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BETTER-EAR-LISTENING VS. COMBINED BILATERAL INFORMATION ACROSS EARS IN ASYMMETRIC HEARING

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ABSTRACT

A growing number of cochlear implant (CI) users have asymmetric hearing, where one ear is aided with a CI, and the other ear has different degrees of useable acoustic hearing, ranging from aided with hearing aids (bimodal CI) to normal hearing (CI-Single-Sided Deaf, CI-SSD). Benefits of these combinations include improved quality of life, better speech intelligibility, and better localization abilities. To further understand the varying individual benefit, predictions from two different physiologically inspired computer model versions were compared to data previously collected from eight bimodal and eight CI-SSD users for speech-in-noise tasks (speech-reception-thresholds, SRTs). One model version predicts an SRT for each ear independently, and chooses the better SRT for each task (better-ear-listening). The other model version uses information from both acoustic and electric hearing to predict an SRT (complementary information).

Both model versions showed a satisfactory fit to the measured data (RMS-Error: 2.7 dB). The complementary information model showed a bimodal benefit (3 dB for bimodal CI, 2 dB for CI SSD), surprisingly only for lateral noise incident, but not for frontal sound incident. A better-ear-listening approach explained most of the observed data, only in few cases the complementary information model matched experimental data better.

Keywords: *Cochlear Implant, Speech intelligibility, Spatial hearing, computational model*

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1. INTRODUCTION

Cochlear implant (CI) listeners with contralateral acoustic hearing (bimodal listeners) or single sided deaf (CI-SSD listeners) show improved speech intelligibility benefits compared to unilateral listeners, particularly in spatially separated speech and noise conditions (e.g. [1]). These benefits of having access to acoustic and electric information in opposite ears are, however, highly variable across individuals. This variability complicates an understanding about how much of the benefits are related to better ear listening, how much are related to complementary usage of information (access to acoustic and electric information), or how much is related to binaural processing. Here we employ a physiologically inspired model to predict group median spatial speech intelligibility of CI SSD and bimodal CI listeners. The model is used either in a “better ear listening” approach or a complementary usage of information approach.

2. METHODS

For comparing model results to actual patient data, patient data was taken from [2]: They measured speech in noise performance in 16 CI listeners, eight of whom were bimodally aided, and eight were CI-SSD. Additionally, eleven normal hearing listeners served as a control group. Matrix-style (e.g. Oldenburg sentence test) sentences were presented in a closed-set format, and speech-shaped noise was added to the sentences. Lists of 20 sentences were used. Spatial rendering of three different sound locations were done by convolving the wave-file with head-related-impulse-responses [3] recorded from microphones located in behind-the-ear hearing aid dummies on an artificial manikin. The three different spatial locations were noise

coming from the left (denoted N-90°), front (denoted N0°), or right (denoted N90°). Speech was always presented from the front (S0°). Target speech reception was 50%, and the SNR changes from first to last presentation of each list adaptively based on the maximum likelihood estimation procedure according to [4].
From the SRTs the following secondary measures were derived: Binaural Summation (sometimes also termed bimodal Benefit, CI-Benefit, or binaural Benefit) was calculated by subtracting the bilateral SRT from the best monaural one. Spatial release from masking (SRM) was calculated by calculating the difference in SRT between lateral noise incident and frontal sound incident.

2.1 Model Details

The model used different features for (impaired) acoustic hearing and electric hearing, which act as inputs for a speech recognition backend (FADE, [6]). The speech recognition backend had a-priori information about the speech token used (Oldenburg Sentence Test, e.g. 50 whole word tokens, with a hidden markov model for transition from silence to word token, and also knows the matrix-like structure of the sentences, thus forming a perfect listener, capable of extracting all available information). Speech and noise tokens (including HRTFs) were exactly the same as in the actual patient data. It outputs a speech reception threshold (SRT) independently for each ear ("better ear listening") or it combines the electric and acoustic feature to one feature set and predicts one SRT from this set (thereby exploiting possible "complementary usage of information").

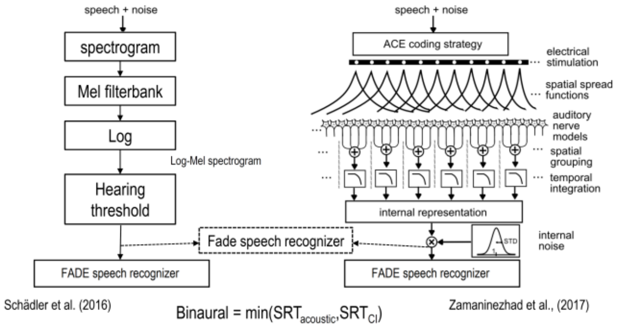

Figure 1. Overview of the model stages. Impaired acoustic model for the left ear, and CI model for the right ear. The FADE speech recognizer backend outputs a SRT using either only the internal representation from one ear as input, or uses the internal representations from both ears concatenated as input. In the case of impaired acoustic hearing, the speech + noise input signal is amplified according to the respective hearing loss.

Hearing loss on the acoustic side was modeled as increased internal noise due to the audiometric thresholds (attenuation), no supra-threshold deficits were taken into account. Aided hearing was simulated by processing the sound stimuli with the research master hearing aid [6] using CAMFIT-gain rule, as in [2]. A mild-to-severe sloping hearing loss was simulated.

CI listening was simulated using a physiologically inspired model of electric hearing [7]. The model simulated ACE coding strategy, an unrolled cochlea with a regular CI insertion, current spread, individual auditory nerve cells (leaky-integrate and fire), taking into account refractoriness, facilitation, and tonotopic organization along the cochlear. More specifically the following model parameters were chosen: Spatial spread of the electric field: 0.3mm, 2200 auditory nerve cells were simulated, and cognitive effects were simulated with a multiplicative Gaussian distributed noise with standard deviation of 0.2 applied to the internal representation. These parameters were empirically chosen such that the median SRT of the CI only data in the actual patient data for frontal sound incident (N0°) matches the corresponding predicted SRT. The acoustic hearing model parameters (default from [5]) matched NH unilateral patient data for frontal sound incident. All the other hearing configurations (bimodal CI, CI-SSD) and noise directions were predicted by the different models.

3. RESULTS

Prediction from the two models in comparison to actual patient data can be found in Fig. 2 for absolute SRTs, Fig. 3 for SRM, and Fig. 4 for binaural Summation. Overall the correlation between modelled SRTs and actual SRTs is high (R^2=0,88, p<0.001, for both models) with a root-mean-squared error of 2.7 dB, leading to a good match between model and actual human performance. Both models are sensitive to changes in spatial scene. For aided hearing unilaterally condition (red), the hearing thresholds are compensated for in the model, resulting in a close match to NH unilateral listening mode (black, taking the assumption that the hearing loss was completely due to audibility). For SRM, the model values are in general higher than the actual patient data, independent of listening mode (unilaterally, bilaterally, or electric side or acoustic side).

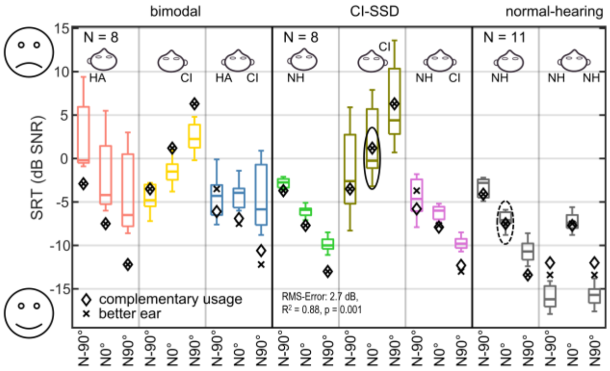

Figure 2. Absolute SRTs for the three different listening groups (bimodal CI, CI-SSD, and NH control group) compared to model predictions (diamonds for complementary use of information model, crosses for better ear listening model). On the x-axis the different noise directions are displayed.

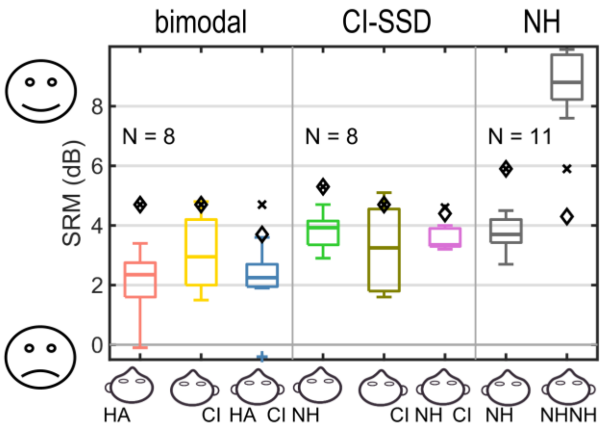

Figure 3. Spatial release from masking for the three different listening groups (bimodal CI, CI-SSD, and NH control group) compared to model predictions (diamonds for complementary use of information model, crosses for better ear listening model). On the x-axis the different hearing configurations are displayed.

For binaural summation, the better ear listening model shows no binaural summation (by design, as there is no interaction between the two ears). The complementary use of information model shows a benefit for N-90 and a decrease for N90. The decrease is of the same order as in the normal hearing control condition. The predicted benefit for N-90 is consistent for both bimodal and CI-SSD groups, and again a bit higher (1-1.5 dB in SRT) than the median of the actual patients.

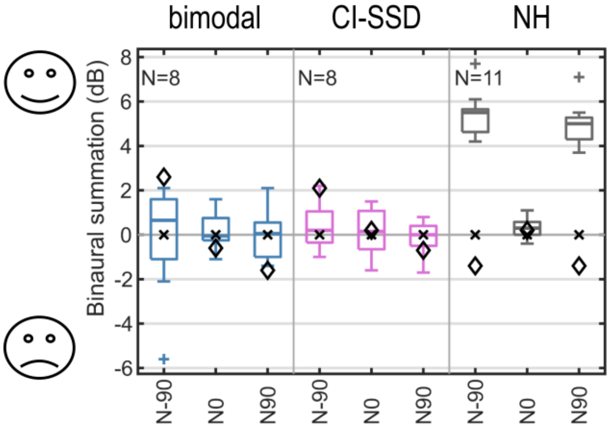

Figure 4. Binaural summation for the three different listening groups (bimodal CI, CI-SSD, and NH control group) compared to model predictions (diamonds for complementary use of information model, crosses for better ear listening model). On the x-axis the different noise directions are displayed.

4. DISCUSSION

There are several small differences between predicted data by the different models and actual patient data:
The model overestimates the SRM independent of feature, due to a "perfect" training of the speech classifier, similar to an experienced patient.
The model for acoustic hearing needs to incorporate subthreshold effects ("Audibility" is restored with MHA). This could be done using tests like tone-detection in noise. Supra-threshold effects were not taken into account here, as no additional measures were conducted during data collection from actual patients. Readily clinically available would be for instance some form of discrimination loss of monosyllabic words.
The combined usage of information model assumes equal contribution of acoustic and electric information, which might not be the best fit [8], and could explain, why there is a benefit for N-90°, and an interference for N90. The combined benefit in actual CI listeners is likely underestimated due to stationary noise masker (less "glimpsing" of acoustic information), anechoic HRTFs, and is noise-direction dependent [2].
This study did not directly investigate the use of binaural processing in bimodal CI and CI SSD. The two models proposed are quite simple, and do not assume any central

interactions or top-down processing (see [9] for a review). However, the comparison to normal hearing control data can serve as guidelines for the achieveable binaural benefit, after acoustic headshadow is accounted for:
Pure binaural processing should yield at least 2 dB SRT benefit in comparable scenarios, see for example the NH binaural summation data reaching 4 dB for lateral sound incident. This is a purely binaural effect, and needs appropiate coding of interaural cues like interaural coherence, time- and level-differences. However, speech in noise might not be the best test to use in clinical practice to show the benefit of having two ears, questionnaires,localisation tasks or binaural masking level difference tests might be more efficient.
Current provision (as of 2025) for bimodal CI for the three major CI manufacturers is in line with the presented outcomes: One manufacturer couples the hearing aid tightly with the CI including synchronizing automatic gain control, and bilateral beamformers. Another aims to minimize the interaural mismatch, and the third mainly focuses on user comfort when streaming audio.

5. CONCLUSION

The models capture the changes in SRT due to different acoustic and electric inputs and due to different spatial scenes. A simple "better ear listening" model explains most of the data in stationary noise for bimodal CI and CI SSD listeners. For noise from the acoustically aided side the complementary usage of information across ears model is more suitable.

6. ACKNOWLEDGMENTS

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