Chapter 8

Summary and concluding remarks

In this study, loudness perception of stationary sounds in hearing–impaired subjects, the modeling of these phenomena, and related problems were investigated. Zwicker's loudness model for normally hearing was adapted to model the measured loudness growth functions of hearing–impaired listeners. Loudness growth functions of hearing–impaired subjects were measured using the categorical scaling technique. In order to validate this technique, it was compared to magnitude estimation (chapter 3). It was concluded that both techniques do not differ fundamentally. In addition, it was investigated whether a strong correlation exists between the amount of hearing loss and psychoacoustic performance in the hearing impaired.

The categorical scaling technique, using 11 categories, was applied for investigating the influence of signal bandwidth on perceived loudness in normal–hearing and hearing–impaired subjects (chapter 5). Loudness growth functions using bandpass filtered noises with different bandwidths were measured. The results for normal–hearing listeners were well in accordance with those reported in the literature obtained by a loudness balancing technique. For normal–hearing listeners the perceived loudness increases with increasing bandwidth ("loudness summation"). In addition, it was shown that loudness summation is strongly reduced in hearing–impaired listeners. It was suggested that this reduction in loudness summation could be caused by two alterations in hearing–impaired listeners: either increased auditory filter bandwidth or less compression in cochlear processing, or a combination of both.

In order to model these measured data, two different approaches to extend Zwicker's loudness model for normal–hearing subjects were applied to take into account sensorineural hearing impairment (chapter 7). A loudness model for the hearing impaired has to account for four perceptual alterations due to hearing impairment: raised absolute threshold, loudness recruitment, reduced frequency selectivity and reduced loudness summation. However, in this study it was supposed that the loudness model for normally hearing has to be extended in two aspects only: raised threshold and loudness recruitment. This is based on the observation that reduced frequency selectivity can to a large extent be accounted for by the broadening of "normal" auditory filters with increasing level. In addition, no further component has to be introduced in the model to account for reduced loudness summation, it might be a consequence of the other alterations.

In the first approach, the "one–component approach", it is assumed that hearing impairment is similar to a masking condition in normal–hearing subjects. Thus, audiometric threshold is modeled by an internal noise which masks faint sounds. Introducing this internal noise yields a steeper loudness function at low and medium sound pressure levels, but a normal loudness function at high levels. This is due to the power law given in the loudness model for calculating specific loudness from excitation patterns. Simply by raising the threshold in the model, a recruitment–like effect is produced. Thus, threshold is the key variable in this approach. However, although the one–component approach predicts few isolated loudness functions of individual hearing impaired and reduced loudness summation correctly, it fails to model most of the measured loudness functions of individual hearing–impaired subjects. It was argued that this failure is due to the large intersubject differences observed in loudness perception. The one–component approach implicitly assumes that two subjects with a similar shape and amount of hearing loss should show a similar performance in psychoacoustic experiments. Instead, very large intersubject differences are observed for various auditory parameters such as, for instance, loudness perception, monaural and binaural auditory filter bandwidths or monaural and binaural temporal resolution (chapter 4). Several sources of the large intersubject variability were discussed. However, neither different etiology nor shortcomings of the experimental techniques appear to account for the large variability.

Among the sources discussed, the most appealing is that the variability commonly observed might be due to different contributions of two different components of sensorineural hearing impairment, i.e., loss of sensitivity and loss of compression. The physiological correlate (chapter 2) of this assumption is that damage to outer hair cells (introducing a "compression loss") and damage to inner hair cells (introducing a "sensitivity loss") probably cause different changes in inner ear mechanics and thus perhaps in psychoacoustic performance. Specifically, it was supposed that a similar shape and amount of audiometric threshold shift could be produced by different contributions of both components of hearing losses. Therefore, the variability in psychoacoustic performance of hearing–impaired subjects might be partly due to different mechanical properties in inner ear mechanics. The one–component approach cannot account for these individual differences. Taking into account more parameters such as the auditory filter bandwidth, does not improve the description of the data. Furthermore, very different mechanisms underly masking and cochlear impairment. For instance, noise–masked normals, i.e., simulated hearing–impaired subjects, and "true" hearing–impaired subjects show different performance in loudness summation. While loudness summation still occurs in noise–masked normals it is strongly reduced in the hearing impaired. This further indicates that masking, and thus the one–component approach, is not an appropriate way of modeling hearing impairment. Overall, predictions based on such an approach yield reasonable results for average data but fail when modeling individual loudness growth functions.

Therefore, a different approach for modeling hearing impairment was proposed, which avoids the above mentioned problems related with the one–component approach. The “two–component” approach is based on the assumption that the exponent of the power law incorporated in the loudness model reflects the nonlinear compressive processing in the cochlea. Physiological models (chapter 6) usually explain recruitment by the loss of active processes due to damage to OHCs resulting in a less compressive cochlear transfer function. Increasing the exponent of the power law means less compressive processing characteristics in the loudness model and resembles these physiological findings. Thus, in this approach, the exponent and the threshold are the key variables. In order to account for the individual differences, the calculated loudness functions were adjusted to match the individual loudness functions measured with narrowband noises by fitting the exponent. Adjusted in this way, the loudness functions measured with broadband noises are correctly predicted without further modifying other parameters such as auditory filter bandwidth.

Overall, the two–component approach accounts more accurately for the physiological findings observed in injured cochleae and describes the data obtained with different stimuli more precisely than the one–component approach.

In summary, one might think of the two–component approach as a simpler version of more complex physiological or psychoacoustical models. It is perhaps surprising that the simple approach presented here correctly describes most individual data and a variety of different effects of loudness perception in the hearing impaired. The wide range of data for which the model can account indicates that this is a promising approach to modeling sensorineural hearing impairment. Given its simplicity, it may be implemented in the design of “intelligent” dynamic compression hearing aids that restore the loudness impression of hearing–impaired listeners to that of normals.