impression that is an essential prerequisite for the Cluster’s further plans to develop the hearing-aid and hearing-support systems of the future.

As concluded in the thesis submitted by Tobias de Taillez (of the Kanu and Hohmann work group) under the supervision of Dr. Tobias Neher, binaural hearing is well supported by a hearing aid when each ear experiences acoustic transparency. This technology also provides a way forward for the thought-controlled hearing solutions of the future: Thanks to collaboration with the Deben working group, the transparent earmold features additional EEG electrodes (Fig. 2). According to Bleichner et al., for subsequent analysis, the main EEG signals can thus be picked up in the auricle using the cEEGrid system. With this brain-computer interface technology, it should be possible to identify certain hearing-aid functions that result from the user’s efforts to hear or to concentrate on an acoustic object and, using this, adjust the hearing aid’s settings to the user’s intention. However, other tasks are also required of the transparent earmold: currently, the suppression of feedback and active background noise in open hearing aids are unresolved issues being tackled by the research group of Prof. Dr. Simon Doclo.

The goal in developing the demonstration transparent setting hearing system is the intelligent hi-fi hearing aid of the future as a hearing assistant, sound environments augmented through virtual reality, and hearing aids, all in one. The researchers at the Cluster of Excellence are convinced that it is only through decisive steps towards developing the highest-quality sound-rendering systems adapted to the individual user that substantial progress can be made for those with low- to moderate hearing impairment. This should be kept as low as possible for these particularly critical first-time users, the entry threshold for a supply of a hearing aid.

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Key Publications

The „Hannover Kuppler“
Improved coupling of active middle-ear implants to the round window

The “vibrant soundbridge” is one of the most successful active middle-ear implants for the treatment of sensorineural hearing loss. Unlike hearing aids attached to the outer ear canal that transmit the amplified sound via air to the tympanic membrane and the intact ossicular chain, the active middle-ear implant is attached to the ossicular chain and uses an electromechanical transformer to vibrate it directly. This requires, at a minimum, a largely intact stapes, i.e. that part of the ossicular chain coupled to the inner ear via the oval window. For those patients where attachment to the stapes is no longer possible, or for whom the transition to the inner ear has ossified, a method has been developed to allow the implant to be attached to a second cochlear opening that is closed by a membrane, the so-called round window.

Since the first implantation of the corresponding floating mass transducer (FMT) on the round window by Colletti in 2005, new ways of treating conductive- and combined hearing loss have been developed. Although the coupling to the round window is now a clinically well-established standard treatment, it suffers from two disadvantages. First, the slightly larger transducer can fit through the smaller round window less easily than through the oval window. Second, the clinical results are quite variable and range from excellent to unsatisfactory. These problems have led to the development of a variety of couplers and the testing and use of many intermediate materials, which, to date, have not proven to resolve the high variability of results.

In experiments with actuators for middle-ear implants, we established that the static pressure at the round window is a decisive factor in the effectiveness of sound transmission to the cochlea. Systematic preliminary tests with the FMT, in which the cable was used as a temporary spring (Salcher et al., 2014), confirmed the transmission effectiveness, but also an increased reproducibility of the coupling. Since the FMT is designed to vibrate as a whole, static pressure forces cannot be realized simply. This led to the design of a holder for the FMT in which it is suspended and can be pressed upon by a spring. An additional coupling element handles the adaptation to the round window and centers itself on its membrane. After several preliminary prototypes, a version used in a systematic series of experiments on the temporal bone was able to demonstrate that an increased transmission effectiveness is possible over a wide range of static pressure forces (Müller et al., 2017).

In addition to demonstrating its feasibility, these experiments also showed that an optimal force range for the transmission of speech could be set to approx. 10 mN. This appears favorable in respect to safety aspects over longer periods of time, because these are forces that can occur with conventional implantation without problems. The first version was manufactured as a sterilizable, custom-made medical device (CMD) by MED-EL. This was used with appropriate safety precautions to treat a patient for whom the commercially available solutions were unsuitable. The audiological results from this implantation showed the expected good transmission characteristics. The Hannover coupler was then further developed in close cooperation with MED-EL, further optimizing the design of the first prototypes using finite element simulations. In particular, the quality of low-frequency transmission was improved, and other design changes were made to make the device easier to use, more robust, and easier to manufacture. The desired properties of the improved version were verified in experiments and the new, improved couplers are now available for use on patients, initially as CMDs.

If the improved prototype delivers improved quality for the patient, plans for preclinical and clinical trials in cooperation with MED-EL are under consideration.

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Key Publications

We don’t just listen with our ears. Listening is an active process, because what we hear depends on what we find interesting and on our expectations based on previous experience. The brain plays a crucial role in complex situations, because it allows us to focus our attention on a particular sound source and thereby ignore other distracting noises. In other words, we hear what we want to hear. Hearing-aid wearers frequently report unsatisfactory listening experiences when many people are speaking at once. Hearing aids amplify sound and can compensate for a partial hearing loss, but they cannot distinguish between important and unimportant sounds. It has thus been a long-term objective of Hearing4All Cluster of Excellence to develop a brain-computer interface for the user control of hearing aids.

Prof. Stefan Debener and his group are working to understand user’s listening intentions and how to use these to control hearing aids. This will allow the devices to be actively adapted to the current listening intention and not just to the listening situation. The brain processes underlying the listening intention leave traces in the electroencephalogram (EEG), a measurement of brain electrical activity made possible by placing sensors on the scalp. If we could use an EEG to record which voices are of interest to a hearing-aid user, this information could be passed on to the device, allowing the chosen sound source to be targeted for amplification and thus improve the listening experience.

In lab settings, it is already possible to use EEG signals to find out - with high levels of precision - which of two audio books being played at the same time the subject chooses to pay attention to. Conventional EEG measurements in the laboratory require sensors to be affixed to subject’s head, with signals transmitted via cable to large signal amplifiers and stored by a computer. To use brain activity to control a hearing aid will require a new approach that will allow EEG signals to be measured in everyday life without negatively impacting the user’s activity. Prof. Stefan Debener and his research group refer to this concept as transparent EEG. The team is developing methods to make the recording of EEG signals as pleasant and as unobtrusive as possible. In the future, they hope to use this miniaturized EEG technology to identify the listening intention of users in real-life situations. This ambitious goal first requires the development of discreet and comfortable measurement electrodes. Sensor strips called cEEGrids have since become commercially available. Like a hearing aid, they are positioned around the ear and allow the user to be out in public without attracting attention (www.ceegrid.com). cEEGrids are flexible, multi-channel, printed sensor arrays adhered around the ear with tape. The sensor strip is combined with a small, light-weight, and wireless signal amplifier, which can be worn without attracting attention while allowing EEG signals to be recorded using an ordinary smartphone. What in the not-so-distant past filled an entire desk will soon fit into a pocket. A direct comparison already showed that the relevant brain signals can be recorded with the transparent EEG.

The current prototype makes it possible to record EEG activity in natural hearing situations outside the lab setting. The ear EEG has already been combined with an experimental hearing aid in the lab. Researchers want to find out which simultaneous sound sources in everyday listening situations a person chooses to pay attention to, and, if possible, in real time. In the future, they will thus be able to demonstrate that EEG signals obtained in everyday settings really can be used to control hearing aids.

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**Key Publications**


The Joint Research Academy in Biomedical Engineering and Science of Hearing and Sensory Systems (JRA) supports young researchers as they make their way from their first degree to academic positions or employment in industry. It combines the graduate programs offered by the participating universities and offers the option of a doctoral degree in the natural sciences, engineering, or a combined medical and science doctorate.

In addition, new PhD and post-doctoral programs are being developed to meet the demands of this complex, interdisciplinary field of research. Once a year, the JRA organizes a Hearing4all summer school aimed at all the young researchers in the Cluster and associated projects. In the summer school, these scientists have the opportunity to present their own projects, get to know what others are doing, and make important contacts. Courses with leading international speakers offer them the chance to deepen their knowledge and expand their horizons. The next generation is also given the opportunity to express their own hopes and dreams for the program and participate actively in the design of the courses.

Another special element is the support offered to ensure work-life balance, such as investments in daycare centers and a mentorship program especially tailored to young women in the field. A special focus has been placed on equal opportunities in the recruitment of talent for the Cluster. The result is that of the junior research group leaders, about 50% are female.

In 2012, the Hearing4all Cluster of Excellence received a €28 million grant for five years from the German Research Foundation.

Among other things, four new W2-grade professorships were established to focus specifically on the Cluster’s mission. These include chairs in communications acoustics and machine learning in Oldenburg and a biomaterials engineering and experimental audiological diagnostics in Hannover. In addition, ten W1 junior research groups were established to work on the entire range of projects pursued by the Cluster. Several pieces of equipment and laboratories were also set up within the framework of the Cluster, including an MRI, a 3-D virtual-reality room, and a GPU computer cluster at the University of Oldenburg; an NIRS and a STED microscope at Hannover, as well as several EEG laboratories at both locations. These state-of-the-art facilities have significantly expanded capacities and allow existing methods and techniques to be enhanced alongside completely new diagnostic methods.

The Future Belongs to the Young

The Joint Research Academy

Bojana Mirkovic is one of the first graduates of the JRA in Oldenburg

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Bridge to Industry

The Translational Research Centre (TRC) coordinates the commercialization of research results by industry, with the hope of developing new products and services.

The TRC supports researchers in identifying patentable results, helps to make contacts among various stakeholders (researchers, bodies, and university transfer offices), and assists them in contract negotiations with industry. The TRC develops structures that govern the handling of IP and patents within the Cluster of Excellence. This includes patent research and the actual patent process. Special consideration is given to the conditions at each location. In addition, the TRC initiates industry-funded research projects that build on the results obtained in the Cluster of Excellence, with an eye to developing specific commercially viable products.

By means of press releases, publications in journals, and appearances at trade fairs such as the EFAS, EUHA, CeBIT, and DGA, the Cluster of Excellence keeps in contact with its target audience. Hearing4all serves as co-organizer of such international congresses as the DGA, DAGA, and BMT. The Cluster of Excellence also considers general public education a part of its task, helping the public to better understand how hearing works and to counter the stigma often associated with hearing aids. Through such measures as open houses, visitor groups, concerts, and the newsletter “CLICK,” Hearing4all helps educate the public about the topic of hearing. With the “musIC 3.0” concert, the Hearing4all Cluster of Excellence is helping to make music enjoyable for cochlear implant users. Press releases and publications in local and national newspapers and magazines inform the general public about current developments in hearing research. As part of its corporate design, the TRC provides instruments that allow for a uniform appearance and support a high recognition value for the Cluster of Excellence.

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