A Model Framework for Simulating Spatial Hearing of Bilateral Cochlear Implant Users

Hongmei Hu[1], Sebastián A. Ausili[2], Ben Williges[3], Jonas Klug[1], Rebecca C. Felsheim[1], Deborah Vickers[3], Mathias Dietz[1]

1. Department of Medical Physics and Acoustics, University of Oldenburg, Germany; 2. Department of Otolaryngology, University of Miami, United States; 3. SOUND Lab, Cambridge Hearing Group, Clinical Neurosciences, University of Cambridge, UK (hongmei.hu@uol.de)

Hearing4all Exzellenzcluster im Auditory Valley · European Research Council, Established by the European Commission · Carl von Ossietzky Universität Oldenburg

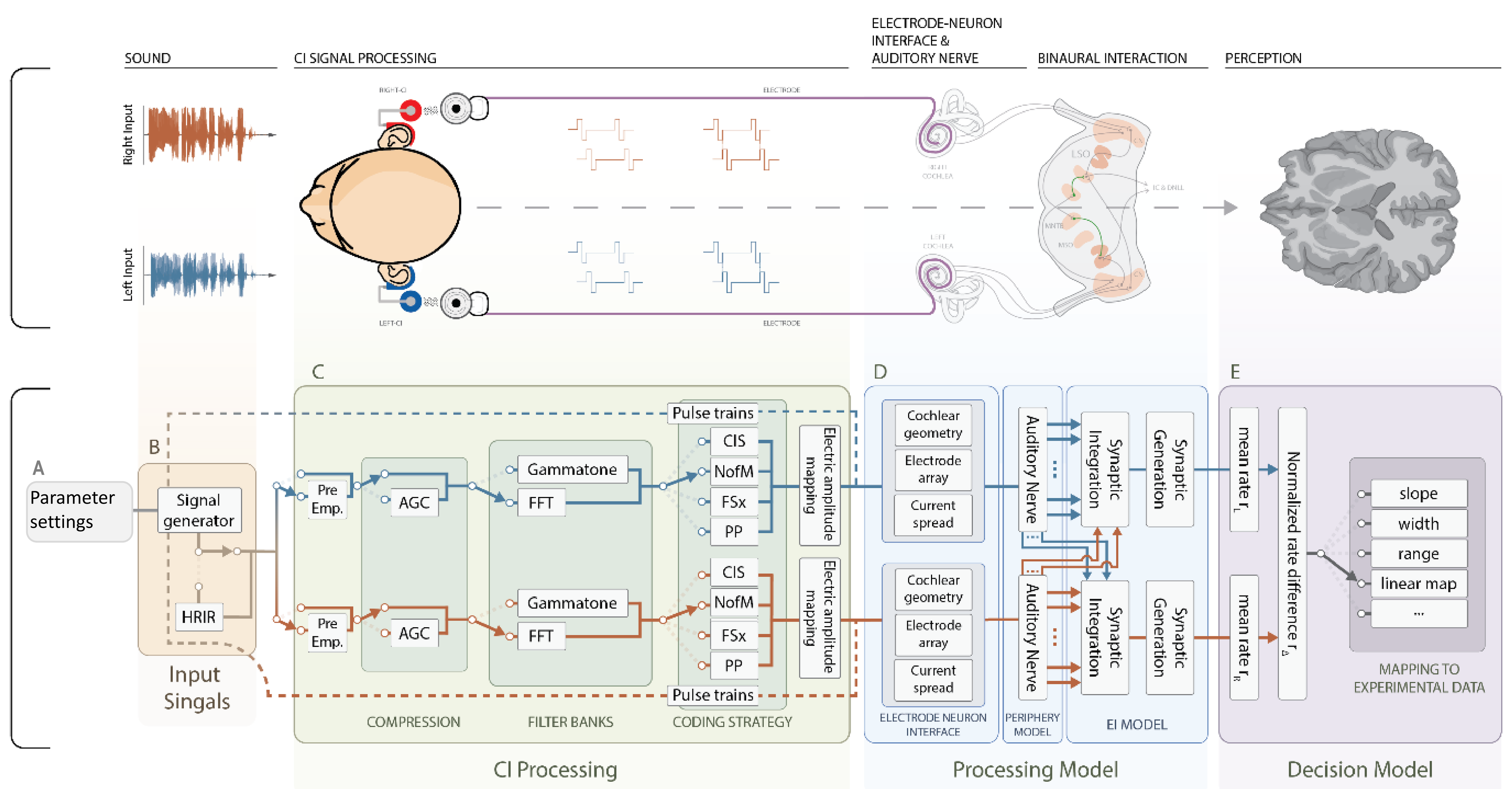
1. Introduction

- The main goal of the project is to develop an open-source model framework for simulating the spatial hearing abilities of bilateral cochlear implant (CI) listeners.
- For that, CI sound processing pipelines were combined with computational auditory models in a modular framework. It includes:
  - binaural signal generation with optional head-related impulse response (HRIR) filtering
  - generic CI sound processing stage not restricted to a specific CI manufacturer
  - electrode-to-neuron transmission
  - binaural interaction
  - a decision model.
- In order to show how to use the framework, a free-field localization experiment was simulated in **Sect. 3**. The signals after different CI processing stages, the neural response rates of the auditory nerve (AN), the binaural excitation-inhibition (EI) neuron, and the simulated function of sound source azimuth are shown step by step.
- Further examples (Sect. 4), such as localization, lateralization, and left-right discrimination performance of bilateral CI users are demonstrated in Sect. 4. These involve different CI stimulation techniques, such as the commonly used free-field, audio line in, and direct stimulation of a single or multiple electrodes.

2. Summary

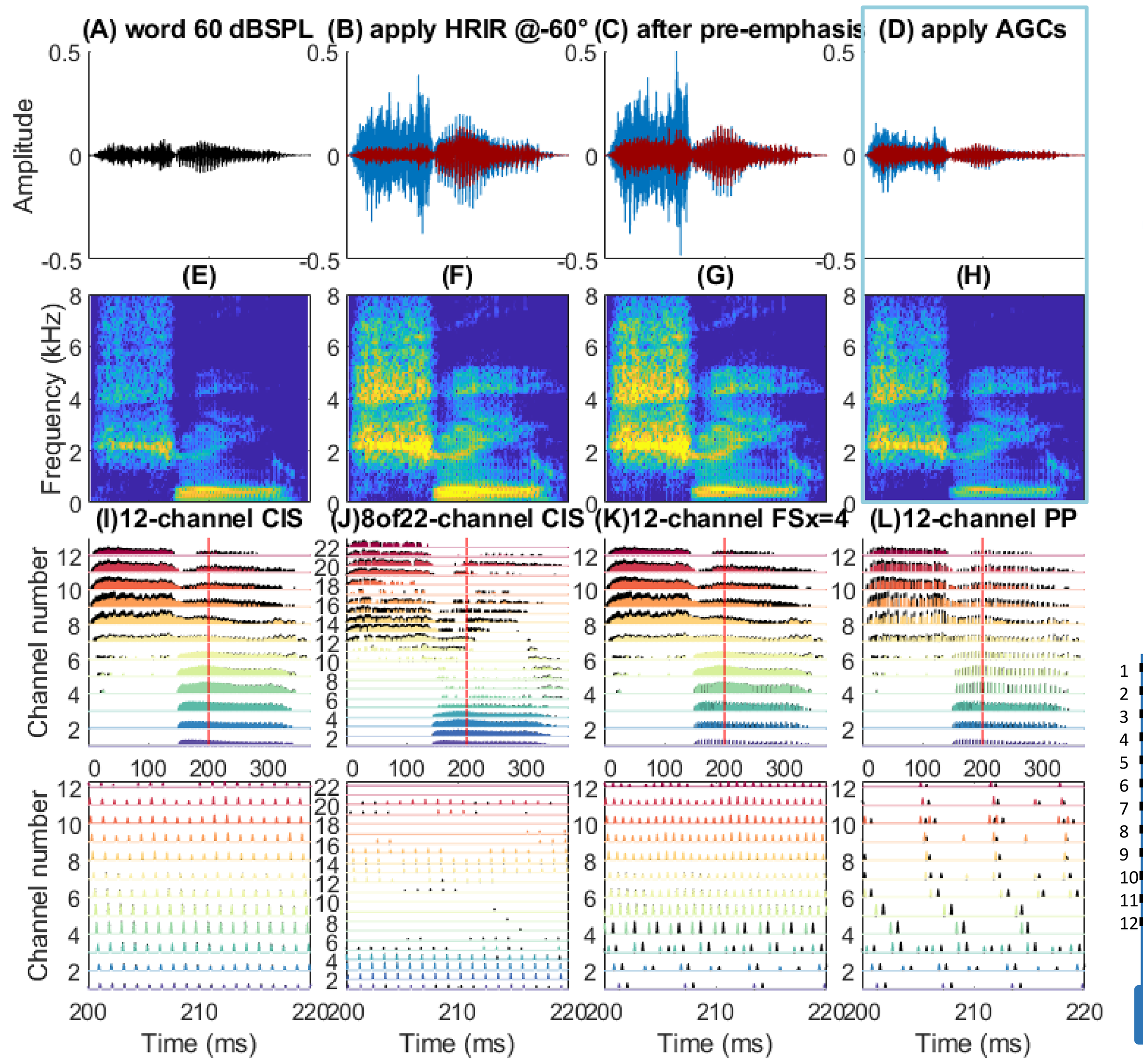
- In general, with the same AN, EI, and the multi-task decision stages, the model was able to capture the average performance of bilateral CI users, for example, the localization, and lateralization judgments, the effect of coding strategies, the input sound level and the bilaterally non-synchronized compressors.
- The MATLAB code of the model framework, the code to reproduce the model data and figures are published open-source. It can be download via the provided **QR code**.

3. Model Framework and Stages

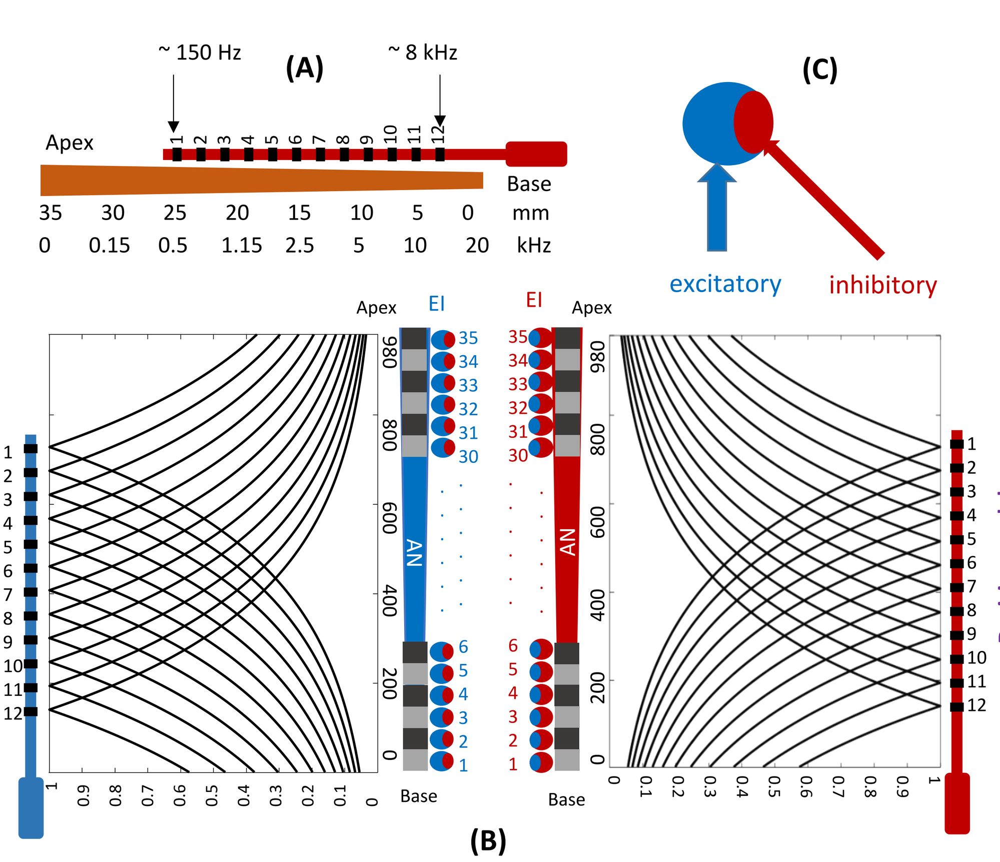


The upper panel ('Simulated Stages') illustrates the "hardware" of different stages, the lower panel ('Model Framework') shows the main five stages of the proposed modular framework). **Abbreviations:** AGC, automatic gain control; CIS, continuous interleaved sampling; NofM, N-of-M channel selection; FSx, fine structure processing; PP, peak picking.

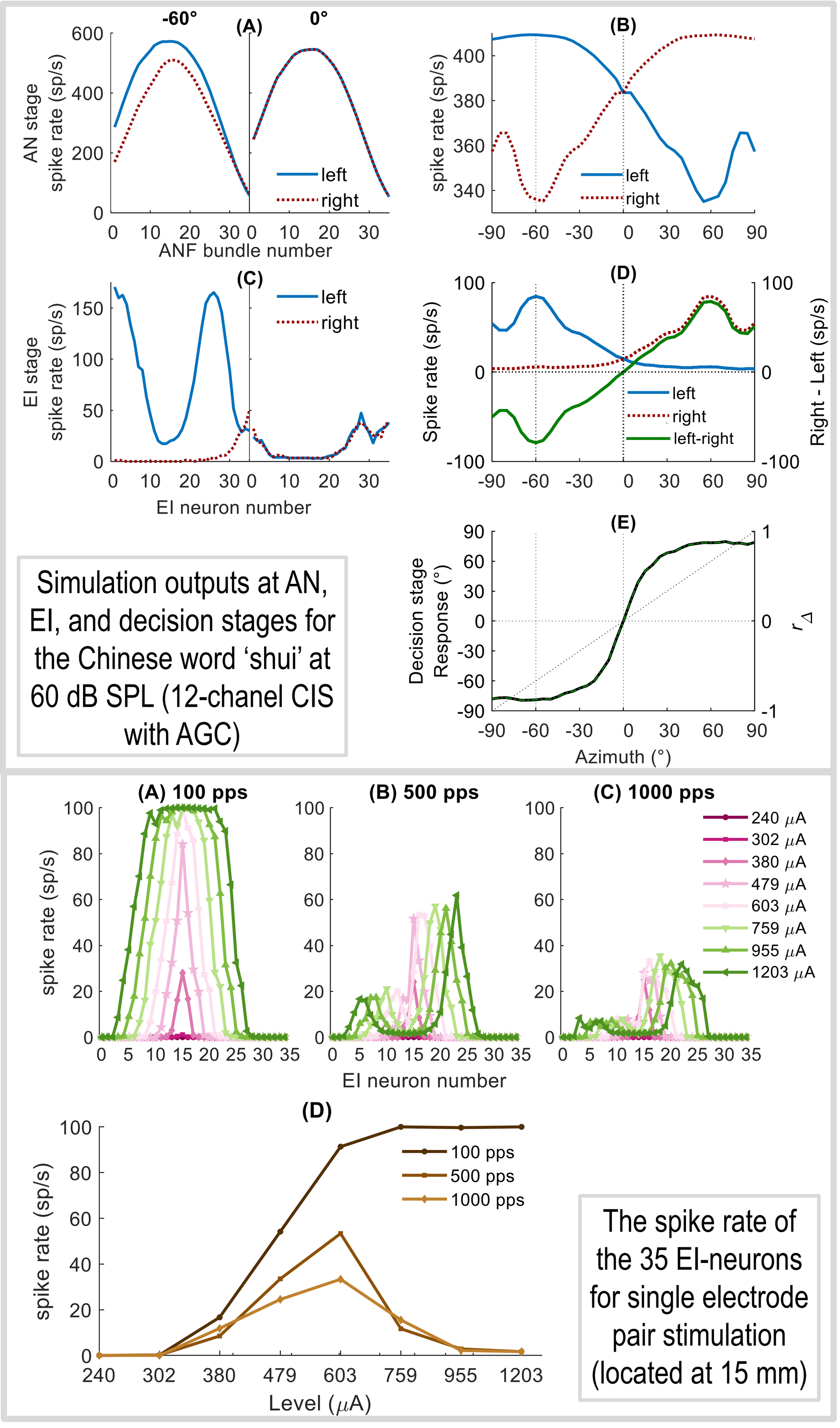
3.1 Signal and CI processing



3.2 Processing model



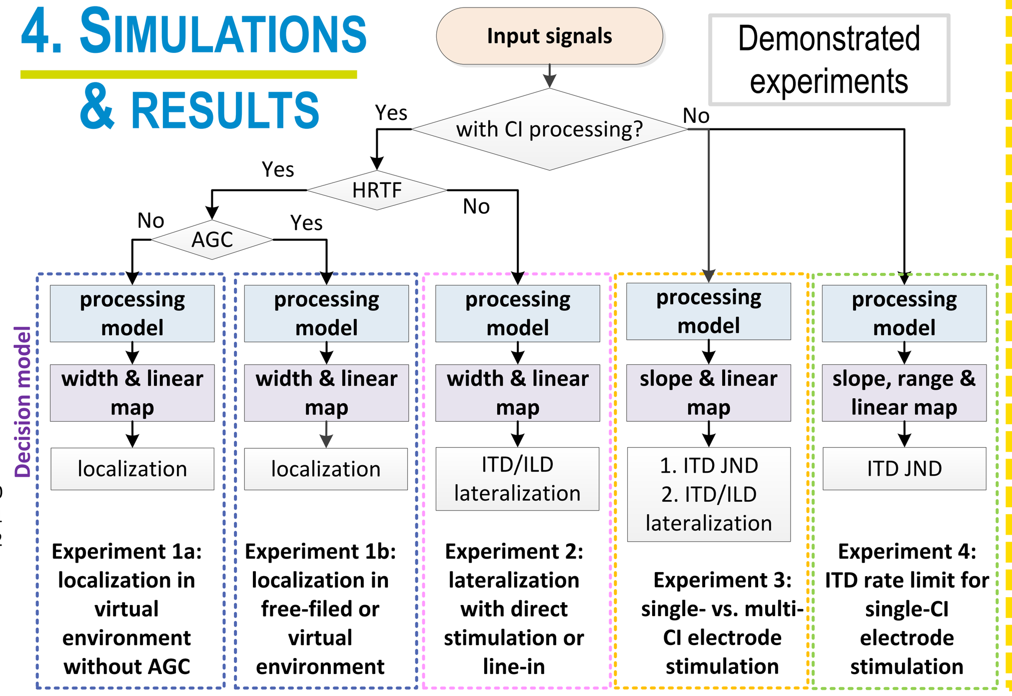
3.3 Outputs at AN, EI, decision stages



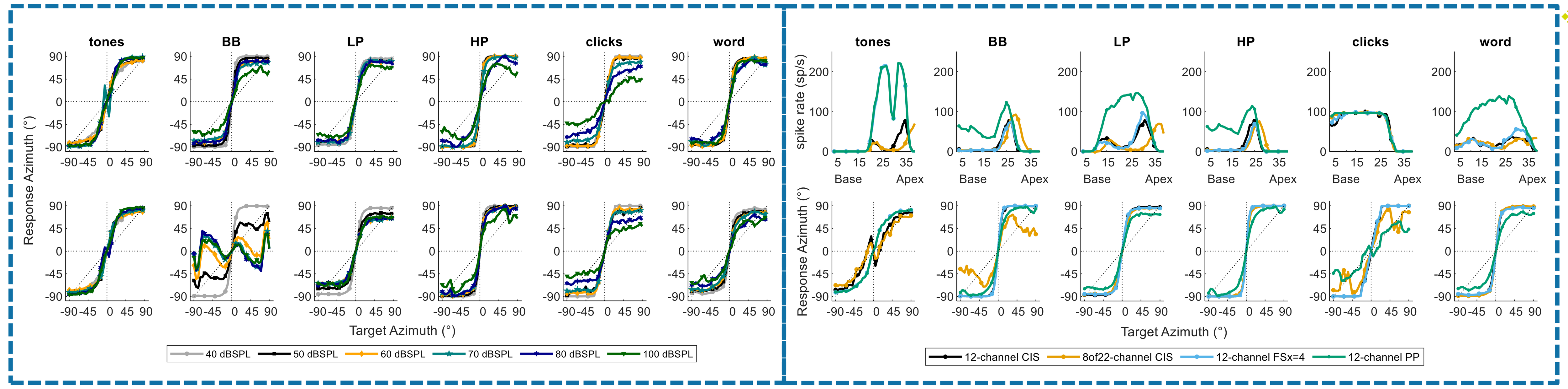
Simulation outputs at AN, EI, and decision stages for the Chinese word 'shui' at 60 dB SPL (12-chanel CIS with AGC)

The spike rate of the 35 EI-neurons for single electrode pair stimulation (located at 15 mm)

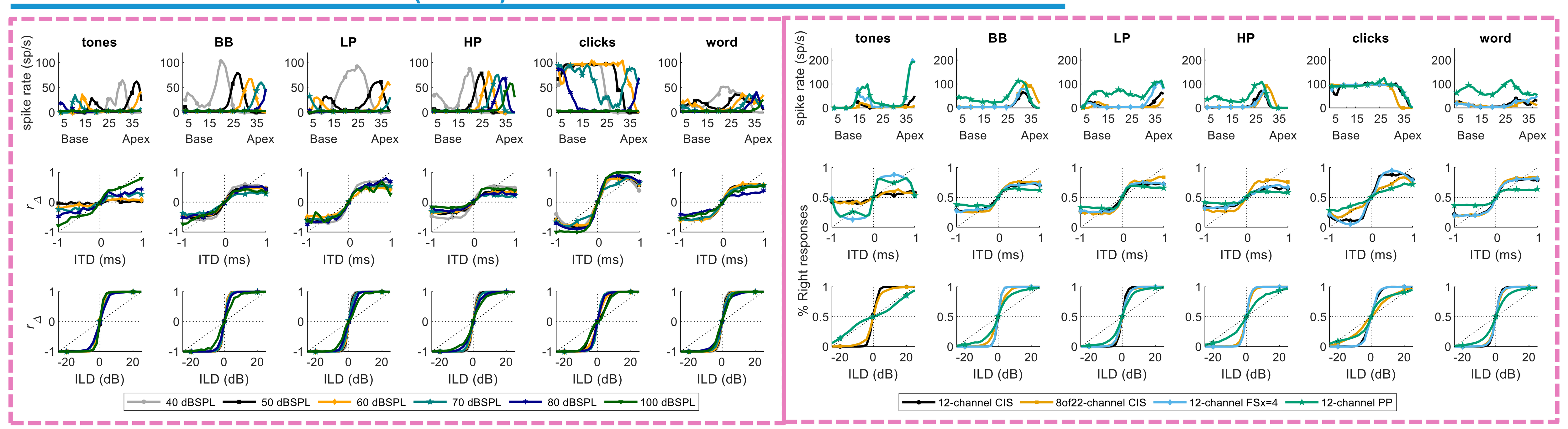
4. Simulations & Results



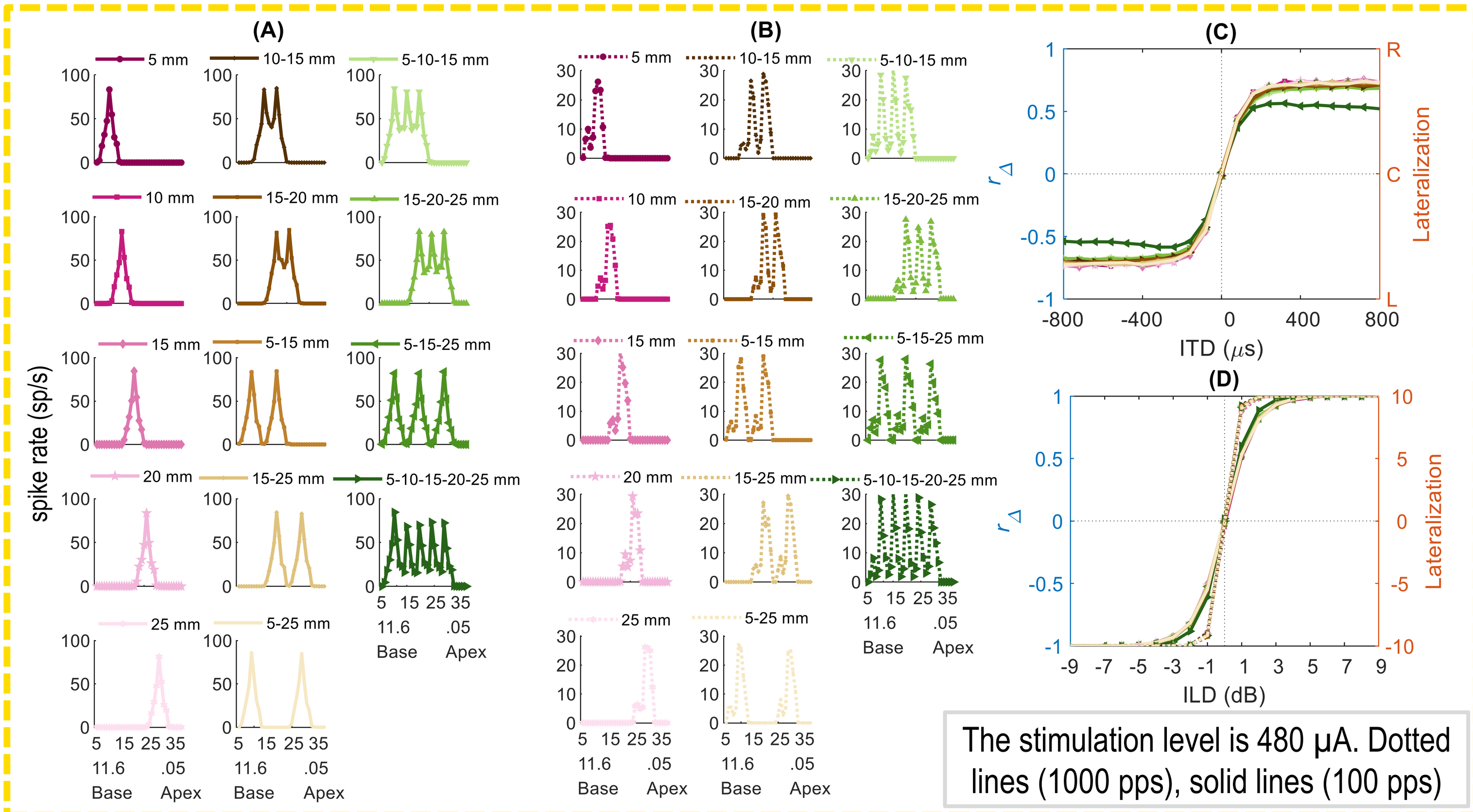
4.1 Localization simulation (Exp. 1)



4.2 Lateralization simulation (Exp. 2)

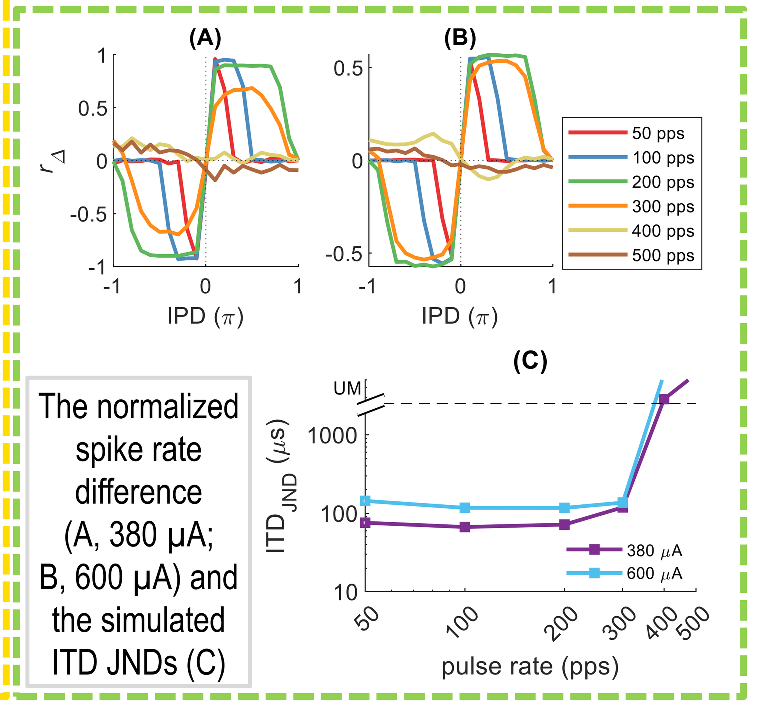


4.3 Single and multiple electrode pair stimulation (Exp. 3)



The stimulation level is 480 µA. Dotted lines (1000 pps), solid lines (100 pps)

4.4 Single electrode pair pulse rate limit (Exp. 4)



The normalized spike rate difference (A, 380 µA; B, 600 µA) and the simulated ITD JNDs (C)

5. Discussion

- **Limitations**
  - Very simplified electrode neuron interface and AN neuron model (replaceable).
  - Although the four coding strategies include most of the technical details of a typical CI speech processor, their implementations, especially for CIS and FSx were partly based on secondary literature.
  - The normalized rate difference and linear mapping functions were used to project the model outputs to different psychoacoustic data. This simplified multi-task decision stage was not able to capture some features in the selected experiments.
  - All demonstrations assumed ideal bilateral synchronization (besides AGC) and bilaterally symmetrical hearing.
    - However, the parameters can be easily adapted by including e.g., asymmetric neuron survival, different electrode insertion depths, spread of excitation, and hearing dynamic range, two non-synchronized independent speech processors, and bilaterally mismatched fittings.
- **Possible applications with further extensions**
  - The framework is designed not only for localization and lateralization experiments. By selecting different stage combinations and different decision models, other applications can be, for example:
    - As a tool to help validating binaural algorithms, designing binaural studies with real CI users or to study implications of binaural fitting.
    - Although the framework was binaural by default, it can be used for monaural purposes or only including certain stages. For example, the CI processing can be used stand alone..
    - Although less straight forward, with third party model extensions or substitutions, it could be used for other applications, e.g., predicting CI users' 1) loudness perception; 2) speech intelligibility ; 3) simulating more complex input systems (e.g., CI users with single-sided deafness or electro- acoustic stimulation) by combining with acoustic periphery models.

References

- G. Ashida, J. Kretzberg, D. J. Tollin: Roles for Coincidence Detection in Coding Amplitude-Modulated Sounds. PLOS Computational Biology 12 (2016) e1004997.
- S. A. Ausili, M. J. H. Agterberg, A. Engel, C. Voelter, J. P. Thomas, S. Brill, A. F. M. Snik, S. Dazert, A. J. Van Opstal, E. A. M. Mylanus: Spatial Hearing by Bilateral Cochlear Implant Users with Temporal Fine-Structure Processing. Frontiers in Neurology 11 (2020).
- S. Fredelake, V. Hohmann: Factors Affecting Predicted Speech Intelligibility with Cochlear Implants in an Auditory Model for Electrical Stimulation. Hear Res 287 (2012) 76-90.
- V. Hamacher: Signalverarbeitungsmodelle Des Elektrisch Stimulierten Gehörs. Ph.D. Ph.D. Thesis, Fak06, RWTH Aachen, Aachen, 2004.
- H. Hu, S. A. Ausili, B. Williges, J. Klug, R. C. Felsheim, D. Vickers, M. Dietz: Matlab Code and Results for the Manuscript Submitted to Acta Acustica 'a Model Framework for Simulating Spatial Hearing of Bilateral Cochlear Implants Users' (Version 1.0). Zenodo. https://doi.org/10.5281/zenodo.7471961.
- H. Hu, J. Klug, M. Dietz: Simulation of Itd-Dependent Single-Neuron Responses under Electrical Stimulation and with Amplitude-Modulated Acoustic Stimuli. JARO (2022).
- H. Hu, M. Dietz, B. Williges, S. D. Ewert: Better-Ear Glimpsing with Symmetrically-Placed Interferers in Bilateral Cochlear Implant Users. JASA 143 (2018) 2128-2141.
- H. Hu, X. Xi, L. L. N. Wong, S. Hochmuth, A. Warzybok, B. Kollmeier: Construction and Evaluation of the Mandarin Chinese Matrix (Cmnmatrix) Sentence Test for the Assessment of Speech Recognition in Noise. Int. J. Audiol. 57 (2018) 838-850.
- A. Ihlefeld, R. P. Carlyon, A. Kan, T. H. Churchill, R. Y. Litovsky: Limitations on Monaural and Binaural Temporal Processing in Bilateral Cochlear Implant Listeners. JARO 16 (2015) 641-652.
- A. Kan, H. G. Jones, R. Y. Litovsky: Lateralization of Interaural Timing Differences with Multi-Electrode Stimulation in Bilateral Cochlear-Implant Users. JASA 140 (2016) EL392-EL398.
- H. Kayser, S. D. Ewert, J. Anemüller, T. Rohdenburg, V. Hohmann, B. Kollmeier: Database of Multichannel in-Ear and Behind-the-Ear Head-Related and Binaural Room Impulse Responses. EURASIP Journal on Advances in Signal Processing (2009) doi: 10.1155/2009/298605
- D. Kelvasa, M. Dietz: Auditory Model-Based Sound Direction Estimation with Bilateral Cochlear Implants. Trends in Hearing 19 (2015) 2331216515616378.
- J. Klug, L. Schmors, G. Ashida, M. Dietz: Neural Rate Difference Model Can Account for Lateralization of High-Frequency Stimuli. JASA 148 (2020) 678-691.
- B. Laback, K. Egger, P. Majdak: Perception and Coding of Interaural Time Differences with Bilateral Cochlear Implants. Hear Res 322 (2015) 138-150.
- O. A. Stakhovskaya, M. J. Goupell: Lateralization of Interaural Level Differences with Multiple Electrode Stimulation in Bilateral Cochlear-Implant Listeners. Ear Hear 38 (2017) e22-e38.
- B. Williges, T. Jürgens, H. Hu, M. Dietz: Coherent Coding of Enhanced Interaural Cues Improves Sound Localization in Noise with Bilateral Cochlear Implants. Trends in Hearing 22 (2018).
- J. Wouters, H. J. McDermott, T. Francart: Sound Coding in Cochlear Implants: From electric pulses to hearing in IEEE Signal Processing Magazine 32 (2015), (2) 67-80.

MATLAB code Download link

Acknowledgements

This work was supported by the European Research Council (ERC) under European Union's Horizon 2020 Research and Innovation Program grant agreement no. 716800 (ERC Starting Grant to Mathias Dietz). Deborah Vickers and Ben Williges were supported by a UK Medical Research Council Senior Fellowship (MR/S002537/1).