Chapter 5

Additivity of loudness across frequency

Abstract

The influence of signal bandwidth on perceived loudness, i.e., additivity of loudness across frequency or "loudness summation", has been extensively studied in normal–hearing as well as in hearing–impaired subjects. Most experiments in the literature have been performed with a loudness balancing technique rather than a scaling technique using, for instance, categorical scaling or magnitude estimation.

In this chapter, the additivity of loudness across frequency is investigated by means of categorical scaling. We sought to determine whether categorical scaling reveals differences in loudness if the stimuli differ in bandwidth. Categorical scaling was performed with 9 normal–hearing and 14 sensorineural hearing–impaired subjects employing bandfiltered noises with bandwidths ranging from 1 – 6 critical bands. For normal–hearing listeners, categorical scaling revealed the loudness summation effects consistent with the literature. In hearing–impaired subjects loudness summation is strongly altered. Although large individual differences are observed, the general finding is that loudness summation is reduced in these subjects. This lack of loudness summation in hearing–impaired listeners could either be explained by increased auditory filter bandwidth or reduced compressive processing in the impaired cochlea. However, it is likely that both mechanisms contribute to the reduced additivity of loudness across frequency.

5.1 Introduction

5.1.1 Additivity of loudness in normal–hearing subjects

In normal–hearing subjects the perceived loudness of a stimulus of fixed overall intensity increases if its bandwidth exceeds a certain critical value (Zwicker et al., 1957; Zwicker and Scharf, 1965; Scharf, 1978; Zwicker and Fastl, 1990). This increase is caused by the way loudness is summed across frequency and is therefore often called "loudness summation". In

order for a narrowband and a broadband noise to be perceived as equally loud, the former has to be presented at a higher overall level.
In normal–hearing subjects loudness summation can be observed with a variety of different stimuli. It occurs either when the spectral separation between two or more tones or the bandwidth of a narrowband noise is increased beyond the so–called critical bandwidth (CB) for loudness. Loudness summation is most prominent at medium levels and less prominent at low and very high levels. In most studies reported so far, loudness summation in normal–hearing and hearing–impaired listeners has been measured using a loudness balancing procedure (cf. section 3.1.1). This method requires subjects to adjust the level of a test stimulus, e.g., a broadband noise or a tone complex, to match a given reference stimulus, e.g., a narrowband noise or a pure tone. However, loudness summation has never been measured using a loudness scaling technique, such as magnitude estimation or categorical scaling.
Loudness summation can been explained in terms of Zwicker's loudness model for stationary signals (Zwicker, 1960). This model assumes that loudness is not directly related to overall stimulus intensity but is related to the sound pressure level within different auditory filters. The output of these auditory filters is converted into the so–called excitation pattern. From these excitation patterns, E, specific loudness, N', (i.e., loudness per critical band) can be deduced using a nonlinear, compressive power law relationship $N' \sim E^{\alpha}$ with $\alpha \approx 0.23$. Overall loudness is obtained by integrating these specific loudness values across auditory filters. As long as the bandwidth of the stimulus is less than one critical band, the excitation patterns, and thus the specific loudness pattern, is constant[1] yielding a constant overall loudness. If the bandwidth exceeds the CB, the specific loudness pattern is altered in such a way that loudness increases with increasing bandwidth (Zwicker and Scharf, 1965; Moore and Glasberg, 1986; Zwicker and Fastl, 1990). In other words, as long as the different stimulus components fall within one auditory filter, their intensities are summed. However, as soon as the stimulus components spread across different auditory filters, their respective specific loudness is calculated first and then specific loudness values are summed, yielding a higher overall loudness. This can easily be demonstrated by the following expression:

$$E_1^{\alpha} + E_2^{\alpha} > (E_1 + E_2)^{\alpha},$$

with $\alpha < 1$ and E_1, E_2 = excitation levels of different signals. Determining the minimum bandwidth of a narrowband noise that produces an increase in loudness with increasing bandwidth, provides an estimate of the auditory filter bandwidth. It is slightly larger than the bandwidths measured by other techniques, such as the notched–noise method (Moore and Glasberg, 1986).
Several parameters are crucial for modelling loudness summation using Zwicker's loudness model. Firstly, the shape and bandwidth of the auditory filters are important, i.e., the slope of their high and low frequency skirts. They determine the shape of the excitation patterns and thus the specific loudness pattern for a given stimulus. Secondly, the exponent α of the

[1] see Moore and Glasberg (1986) for a more detailed discussion

power law relationship between excitation patterns and specific loudness is important. The role of the exponent α in loudness summation can easily be demonstrated by the following expression:

$$E_1^{\alpha_1} + E_2^{\alpha_1} - (E_1 + E_2)^{\alpha_1} > E_1^{\alpha_2} + E_2^{\alpha_2} - (E_1 + E_2)^{\alpha_2}$$

with $\alpha_1 < \alpha_2 < 1$ and E_1, E_2 = excitation levels of different signal components. Increasing the exponent α diminishes the difference between summing intensities first and then compressing and first compressing and then summing (compressed) intensities. For $\alpha = 1.0$ this difference is zero. Thus, increasing the exponent yields less loudness summation.

Taken together, a reduction in loudness summation can be modeled by either increasing the bandwidth of auditory filters or increasing the exponent α of the power law. Increasing the auditory filter bandwidth increases the spectral range over which intensities are summed and thus reduces loudness summation. Increasing the exponent reduces the effect of the compressive power law transformation when calculating the specific loudness in different frequency bands before summing them.

Both of these parameters usually are increased in injured cochleae, as was pointed out in chapter 2. Therefore, loudness summation should be altered in hearing–impaired listeners. Thus, in the hearing impaired, the difference in level between a narrowband and a broadband noise that produces the same loudness should be smaller than normal or even completely vanished. In the next section loudness summation in hearing–impaired listeners will be discussed.

5.1.2 Additivity of loudness in hearing–impaired subjects

Scharf and Hellman (1966) reported reduced loudness summation in people suffering from a sensorineural hearing loss. They compared loudness summation in normal–hearing subjects, in patients with a pure conductive hearing loss and in listeners with a pure sensorineural hearing loss. When compared at the same sensation level (SL) as normal–hearing listeners, loudness summation was only reduced in patients suffering from sensorineural hearing loss but not in subjects with a conductive hearing loss. They suggested that loudness summation could provide an important clinical tool for distinguishing conductive and sensorineural hearing impairement. Furthermore, loudness summation could provide an important psychoacoustic measure of sensorineural hearing impairment.

Several studies (for a review see Tyler, 1986) investigated the potentials of loudness summation as a measure of sensorineural hearing impairment and tried to solve the following three problems. Firstly, does loudness summation provide a reliable estimate of auditory filter bandwidth? Bonding (1981) and Florentine et al. (1980) compared critical bandwidth measured by means of loudness summation and psychoacoustical tuning curves. Both studies found no systematic correlation between the two measures of auditory filter bandwidth. Thus, loudness summation provides no reliable tool for measuring auditory filter bandwidth in impaired listeners. This result is consistent with the observation that loudness summation overestimates the auditory filter bandwidth in normal–hearing subjects.

Secondly, is the reduction in loudness summation correlated with the etiology of the hearing loss? Bonding (1981) measured loudness summation in groups of patients with a different etiology of their hearing loss, including Méniere's syndrome, presbyacusis, acoustic neuroma, hereditary hearing loss, uncertain origin and salicylate–induced hearing loss. Bonding's study revealed no apparent correlation between loudness summation and origin of pathology. Thirdly, does a systematic correlation exist between the reduction of loudness summation and the audiometric threshold? A comparison across different studies revealed no such correlation (Tyler, 1986). Both extremes, normal loudness summation in subjects with a large sensorineural hearing loss and strongly reduced loudness summation in subjects with a mild hearing loss, have been reported in the literature. Thus, the scatter in the correlation between audiometric threshold and loudness summation is similar to the scatter between threshold and different auditory parameters (cf. discussion in chapter 4).

In all the above mentioned studies, loudness summation was measured using a loudness balancing method. Loudness balancing measures differences in perceived loudness but not loudness functions on a subjective scale. However, measuring loudness functions on this scale is very important for developing and examining a reliable model for loudness perception in normal–hearing and hearing–impaired listeners. Therefore, in this study the method of categorical scaling is used to measure loudness functions for stimuli with differing bandwidth.
A model to describe reduced loudness summation was proposed by Florentine and Zwicker (1979). However, they considered only results obtained with a loudness balancing technique and thus only differences in loudness. The model proposed by Florentine and Zwicker predicts these loudness differences rather well but fails to predict measured loudness functions (cf. discussion in chapter 7). In chapter 7, a different approach is presented to model the data obtained in the present chapter.
Two experiments with stimuli differing in bandwidth were carried out. In the first experiment loudness scaling using only narrowband noises (one critical band wide) was performed. In the second experiment loudness scaling was performed using signals with bandwidths ranging from 2 to 6 critical bands. The center frequencies of these signals were selected from the same spectral range as the narrowband signals in the first experiment.

5.2 Method

Subjects

Nine normal–hearing and 14 sensorineural hearing–impaired subjects were used. The audiometric thresholds of the normal–hearing listeners in the frequency range considered here were below 10 dB HL. 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 below 5 dB. The individual audiometric data are presented in appendix C.

Stimuli

Center Frequency / Hz	Bandwidth / Hz	Bandwidth / CB
Narrowband Signals		
1370	210	1
1600	240	1
1850	280	1
2150	320	1
2500	380	1
2925	450	1
Broadband Signals		
1480	450	2
1635	730	3
1795	1050	4
1985	1430	5
2210	1880	6

Table 5.1: *Center frequencies and bandwidths of the signals in units of Hz and critical bands (CB).*

Frozen noisebands with different center frequencies and different bandwidths were employed as stimuli. The center frequencies of the signals and their respective bandwidths in units of Hz and critical bands are given in Tab. 5.1. The noise bands were centered at frequencies between 1370 Hz and 2925 Hz, i.e., between 10 and 15 Bark. In the first experiment, the bandwidth was about one critical band, i.e., approximately 20 % of the center frequency. The cut–off frequencies were chosen according to Tab. 6.1, p. 142 of Zwicker and Fastl (1990).

The stimuli for the second experiment were generated by successively combining the narrowband noises from the first experiment as shown schematically in Fig. 5.1. The signals were generated off–line. Initially 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

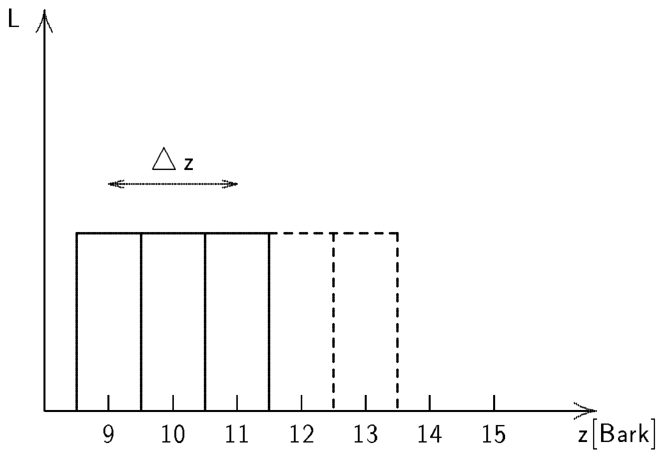

Fig. 5.1: *Schematic representation of the generation of the broadband noise signals. The overall level L is plotted versus center frequency on a bark scale.*

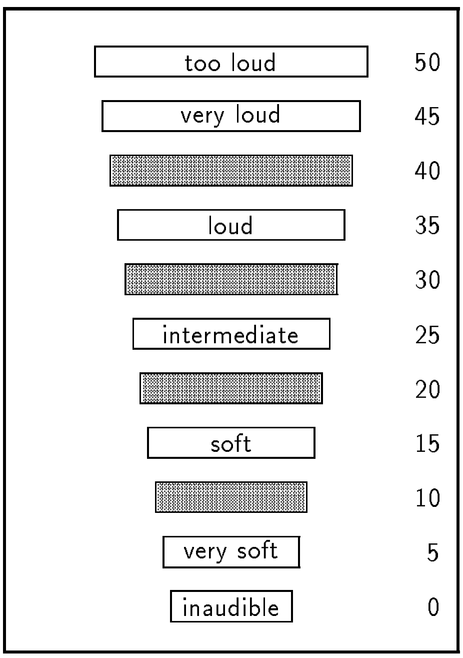

Fig. 5.2: *Schematic plot of the different categories from which subjects had to select.*

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 to the subjects.
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). During the orientation phase prior to the actual scaling experiment, audiometric thresholds and individual UCLs were determined by presenting each stimulus to the subjects at ascending levels starting 10 dB below the standard pure tone audiometric thresholds. Subjects had to indicate when they heard the stimulus for the first time and when the loudness of the stimulus fell in the category "too loud". In the actual experiment, the stimuli were presented in random order (with a restricted stepsize). Each stimulus was presented twice during one run. The experiments were repeated once within 10 days.

5.3 Results

Figure 5.3 shows a typical result of measured loudness functions using stimuli with two different bandwidths (one critical band and five critical bands). The upper panel shows the curves of a normal–hearing and the lower panel those of a hearing–impaired subject. Obviously, linear functions provide a good description of the measured loudness curves. Therefore, linear functions with parameters slope m and intermediate loudness level[2] L_{25}

f [Hz]	Δf [Hz]	m [CU/dB]	L_{25} [dB HL]
1370	210	.52 (.10)	61.6 (7.8)
1600	240	.56 (.10)	63.6 (7.1)
1850	280	.55 (.13)	65.4 (7.2)
2150	320	.54 (.19)	68.5 (10.9)
2500	380	.53 (.15)	70.8 (9.6)
2925	450	.53 (.14)	68.4 (5.7)
1480	450	.51 (.06)	57.3 (6.2)
1635	730	.52 (.10)	59.1 (6.4)
1795	1050	.52 (.09)	59.1 (5.9)
1985	1430	.50 (.09)	58.5 (4.2)
2210	1880	.51 (.14)	60.6 (7.0)

Table 5.2: *Means (standard deviation) of the fitted parameters (slope m and intermediate loudness level L_{25}) of 9 normal–hearing subjects. In the upper part of the table the results for the narrowband stimuli are shown, and in the lower part those for the broadband signals. f is the center frequency and Δf the bandwidth of the signals.*

[2] The level of the category "intermediate" = 25.

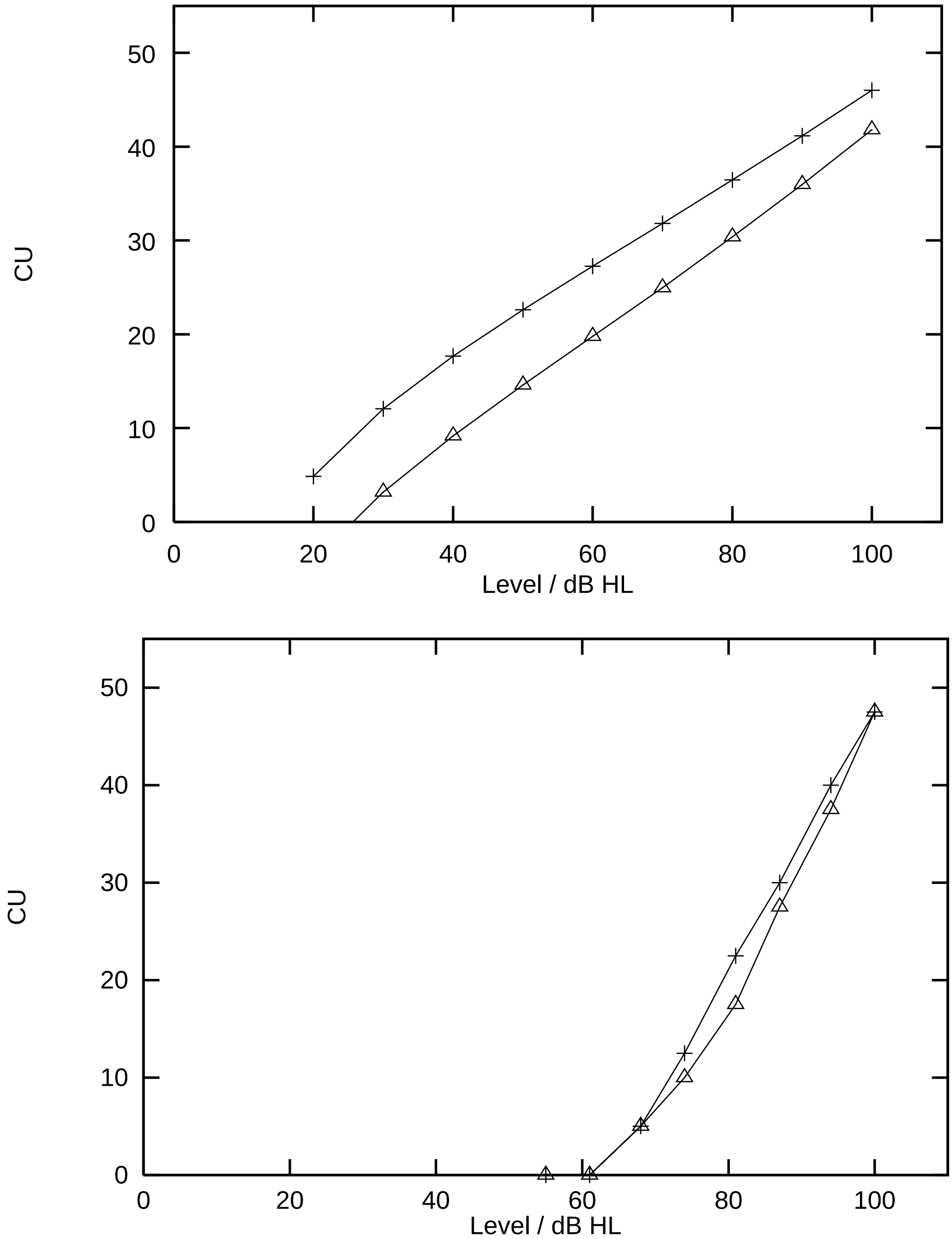

Fig. 5.3: *Loudness functions (loudness in categorical units (CU) versus level) of a normal hearing (upper panel) and a hearing impaired subject (lower panel, subject HF) for two signals with different bandwidths.* △ *indicate the results obtained using a one–critical–band–wide signal centered at 2150 Hz and + mark the results of a five–critical–bands–wide signal centered at 1985 Hz.*

were fitted individually to the measured loudness functions of normal–hearing and hearing–

impaired subjects in each experimental condition. Thus, a relationship of the form

$$CU = m \cdot (L - L_{25}) + 25 \quad (5.1)$$

is obtained between categorical loudness (CU) and level L in dB HL.

Results for normal–hearing subjects

Mean results of 9 normal–hearing subjects, i.e., slope m and intermediate loudness level L_{25}, are shown in Tab. 5.2. For the narrowband stimuli, the intermediate loudness level L_{25} depends on frequency. It increases with increasing frequency. This is not observed for the broadband stimuli where the level L_{25} is nearly constant across frequency. However, the difference between the level L_{25} of the narrowband and the L_{25} of the broadband stimuli increases with increasing frequency and increasing bandwidth. Thus, the categorical scaling technique seems to reveal differences in perceived loudness due to differences in stimulus bandwidth. In addition, the slopes of loudness functions derived from the narrowband stimuli are slightly larger than those derived from broadband stimuli. This yields a reduction of loudness summation at high sound pressure levels (Fig. 5.3).
From the linear functions, loudness values in categorical units can be calculated for different sound pressure levels. Thus, the level required for a narrowband stimulus to match the loudness of a broadband stimulus can be determined by calculating the loudness of a broadband noise at a defined level and then calculating the level of the narrowband noise for the same loudness. It is not possible to directly compare the results of the narrowband and the broadband stimuli since the center frequencies of narrowband and broadband stimuli do not coincide. Furthermore, the parameters m and L_{25} of the narrowband signals depend on frequency. However, in order to compare the two conditions, loudness functions for the narrowband stimuli at the respective frequencies of the broadband signals were constructed by linearly interpolating the parameters m and L_{25} of the two neighbouring narrowband signals. In Fig. 5.4 the level L of a narrowband noise required to match the loudness of a broadband noise is plotted as a function of the bandwidth of the broadband noise for different overall levels of the broadband noise. For comparison, the results of a similar experiment performed by Zwicker et al. (1957) are plotted as open circles connected with dotted lines. They measured loudness summation using a loudness balancing procedure. In their experiments, subjects adjusted the level of a 210–Hz wide noise band centered at 1420 Hz to match the loudness of a noise with variable bandwidth also centered at 1420 Hz. The level differences obtained with the categorical scaling technique are in good agreement with the results obtained by Zwicker et al. Furthermore, the results obtained with the categorical scaling technique show less loudness summation at high sound pressure levels, in accordance with the results obtained by Zwicker et al.

Results for hearing–impaired subjects

The results of the hearing–impaired subjects were evaluated in the same way as those for normals described above. In table 5.3 the individual results of the 14 hearing–impaired subjects are shown, i.e., individual slopes m and individual intermediate loudness levels L_{25}.

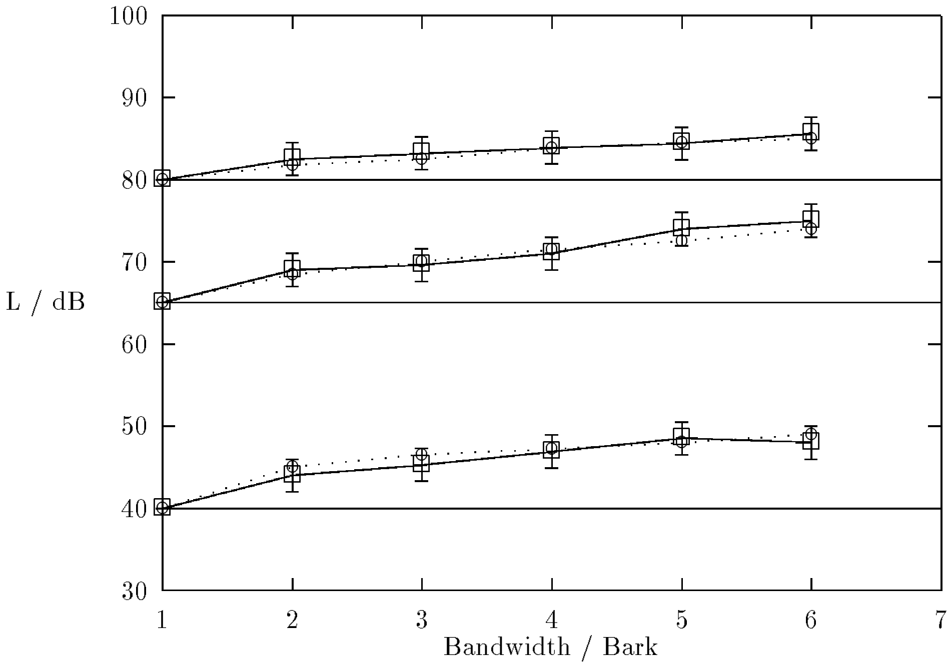

Fig. 5.4: *The level L of a narrowband noise required to match the loudness of a broadband noise with overall levels of 40, 65 and 80 dB HL is plotted versus bandwidth of the broadband stimuli.* □ *connected with the solid lines are the results of the categorical scaling experiments.* ○ *connected with the dotted lines are taken from Zwicker et al. (1957), their Fig. 8.*

For hearing–impaired subjects with a constant hearing loss across frequency, the observed dependence of level L_{25} on the frequency of narrowband signals is similar to that of normals (e.g., subjects AP, HF, MU, RS). However, in contrast to the results of normal–hearing subjects, this dependence is also observed for the broadband stimuli. Thus the difference between L_{25} of narrowband and broadband signals is considerably less in the hearing–impaired than in the normal–hearing subjects. This indicates reduced loudness summation in hearing–impaired listeners. This is also evident from Fig. 5.3 where loudness functions are plotted for normal–hearing (upper panel) and hearing–impaired subjects (lower panel) for two different signal bandwidths. While the loudness for the normal–hearing subjects differs markedly for the two stimulus conditions, the loudness for the hearing–impaired subjects is almost identical. Furthermore, no systematic difference is observed between the slopes obtained with narrowband stimuli and those obtained with broadband stimuli. Thus, unlike in normal–hearing subjects, loudness summation in hearing–impaired listeners does not depend on level.

In Fig. 5.5 the level differences ΔL required to obtain equal loudness between narrowband and broadband signals are plotted as a function of the bandwidth of the broadband noise. These level differences have been determined from the fitted loudness functions in the same

		Narrowband Stimuli						Broadband Stimuli				
VP		1375.	1600.	1860.	2160.	2500.	2925.	1480.	1635.	1795.	1985.	2210.
AP	m	1.10	1.34	1.34	1.31	1.37	1.06	0.99	1.48	1.15	1.02	1.06
	L_{25}	87.62	88.01	89.88	93.13	93.39	93.72	88.71	88.67	90.29	91.42	94.12
AW	m	1.01	1.02	1.17	1.19	1.24	1.39	0.84	1.11	1.10	0.98	1.08
	L_{25}	72.86	74.21	78.10	80.40	86.84	85.70	75.07	77.56	78.55	76.89	80.98
CS	m	1.12	1.19	1.35	1.22	1.23	1.41	1.55	1.51	1.37	1.41	1.41
	L_{25}	91.12	90.21	91.59	92.61	95.30	99.47	88.79	91.65	92.48	89.84	95.50
EH	m	1.10	1.23	1.34	1.32	1.24	1.03	1.08	1.33	1.43	1.40	1.31
	L_{25}	79.89	85.15	92.51	95.67	97.21	98.08	79.16	86.53	87.90	88.83	91.04
HF	m	1.46	1.38	1.42	1.44	1.84	1.83	1.37	1.50	1.36	1.53	1.34
	L_{25}	76.90	77.87	80.30	84.82	83.61	84.46	77.99	79.41	80.26	80.85	83.22
HK	m	0.69	0.74	0.65	0.64	0.65	0.55	0.63	0.66	0.76	0.71	0.60
	L_{25}	84.33	86.79	89.09	92.67	95.69	98.50	91.37	89.60	87.40	90.36	93.48
JC	m	1.63	1.79	2.15	2.22	2.29	1.74	1.95	1.94	2.58	2.28	2.79
	L_{25}	88.45	92.53	94.77	100.71	101.27	103.71	89.87	90.67	94.29	93.54	96.39
JKl	m	0.83	0.88	0.94	0.67	0.85	1.16	0.94	1.16	1.09	1.18	0.98
	L_{25}	88.24	89.16	92.19	94.75	96.93	101.64	88.54	92.88	91.75	93.52	93.89
JKn	m	0.82	0.74	0.84	0.64	0.77	0.86	0.83	0.92	0.94	0.83	0.94
	L_{25}	88.60	92.68	94.49	94.43	95.36	96.95	88.01	86.97	90.27	91.00	90.64
MU	m	1.21	1.04	1.14	0.95	0.85	0.75	1.03	1.19	1.20	1.16	1.07
	L_{25}	96.39	96.11	97.30	101.81	103.14	104.75	95.82	95.23	95.83	96.86	97.96
RB	m	0.55	0.72	0.77	0.61	0.65	0.90	0.57	0.61	0.73	0.78	1.32
	L_{25}	81.01	86.67	92.74	95.51	95.14	92.15	92.10	90.69	94.48	92.66	94.03
RS	m	1.02	0.95	0.98	0.89	0.71	0.79	0.94	0.82	0.84	1.15	0.87
	L_{25}	78.52	81.52	81.92	86.56	88.31	89.07	79.67	79.34	80.28	82.06	84.03
RW	m	0.86	0.85	0.93	0.92	0.94	1.20	0.85	1.23	0.97	0.86	0.91
	L_{25}	90.18	92.12	92.97	92.51	95.96	95.97	91.87	90.19	91.33	93.54	95.86
UH	m	0.80	1.54	2.24	1.63	0.76	1.09	1.15	1.86	1.19	0.84	1.03
	L_{25}	87.48	88.90	89.42	92.93	95.54	96.75	88.12	88.94	90.00	91.04	92.06

Table 5.3: *Individual results, i. e. individual slopes m and individual comfortable loudness levels L_{25}, of categorical scaling experiments with narrowband and broadband stimuli of 14 hearing–impaired listeners.*

way as described for normal–hearing subjects. The narrowband and broadband signals are compared at the level L_{25} yielding the loudness "intermediate", i.e., 25 in categorical units. For comparison, the level difference for normal–hearing subjects (◇) is plotted as well. It is evident from both panels of Fig. 5.5 that despite large individual differences, loudness summation is strongly reduced in all hearing–impaired listeners. The upper panel of Fig. 5.5 shows the results of 11 hearing–impaired subjects (group 1) who did not exhibit a

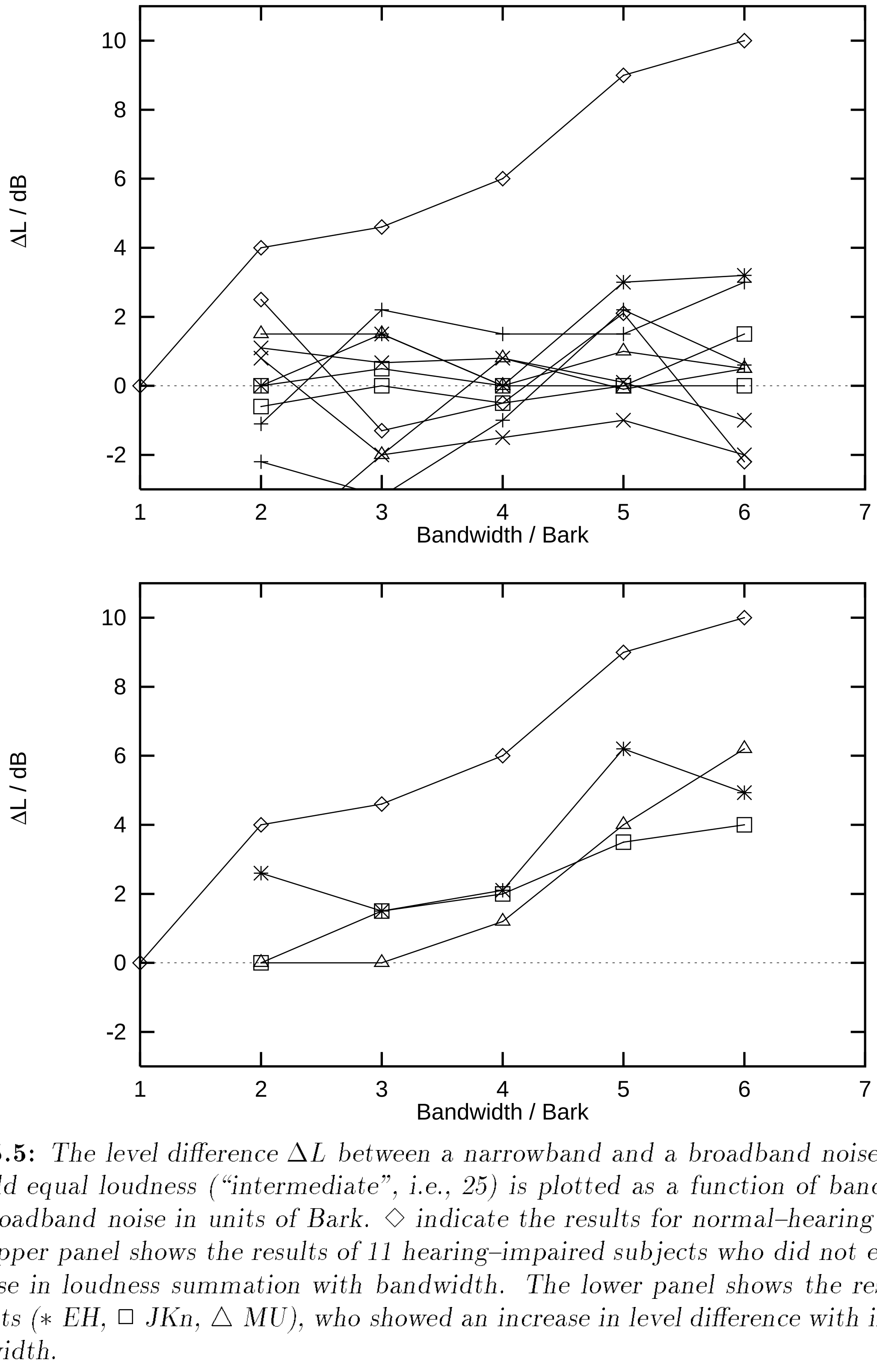

Fig. 5.5: *The level difference ΔL between a narrowband and a broadband noise required to yield equal loudness ("intermediate", i.e., 25) is plotted as a function of bandwidth of the broadband noise in units of Bark. ◇ indicate the results for normal–hearing subjects. The upper panel shows the results of 11 hearing–impaired subjects who did not exhibit an increase in loudness summation with bandwidth. The lower panel shows the results of 3 subjects (∗ EH, □ JKn, △ MU), who showed an increase in level difference with increasing bandwidth.*

significant increase in loudness with increasing bandwidth. For all 11 subjects the level difference ΔL is nearly constant across bandwidth and always less than 3.5 dB. The lower panel of Fig. 5.5 shows the results of 3 subjects (group 2: EH, JKn, MU) who showed an increase in loudness with increasing bandwidth. The results of both groups differ qualitatively although the subjects do not show any obvious differences in type or amount of hearing loss across groups. In group 2, the curves relating ΔL to bandwidth, show a shape similar to that of normals but shifted to lower a level differences ΔL. Thus, they show an increase of level difference with bandwidth although it is much less than in normals. For group 1, a large individual scatter across bandwidth occurs and no systematic increase of level difference with bandwidth is observed. Note, however, that the increase in group 2 is still within the scatter range of group 1. It may therefore be that this increase in group 2 is simply due to chance. Furthermore, in the data of subject MU ($*$) the difference of nearly 6 dB at the highest bandwidth might be caused by the procedure for evaluating the data. Linear functions were fitted to the data. The slope m of the loudness function of the broadband stimulus centered at 2210 Hz is larger than that for the corresponding narrowband stimulus centered at 2160 Hz. This causes different L_{25} values since the threshold is the same for both frequencies. However, the lower slope is mainly caused by scaling the two largest stimulus levels of the narrowband signal different from all lower levels. If these two points are not taken into account, a larger slope for the loudness function for the narrowband signal, and thus markedly less loudness summation (approximately 3 dB), is obtained.

5.4 Discussion

The dependence of the levels L_{25} of the narrowband noises on frequency is probably due to the fact that no standard correction for "hearing level" exists for the earphone used at the frequencies employed in this study. Therefore, the calibration might not give the correct HL levels. However, this incorrect calibration appears to mainly cause a parallel shift of the derived L_{25} values. The increase of perceived loudness with increasing bandwidth in normal–hearing listeners calculated from the measured loudness functions, is well in line with the results obtained with different techniques like loudness balancing. The categorical scaling technique correctly revealed the dependence of perceived loudness on signal bandwidth as well as the dependence of this latter effect on level for normal–hearing listeners. Thus, it appears to be an appropriate method for investigating different aspects of loudness perception.

Furthermore, the results of the hearing–impaired subjects are also in accordance with the literature. Despite large interindividual differences, loudness summation is strongly reduced in all hearing–impaired subjects. The same finding has been reported in many different studies as was discussed in section 5.1.2.

Reduced loudness summation in hearing–impaired listeners could be explained by two alterations usually observed in these subjects. Firstly, usually the bandwidth of auditory filters is increased in hearing–impaired subjects. As was pointed out in section 5.1.1, this would cause a reduction in loudness summation. Auditory filters must then be strongly broadened, since in most subjects even a bandwidth of almost 2 kHz (i.e., 6 critical bands) yields no increase in perceived loudness at all. However, in Fig. 4.3 measured auditory filter bandwidths are plotted as a function of audiometric threshold. This figure indicates that subjects with a large amount of hearing loss ($>$ 50 dB) on average show a broadening of auditory filters by a factor of two to three. Florentine and Zwicker (1979) pointed out that in their model, increasing the filter bandwidth by a factor of three did not fully account for the measured reduction of loudness summation. The second parameter which is also crucial for loudness summation is the exponent α of the power law for calculating specific loudness from the excitation pattern. Increasing α also reduces loudness summation. It will be shown in chapter 7 that reduced loudness summation can be mainly accounted for by modifying this parameter.

As was already mentioned above, large individual differences in loudness summation were observed in the hearing–impaired data. The hearing–impaired subjects were divided into two groups which differed in the obtained loudness summation. Group 2 showed some increase in level difference ΔL with increasing bandwidth while no such increase was found for group 1. Group 1 shows a large individual scatter in level difference across bandwidths. What might cause this difference between the two groups? Firstly, this might be due to differences in the shape of auditory filter bandwidths of the subjects of group 2 compared to the bandwidths of subjects of group 1. If so, the bandwidth of auditory filters of group 2 should be smaller than the bandwidths of the subjects of group 1. Since no measurement of auditory filter bandwidth was performed, this point cannot be unequivocally addressed. However, it is unlikely, since the results of group 2 can be modeled without any further modification of the model applied, as is discussed in chapter 7. Specifically, the auditory filter shapes used in the model do not differ for both groups. A second difference might be the amount of increase of the exponent α in both groups. Less increase of the exponent causes less loudness summation but is also associated with a lower slope in the loudness function. However, the two groups do not differ significantly in the slopes of measured loudness functions. Furthermore, since the overall scatter obtained for group 2 is within the scatter range of group 1, and since the results of subject MU might be due to the way the data were evaluated, the increase in level difference with bandwidth observed for group 2 may be simply due to chance.

5.5 Conclusions

In this chapter it was shown that categorical scaling with 11 categories revealed changes in perceived loudness with stimulus bandwidth consistent with those found using other methods. Furthermore, it was shown that loudness summation is strongly reduced in hearing–impaired listeners. Thus, it is concluded that categorical loudness scaling is an appropriate

technique to investigate different aspects of loudness perception in normal–hearing as well as in hearing–impaired listeners.
The large reduction in loudness summation observed with hearing–impaired listeners is probably not due solely to a reduction in frequency selectivity; instead, the reduction in compressive processing must also be taken into account.