Visualization of auditory nerve fiber activation under natural and electrical stimulation

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Project background and description

Hearing is a sense which is enabled due to the interplay of several organs in the human ear, which are depicted in figure 1. The cochlea, one of those organs, is the sensory organ ultimately responsible for converting sound waves into electrical signals, which the brain can interpret as sound. Shaped like a small spiral or snail shell, it contains a thin structure called the Basilar Membrane, which runs along its length. When a sound enters the ear, the Basilar Membrane vibrates, but its vibration is location-dependent—high-pitched sounds (high frequencies) cause vibrations near the base (closest to the outer ear), while low-pitched sounds (low frequencies) vibrate near the apex (at the top of the spiral). This selective vibration is the mechanism of how complex sounds are decoded, in order for the brain to be able to interpret them. On the Basilar Membrane lies the Organ of Corti, which houses the so-called inner hair cells. These inner hair cells are connected to neurons of the auditory nerve, forming the pathway that carries sound information to the brain. When a particular location on the Basilar Membrane vibrates as a response to a specific frequency, the corresponding inner hair cells will activate their attached neurons, and send electrical signals to the brain, allowing us to perceive sound.

For people with severe hearing loss, the underlying cause is most often damage to or loss of inner hair cells, typically due to aging, loud noise exposure, or illness. Without functioning inner hair cells, the brain cannot receive sound signals. However, usually many neurons in the auditory nerve remain intact. Cochlear Implants (CIs) bypass damaged inner hair cells by directly stimulating these neurons, using tiny electrodes inserted into the cochlea. By applying electrical currents to specific electrodes and, consequently, specific locations, these implants can activate nearby neurons, enabling users to hear again.

We aim to **create a visualization** that demonstrates how auditory nerve activation differs between normal hearing and hearing aided by CIs. As we have detailed simulation data of the excitation patterns in the auditory nerve, we want to use it to generate an accurate representation, which should still be understandable and accessible for a general audience.

Previous work

Currently, we have animations of action potentials (APs) ($\hat{=}$ neuronal signals) in auditory nerve neurons under **electrical stimulation** by cochlear implants (CI). A screenshot of one such animation can be seen in figure 2, the full animations can be viewed here and here.

- The animations depict 400 neurons representing the human auditory nerve, arranged in a realistic 3D representation based on anatomical data

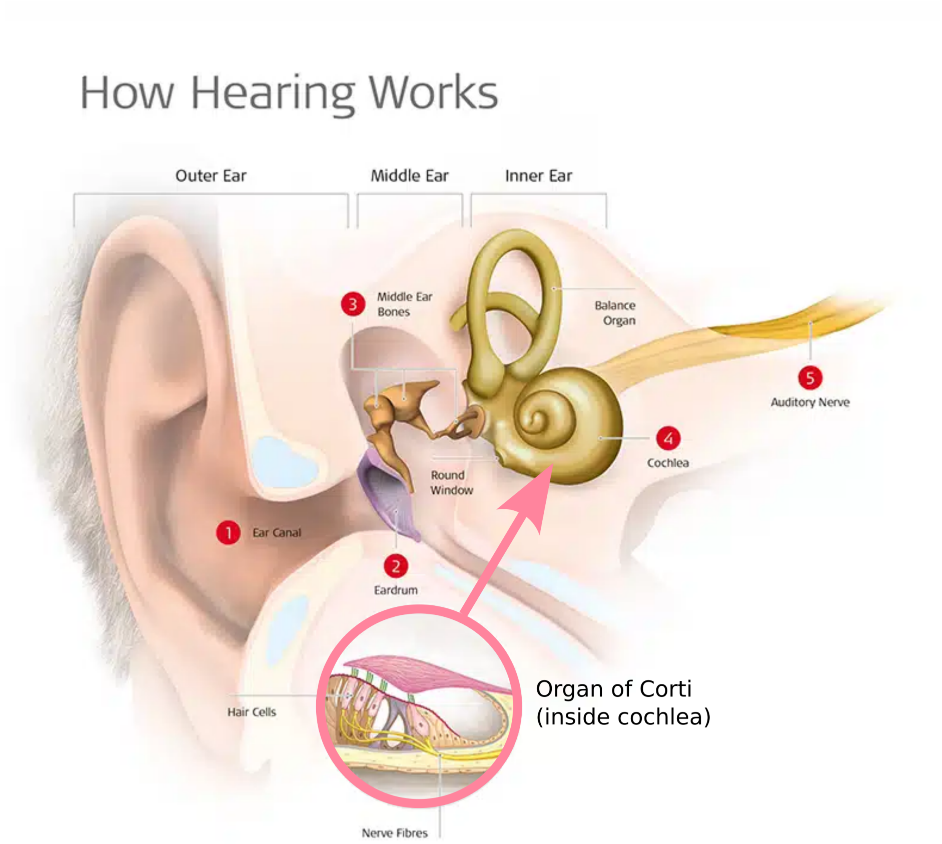

Figure 1: Schematic illustration of the human ear. Adapted from MED-EL ([MED-EL, 2020]).

- APs were "encoded" by applying neuronal membrane potential values from simulations to a colormap and mapping them onto the modeled neuronal paths. This means that when an AP is triggered, the corresponding neuron is visually activated by a change in color and/or shape
- The neuronal membrane potential values were obtained from computer simulations of auditory nerve responses to CI stimulation (for details on the model see [Croner et al., 2022])
- The animations are slowed down: APs, which typically last around one millisecond, are stretched to several seconds in order to show their propagation
- The activation of neurons is based on stimulation by a single CI electrode. This corresponds to a sound with a single frequency, e.g., a "beep tone"

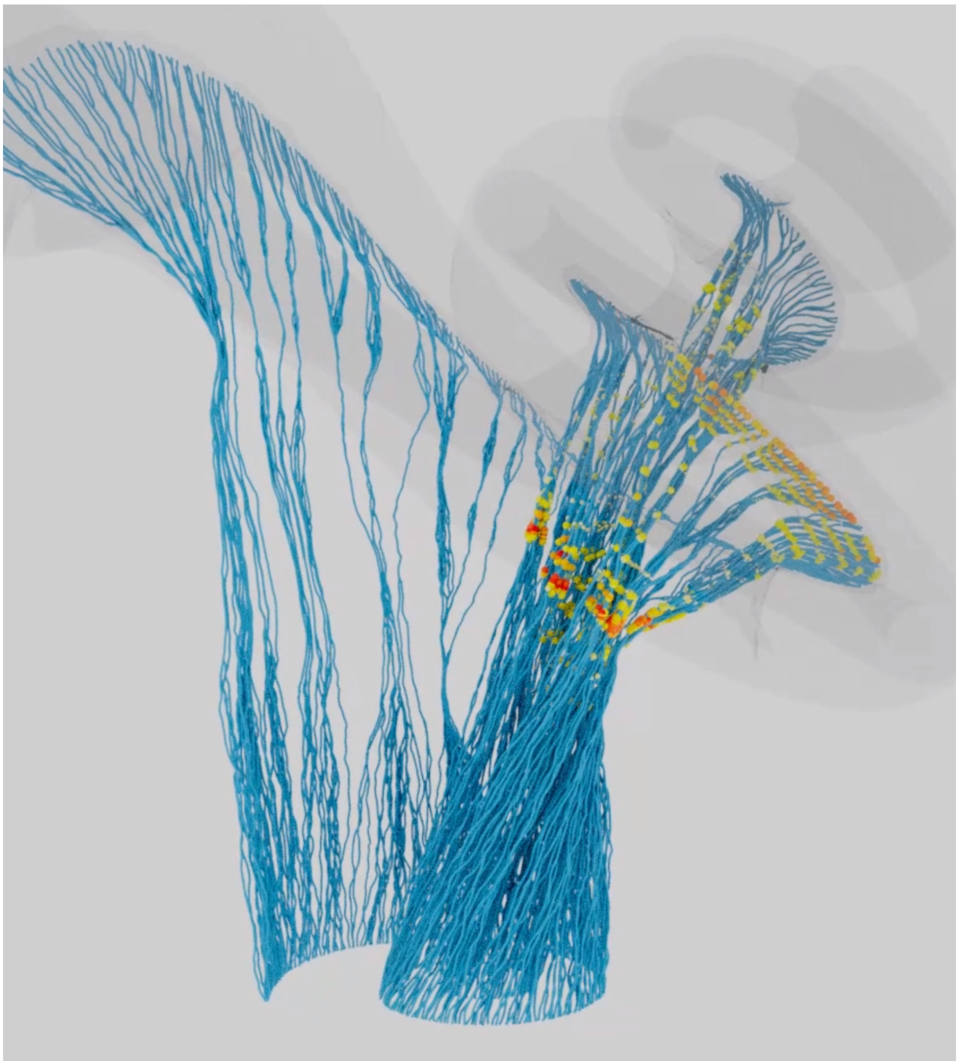

Figure 2: Rendering of neurons in the human auditory nerve. Yellow-red bubbles indicate activation of neurons by a cochlea implant. Cochlear scalae and cochlea implant electrode are shown as shadows.

Inter-disciplinary project

For future projects, different tasks are open to be completed, listed in the following. All tasks are available for IDPs, but we expect only a subset of the tasks to be completed within a single IDP. Tasks will either be completed in Blender with Python, or in a game engine. The project is set to start in summer semester 2025, and the accompanying lecture will be Neuroprosthetics, where the function of human hearing and the auditory nerve will be explained.

- General integration into a video sequence showing the neurons in **surrounding morphology**, similar to figure 1 but as a video
  - Possible progression with zoom: head → outer ear → middle ear → inner ear → cochlea → cochlea cross section → Organ of Corti → hair cells and connected neurons → zooming back out to all neurons of the auditory nerve
  - For cochlea, cochlea cross section, and neurons of the auditory nerve, we have 3D models and µCT scans available
  - Representation of the Organ of Corti in 3D may be very work intensive, a 2D overlay may be acceptable
  - Models for head and outer-middle-inner ear depiction could be obtained from open access platforms, such as from Open Anatomy Project or embodi3D. For head, we also have MRI scans available, but no (detailed) 3D models.
- **Improvement** of the **existing** visualization of activated neurons (slowed down, electric hearing version)
- Visualization of neuron activation for a **healthy ear** (normal hearing version)
  - Visualizations should be analogous to the existing animations, i.e., slowed down and same "beep tone", with the same model anatomy. Normal hearing excitation of the auditory nerve will be based on the model from [Zilany et al., 2014].
  - Comparison of visualizations healthy ear versus implanted ear are to be included (electric hearing vs normal hearing)
- Visualization of neuron activation in the auditory nerve at **real-time speed**, for both healthy ear and implanted ear
  - In this case, the propagation of signals cannot be visually represented. Neuron activation can instead be shown, for example, through a flash, "shimmer," or "glow" of entire neurons
  - Unlike the slowed-down visualization, this approach can also represent more complex sounds or sequences, such as speech or music
- In addition to the videos, we also have a VR environment of one of our cochlea models, including neurons which are activated by sound. Further **improvements in VR environment** are desired, e.g. better navigation and inclusion of biological structures. For a short description, see here.

References

[Croner et al., 2022] Croner, A. M., Heshmat, A., Schrott-Fischer, A., Glueckert, R., Hemmert, W., and Bai, S. (2022). Effects of degrees of degeneration on the electrical excitation of human spiral ganglion neurons based on a high-resolution computer model. *Frontiers in Neuroscience*, 16.

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[Zilany et al., 2014] Zilany, M. S. A., Bruce, I. C., and Carney, L. H. (2014). Updated parameters and expanded simulation options for a model of the auditory periphery. *The Journal of the Acoustical Society of America*, 135(1):283–286.