Chapter 4

Categorical loudness scaling in hearing–impaired listeners

Abstract

Most sensorineural hearing–impaired subjects show the recruitment phenomenon, i.e., loudness functions grow at a higher rate than in normal–hearing subjects. In this chapter, the correlation between audiometric threshold shift and slope of loudness function of 67 sensorineural hearing–impaired subjects is exammed. Loudness functions are measured using a one–step categorical scaling technique with 11 categories. It is shown that on average the slopes of loudness functions increase with increasing hearing loss but no strong correlation between audiometric threshold and slope of loudness functions is observed. Subjects with a similar amount of hearing loss sometimes show very different slopes in their loudness functions. A similar result has been reported for other psychoacoustic tasks like measurement of auditory filter bandwidth. No strong correlation has been found between audiometric threshold and filter bandwidth. Several sources, like different etiology or types of hearing losses, or shortcomings of the experimental techniques, might contribute to these large intersubject differences.

4.1 Introduction

Growth–of–loudness functions provide an important clinical tool to characterize sensorineural hearing impairment. The one–step categorical scaling technique provides a clinically applicable means to determine these curves. The reliability and accuracy of this technique has been studied intensively (Kießling et al., 1993; Hellbrück, 1993; Kießling et al., 1994; Boretzki et al., 1994; Kollmeier and Hohmann, 1995). However, it is still unresolved whether this provides more information about sensorineural hearing–impaired subjects than a pure tone audiogram. If it does not contain more information, then a strong correlation should exist between audiometric thresholds and the results of loudness scaling, e.g., the slopes of loudness functions. Hence, the slopes of the loudness functions should be predictable from the pure tone audiogram. Thus loudness scaling would be dispensable in routine audiometry and the selection and fitting of hearing aids. In addition, sensorineural hearing loss could be modelled in a straightforward way with few parameters. To test this hypothesis, the correlation between audiometric threshold and slope of loudness function is investigated in the following section.

4.2 Method

The loudness functions of 67 sensorineural hearing–impaired subjects have been measured by V. Hohmann and I. Holube. Parts of these results have been presented elsewhere (Hohmann, 1993; Kollmeier and Hohmann, 1995). However, the correlation between audiometric threshold and slope of loudness function has not yet been investigated for the whole data base.

Subjects

In the experiments, 67 sensorineural hearing–impaired subjects participated voluntarily. Sensorineural hearing impairment was diagnosed by routine audiometry in the ENT Department of the University Clinic of Göttingen. The air–bone gap of the hearing–impaired listeners was always below 6 dB.

Stimuli

Narrowband frozen noises centered at the audiological frequencies, 250, 500, 1000, 2000, 4000 and 6000 Hz, are employed as stimuli. Their bandwidth was one third octave. The signals were generated off–line. Initally, a Gaussian white noise (duration 3 s) was generated at a sampling rate of 25 kHz. It was Fourier–transformed and bandpass filtered at the respective center frequency and with the respective bandwidth. After transforming these signals back to the time domain, they were windowed with a rectangular window (2 s duration including 50 ms cosine–ramps).

Procedure

During the experiments the subjects were seated in a sound–attenuating chamber. The signals were presented monaurally via headphones (BeyerDynamic DT 48) to the subjects. Their task was to judge perceived loudness in a one–step procedure using a categorical scale with 11 categories. Figure 5.2 shows the different categories available to the subjects during the loudness scaling procedure. Subjects' responses were recorded using a handheld touch screen (Epson ETH–10) connected to a PC via a serial port (RS232). This screen has a touch–sensitive display on which written instructions or different scales can be presented to the subjects. The categories were displayed on the screen after each presentation of the stimulus. The column at the right side of Fig. 5.2 shows the numbers assigned to the different categories for evaluating the data. These numbers were not displayed on the screen during the presentation of the categories.
Each noise band was presented at eight levels equispaced on a dB scale covering the entire dynamic range defined by audiometric threshold and uncomfortable loudness level (UCL).

In a first experiment, audiometric thresholds and individual UCLs were determined by presenting each stimulus to the subjects at ascending levels starting 10 dB below standard pure tone thresholds. Subjects had to indicate when they heard the stimulus for the first time, defining threshold, and when the loudness of the stimulus fell in the category "too loud", defining UCL. In the second experiment, the stimuli were presented in random order (with a restricted stepsize). Each stimulus was presented twice during one run. The experimental parameters were chosen according to the results of a joint research project (Kollmeier and Hohmann, 1995; Kießling et al., 1994; Kießling et al., 1993; Hohmann, 1993).

4.3 Results and discussion

Linear functions with the parameters slope m and intermediate loudness level[1] L_{25} were fitted to the measured loudness functions. Thus a linear relationship of the form

$$CU = m \cdot (L - L_{25}) + 25 \tag{4.1}$$

was obtained between loudness in categorical units (CU) and sound pressure level L on a dB scale.

Figure 4.1 shows a typical loudness function for normal–hearing listeners and a function for one hearing–impaired subject. The loudness function, i.e., loudness in categorical units versus level, is plotted for six different center frequencies. For the loudness curves of normal–hearing subjects, linear functions fitted to the average data of 9 subjects are plotted. Obviously, linear functions provide a good description of the loudness functions for hearing–impaired subjects when applying this scaling technique. Furthermore, the well known recruitment phenomenon can be observed: In regions with normal audiometric thresholds (250 and 500 Hz) growth of loudness is normal, while at frequencies with increased threshold (1000 – 6000 Hz), an increase in rate of growth of loudness is observed.

In Fig. 4.2 the slopes of the loudness functions of all different frequencies of all 67 hearing–impaired subjects are plotted as a function of hearing loss. On average, the slope of the loudness function increases with increasing hearing loss, but a large intersubject variability is observed. Surprisingly, even for a large amount of audiometric threshold shift, quite shallow loudness functions sometimes occur. A similar result has been reported by Kießling et al. (1994). For moderate to severe hearing losses, they also reported either no further increase in slope with increasing hearing losses above a certain amount of hearing loss or even quite shallow loudness functions. Since only subjects with sloping high frequency hearing losses participated in their study, shallow loudness functions combined with significant hearing loss occured mainly at high frequencies. Kießling et al. speculated that a neural component of hearing loss could be the origin of these results.

Two further explanations could be proposed to explain both our findings and the results of Kießling et al. Firstly, recruitment could be explained as being caused by abnormal growth

[1] The level of the category "intermediate" = 25 in categorical units.

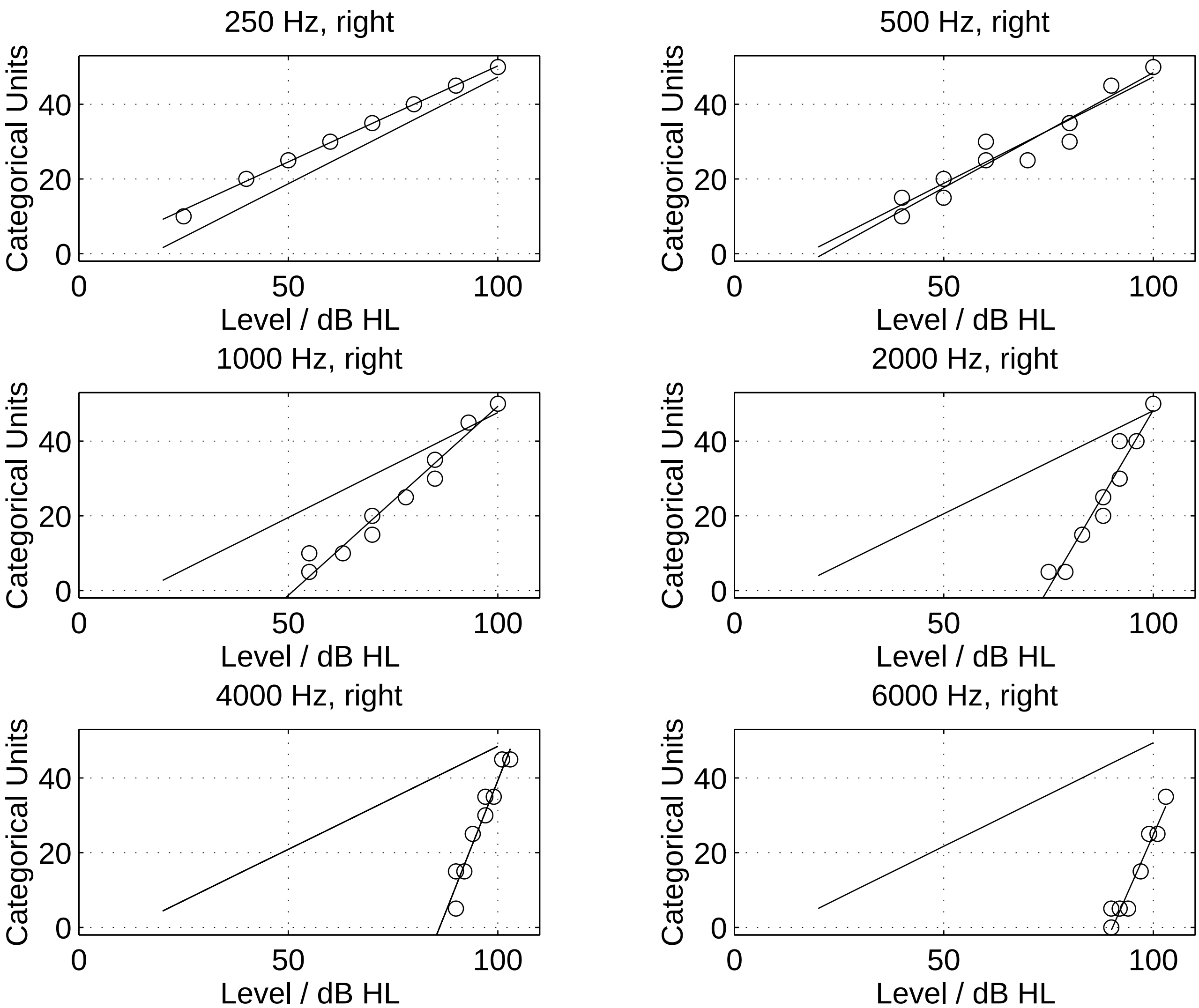

Fig. 4.1: *Comparison of the loudness scaling results for normal–hearing (average of nine subjects, —) and one hearing–impaired (○) subject (JC). For the loudness functions of the normal–hearing subject the fitted linear functions are employed. At frequencies where the hearing–impaired subject has normal thresholds (250 – 500 Hz) the growth of loudness function is also normal, while at frequencies with increased threshold (1000 – 6000 Hz) the slope of the growth of loudness functions increase with increasing threshold, i.e., recruitment occurs. The loudness curves are measured using the one–step categorical scaling technique with 11 categories.*

of spread of excitation (Evans, 1975). Thus, by restricting spread of excitation, the growth of loudness with level should be reduced. Hellman (1994) measured growth of loudness in subjects with a very steeply sloping hearing loss. At the "cut–off" frequency, i.e., the frequency where hearing loss begins, measured loudness functions increased at a lower rate than at frequencies with normal thresholds. She explained the results as being caused by a restricted increase in spread of excitation due to the very steeply increasing hearing loss. Similarily, at high frequencies and in cases of highly elevated thresholds, spread of excitation could also be restricted, yielding either shallow loudness functions or at least no further increase in slope of loudness function with increasing hearing loss.

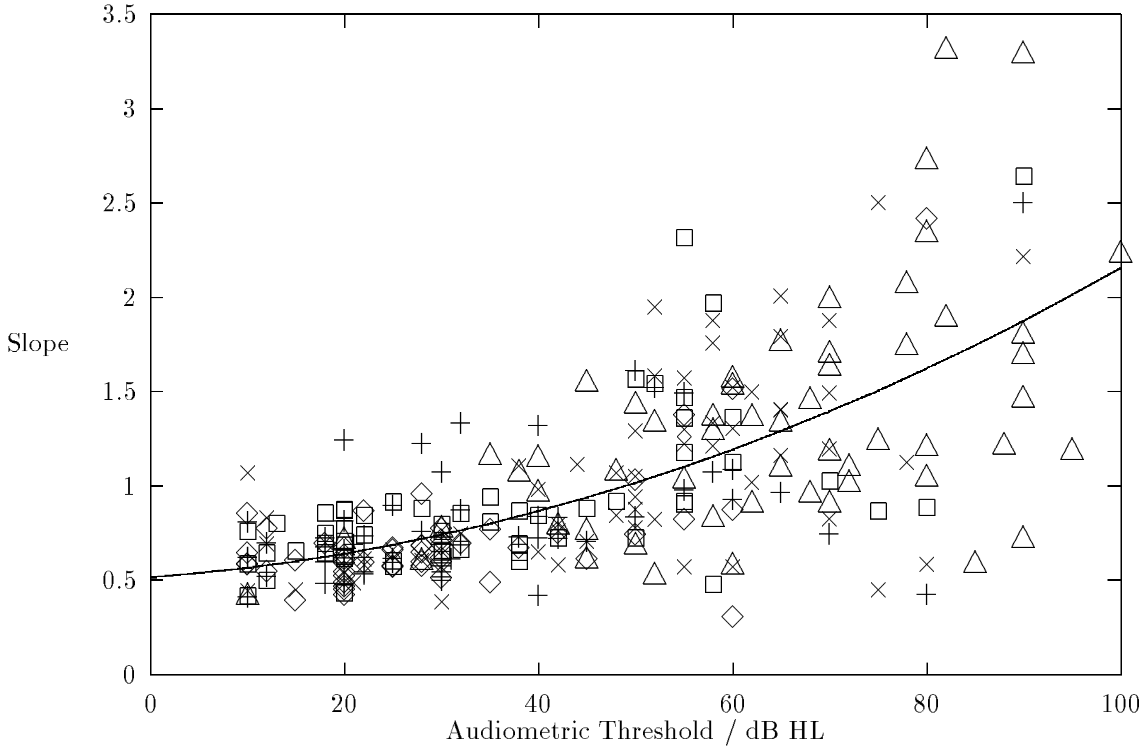

Fig. 4.2: *Slopes of loudness functions of 67 sensorineural hearing–impaired subjects as a function of audiometric threshold. The slopes were measured with categorial scaling technique. All subjects suffered from a sensorineural hearing loss. Note that, even for large hearing losses, quite shallow loudness functions occur. Different symbols represent different center frequencies of the narrowband noises. The solid curve represents the regression curve.* $\diamond$*: 0.25 kHz,* $\square$*: 0.5 kHz,* $+$*: 1 kHz,* $\times$*: 2 kHz,* $\triangle$*: 4 kHz.*

The second explanation is based on different types of damage to the Organ of Corti and altered basilar membrane mechanics as was described in chapter 2. If the hearing loss exceeds about 60 dB, most OHCs are probably damaged. Thus, further increases in audiometric threshold would be due to damage to IHCs only, yielding no further steepening of loudness functions. If the hearing loss is further increased, large parts of the IHC population are

probably damaged, yielding shallow loudness functions. Furthermore, strong damage to IHCs yields much less input via afferent fibers to higher stages of the auditory pathway resulting in a degeneration of these stages and thus perhaps causing a neural component of hearing loss as was suggested by Kießling et al. (1994).
In order to help clarify this point, the question has to be addressed whether a large audiometric threshold shift combined with a shallow loudness function only occurs at high frequencies. Therefore, the data given in Fig. 4.2 are plotted with different symbols for different center frequencies. Obviously, the lack of correlation between hearing loss and slope of loudness functions the same for all different center frequencies, since the variability is similar, regardless of frequency and even at very low frequencies. The correlation coefficient across all frequencies between the audiometric thresholds and the slopes of loudness functions was 0.65, $p < 0.0001$ (Spearman's rank correlation coefficient (Sachs, 1992)). Thus, a highly significant but only moderate correlation exists. The intersubject variability also increases strongly with increasing absolute threshold causing a larger scatter for severe hearing losses than for low to medium hearing losses. Thus, due to the restriction of the slopes to "normal" values (i.e., lower boundary) and the increase in variance with increasing absolute threshold, the distribution of slopes expands solely towards greater values yielding an increase in the mean slope.
A similar relation between audiometric threshold and an auditory parameter can also be observed in a number of other psychoacoustical experiments. Kinkel (1990), Kollmeier (1990) and Holube (1993) have demonstrated this for a battery of auditory tests including monaural and binaural temporal and spectral resolution as well as different speech tests in quiet and noise. Stone (1994), Moore (1995) and Hétu and Tran–Quoc (1995) also reported that no strong correlation between audiometric threshold and auditory filter bandwidth exists. In Fig. 4.3 auditory filter bandwidth is plotted as a function of audiometric threshold. The filter bandwidths have been measured by Moore, Peters and Stone (Stone et al., 1992; Stone, 1994; Moore, 1995) with a notched–noise technique. Obviously the scatter in this figure is similar to that of Fig. 4.2. Again, the variability of filter bandwidth is about the same for all frequencies. A similar finding was also reported by Hétu and Tran–Quoc (1995).
In summary, no strong correlation between audiometric threshold shift and alteration in different psychoacoustic tasks can be found. Why is the psychoacoustic performance of sensorineural hearing–impaired listeners so variable for a given amount of hearing loss? This variability could be caused by several factors:

1. It could be simply due to "measurement errors". However this is highly improbable because the same scatter occurs for *all* kinds of measurement techniques and psychoacoustical tasks: Categorical scaling (this study, Kießling et al. (1994)) and magnitude estimation (Hellman (1993) Fig. 1.6 and Hellman and Meiselman (1990) Fig. 8) for loudness measurement; notched–noise (Stone, 1994; Hétu and Tran-Quoc, 1995), rippled–noise and psychoacoustic tuning curves (Tyler, 1986; Moore, 1995) for the measurement of auditory filter bandwidth; monaural and binaural temporal resolution and speech tests (Kinkel, 1990; Kollmeier, 1990; Holube, 1993).

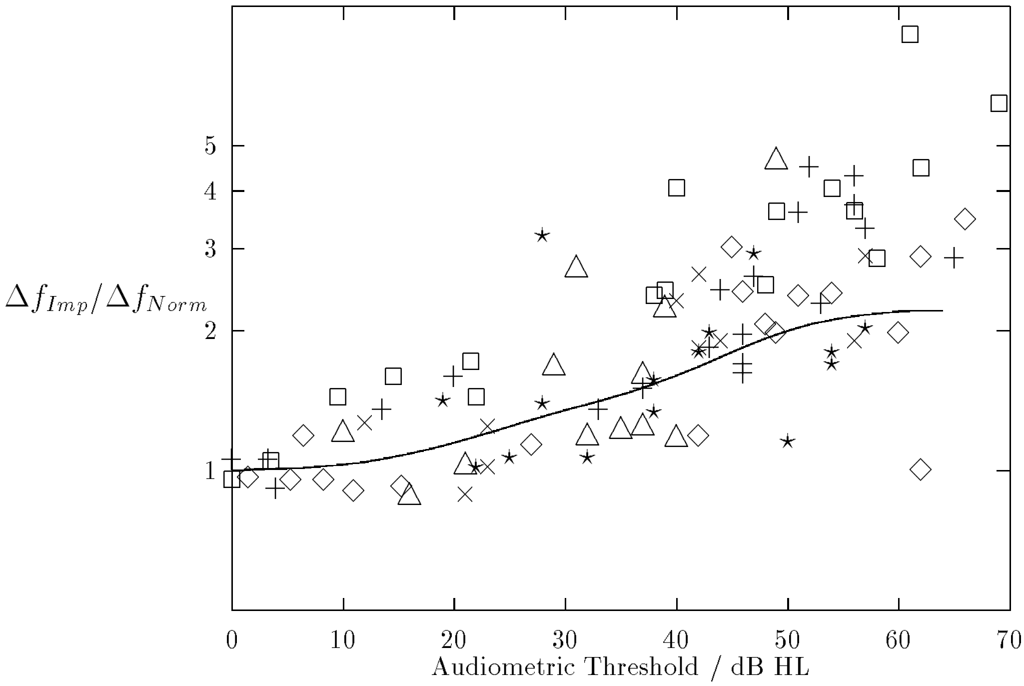

Fig. 4.3: *Correlation between bandwidth of auditory filters and audiometric threshold. Filter bandwidths Δf are plotted as the ratio of impaired Δf_{Imp} and normal Δf_{Norm} bandwidth. The solid line represents the increase of auditory filters bandwidth with level in normal–hearing subjects. Filter bandwidths were measured with a notched–noise technique. All subjects suffered from a pure sensorineural hearing loss. Note that even for large amount of hearing losses quite normal filter bandwidths occur. Different symbols represent different frequencies. Adapted from Stone (1994), his Fig. 11.8. $\triangle$: 0.4 kHz, $\times$: 0.5 kHz, $\star$ 0.8 kHz, $\diamond$: 1.0 kHz $+$: 2.0 kHz, $\square$: 4.0 kHz. By courtesy of M. Stone.*

2. Another source of variability could be a different etiology of hearing loss, i.e., different origins of hearing loss like noise, ototoxic drugs or hereditary hearing losses. However, the same scatter occurs if subjects have a similar etiology (for instance noise–induced hearing loss): Hellman and Meiselman (1990) for loudness perception; Laroche et al. (1992), Hétu and Tran–Quoc (1995), for the measurement of auditory filter bandwidth.

3. The diagnostic procedure for sensorineural hearing impairment allows for a difference between air conduction and bone conduction thresholds of up to 10 dB for diagnosing a pure sensorineural hearing loss. However, the difference between air conduction and bone conduction thresholds of the subjects employed in this study was always below 6 dB.

4. In chapter 2 another source of variability has been discussed: different damage pattern in the Organ of Corti. Psychoacoustical performance might strongly depend on which cells are damaged in the Organ of Corti. Loss of IHCs is assumed to solely cause a

reduced sensitivity while loss of OHCs probably causes both, a reduced sensitivity and a loss of the nonlinear cochlear processing. Thus, two different components of sensorineural hearing loss might be distinguished: a reduction in sensitivity ("sensitivity loss") and a reduction in compressive processing ("compression loss") Unfortunately, at present there are no diagnostic techniques for distinguishing between these two components of cochlear damage.

Therefore, probably there is not one single cause of the large variability observed, but it is a combination of the above mentioned different causes. However, the different mechanical properties discussed as the last cause appears to explain the effect of sensorineural hearing loss in an appealing and promising way.

4.4 Conclusions

The results indicate that usually the slopes of loudness functions increase with increasing audiometric threshold, but large intersubject differences are observed. These differences also increase, regardless of frequency, with increasing hearing loss. A similar scatter is observed for other psychoacoustical tasks like measurement of auditory filter bandwidth or temporal resolution. Neither different etiology nor shortcomings of the experimental techniques appear to account for the variability. Among the possible causes 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.