Refining a model of hearing impairment using speech psychophysics

The premise of this study is that models of hearing, in general, and of individual hearing impairment, in particular, can be improved by using speech test results as an integral part of the modeling process. A conceptual iterative procedure is presented which, for an individual, considers measures of sensitivity, cochlear compression, and phonetic confusions using the Diagnostic Rhyme Test (DRT) framework. The suggested approach is exemplified by presenting data from three hearing-impaired listeners and results obtained with models of the hearing impairment of the individuals. The work reveals that the DRT data provide valuable information of the damaged periphery and that the non-speech and speech data are complementary in obtaining the best model for an individual.

Efficient estimates of cochlear hearing loss parameters in individual listeners

It has been suggested that the level corresponding to the knee-point of the basilar membrane (BM) input/output (I/O) function can be used to estimate the amount of inner- and outer hair-cell loss (IHL, OHL) in listeners with a moderate cochlear hearing impairment Plack et al. (2004). According to Jepsen and Dau (2011) IHL + OHL = HLT [dB], where HLT stands for total hearing loss. Hence having estimates of the total hearing loss and OHC loss, one can estimate the IHL. In the present study, results from forward masking experiments based on temporal masking curves (TMC; Nelson et al., 2001) are presented and used to estimate the knee-point level and the compression ratio of the I/O function. A time-efficient paradigm based on the single-interval-up-down method (SIUD; Lecluyse and Meddis (2009)) was used. In contrast with previous studies, the present study used only on-frequency TMCs to derive estimates of the knee-point level. Further, it is explored whether it is possible to estimate the compression ratio using only on-frequency TMCs. 10 normal-hearing and 10 hearing-impaired listeners (with mild-to-moderate sensorineural hearing loss) were tested at 1, 2 and 4 kHz. The results showed a reasonable reliability and may be applicable to individualized hearing-aid fitting. © 2013 Acoustical Society of America.
Simulating psychophysical tuning curves in listeners with dead regions

Objective: This study investigates the relation between diagnosis of dead regions based on the off-frequency psychophysical tuning curve (PTC) tip and the frequency and level of the probe tone. Design: A previously developed functional model of auditory processing was used to simulate the complete loss of inner hair cells (IHC), dysfunction of outer hair cells (OHC), complete loss of IHCs in combination with OHC dysfunction, and IHC insensitivity. The model predictions were verified through comparison with experimental data. Study sample: This study compares PTC data of five normal-hearing listeners and six hearing-impaired listeners with model-simulated PTC data. Results: It was shown that OHC activity and IHC insensitivity may significantly alter the shift of PTC tips with increasing probe level. Conclusions: Model results suggest that OHC activity and IHC insensitivity can change the outcome of dead region diagnosis using PTCs. Supplementary to PTC dead region diagnostic information, model results may provide additional information regarding the edge frequency of a dead region and OHC function.

A computational model of auditory stream segregation based on a temporal coherence analysis

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A physiologically inspired model of auditory stream segregation based on a temporal coherence analysis

The ability to perceptually separate acoustic sources and focus one's attention on a single source at a time is essential for our ability to use acoustic information. In this study, a physiologically inspired model of human auditory processing [M. L. Jepsen and T. Dau, J. Acoust. Soc. Am. 124, 422-438, (2008)] was used as a front end of a model for auditory stream segregation. A temporal coherence analysis [M. Elhilali, C. Ling, C. Micheyl, A. J. Oxenham and S. Shamma, Neuron. 61, 317-329, (2009)] was applied at the output of the preprocessing, using the coherence across tonotopic channels to group activity across frequency. Using this approach, the described model is able to quantitatively account for classical streaming phenomena relying on frequency separation and tone presentation rate, such as the temporal coherence boundary and the fission boundary [L. P. A. S. van Noorden, doctoral dissertation, Institute for Perception Research, Eindhoven, NL, (1975)]. The same model also accounts for the perceptual grouping of distant spectral components in the case of synchronous presentation. The most essential components of the front-end and back-end processing in the framework of the presented model are analysed and future perspectives discussed.

Behavioral estimates of basilar-membrane input-output in normal-hearing listeners

To characterize human cochlear processing it would be beneficial to behaviorally estimate the basilar membrane (BM) input-output (I/O) function. In recent studies, forward masking has been used to estimate BM compression. In this study, a growth-of-forward-masking (GOM) paradigm (e.g., Oxenham and Plack, 1997) was extended to also estimate the knee point of the I/O function between linear and compressive processing. If a low-level signal is masked by an on-frequency masker, such that the signal is processed linearly and the masker compressively according to the I/O function, then a steeper GOM function is expected than that obtained for a high-level signal where both masker and signal are processed compressively. The knee point can be estimated at the input level where the GOM slope changes significantly. Data were collected from seven normal-hearing listeners. The method was found to provide estimates of the BM I/O function for a wider range of input levels than in previously suggested methods, due to the additional estimates of the knee points.
Characterizing auditory processing and perception in individual listeners with sensorineural hearing loss
This study considered consequences of sensorineural hearing loss in ten listeners. The characterization of individual hearing loss was based on psychoacoustic data addressing audiometric pure-tone sensitivity, cochlear compression, frequency selectivity, temporal resolution, and intensity discrimination. In the experiments it was found that listeners with comparable audiograms can show very different results in the supra-threshold measures. In an attempt to account for the observed individual data, a model of auditory signal processing and perception [Jepsen et al., J. Acoust. Soc. Am. 124, 422–438 (2008)] was used as a framework. The parameters of the cochlear processing stage of the model were adjusted to account for behaviorally estimated individual basilar-membrane inputoutput functions and the audiogram, from which the amounts of inner hair-cell and outer hair-cell losses were estimated as a function of frequency. All other model parameters were left unchanged. The predictions showed a reasonably good agreement with the measured individual data in the frequency selectivity and forward masking conditions while the variation of intensity discrimination thresholds across listeners was underestimated by the model. The model and the associated parameters for individual hearing-impaired listeners might be useful for investigating effects of individual hearing impairment in more complex conditions, such as speech intelligibility in noise.

Modeling auditory grouping based on a temporal coherence analysis
Current models of auditory streaming rely primarily on frequency separation for sound segregation. However, spectral components that are well separated in frequency are no longer heard as separate streams if presented synchronously rather than consecutively. Elhilali et al. [1] suggested a conceptual model to account for grouping based on synchrony, but the model was not evaluated with experimental data. In this study, it was experimentally tested how the temporal overlap between spectral components affected the perception of one or two streams. This was investigated for a range of tone-repetition rates. The data suggested that the perceptual organization depends on the absolute asynchrony of the tones. When the asynchrony of the tones was less than 20-44 ms, the tones were organized into the same perceptual stream, and when the asynchrony was larger, two separate streams were perceived. The conceptual model performed well in the tested conditions, however, some issues associated with the peripheral processing stages in the model were observed, caused by the frequency dependent delay of the filters. An alternative peripheral model is thus required for the conceptual model to function properly.
Towards a binaural modelling toolbox
The Auditory Modelling Toolbox (AMToolbox) is a new Matlab / Octave toolbox for developing and applying auditory perceptual models and in particular binaural models. The philosophy behind the project is that the models should be implemented in a consistent manner, well documented and user-friendly in order to allow students and researchers to actively work with current models and further develop existing ones. In addition to providing the models, it is a goal of the project to collect published human data and definitions of model experiments. This will simplify the verification of models by running the model experiments and comparing the predictions to human data. The software is released under the GNU Public License (GPL) version 3, and can be downloaded from http://amtoolbox.sourceforge.net.

Modeling auditory processing and speech perception in hearing-impaired listeners
A better understanding of how the human auditory system represents and analyzes sounds and how hearing impairment affects such processing is of great interest for researchers in the fields of auditory neuroscience, audiology, and speech communication as well as for applications in hearing-instrument and speech technology. In this thesis, the primary focus was on the development and evaluation of a computational model of human auditory signal-processing and perception. The model was initially designed to simulate the normal-hearing auditory system with particular focus on the nonlinear processing in the inner ear, or cochlea. The model was shown to account for various aspects of spectro-temporal processing and perception in tasks of intensity discrimination, tone-in-noise detection, forward masking, spectral masking and amplitude modulation detection. Secondly, a series of experiments was performed aimed at experimentally characterizing the effects of cochlear damage on listeners’ auditory processing, in terms of sensitivity loss and reduced temporal and spectral resolution. The results showed that listeners with comparable audiograms can have very different estimated cochlear input-output functions, frequency selectivity, intensity discrimination limens and effects of simultaneous- and forward masking. Part of the measured data was used to adjust the parameters of the stages in the model, that simulate the cochlear processing. The remaining data were used to evaluate the fitted models. It was shown that an accurate simulation of cochlear input-output functions, in addition to the audiogram, played a major role in accounting both for sensitivity and supra-threshold processing. Finally, the model was used as a front-end in a framework developed to predict consonant discrimination in a diagnostic rhyme test. The framework was constructed such that discrimination errors originating from the front-end and the back-end were separated. The front-end was fitted to individual listeners with cochlear hearing loss according to non-speech data, and speech data were obtained in the same listeners. It was shown that most observations in the measured consonant discrimination error patterns were predicted by the model, although error rates were systematically underestimated by the model in few particular acoustic-phonetic features. These results reflect a relation between basic auditory processing deficits and reduced speech perception performance in the listeners with cochlear hearing loss. Overall, this work suggests a possible explanation of the variability in consequences of cochlear hearing loss. The proposed model might be an interesting tool for, e.g., evaluation of hearing-aid signal processing.
Modelling a damaged cochlea: beyond non-speech psychophysics

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Predicting effects of impaired cochlear processing on consonant discrimination in stationary noise

Cochlear hearing loss is typically associated with reduced sensitivity due to inner hair-cell (IHC) and outer hair-cell (OHC) dysfunction. OHC dysfunction also leads to supra-threshold deficits, such as reduced basilar-membrane (BM) compression as well as reduced frequency selectivity and temporal resolution. Listeners with a cochlear damage typically have difficulties with speech understanding in the presence of background noise. In this study, the goal was to investigate the relation between individual consonant confusions in stationary noise and deficits in cochlear signal-processing as characterized by the audiogram and estimates of the BM input-output characteristics. Cochlear processing in individual listeners was simulated using a computational model of auditory signal processing and perception (CASP) and was used as a front end in a consonant discrimination system. Individual error patterns from a Diagnostic Rhyme Test (DRT) were measured and analyzed in terms of acoustic-phonetic features. This was done for three listeners with cochlear hearing loss and at two signal-to-noise ratios. It is shown that the predicted errors patterns matched the measured patterns in most conditions. Thus, an incomplete representation of the speech sounds due to deficits in cochlear processing could be related to the performance in the speech perception task. In addition, it was studied to what extent the data could be accounted for based on reduced sensitivity only – assuming that BM compression, frequency selectivity and temporal resolution are the same as in normal-hearing listeners. For two out of the three listeners, the supra-threshold deficits needed to be included in order to account for the data, while for the third listener, the predicted error rates were similar for the two model versions. Overall, the results suggest a clear relation between deficits in cochlear signal processing and consonant identification error patterns, and indicate that the supra-threshold deficits associated with a cochlear damage need to be taken into account. The findings might be interesting for applications, such as the evaluation of hearing-instrument signal processing, where the effects of specific processing strategies can be simulated for individual hearing losses.
Effects of pulsing of the target tone on the audibility of partials in inharmonic complex tones
The audibility of partials was measured for complex tones with partials uniformly spaced on an ERBN-number scale. On each trial, subjects heard a sinusoidal "probe" followed by a complex tone. The probe was mistuned downwards or upwards (at random) by 3% or 4.5% from the frequency of one randomly selected partial in the complex (the "target"). The subject indicated whether the target was higher or lower in frequency than the probe. The probe and the target were pulsed on and off and the ramp times and inter-pulse intervals were systematically varied. Performance was better for longer ramp times and longer inter-pulse intervals. In a second experiment, the ability to detect which of two complex tones contained a pulsed partial was measured. The pattern of results was similar to that for experiment 1. A model of auditory processing including an adaptation stage was able to account for the general pattern of the results of experiment 2. The results suggest that the improvement in ability to hear out a partial in a complex tone produced by pulsing that partial is partly mediated by a release from adaptation produced by the pulsing, and does not result solely from reduction of perceptual confusion.

A computational model of human auditory signal processing and perception
A model of computational auditory signal-processing and perception that accounts for various aspects of simultaneous and nonsimultaneous masking in human listeners is presented. The model is based on the modulation filterbank model described by Dau et al. [J. Acoust. Soc. Am. 102, 2892 (1997)] but includes major changes at the peripheral and more central stages of processing. The model contains outer- and middle-ear transformations, a nonlinear basilar-membrane processing stage, a hair-cell transduction stage, a squaring expansion, an adaptation stage, a 150-Hz lowpass modulation filter, a bandpass modulation filterbank, a constant-variance internal noise, and an optimal detector stage. The model was evaluated in experimental conditions that reflect, to a different degree, effects of compression as well as spectral and temporal resolution in auditory processing. The experiments include intensity discrimination with pure tones and broadband noise, tone-in-noise detection, spectral masking with narrow-band signals and maskers, forward masking with tone signals and tone or noise maskers, and amplitude-modulation detection with narrow- and wideband noise carriers. The model can account for most of the key properties of the data and is more powerful than the original model. The model might be useful as a front end in technical applications.
Estimating the basilar-membrane input-output function in normal-hearing and hearing-impaired listeners

To partly characterize the function of cochlear processing in humans, the basilar membrane (BM) input-output function can be estimated. In recent studies, forward masking has been used to estimate BM compression. If an on-frequency masker is processed compressively, while an off-frequency masker is transformed more linearly, the ratio between the slopes of growth of masking (GOM) functions provides an estimate of BM compression at the signal frequency. In this study, this paradigm is extended to also estimate the knee-point of the I/O-function between linear processing at low levels and compressive processing at medium levels. If a signal can be masked by a low-level on-frequency masker such that signal and masker fall in the linear region of the I/O-function, then a steeper GOM function is expected. The knee-point can then be estimated in the input level region where the GOM changes significantly. Data were collected from eight normal-hearing (NH) and five hearing-impaired (HI) listeners with mild to moderate sensorineural hearing loss. Both groups showed large inter-subject but low intrasubject variability. When the knee-point could be estimated for the HI listeners it was shifted towards higher input levels and compression was similar to that of NH listeners.

Modeling auditory perception of individual hearing-impaired listeners

Models of auditory signal processing and perception allow us to generate hypotheses that can be quantitatively tested, which in turn helps us to explain and understand the functioning of the auditory system. Here, the perceptual consequences of hearing impairment in individual listeners were investigated within the framework of the computational auditory signal processing and perception (CASP) model of Jepsen et al. [ J. Acoust. Soc. Am., in press]. Several parameters of the model were modified according to data from psychoacoustic measurements. Parameters associated with the cochlear stage were adjusted to fit the basilar membrane (BM) input/output function estimated from forward masking experiments. The absolute sensitivity of the model was adjusted according to the pure-tone audiogram, and the variance of the internal noise in the model adjusted to predict measured just noticeable differences (JNDS) in intensity discrimination tasks. Simultaneous- and forward-masking experiments with noise maskers were used to test to what
extent the model can account for the recovery from forward masking. Notched-noise masking was considered to test the model's ability to account for individual frequency selectivity. Three groups of listeners were considered: (a) normal hearing listeners; (b) listeners with a mild-to-moderate sensorineural hearing loss; and (c) listeners with a severe sensorineural hearing loss. A fixed set of model parameters were derived for each hearing-impaired listener. The simulations showed that, in most cases, the reduced or absent cochlear compression, associated with outer hair-cell loss, quantitatively accounts for broadened auditory filters, while a combination of reduced compression and reduced inner hair-cell function accounts for decreased sensitivity and slower recovery from forward masking. The model may be useful for the evaluation of hearing-aid algorithms, where a reliable simulation of hearing impairment may reduce the need for time-consuming listening tests during development.
narrowband noises, forward masking with (on- and off-frequency) noise- and pure-tone maskers, and amplitude
modulation detection using different noise carrier bandwidths. One of the key properties of the model is the combination of
the fast-acting cochlear compression with the slower compression realized in the adaptation stage of the model. Both play
a crucial role for the success of this model.

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