Modeling individual loudness perception in cochlear implant recipients with normal contralateral hearing

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Use of acoustic and electric models may make the fitting of bimodal patients more efficient. The electric loudness model (McKay *et al.*, 2003) was extended to account for simultaneous and high-rate stimulation. Both acoustic and electric loudness models require clinical audiometric data for individualization. While the availability of an individual's thresholds is essential to achieve accurate model predictions, average values of electric field spread can be used for calculating group data. The use of individual spatial spread functions may further improve model predictions, allowing individual predictions and hence automating bimodal loudness balancing.

INTRODUCTION

Due to widening candidacy criteria for provision of cochlear implants (CIs), more and more CI recipients have aidable contralateral hearing and, thus, wear a hearing aid (HA) in addition to their CI. This bimodal configuration is used worldwide by about 30% of all CI recipients (Scherf and Arnold, 2014) and has been shown to improve speech understanding in noise, localization, sound quality and music perception (Ching *et al.*, 2007). In order to achieve the maximum bimodal benefit for an individual patient, balancing of loudness across ears is regarded to be important (Francart and McDermott, 2013; Dorman *et al.*, 2014). Manual adjustment of HA and CI, however, is very tedious and time-consuming as there are many parameters to be optimized, such as channel gains, compression ratio and knee-points, M- and T-Levels, input dynamic range and sensitivity. Typically, two different fitting modules are used by the clinician. As a consequence, in clinical practice, loudness is often not balanced and, thus, the patient may not obtain the maximum bimodal benefit.

A possible way to speed up bimodal loudness balancing is to use loudness models. Ideally, such models would be individualized for a given patient. This would then help predict both individual acoustic and electric loudness, automatically finding the HA and CI parameters that lead to balanced loudness for a large variety of relevant stimuli. Research on acoustic loudness models started in the late 1950s (Zwicker, 1958). Hence, today acoustic loudness is probably the best understood hearing sensation and broadly validated loudness models for normal-hearing and hearing-impaired listeners are available (e.g., Moore and Glasberg 1997; Chalupper and Fastl, 2002). In contrast, work on electric loudness models started rather recently (McKay *et al.*, 2003) and, thus, a large number of effects in electric loudness perception still

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needs further investigation. The general structure of electric and acoustic loudness models, however, seems to be the same (Fig. 1). First, an acoustic free-field stimulus is converted into the respective spatial excitation pattern inside the cochlea. Next excitation is transformed into specific loudness in Sone per critical band. Finally, specific loudness is summed across all critical bands to calculate overall loudness in Sone. As categorical loudness scaling is often used in behavioural measurements of loudness, Sone have to be converted into categorical units (CU).

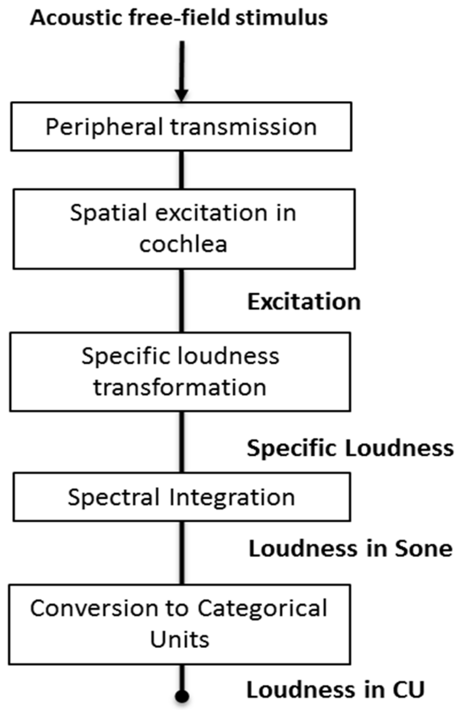

Fig. 1: General structure of loudness models.

The "practical" electric loudness model of McKay *et al.* (2003) is based on the simplifying assumption that each electrode contributes independently to overall loudness and thus, any explicit modelling of electric field interactions is not required. As a consequence, this model does not comprise a stage to calculate spread of excitation across electrodes, but directly converts current amplitudes of a CI's pulse pattern into specific loudness. This approach is valid for channel rates between 200 pulses per second (pps) and 1000 pps and overall pulse rates between 500 pps and 4000 pps, but is not valid for simultaneous or analog electric stimulation. At present, however, some advanced coding strategies use simultaneous stimulation for current steering and pulse rates of more than 1000 pps (e.g., Advanced Bionics HiRes Fidelity 120, Nogueira *et al.*, 2009). Chalupper et al. (2015) used the "practical" model to predict loudness summation of CI recipients using Advanced Bionics' HiRes Fidelity 120 and concluded that the model overestimates the loudness summation effect and that spread of excitation needs to be accounted for. Additionally, lack of behavioural M- and T-levels and use of fluctuating noises complicate the model calculations.

The purpose of the present study was to investigate whether a modified electric loudness model could be used for balancing electric and acoustic loudness. CI recipients with normal contralateral hearing were studied as special case of bimodal users to avoid modelling the signal processing and coupling acoustics of hearing aids.

ELECTRIC AND ACOUSTIC LOUDNESS MODEL

Structure

For the calculation of acoustic loudness the dynamic loudness model (DLM, Chalupper and Fastl, 2002) was used. As only stationary stimuli and unaided acoustic hearing were used in this study, dynamic blocks of the DLM (forward masking, temporal integration) and HA signal processing were not included in the calculation (see Fig. 2). The "practical" electric loudness model was extended by explicitly modelling electric field spread according to Hamacher (2004). A simulation of the signal processing blocks of HiRes Fidelity 120 was used to calculate electrodograms for acoustic free-field stimuli. An individualized specific loudness transform was employed to calculate specific loudness patterns across critical band rate from acoustic excitation patterns and spatial electric field, respectively. To convert Sone into CU, a cubic fit function using four parameters as suggested by Heeren *et al.* (2013) was applied.

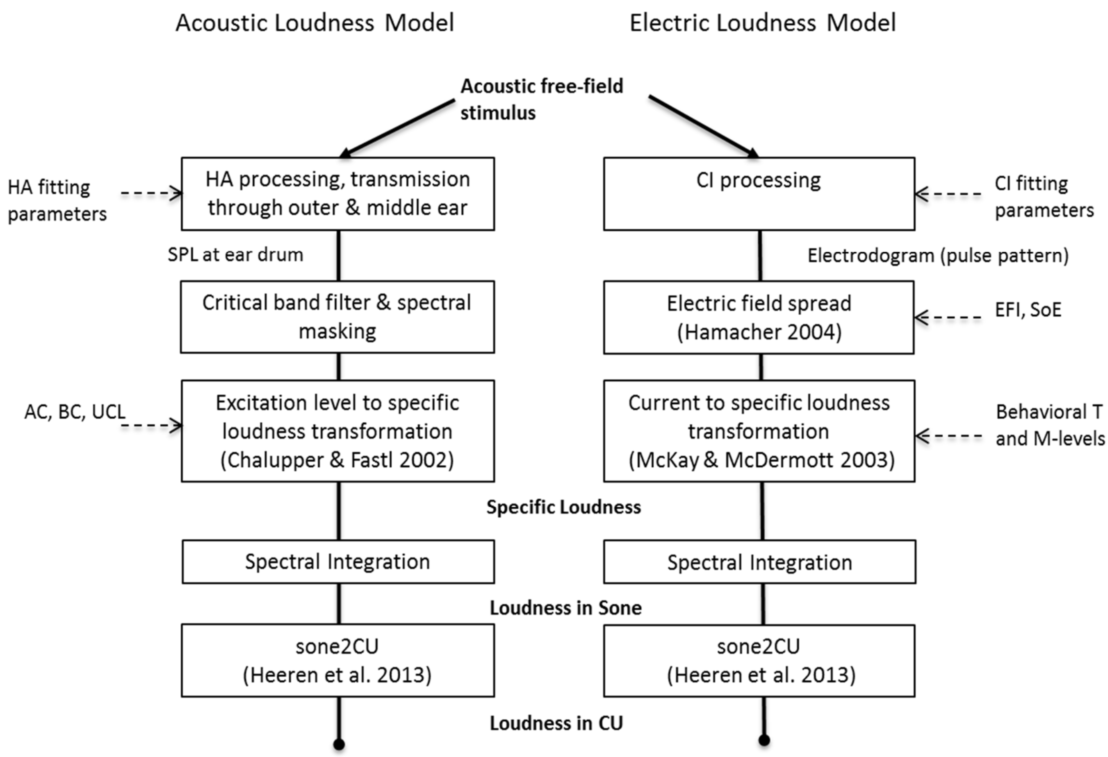

Fig. 2: Block diagram of electric and acoustic loudness models.

Electric field spread

The electric field spread was calculated using a double-sided one-dimensional exponentially decreasing function with a spread constant lambda. It is generally assumed that the spread constant varies substantially across CI patients, type of electrode arrays and electrodes within an array. Based on considerations in Fredelake and Hohmann (2012), lambda values (exponential spatial decay constants) of 1 mm and 10 mm were included in loudness model calculations. Figure 3 shows the resulting electric fields for simultaneous stimulation of two adjacent electrodes.

Individualization

To individualize the acoustic loudness model, unaided air conduction thresholds (AC) were used to adapt the parameters of the specific loudness transformation. For individualization of the electric loudness model, the individual maps of the CI recipients were employed in the simulation of the CI signal processing. Additionally, the parameters of loudness growth function given by McKay *et al.* (2003) were individually fitted to subjects' behavioural T-level.

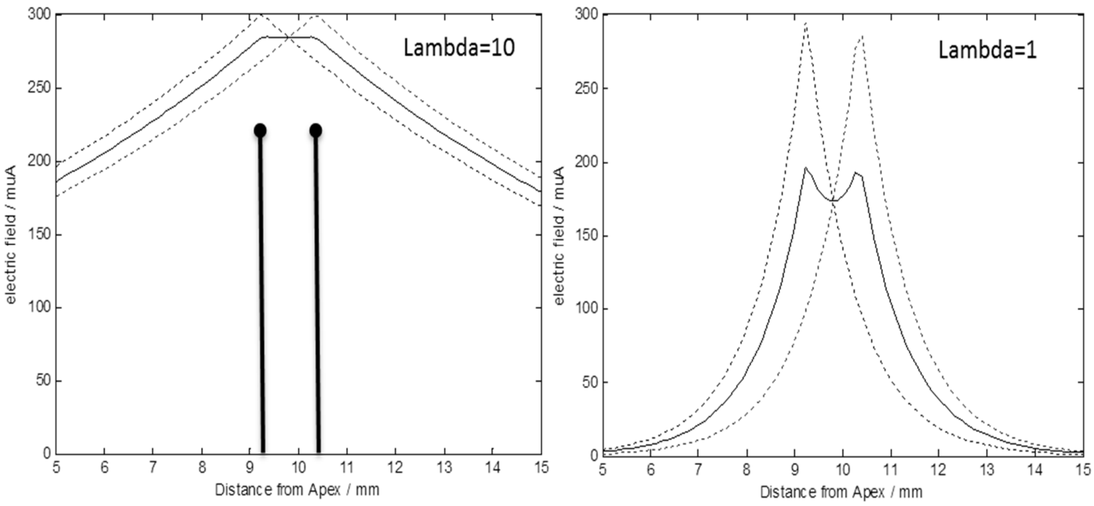

Fig. 3: Spatial spread of electric field for simultaneous stimulation. Left: spread function with lambda = 10. Right: spread function with lambda = 1.

EVALUATION

Data from a study with single-sided deaf CI-recipients conducted by Büchner et al. (2013) were used to evaluate the acoustic and electric loudness models.

Methods

Five CI recipients with contralateral thresholds of better than 30 dB HL below 4 kHz participated in this study. All stimuli were presented via direct audio input (DAI) and headphone to CI and normal-hearing ear, respectively. The fitting of the CI was adjusted to achieve balanced loudness perception: T-levels were set to behaviourally measured T-levels. M-levels were adjusted until subjects indicated the same interaural loudness for narrow band noises presented at 80 dB SPL. Input Dynamic Range (IDR) was modified to balance loudness for speech shaped noise presented at 50 and 80 dB SPL. To verify the result of this fitting approach, loudness scaling was administered for both the electric and acoustic ears separately.

Results

The modified electric loudness model is able to predict loudness of narrowband stimuli with a similar accuracy as acoustic loudness models. Typical cases for acoustic modelling and electric modelling are shown in Fig. 4 and Fig. 5, respectively. The selection of lambda did not affect the accuracy of the electric model predictions.

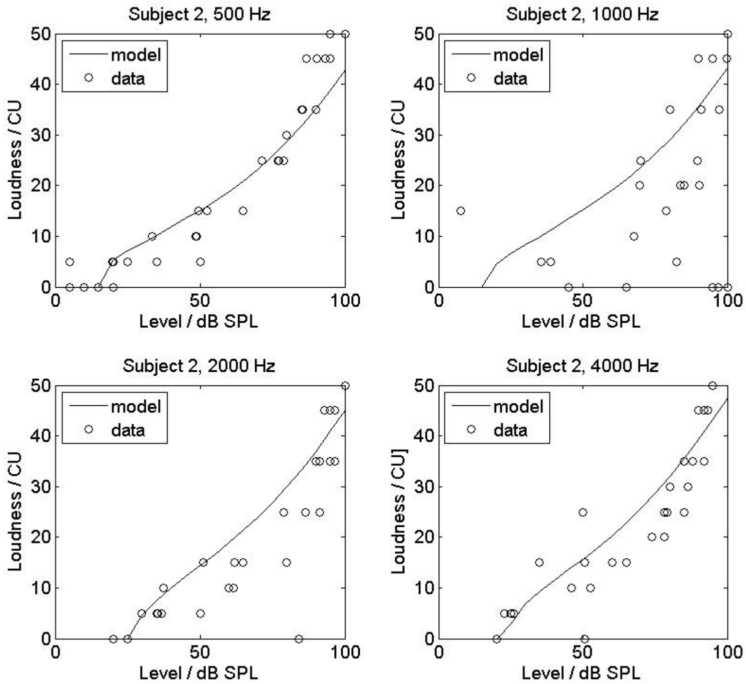

Fig. 4: Individual acoustic model predictions and behavioural data for narrowband stimuli.

In order to evaluate the models for broad-band sounds, acoustic and electric loudness growth curves for speech were calculated using the same parameters as for modelling the loudness of narrowband stimuli. Recall that during fitting, loudness of speech noise was balanced for 50 dB SPL and 80 dB SPL. Assuming that both models are valid for narrowband stimuli, the level difference at the same calculated loudness for speech can be used to evaluate model predictions for broadband sounds. Figures 6 and 7 indicate that selection of lambda can make a substantial difference for some subjects. Thus, further individualization of the electric model by using individual and electrode-specific spread functions has the potential to improve the model predictions for the individual listener. Individual spread functions can be derived from impedance measurements between electrodes (“electric field imaging”) or individual electrically evoked compound action potential (ECAP) data.

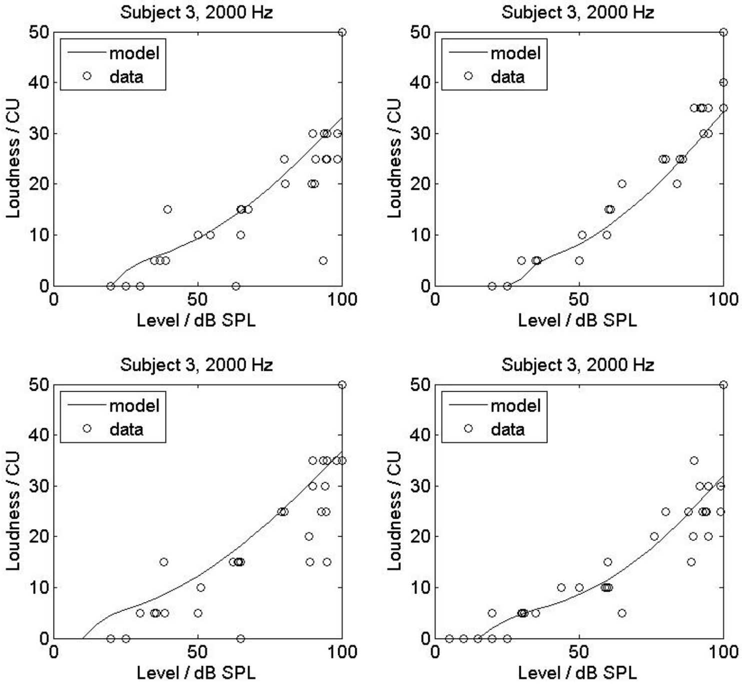

Fig. 5: Individual electric model predictions and behavioural data for narrowband stimuli.

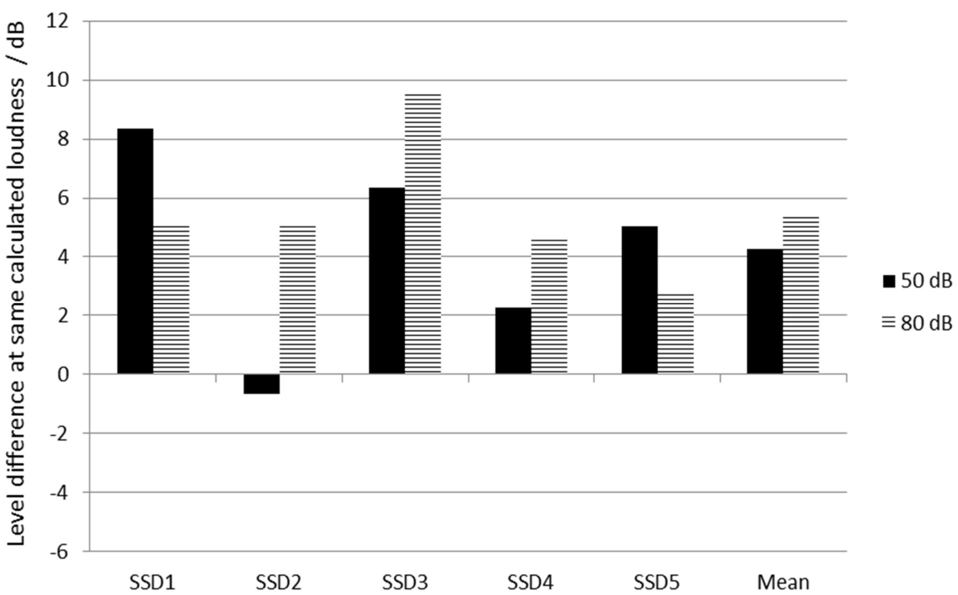

Fig. 6: Individual model predictions and behavioural data for loudness summation with lambda = 10.

On average, with a spatial spread of 10 mm, the loudness summation effect for broad-band stimuli is underestimated, while a spread of 1 mm results in an average prediction error of less than 2.5 dB. While this should be sufficient for modelling group differences, this approach presumably is not accurate enough to automate loudness balancing, as there are deviations for individuals by more than 5 dB. Moreover, the prediction of loudness of time-varying stimuli needs to be modelled and verified (Francart *et al.*, 2014).

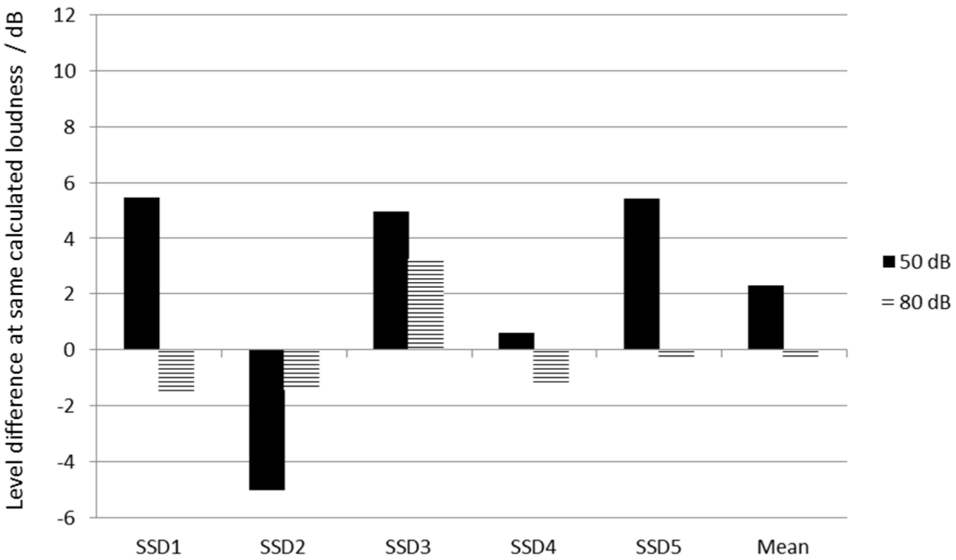

Fig. 7: Individual model predictions and behavioural data for loudness summation with lambda = 1.

CONCLUSIONS

In order to predict the loudness of CI coding strategies employing current steering and high pulse rates, electric loudness models must incorporate a stage to simulate the spatial electric field within the cochlea. Using standard audiometric data (electric and acoustic thresholds) allows the prediction of loudness for stationary stimuli on a group level. For the application of loudness models to automatically adjust fitting parameters of CI and HA to achieve a balanced interaural loudness, however, further individualization appears to be required. Electric field imaging, or electrically evoked compound action potentials, could be used to individualize spatial spread functions and, thus, improve the accuracy of individual loudness predictions.

REFERENCES

Büchner, A., Geissler, G., Lenarz, T., Lesinski-Schiedat, A., Chalupper, J., Brendel, M., and Fredelake, S. (**2014**). "Lautheitswahrnehmung bei einseitig tauben Cochlea-Implantat-Trägern," 17. Jahrestagung der Deutschen Gesellschaft für Audiologie (DGA), Oldenburg.

Chalupper, J. and Fastl, H., (**2002**). "Dynamic Loudness Model (DLM) for normal and hearing-impaired listeners", Acta Acust. United Ac., **88**, 378-386.

Chalupper, J., Schulz, J., Elke Devocht, E., George, E., and Fredelake, S. (**2015**). "Modeling the effects of pulse width and acoustic bandwidth on electric loudness perception," 18. Jahrestagung der Deutschen Gesellschaft für Audiologie (DGA), Bochum.

Ching, T.Y., van Wanrooy, E., and Dillon, H. (**2007**). "Binaural-bimodal fitting or bilateral implantation for managing severe to profound deafness: A review," Trends Amplif., **11**, 161-192.

Dorman, M.F., Loizou, P., Wang, S., Zhang, T., Spahr, A., Loiselle, L., and Cook, S. (**2014**). "Bimodal cochlear implants: The role of acoustic signal level in determining speech perception benefit," Audiol. Neurotol., **19**, 234-238.

Francart, T. and McDermott, H.J. (**2013**). "Psychophysics, fitting, and signal processing for combined hearing aid and cochlear implant stimulation. Review," Ear. Hearing, **34**, 685-700

Francart, T., Innes-Brown, H., McDermott, H.J., and McKay, C.M. (**2014**). "Loudness of time-varying stimuli with electric stimulation," J. Acoust. Soc. Am., **35**, 3513-3519.

Fredelake, S. and Hohmann, V. (**2012**). "Factors affecting predicted speech intelligibility with cochlear implants in an auditory model for electrical stimulation," Hear. Res., **287**, 76-90.

Hamacher, V. (**2004**). *Signalverarbeitungsmodelle des elektrisch stimulierten Gehörs*. Ph.D. thesis, RWTH Aachen. Wissenschaftsverlag Mainz in Aachen, 1. Edition.

Heeren, W., Hohmann, V., Appell, J.E., and Verhey, J.L. (**2013**). "Relation between loudness in categorical units and loudness in phons and sones," J. Acoust. Soc. Am., **133**, EL314-319.

McKay, C.M., Henshall, K.R., Farrell, R.J., and McDermott, H.J. (**2003**). "A practical method of predicting the loudness of complex electrical stimuli," J. Acoust. Soc. Am., **113**, 2054-2063.

Moore, B.C.J. and Glasberg, B. (**1997**). "A model of loudness perception applied to cochlear hearing loss," Audit. Neurosci., **3**, 289-311.

Nogeira, W., Litvak, L., Edler, B., Ostermann, J., and Büchner, A. (**2009**). "Signal processing strategies for cochlear implants using current steering," EURASIP J. Adv. Sig. Proc., **2009**, 1-20.

Scherf, F. and Arnold, L. (**2014**). "Exploring the clinical approach to the bimodal fitting of hearing aids and cochlear implants: Results of an international survey," Acta Otolaryngol., **134**, 1151-1157.

Zwicker, E. (**1958**). "Über psychologische und methodische Grundlagen der Lautheit", Acustica, **8**, 237-258.