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Research Paper

A physiologically-inspired model reproducing the speech intelligibility benefit in cochlear implant listeners with residual acoustic hearing

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ABSTRACT

This study introduces a speech intelligibility model for cochlear implant users with ipsilateral preserved acoustic hearing that aims at simulating the observed speech-in-noise intelligibility benefit when receiving simultaneous electric and acoustic stimulation (EA-benefit). The model simulates the auditory nerve spiking in response to electric and/or acoustic stimulation. The temporally and spatially integrated spiking patterns were used as the final internal representation of noisy speech. Speech reception thresholds (SRTs) in stationary noise were predicted for a sentence test using an automatic speech recognition framework. The model was employed to systematically investigate the effect of three physiologically relevant model factors on simulated SRTs: (1) the spatial spread of the electric field which co-varies with the number of electrically stimulated auditory nerves, (2) the “internal” noise simulating the deprivation of auditory system, and (3) the upper bound frequency limit of acoustic hearing. The model results show that the simulated SRTs increase monotonically with increasing spatial spread for fixed internal noise, and also increase with increasing the internal noise strength for a fixed spatial spread. The predicted EA-benefit does not follow such a systematic trend and depends on the specific combination of the model parameters. Beyond 300 Hz, the upper bound limit for preserved acoustic hearing is less influential on speech intelligibility of EA-listeners in stationary noise. The proposed model-predicted EA-benefits are within the range of EA-benefits shown by 18 out of 21 actual cochlear implant listeners with preserved acoustic hearing.

1. Introduction

Due to advances in surgical techniques and design of short and delicate electrode arrays, there is the possibility to preserve acoustic hearing after cochlear implantation for a subgroup of CI candidates, whose apical auditory nerves can still be stimulated acoustically. The acoustic stimulation is often amplified using a hearing aid (HA). This group of CI users that receives both electric and acoustic stimulation in the same ear are called electro-acoustic (EA) or hybrid listeners.

Several clinical studies show a benefit in speech intelligibility for EA stimulation in comparison with electric-only or ipsilateral acoustic-only stimulation both in quiet and in noise. This EA-benefit is either expressed as a gain in percent of correctly understood words or sentences, or as an improvement in dB of the speech reception threshold (SRT), which is the signal-to-noise ratio (SNR) resulting in 50% correct recognition of the speech material. EA-benefits of about 0%–30% were found for monosyllables in quiet (Gstoettner et al., 2006) and of about 25%–50% for sentences in noise (Kiefer et al., 2005). James et al. (2006) measured on average 12% improvement in an open-set speech recognition task in quiet for EA stimulation in comparison with electric-only stimulation and about 14% speech recognition improvement in a multi-talker babble noise condition. Lenarz et al. (2009) found higher EA-benefits in EA listeners who had a short duration of hearing loss prior to implantation compared to listeners with longer duration of hearing loss using the German matrix sentence test (Wagener et al., 1999) in stationary noise. However, Lenarz et al. (2009) also reported a large learning effect on speech intelligibility of the latter

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Abbreviations

AI	articulation index
AN	auditory nerve
ASR	automatic speech recognizer
BF	best frequency
CI	cochlear implant
DRNL filter	dual resonance non linear filter
DTW	dynamic time warp
EA	electro-acoustic
EAS	electro-acoustic stimulation
FADE	framework for auditory discrimination experiments
GMM	Gaussian mixture model
HA	hearing aid
HI	hearing impaired
HMM	hidden Markov model
HSR	high spontaneous rate
I	current amplitude of the electric pulse (A)
$\tilde{I}$	local input current amplitude stimulating one nerve cell (A)
IR	internal representation
λ	constant of spatial spread function (mm)
MCL	most comfortable level
N	auditory nerve cell number
NH	normal hearing
NSIM	neurogram similarity index measure
PA	participant
PPS	pulse per second
SDT	signal detection theory
SII	speech intelligibility index
SNR	signal to noise ratio
SRT	speech reception threshold
σ	standard deviation of internal noise
TCL	threshold current level
x_{el}	position of electrode (mm)
x_n	position of the nerve cell on the basilar membrane (mm)

group. A multi-center study by Lenarz et al. (2013) gives a comprehensive overview over the EA-benefit using different speech recognition tests. They observed a significant average EA-benefit of 20% or 2 dB SRT-improvement for a large number of EA listeners. Turner et al. (2010) reported around 5 dB improvement in mean SRTs for recognition of spondees using competing talker-noise. In general, EA-benefit in terms of speech perception was reported to show high inter-individual variability across patients.

Less inter-individual variability was found in studies simulating the effect of EA stimulation using vocoders. In these studies, normal-hearing (NH) listeners were asked to recognize speech that was processed in order to simulate the restrictions present in electric hearing with and without simultaneously adding a simulation of residual acoustic hearing (which was mostly realized by low-pass filtering the speech). Dorman et al. (2005) found an EA-benefit of 15%–30% in a quiet listening and in a multi-talker babble noise condition, depending on the distribution of frequency content across electric and acoustic part of the simulation. Qin and Oxenham (2006) found EA-benefits of up to 6 dB in a competing talker listening condition and around 4 dB in stationary speech-shaped noise condition. An EA-benefit was also reported by Williges et al. (2015) for different simulated listener types in different spatial arrangements of speech and stationary noise. The monaural EA-benefit in SRT was found to be about 2 dB for a word recognition task in stationary speech-shaped noise. In summary, vocoder studies are important for systematically investigating how different signal processing algorithms, external characteristics of speech and noise, and patient-specific characteristics affect the EA-benefit. However, they require extensive and time consuming experiments with NH listeners. Furthermore, it is unclear to what extent the auditory nerve response in vocoder-stimulated NH listeners resembles the response in actual EA subjects. An investigation of quantitative computer models of EA listening and a comparison of model simulations with vocoder and human data therefore seems indicated to enlarge the understanding of information coding in the EA-stimulated auditory system.

Completely virtual listeners, i.e., computer models, can be valuable tools to investigate the effect of EA stimulation on speech intelligibility. Computer models mimicking the auditory physiology and the implanted prosthesis can help to clarify the role of different physiological or CI-related parameters (e.g., residual hearing, electrode location) on speech perception and shed light on the mechanisms that lead to an EA-benefit. Furthermore, such models could be used to objectively quantify expected EA-benefit depending on different signal processing strategies used across the two devices, allowing a large number of parameters in these algorithms to be tested. The most promising signal processing strategies could then further be evaluated with simulated and actual EA listeners.

The articulation index (AI, ANSI, 1969) and the speech intelligibility index (SII, ANSI, 1997) as classical speech intelligibility models may not be sufficient tools for these tasks. These models evaluate "macroscopic" features of speech and noise, such as long-term average spectra, and are based on the assumption that different frequencies contribute with different weights to speech intelligibility. Although these models have reasonably accurate prediction for speech intelligibility of NH and hearing-impaired (HI) listeners (Pavlovic et al., 1986), they are tailored to acoustic hearing and do not account for the restrictions of electric hearing (e.g., missing transmission of temporal fine structure due to constant pulse rate (Nogueira et al., 2005) or different amounts of electric field spatial spread). Thus, these models give little attention to auditory physiology and do not offer a basis for exploring the effect of different physiological factors of impairment on speech intelligibility. Furthermore, these models need a priori knowledge about separated clean speech and noise, which is difficult to obtain in case the processing of the speech-noise mixture is nonlinear, as it is the case in most hearing aids and CIs.

Speech intelligibility models that evaluate the "microscopic" features of noisy speech (spectro-temporal fluctuations and temporal fine structure) and incorporate details of the auditory physiology may be better suited for studying the EA-benefit. Microscopic models mimic different processing blocks of the auditory system either closely to the physiology or in a functional way. Holube and Kollmeier (1996) and Jürgens and Brand (2009) introduced such auditory models based on a psychoacoustical approach to predict speech intelligibility in HI and NH listeners. These models were used to investigate different physiological parameters on predicted speech intelligibility. For speech intelligibility in CI users, Stadler and Leijon (2009) used a physiologically-inspired model to predict the influence of spectral resolution on CI users' speech recognition performance. Fredelake and Hohmann