Binaural spectral selectivity in normal-hearing and hearing-impaired listeners

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Abstract

When listening to relevant acoustic signals (e.g., speech) in a complex acoustic environment (e.g., a cocktail party), the human auditory system can utilize, among other cues, frequency selectivity and binaural hearing to separate wanted from unwanted sound components. This thesis investigates how these two cues interact by measuring and modeling frequency selectivity in monaural and binaural conditions for both normal-hearing (NH) and hearing-impaired (HI) subjects.

The principal experimental paradigm in measurement and simulation is the notched-noise experiment. Though this is the classical experiment to investigate frequency selectivity (de Boer and Bos, 1962; Patterson, 1976) it was hardly (Hall *et al.*, 1983) conducted in a dichotic condition before.

In contrast to a narrowband or broadband masker without notch where the binaural masking-level difference (BMLD) is nearly constant as a function of masker spectrum level, the BMLD obtained in the notched-noise experiment decreases with increasing notch width. This is at odds with two hypotheses (Hall *et al.*, 1983; van de Par and Kohlrausch, 1999) that assume the same level dependence of the BMLD as in a narrowband or broadband masker without notch, respectively, for the notched-noise experiment. In addition, recent models implementing the van de Par and Kohlrausch (1999) hypothesis (Zerbs, 2000; Breebaart *et al.*, 2001a) fail to predict the dichotic thresholds in notched noise if the auditory filter parameters are fitted to the diotic threshold data.

The measured threshold data support a significant modification of current models by assuming that frequency selectivity is slightly worse in dichotic conditions than in diotic or monaural conditions. This can be implemented, e.g., by adding portions of the outputs of the adjacent filters to the filter centered at the signal frequency.

Moreover, the best fit to the data obtained for the signal frequencies of 250, 500, 1000, and 2000 Hz is achieved if the difference between auditory filter attenuation characteristics derived from diotic and dichotic thresholds is assumed to increase with decreasing signal frequency.

In order to assess the influence of hearing impairment on the broadening of the auditory filters for dichotic listening, the ratios of binaural to monaural auditory filter width measured for a 500-Hz signal in notched noise were found to be the same for NH and HI subjects. This indicates no additional retrocochlear impair-

ment in the HI subjects tested here. Moreover, no specific binaural impairment factor has to be assumed in the HI subjects since in two subjects a nonzero BMLD in combination with the non-perceptibility of Huggins' pitch was found.

Taking together, the notched-noise test paradigm can also be used to assess frequency selectivity in binaural (dichotic) conditions in NH and HI subjects if the finding of broader "effective" auditory filters in binaural listening is adequately accounted for.

Kurzfassung

In einer komplexen Hörsituation, zum Beispiel einer Cocktail-Party, kann das Hörsystem des Menschen Nutzsignale wie etwa Sprache von unerwünschten akustischen Eindrücken trennen. Es nutzt dazu unter anderem Frequenzselektivität und binaurales Hören. In dieser Arbeit wird durch Messungen und Modellierung der Frequenzselektivität in monauralen und binauralen Hörversuchen mit Normalhörenden (NH) und Schwerhörenden (SH) untersucht, wie Frequenzselektivität und binaurales Hören wechselwirken.

Das in dieser Arbeit meistbenutzte Versuchsparadigma ist das des Bandstopexperiments. Obwohl dies das klassische Experiment zur Untersuchung der Frequenzselektivität ist (de Boer und Bos, 1962; Patterson, 1976), wurde es bisher kaum (Hall *et al.*, 1983) mit dichotischen Stimuli durchgeführt.

Im Gegensatz zu einem Schmalbandverdecker oder einem Breitbandverdecker ohne spektrale Lücke, bei denen sich als Funktion der spektralen Leistungsdichte des Verdeckers ein nahezu konstanter binauraler Gewinn ergibt, nimmt der binaurale Gewinn im Bandstopexperiment mit zunehmender Lückenbreite ab. Dies widerspricht zwei Hypothesen, die für das Bandstopexperiment dieselbe Pegelabhängigkeit des binauralen Gewinns wie bei einem Schmalbandverdecker (Hall *et al.*, 1983) oder Breitbandverdecker ohne Lücke (van de Par und Kohlrausch, 1999) annehmen. Zudem sind derzeitige Hörmodelle (Zerbs, 2000; Breebaart *et al.*, 2001a), die die Hypothese von van de Par und Kohlrausch (1999) umsetzen, nicht in der Lage, die dichotischen Schwellen im Bandstopexperiment vorherzusagen, wenn ihre Filterparameter an die diotischen Schwellen angepasst worden sind.

Die gemessenen Schwellen legen eine Veränderung derzeitiger Hörmodelle dahingehend nahe, dass die Frequenzselektivität in dichotischen Konditionen leicht schlechter als in diotischen oder monauralen Konditionen ist. Dies kann im Modell etwa dadurch umgesetzt werden, dass man Anteile des Ausgangs benachbarter Filter zu dem an der Signalfrequenz zentrierten Filter addiert.

Ferner erhält man die beste Anpassung an die Daten für die Signalfrequenzen 250, 500, 1000 und 2000 Hz, wenn man annimmt, dass der Unterschied zwischen den aus den diotischen und dichotischen Schwellen abgeleiteten Filterformen mit abnehmender Signalfrequenz zunimmt.

Um den Effekt einer Schwerhörigkeit auf die Verbreiterung der auditorischen Filter bei dichotischen Stimuli zu untersuchen, wurden bei einer Signalfrequenz

von 500 Hz monaurale und binaurale Filterbreiten bestimmt. Das Verhältnis binauraler zu monauraler Filterbreite ist bei NH und SH gleich. Dies deutet auf keine zusätzliche retrokochleäre Verschlechterung bei den hier teilnehmenden SH hin. Ferner konnte in der Studie kein einheitlicher binauraler Verschlechterungsfaktor gefunden werden, denn zwei der SH zeigten einen binauralen Gewinn, konnten aber keinen Huggins-Pitch wahrnehmen.

Zusammengenommen kann das Bandstop-Paradigma auch für die Untersuchung der Frequenzselektivität in binauralen (dichotischen) Konditionen benutzt werden, wenn man berücksichtigt, dass die Filter effektiv etwas breiter sind.

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1. Introduction

The human auditory system is able to analyze complex listening situations such as filtering out one speaker in an environment where a lot of people are talking. Probably the most important basis for the performance of the auditory system is that it receives different inputs to the two ears (binaural hearing). Depending on the position of the sound source and the spectrum of the emitted sound, the sounds arriving at the two ears contain interaural differences in time, phase, and level that are evaluated by the auditory system.

One method to investigate binaural hearing are psychoacoustic experiments. In such experiments, stimuli are presented to subjects and the subjects are asked to report what they have perceived, for instance, by pressing a button on a computer keyboard. Since the results rely on the reports of the participating subjects, psychoacoustic experiments are subjective measurements, i.e., they depend on the cooperation of the subjects.

Natural stimuli vary in a lot of physical parameters at the same time. For a better control of stimulus parameters in psychoacoustical experiments artificial stimuli, such as sinusoids, are mostly used. One classical psychoacoustic experiment is the masking experiment: In this experiment, the threshold for one stimulus is measured in the presence of another. Mostly, one of the stimuli is held constant in level, the other stimulus is varied in level and a detection threshold for perceiving one stimulus in the presence of the other stimulus is determined. In the case of a sinusoid masking a sinusoid, there are various interactions (e.g., beatings and nonlinear distortion) between the sinusoids so that thresholds also depend on the frequency ratio or difference of the sinusoids. To exclude these effects later studies used a narrowband noise to mask a sinusoid. The use of a noise masker and a sinusoidal signal to be detected is still a common experimental paradigm that is used in most experiments of the present study as well.

Though psychoacoustic experiments are subjective and show a large intersubject variability at least in some experimental conditions, the basic results are similar across subjects and open applications in the field of digital signal processing: Compressive audio coding is based on results of psychoacoustic masking experiments (Brandenburg and Stoll, 1994). Speech transmission used in cellular telephones uses models of auditory processing developed on the basis of psychoacoustic experiments (Kollmeier *et al.*, 2008).

1.1. Frequency selectivity

One of the means by which the auditory system analyzes sounds is a frequency decomposition.

Ohm (1843) suggested that the auditory system decomposes a complex sound into sinusoidal components, that is, acts as a Fourier analyzer. Helmholtz (1863) proposed that different parts of the ear sense different frequencies (i.e., a tonotopic organization). Von Békésy (1942, 1943) showed that the frequency decomposition in the cochlear does not work on the basis of resonance but that there is a traveling wave on the basilar membrane and the location of its vibration maximum depends on the frequency of the incoming sound.

The frequency decomposition of the auditory system results in a certain frequency selectivity. *Frequency selectivity* refers to the ability to resolve the sinusoidal components in a complex sound (Moore, 2003). Technically, the frequency selectivity of the auditory system can be imagined as implemented by a bank of bandpass filters with overlapping passbands. The attenuation characteristics or shape of these *auditory filters* can be assessed in several psychoacoustic experiments. Two of them are the bandwidening experiment and the notched-noise experiment.

In the *bandwidening experiment* a sinusoidal signal is masked by a signal-centered noise masker whose bandwidth is the parameter of variation. In the *notched-noise experiment* a sinusoidal signal is presented within a spectral notch of variable width in a broadband noise masker.

Fletcher (1940) conducted a bandwidening experiment using a noise masker of constant spectrum level and found an increase in signal threshold with increase in masker bandwidth up to a certain *critical bandwidth*. Increasing the masker bandwidth beyond this critical bandwidth did not lead to higher thresholds for the signal. A bandwidening experiment similar to Fletcher's was conducted by several other researchers (e.g., Schafer *et al.*, 1950; Hamilton, 1957; Zwicker *et al.*, 1957; Greenwood, 1961; Swets *et al.*, 1962). [1]

However, a problem of the bandwidening method was pointed out by de Boer (1962): The rate of fluctuations of the noise masker depends on its bandwidth and detection thresholds are not solely determined by the masker energy as previously assumed, but also by these bandwidth-dependent noise masker fluctuations. Additionally, the bandwidening experiment does not yield a very good estimate of the shape of the auditory filter since the dynamic range of detection thresholds is limited to about 10 dB.

Due to these limitations of the bandwidening experiment, the notched-noise experiment (de Boer and Bos, 1962; Patterson, 1976) became the standard experiment to investigate the frequency selectivity of the auditory system. Notched-noise experiments were conducted with normal-hearing (NH) subjects (e.g., Weber, 1977; Patterson and Henning, 1977; Patterson and Nimmo-Smith, 1980; Lutfi and Patterson, 1984; Moore *et al.*, 1990; Rosen and Stock, 1992; Glasberg and Moore, 2000; Baker and Rosen, 2006) and hearing-impaired (HI) subjects (e.g., Tyler *et al.*, 1984; Glasberg and Moore, 1986; Peters and Moore, 1992; Sommers and Humes, 1993; Leek and Summers, 1993; Baker and Rosen, 2002).

1.2. Binaural frequency selectivity

All studies cited above used stimuli that were presented either monaurally or *diotically* (i.e., the same stimulus to both ears). To investigate the binaural signal processing of the auditory system different stimuli are presented to both ears (*dichotic* stimulus presentation).

Seebeck (1846) pioneered in the investigation of tones with interaurally different phases. Hirsh (1948) and Licklider (1948) contributed to the foundations of binaural hearing research in that they found lower thresholds and a clear benefit in speech intelligibility, respectively, due to an opposite interaural phase difference of signal and masker.

The interaural difference in phase or time is usually given as a subscript to the capital letter N for noise and S for signal. NoSo, for example, denotes a diotic stimulus configuration with no interaural difference neither in the noise masker nor in the signal; NoSπ denotes a dichotic stimulus configuration where a diotic noise masker contains an antiphasic signal. When a signal is presented only to

[1] For a more detailed review see Chapter 2.

one ear, this is denoted by the subscript m, for instance NoSm. Since the auditory system cannot gain any information from comparing the stimuli to both ears in the NoSo condition, the term "monaural" is used for parameters derived from NoSo thresholds as well. The term "binaural", in contrast, refers to listening situations where information can be gained from an interaural comparison of stimuli and parameters derived from these thresholds. Though strictly speaking the NoSo condition is a binaural condition as well, in the present study the term "binaural" will be used in the narrow sense only for dichotic conditions. The difference of detection thresholds in the diotic stimulus condition NoSo and a dichotic stimulus condition, mostly NoSπ, is termed *binaural masking-level difference* (BMLD) [2].

Bourbon and Jeffress (1965) conducted a bandwidening experiment in NoSo and NoSπ masking condition. The signal frequency was 500 Hz. For the NoSo stimulus, they measured an increase in thresholds up to a masker bandwidth of about 150 Hz. For the NoSπ stimulus, however, an increase of thresholds with increasing bandwidth was observed up to 300 Hz. This observation led to the assumption that the critical bandwidth of the auditory system was larger for dichotic stimuli than for diotic or monaural stimuli; this apparently larger bandwidth was termed "binaural" critical bandwidth. Despite of the fact that de Boer (1962) pointed out the problems of masker fluctuations in the bandwidening experiment (see above) that reduce its value to derive critical bandwidths, this experiment was measured repeatedly in diotic and dichotic condition (Metz *et al.*, 1968; Wightman, 1971; Sever and Small, 1979; Hall *et al.*, 1983; Zurek and Durlach, 1987; Staffel *et al.*, 1990; Cokely and Hall, 1991; van de Par and Kohlrausch, 1999), probably because of the large discrepancy of monaural and binaural critical bandwidth that called for an explanation.

Within these studies there are two explanatory approachs for the striking difference between the critical-bandwidth estimates derived from NoSo and NoSπ thresholds of the bandwidening experiment that will be discussed in the present study:

- Hall *et al.* (1983) assume that binaural detection in broadband noise is based on many auditory filters centered not only at the signal frequency, but at frequencies of the whole spectrum of the masking noise. The signal improves the signal-to-noise ratio (SNR) in filters centered at or near the signal frequency, but not in other auditory filters. A lot of filters remote from the

[2] The term "masking-level difference" was coined by Webster *et al.* (1951).

signal frequency will not contain any interaural differences and thus hamper detection of an Sπ sinusoid by signaling the auditory system no interaural difference. This detrimental across-channel process will reduce with reduction in masker bandwidth which will lead to a decrease of NoSπ thresholds at masker bandwidths larger than the (monaural) critical bandwidth. Since there is no masker in large spectral distance from the signal in a signal-centered narrowband masking experiment, Hall *et al.* (1983) suggested this experiment to determine the BMLD in the notched-noise experiment as well.

- In contrast, van de Par and Kohlrausch (1999) assume that, for dichotic stimuli, the auditory system is able to integrate information over auditory filters when the masker bandwidth is narrow: In an auditory filter centered close to the signal frequency the SNR is high if the signal is masked by a signal-centered narrowband noise since both signal and masker are attenuated by the filter. If the masker is broadband, the signal, but not the masker is attenuated which leads to a lower SNR in this filter. In the beneficial across-channel process assumed by van de Par and Kohlrausch (1999) combining the information across auditory filters yields an advantage in binaural detection that reduces with increase in noise masker bandwidth.

Thus, for binaural detection, van de Par and Kohlrausch (1999) assume an additional benefit in a narrowband masker whereas Hall *et al.* (1983) assume a disadvantage in a broadband masker. Since the explanation of van de Par and Kohlrausch (1999), also implemented in models of binaural perception (Zerbs, 2000; Breebaart *et al.*, 2001a), the investigation of the binaural bandwidening experiment seems to have come to an end.

Though the notched-noise paradigm is the classical experiment to determine auditory filter bandwidth since the study by Patterson (1976) to date, except for Hall *et al.* (1983) there has been no experimental threshold data of the notched-noise experiment in NoSπ condition that could be related to thresholds measured in the NoSo condition.

Apparently, the beneficial across-channel process hypothesized by van de Par and Kohlrausch (1999) has no effect if the noise masker is broadband regardless whether the masker contains a spectral notch or not. In this case the SNR obviously is highest in the filter centered at the signal frequency. For these reasons van de Par and Kohlrausch (1999) conjectured a similar monaural and binaural critical bandwidth for all experiments where a tonal signal is used together with a broadband masker.

Testing this hypothesis by the comparison of a notched-noise experiment with an experiment where a sinusoid is masked by a broadband noise without notch, but various spectrum levels (referred to as "broadband experiment") was the starting point of the present study (Chapter 3).

1.3. Thesis overview

1.3.1. Aims of the thesis

The aims of the present dissertation are as follows:

- Test the hypothesis of van de Par and Kohlrausch (1999) that binaural detection is restricted to the on-frequency filter in all broadband masking conditions.
- Test the hypothesis by Hall *et al.* (1983) that the level dependence of the BMLD in notched noise is determined by that measured for a narrowband noise of varying spectrum level.
- Measure NoSπ thresholds in notched noise for more signal frequencies than Hall *et al.* (1983).
- Measure the notched-noise and broadband experiment in NoSo and NoSπ conditions for sensorineural HI subjects as well to investigate the hypothesis of van de Par and Kohlrausch (1999) with subjects who show more linear auditory filtering than NH subjects.
- Provide suggestions for successful modeling of the measured thresholds.
- Further the understanding of the binaural signal processing of the human auditory system.

1.3.2. Outline of the thesis

Chapter 2: Frequency selectivity: A historical review

This chapter provides an overview in more detail about the history of the investigation of auditory filter bandwidth than this introduction does. From the variety of psychoacoustic masking experiments to assess frequency selectivity this overview focusses on the bandwidening paradigm and the notched-noise paradigm. These two experiments are first described in monaural or diotic and after that in binaural or dichotic condition.

Chapter 3: The role of across-frequency processes in dichotic listening conditions

The concept of a wider binaural bandwidth has been challenged by van de Par and Kohlrausch (1999) who hypothesized a beneficial across-channel process that is only in effect in dichotic masking conditions when the masker is a narrowband noise centered at the signal frequency. They furthermore hypothesized the same critical bandwidth in diotic and dichotic masking conditions in all broadband masking situations. The aim of Chapter 3 is to disprove the second part of this hypothesis: There appears to be a beneficial across-channel interaction in dichotic narrowband masking, but the on-frequency filter is not the only determinant of dichotic tone detection in broadband masking. For experimental evidence of this, the threshold data obtained for a 500-Hz sinusoid in phase (So) and in antiphase (Sπ) in a notched-noise, broadband-noise, and narrowband-noise experiment are compared relating to the level dependence of the BMLD. It is shown that a binaural model (Breebaart *et al.*, 2001a) implementing the beneficial across-channel process proposed by van de Par and Kohlrausch (1999) is not able to predict the diotic and dichotic thresholds of the notched-noise experiment when using the same parameters for the frequency selectivity of the model.

Chapter 4: Notched-noise masking in NoSo and NoSπ condition at various center frequencies

Since Chapter 3 demonstrated a different level dependence of the BMLD in notched noise in contrast to narrowband or broadband noise without notch, the aim of this chapter is to investigate the signal-frequency dependence of the BMLD in the notched-noise experiment. For this reason, NoSo and NoSπ detection thresholds for sinusoids of 250, 500, 1000, and 2000 Hz in a notched-noise masker are measured as a function of notch width. Two additional experiments are conducted at the signal frequency of 500 Hz: To test whether the apparently wider binaural filter bandwidth is merely due to an interaural asymmetry of auditory filters, monaural left and right thresholds in notched noise are measured. To investigate the interaction of diotic noise masker and a signal containing an IPD as a function of notch width, just-noticeable IPDs are measured against a reference IPD of zero at a signal level 3 dB above the respective NoSo threshold. For all signal frequencies, the BMLD shows a roughly exponential decay as a function of relative notch width (notch width divided by signal frequency). The difference in auditory filter width between estimates derived from NoSo and NoSπ thresholds is most prominent at the lowest signal frequency and decreases with increasing signal frequency. A model incorporating a detrimental across-channel process for dichotic stimuli is able to predict the measured thresholds.

Chapter 5: Monaural and binaural frequency selectivity in hearing-impaired subjects

This chapter reports the results of the same notched-noise experiment and broadband experiment as in Chapter 3, but with HI subjects to investigate whether similar results as in NH subjects are also found in subjects whose auditory filters can be assumed to be more linear. Auditory filter shapes are fitted to the diotic as well as to the dichotic thresholds using a power spectrum model. As a second measure of binaural auditory processing apart from NoSπ thresholds the ability to perceive Huggins' pitch (a purely binaural pitch based on interaural phase differences in a certain frequency region of a broadband noise) is tested in the HI subjects to investigate the relation between Huggins-pitch perceptibility and the BMLD. If there is one common factor that impairs binaural processing in HI subjects, the Huggins-pitch perceptibility should decrease in a similar degree as the BMLD in broadband noise. Auditory filter bandwidth is larger for both HI subjects compared to NH subjects and in the NoSπ condition compared to the NoSo condition. The ratio of binaural divided by monaural filter-width estimates, however, is similar in HI and NH subjects.

Appendices

The Appendices contain material not presented in Chapter 3–5 to keep them concise and an additional experiment using a binaural spectral masking pattern paradigm.

2. Frequency selectivity: A historical review

Frequency selectivity refers to the ability of the auditory system to resolve the sinusoidal components in a complex sound (Moore, 2003). It is usually investigated in masking experiments. In contrast to frequency selectivity, *frequency discrimination* stands for the just-noticeable difference in frequency of sinusoids.

Ohm (1843) enunciated a theory, later referred to as Ohm's acoustical law, that the auditory system decomposes a complex sound into sinusoidal components similarly to a Fourier analysis. Helmholtz (1863) proved this law and suggested that different parts of the ear sense tones of different frequency. Von Békésy (1942, 1943) was able to demonstrate that there is a vibration maximum on the basilar membrane and that its location is frequency dependent. He was also able to show that the excitation of the basilar membrane is a traveling wave, not a simple resonance phenomenon.

Frequency selectivity can be measured in various experiments. In the following of this section the result of basically two different psychoacoustic masking experiments will be reported: On the one hand an experiment where a signal-centered noise masker is varied in bandwidth. This experiment is called bandwidening experiment. On the other hand the spectral counterpart of the bandwidening experiment, the notched-noise experiment. In this experiment the width of a notch in the masker spectrum around the signal frequency is varied. Both types of experiments were used to investigate frequency selectivity.

Sec. 2.1 deals with "monaural" experiments where either a stimulus is presented only to one ear or the same stimulus is presented to both ears such that the auditory system cannot take advantage from interaural differences of the stimulus. Sec. 2.2 deals with "binaural" experiments where the effect of interaural differences of the stimulus is investigated.

2.1. Frequency selectivity

2.1.1. Bandwidening experiment

Fletcher (1940) conducted a bandwidening experiment at a constant spectrum level of the noise masker. He reported that masking noise of frequencies outside a certain *critical band* around the signal frequency does not influence threshold. The critical bandwidth can be interpreted technically as the pass-band of a bandpass filter, the *auditory filter*. For simplicity reasons at first a rectangular attenuation characteristic of the auditory filter was assumed. The frequency decomposition of the auditory system can effectively be modeled as a bank of overlapping bandpass filters and threshold is determined by the masker energy in the filter centered at or near the signal frequency.

To determine the critical band, Fletcher (1940) fitted a line with a fixed slope of 3 dB/octave and a horizontal line to the masked threshold data [1]. The abscissa of the point of intersection of these two lines was used as a critical-bandwidth estimate. In this way Fletcher (1940) obtained critical bandwidths of 50, 50, 65, and 100 Hz for the signal frequencies of 250, 500, 1000, and 2000 Hz, respectively. Thus, the critical band broadens with increasing signal frequency. However, Fletcher (1940) noted that these widths of the critical bands might be wrong by a factor of 2 due to only a few data points per signal frequency, but at least their order of magnitude was right.

Further bandwidening experiments were conducted by, e.g., Schafer *et al.* (1950); Hamilton (1957); Zwicker *et al.* (1957); Greenwood (1961) and Swets *et al.* (1962). The threshold data obtained by Schafer *et al.* (1950) do not show a sharp break at the critical bandwidth that would result from the attenuation characteristic of a rectangular filter as assumed by Fletcher (1940). Schafer *et al.* (1950) approximated the attenuation characteristic of the auditory filter by the resonance curve of a simple tuned circuit. Zwicker *et al.* (1957) showed that the concept of the critical band also applies to loudness summation and, furthermore, measured the critical bandwidth in three other methods. They reported a critical-bandwidth estimate consistent across methods that is about two-and-a-half times as wide as the estimate derived by Fletcher (1940). Critical-band estimates larger than those of Fletcher (1940) were also reported by Hamilton (1957) and Greenwood (1961), whereas Swets *et al.* (1962) conjectured the possibility of a task-dependent fre-

[1] Fletcher (1940)'s Fig. 17 was reproduced in Schafer *et al.* (1950) and Hamilton (1957).

quency selectivity that would render the term “the” critical band unsuitable and reported critical-band estimates between 40 and 100 Hz at the signal frequency of 1 kHz.

The different critical-bandwidth estimates across studies reveal that these estimates depend on the experimental paradigm, assumptions made, and other criteria (see also Sever and Small, 1979). Though critical-bandwidth estimates differed, their dependence on signal frequency was similar.

Besides the question on how to derive a critical-bandwidth estimate from the threshold data, two fundamental problems are inherent to the bandwidening experiment: One problem is its limited dynamic range. For a given noise masker spectrum level, thresholds for all bandwidths are within a range of levels of about 10 dB. Hence, taking into account the standard deviation of the thresholds, the bandwidening experiment does not yield a very good estimate of the shape of an auditory filter. Another problem of the bandwidening paradigm is the masker envelope statistics (de Boer, 1962): The rate of fluctuations of a noise masker increases with bandwidth. Narrowband noises sound like tones of slowly varying intensity, whereas broadband noises yield a smooth sensation. The slow masker envelope fluctuations of a narrowband noise result in an increase in threshold that is not due to masker energy.

2.1.2. Notched-noise experiment

A noise with a spectral gap or notch was already used by Webster *et al.* (1952) to mask sinusoids of various frequencies within and outside the notch.

The first experiment where a sinusoidal signal of a fixed frequency was masked by a broadband noise with a variable spectral gap at the signal frequency was reported by de Boer and Bos (1962). They reported a critical-bandwidth estimate slightly larger than that of Zwicker *et al.* (1957) and hypothesized already that the auditory filter might be centered at a frequency different from the signal frequency to improve the signal-to-noise ratio (SNR).

After experiments with a masking noise below or above the signal frequency (Patterson, 1974), Patterson (1976) used a notched-noise experiment to determine auditory filter shapes by varying the notch width for a fixed signal frequency. If masker spectrum level is chosen high enough, this notched-noise experiment extends the dynamic range of thresholds to more than 30 dB and thus solves one of the problems of the bandwidening experiment. Masker spectrum level was held constant at 40 dB/Hz; signal level was varied to determine thresholds. Patterson (1976) measured masked thresholds for sinusoids of 0.5, 1, and 2 kHz. All notches were arithmetically centered at the respective signal frequency. Patterson (1976) assumed a symmetric filter and derived its attenuation characteristic that was described as the first derivative of a polynomial fitted to the threshold curve. A Gaussian yielded a good approximation for the pass-band as well; in the filter tails, however, the attenuation of the auditory filter did not fall as fast as the Gaussian.

The notched-noise experiment became the classical psychoacoustic paradigm to assess frequency selectivity. Notched-noise experiments were conducted with normal-hearing (NH) subjects (e.g., Weber, 1977; Patterson and Henning, 1977; Patterson and Nimmo-Smith, 1980; Lutfi and Patterson, 1984; Moore *et al.*, 1990; Rosen and Stock, 1992; Glasberg and Moore, 2000; Baker and Rosen, 2006) and hearing-impaired (HI) subjects (e.g., Tyler *et al.*, 1984; Glasberg and Moore, 1986; Peters and Moore, 1992; Sommers and Humes, 1993; Baker and Rosen, 2002).

Patterson and Henning (1977) investigated the effect of stimulus variability on the thresholds of a notched-noise experiment by comparing the results of Patterson (1976) to a stimulus condition where two sinusoids of fixed level and varied frequency separation masked a narrowband target noise [2]. Patterson and Henning (1977) reported a good correspondence of the measured thresholds to the filter shapes derived in Patterson (1976). Thus, a problem with the bandwidth dependence of noise-masker envelope fluctuations (de Boer, 1962) does not occur in the notched-noise experiment.

Weber (1977) extended the measurements of Patterson (1976) to a large range of spectrum levels and showed that the auditory filter broadens with increase in level. Later studies on the level dependence of the auditory filter were conducted by, e.g., Lutfi and Patterson (1984); Rosen and Stock (1992); Glasberg and Moore (2000); Baker and Rosen (2002) and Baker and Rosen (2006). The investigation of level dependence in these studies was combined with measurements of the asymmetry of the auditory filter (see, e.g., Patterson and Nimmo-Smith, 1980). At high masker levels the noise band below the signal frequency dominates the masking (Lutfi and Patterson, 1984), i.e., the lower skirt of the auditory filter is shallower than the upper. Auditory filter asymmetry tends to increase with level (Moore *et al.*, 1990).

[2] A similar experiment, but with sinusoids as maskers and signal, was conducted by Green (1965).

Auditory filter bandwidth increases with level; this increase increases with signal frequency from 125 to 1000 Hz with little or no effect of level at 125 Hz (Rosen and Stock, 1992). Auditory filtering shows more linear behavior for impaired ears even with a mild hearing loss (Baker and Rosen, 2002).

The investigation of filter asymmetry brought a need of an asymmetric function for modeling the attenuation characteristics of the auditory filter. Patterson and Nimmo-Smith (1980) analysed their thresholds using a power spectrum model under the assumption that the general form of the auditory filter can be described by a *rounded exponential (roex)*, i.e., two back-to-back negative exponentials with the peak smoothed and the tails raised. Different parameters for the lower and upper exponential were allowed to account for asymmetry. For the signal frequency of 2 kHz, Patterson and Nimmo-Smith (1980) reported a pass-band (*3-dB down notch width*, the distance of the two points where the attenuation of the filter is 3 dB relative to the filter center frequency) of 220 Hz, steep skirts (100 dB/octave), and shallower filter tails (about 40 dB/octave) 30–35 dB down from the peak.

Based on the roex filter more sophisticated functions of a level-dependent attenuation characteristic have been developed (Rosen and Baker, 1994; Glasberg *et al.*, 1999; Glasberg and Moore, 2000). Glasberg and Moore (2000), for example, used an auditory filter model that consisted of a sharply tuned, level-dependent tip filter and a broader, level-independent tail filter.

A study Patterson *et al.* (1982) conducted with subjects aged between 23 and 75 years who were normal hearing or had a mild hearing loss drew the conclusions that the pass-band of the auditory filter broadens progressively with age and dynamic range decreases with age like the audiogram. The observation of an aging of the auditory filters elicited further studies (Peters and Moore, 1992; Sommers and Humes, 1993). Peters and Moore (1992) found no clear differences in filter characteristics between young and elderly HI subjects. Filters tended to broaden with increasing hearing loss, but some HI subjects with mild losses had normal filters. Sommers and Humes (1993) did not find a significant difference between NH young and elderly subjects. Furthermore, the filter bandwidth derived for noise-masked young NH subjects was comparable to that of HI subjects with a corresponding degree of actual hearing loss. The efficiency of signal detection was not significantly different between young and elderly subjects with the same degree of hearing loss. However, filter shapes derived from elderly HI subjects might be more asymmetric than those derived from noise-masked young NH subjects.

2.2. Binaural frequency selectivity

Seebeck (1846) wrote one of the earliest articles also concerned with binaural hearing. He used the sounds of sirens to the left and right ears to investigate the influence of phase differences of tones of the same frequency. The perceived loudness increased with the tone to the right ear independently of the difference in interaural phase, i.e., Seebeck (1846) did not find destructive interference between the two ear signals.

More than 100 years later, Hirsh (1948) measured detection thresholds for sinusoids of various frequencies in masking noise. He used all interaural combinations of in-phase and antiphase masker and signal and reported the lowest thresholds when noise masker and signal had opposite interaural phase angles. Licklider (1948) reported a clear benefit in speech intelligibility if an interaurally inverted speech signal was presented together with an identical masking noise to both ears.

2.2.1. Bandwidening experiment

Bourbon and Jeffress (1965) conducted an experiment similar to the bandwidening experiment by Fletcher (1940), but they also used dichotic stimuli. The signal frequency was 500 Hz. For the NoSo stimulus, they measured an increase in thresholds up to a masker bandwidth of about 150 Hz. For the NoSπ stimulus, however, an increase of thresholds with increasing bandwidth was observed up to 300 Hz.

This observation led to the assumption that the "binaural" auditory filter bandwidth was larger than the monaural.

Bandwidening experiments with dichotic stimuli were also conducted by, e.g., Metz *et al.* (1968); Wightman (1971); Sever and Small (1979); Hall *et al.* (1983); Zurek and Durlach (1987); Staffel *et al.* (1990); Cokely and Hall (1991) and van de Par and Kohlrausch (1999).

The main finding of Wightman (1971) was that, for NoSo thresholds, off-frequency listening enabled by a narrowband masker and short ramps at signal on- and offset, considerably lowers thresholds, whereas this effect cannot be observed for NoSπ thresholds. Wightman (1971) found an explanation for different BMLDs measured before by Metz *et al.* (1968) and Wightman (1969) in very similar narrowband maskers in the fact that the filtering to generate the noise masker in Metz *et al.* (1968) was such that it masked the off-frequency excitation by the sig-

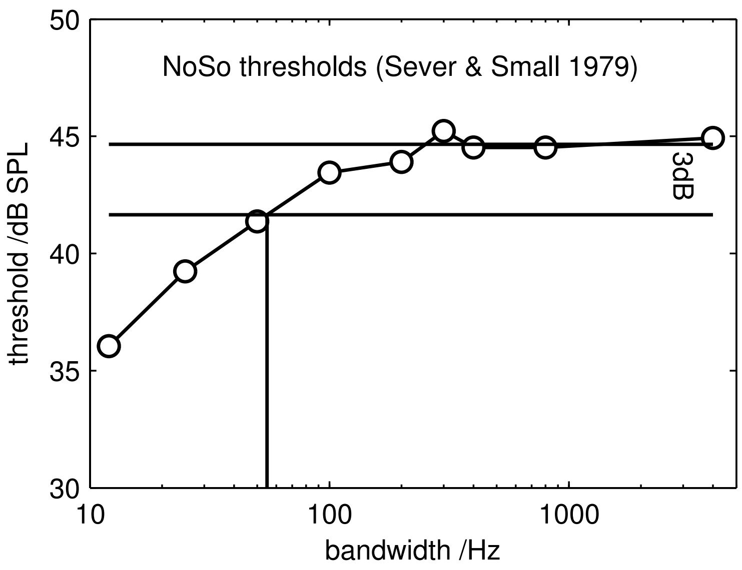

Figure 2.1.: Piecewise linear technique: Mean NoSo detection thresholds from Sever and Small (1979) for a sinusoid of 500 Hz. The upper horizontal line is the average of the thresholds at the three largest masker bandwidths. The lower horizontal line is a parallel 3 dB below. The estimate for the critical bandwidth is the intersection point of the lower horizontal line with the lines linearly connecting the data points. The vertical line indicates the critical-bandwidth estimate.

nal and thus resulted in higher NoSo thresholds than Wightman (1969). Without off-frequency listening Wightman (1971) reported a BMLD that is monotonically increasing with decrease in masker bandwidth.

Sever and Small (1979) and Hall *et al.* (1983) used two different techniques to estimate the critical bandwidth from the measured data points: Both methods assume that thresholds increase with increase in masker bandwidth, but reach a horizontal asymptote at a critical bandwidth.

In the first technique (*piecewise linear technique*, depicted in Fig. 2.1), the asymptote was estimated as the average of the two (Hall *et al.*, 1983) or three (Sever and Small, 1979) thresholds at the largest masker bandwidths. The thresholds at narrower bandwidths were connected by straight lines (piecewise linear fit). The 3-dB down point used as the bandwidth estimate was the frequency at which one of the straight lines intersected a horizontal line 3 dB down from the asymptote.

The second technique (*two straight-lines technique*, depicted in Fig. 2.2) was

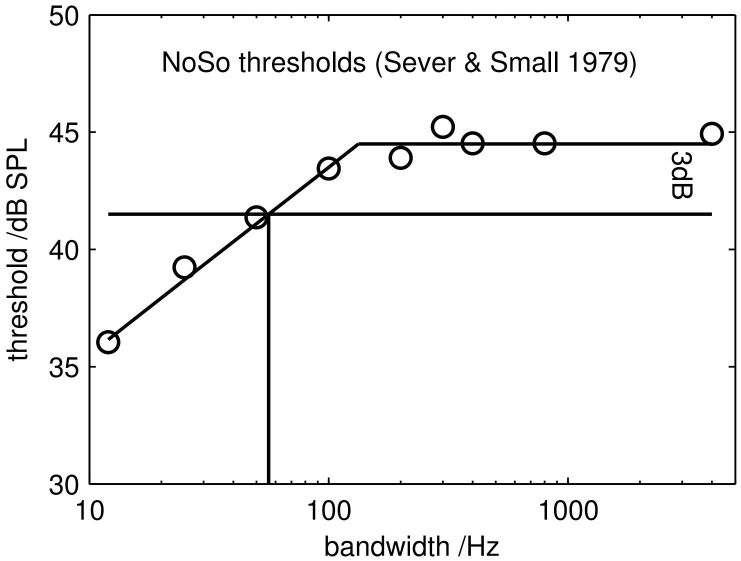

Figure 2.2.: Two straight-lines technique: Mean NoSo detection thresholds from Sever and Small (1979) for a sinusoid of 500 Hz. Two lines were fitted to these thresholds in a least-squares procedure: The fit parameters were the slope and the intercept of the line with a positive slope and the intercept of the upper horizontal line that necessarily had a slope of 0 dB/octave. The lower horizontal line is a parallel 3 dB below the upper. The estimate for the critical bandwidth is the intersection point of the lower horizontal line with the line with the positive slope. The vertical line indicates the critical-bandwidth estimate.

based on the assumption (Fletcher, 1940; Schafer *et al.*, 1950) that the function relating threshold to bandwidth on a logarithmic frequency axis can be described with two straight lines: A line with a positive slope while thresholds are increasing with bandwidth and a horizontal asymptote for thresholds beyond critical bandwidth. These two lines were fitted with the three parameters slope and intercept of the sloping line and intercept of the asymptote in a least-squares fit. The frequency at which the sloping line intersected a horizontal line 3 dB down from asymptote was used as a bandwidth estimate. Fletcher (1940) derived his critical bandwidth using the second technique but he used the frequency at which the two lines fitted to the thresholds intersected as a critical-bandwidth estimate. Sever and Small (1979) chose the point of intersection with a horizontal line 3 dB down from asymptote because this point is less sensitive to small changes in slope.

For the signal frequency of 500 Hz, Sever and Small (1979) reported critical-bandwidth estimates of about 55 and about 83 Hz in the NoSo and NoSπ condition [3], respectively. At the same spectrum level of 30 dB/Hz, Hall *et al.* (1983) report smaller (about 42 Hz) estimates for the NoSo condition and wider (about 88 Hz) for the NoSπ condition. The difference between these estimates was significant, whereas it was not significant in the study by Sever and Small (1979) for the estimates derived with the two straight-line technique. Sever and Small (1979) did not find a significant difference in critical-bandwidth estimates between NmSm and NoSo thresholds.

The critical-bandwidth estimate derived from the thresholds of the NoSπ condition increases with masker spectrum level, whereas the estimate derived from the NoSo thresholds is rather constant (Hall *et al.*, 1983): At a small spectrum level there is no significant difference between the estimates of the two interaural conditions; at the spectrum level of 50 dB/Hz the estimates are below 50 Hz in the NoSo and above 200 Hz in the NoSπ condition. Hall *et al.* (1983) contrasted their bandwidening experiment with its spectral counterpart, a notched-noise experiment (see Sec. 2.2.2 below).

Zurek and Durlach (1987) conducted a bandwidening experiment with sinusoidal signals of 250 Hz and 4 kHz using a noise masker of a fixed level of 80 dB SPL. Since they used a constant masker level, NoSo thresholds remained rather constant for the narrow masker bandwidths and decreased with about -

[3] Thresholds are averaged over the two analysis techniques here. The values for the two techniques are given in Tab. 2.1.

Author(s)	L_S /dB/Hz	NoSo CB /Hz	NoSπ CB /Hz
Bourbon and Jeffress (1965)	?	150	300
Sever and Small (1979)	30	57 (53)	79 (86)
Hall *et al.* (1983)	30	43 (40)	85 (91)
	50	42 (47)	260 (220)
Staffel *et al.* (1990)	60	44.7	114.8

Table 2.1.: Critical-bandwidth (CB) estimates derived from diotic and dichotic thresholds in bandwidening experiments at a signal frequency of 500 Hz and a fixed spectrum level L_S. The CB estimates enclosed in parentheses were derived using the piecewise linear technique. The other CB estimates were derived using the two straight-lines technique except for the estimates given by Bourbon and Jeffress (1965) where the values denote the noise masker bandwidth at which thresholds ceased to increase.

3 dB/octave for bandwidths larger than the critical bandwidth. In spite of the constant masker level, NoSπ thresholds increased with an increase in masker bandwidth for narrow masker bandwidths until they decreased as well, but from a wider critical bandwidth on than the NoSo thresholds. Results across the three subjects were more consistent for the 250-Hz than for the 4-kHz signal frequency. As a critical-bandwidth estimate, Zurek and Durlach (1987) used the smallest bandwidth where the derivative of a polynomial fitted to the thresholds was -2 dB/octave. The results were rather different across subjects, but the critical-bandwidth estimates for the NoSπ condition were much larger than those for the NoSo condition. Zurek and Durlach (1987) suggested sluggishness of the binaural system (Kollmeier and Gilkey, 1990) as an explanation for the increasing NoSπ thresholds with increase in bandwidth for narrow bandwidths: The rate of masker fluctuations is small at narrow bandwidths. For this reason the interaural differences in intensity and timing due to the Sπ signal vary slowly. If the noise-masker bandwidth is increased, the rate of change of these interaural cues will increase. Due to binaural sluggishness this is supposed to be the reason for the NoSπ threshold increase with bandwidth for narrow bandwidths.

Staffel *et al.* (1990) examined the effect of cochlear hearing loss on the critical bandwidth derived from NoSo and NoSπ thresholds in a bandwidening experiment. Thresholds of NH subjects were measured as well as a control group. The signal frequency was 500 Hz as in the study by Hall *et al.* (1983). Staffel *et al.*

(1990) used a spectrum level of 60 dB/Hz and the two straight-lines technique (Fig. 2.2) to determine the 3-dB down bandwidths as critical-bandwidth estimates. For NH subjects, their estimates were 45 Hz for the NoSo and 115 Hz for the NoSπ thresholds. Though it is more than twice the monaural size, the NoSπ critical bandwidth of 115 Hz is small compared to above 200 Hz Hall *et al.* (1983) reported for the smaller spectrum level of 50 dB/Hz. For HI subjects, critical-bandwidth estimates showed a large interindividual variability and were on average 65 and 146 Hz for the NoSo and NoSπ thresholds, respectively. The motivation for the study by Staffel *et al.* (1990) was the hypothesis that a larger NoSπ critical bandwidth might be due to an interaural asymmetry in monaural critical bandwidths: The decorrelation because of interaural asymmetry is reduced when the masker bandwidth becomes smaller and for this reason NoSπ thresholds decrease at larger bandwidths than the monaural critical bandwidth. However, the results by Staffel *et al.* (1990) did not support a strong association between interaural asymmetry of monaural critical bands and the NoSπ critical bandwidth.

A bandwidening experiment with a noise masker of varying interaural correlation masking an Sπ sinusoid at 500 Hz was conducted by van der Heijden and Trahiotis (1998). They observed a wider binaural critical bandwidth only if the interaural correlation of the masking noise was very close or equal to unity and, consequently, question the notion of a wider binaural bandwidth.

Like Zurek and Durlach (1987), van de Par and Kohlrausch (1999) conducted bandwidening experiments with a constant overall masker level. They measured detection thresholds for sinusoids of 0.125, 0.25, 0.5, 1, 2, and 4 kHz in NoSo, NπSo, and NoSπ condition. Though the experiment was similar to that of Zurek and Durlach (1987), van de Par and Kohlrausch (1999) did not report increasing NoSπ thresholds with bandwidth in the range of narrow bandwidths except for the 125-Hz signal frequency where a slight increase can be observed. Van de Par and Kohlrausch (1999) gave the following explanation for the apparently wider critical band in some dichotic conditions: In dichotic masking conditions, the auditory system is able to combine information from several auditory filters beneficially. The utility of an auditory filter for detection of the signal depends on the SNR within this filter. Since the auditory filters are positioned at different frequencies, the SNR in a broadband masker becomes lower with increasing distance in frequency to the signal. In the case of a narrowband masker centered at the signal frequency, however, signal as well as masker are attenuated by a filter centered remote from the signal frequency and the SNR remains high. This beneficial across-channel process ceases with increase of masker bandwidth.

Zerbs (2000) and Breebaart *et al.* (2001a) developed binaural models of auditory perception and implemented this idea by van de Par and Kohlrausch (1999). For all broadband maskers, van de Par and Kohlrausch (1999) excluded the beneficial across-channel process and assumed a critical bandwidth similar to that measured in the NoSo masking condition.

2.2.2. Notched-noise experiment

Hall *et al.* (1983) transferred the notched-noise paradigm to binaural psychoacoustics. They compared NoSo and NoSπ thresholds of a notched-noise experiment and a bandwidening experiment for three different masker spectrum levels. The method to estimate the critical bandwidth was the piecewise linear technique (Fig. 2.1) they used also for their bandwidening experiment, except for the fact that the threshold value of the horizontal line was solely determined by the threshold in the condition without notch. For all three spectrum levels, critical-band estimates derived from the NoSπ thresholds were somewhat wider than those derived from the NoSo thresholds. There was a significant difference only for the spectrum level of 50 dB/Hz. Hall *et al.* (1983) reported less steep threshold curves for the NoSπ compared to the NoSo condition except for the lowest spectrum level where an apparent floor effect determined thresholds.

As seen above, there are very many studies concerning the bandwidening or the monaural or diotic notched-noise experiment, but except for Hall *et al.* (1983) there are no measurement data of a notched-noise experiment in dichotic conditions.

The idea of a beneficial across-channel process (van de Par and Kohlrausch, 1999) is able to explain the striking difference in critical-bandwidth estimates derived from NoSo and NoSπ thresholds of the bandwidening experiment. This beneficial across-channel process does not work in a broadband masking condition. However, from this it must not be concluded that the operational binaural critical bandwidth is similar to the monaural critical bandwidth in all broadband masking conditions.

It might be expected that the level dependence of the BMLD is different in the notched-noise experiment and an experiment with a broadband noise without notch of different levels since in masking patterns (thresholds measured for sinusoids of various signal frequencies below, within, and above a fixed narrowband noise masker) the BMLD drops rapidly when the sinusoid is outside the spectrum of the masking noise (Zwicker and Henning, 1984) [4].

[4]Results of binaural masking patterns similar to Zwicker and Henning (1984) can be found in App. B.

3. The role of across-frequency processes in dichotic listening conditions [1]

Abstract

In the bandwidening experiment with a diotic noise masker, an apparently wider critical bandwidth has often been reported when a dichotic signal (Sπ) is used instead of a diotic signal (So). Two competing across-channel processes were proposed to account for this apparently wider critical bandwidth: (i) A detrimental across-channel effect reducing the binaural masking-level difference (BMLD) for broadband maskers and (ii) a beneficial across-channel integration of information for narrowband maskers. The two hypotheses result in different predictions of the BMLD in the notched-noise experiment: According to the first hypothesis, the change in BMLD with notch width is determined by the level dependence of the BMLD for a narrowband masker centered at the signal frequency, whereas the second hypothesis predicts that it is determined by the level dependence of the BMLD for a broadband masker. To test the hypotheses, masked thresholds of a diotic or dichotic 500-Hz signal were measured for a diotic notched-noise masker as a function of notch width. In addition, thresholds were measured for a diotic broadband and narrowband masker as a function of masker level. The data indicate that neither of the two hypotheses is able to predict the continuous decrease of the BMLD as the notch width increases.

[1] Parts of this paper were presented at the 2006 meeting of the Deutsche Gesellschaft für Akustik (Nitschmann and Verhey, 2006). Reprinted with permission from Nitschmann *et al.* (2009). Copyright 2009, Acoustical Society of America.

3.1. Introduction

A fundamental characteristic of the auditory system is its frequency selectivity which can be modeled as a bank of overlapping bandpass filters (e.g., Patterson and Nimmo-Smith, 1980; Moore, 2003). One way to characterize auditory frequency selectivity is the critical bandwidth which is determined in the bandwidening experiment (Fletcher, 1940). In the bandwidening experiment, the threshold of a tone is measured in the presence of a signal-centered noise masker as a function of masker bandwidth. Several authors have used such an experimental paradigm to get insights into the frequency selectivity of the binaural system (e.g., Bourbon and Jeffress, 1965; Wightman, 1971; Sever and Small, 1979; Hall *et al.*, 1983; Zurek and Durlach, 1987). They measured thresholds in a condition where the signal had an interaural phase difference of 180° in the presence of a diotic masker. This condition is commonly referred to as NoSπ condition. For comparison, they also estimated the monaural critical bandwidth by measuring thresholds in the NoSo condition, where both signal and masker were presented diotically. Their threshold data showed that NoSπ thresholds increased as the masker bandwidth increased even beyond the critical bandwidth that was derived from the NoSo thresholds. Thus, the difference between the thresholds in the diotic and the dichotic condition, referred to as the binaural masking-level difference (BMLD), decreased as the bandwidth increased. This result was initially interpreted as a poorer frequency selectivity of the binaural system compared to that of the monaural pathway (see also Sondhi and Guttman, 1966; Yama and Robinson, 1982). However, two later studies (Hall *et al.*, 1983; van de Par and Kohlrausch, 1999) argued that the frequency selectivity is the same for the monaural and binaural system and that the apparently larger binaural critical bandwidth in the bandwidening experiment may reflect a process across critical bands (across-channel process). The nature of the across-channel process differs between the two studies being either beneficial (van de Par and Kohlrausch, 1999) or detrimental (Hall *et al.*, 1983). The present study investigates if these hypotheses can also account for the data of a notched-noise experiment which is another experiment commonly used to characterize the frequency selectivity of the auditory system (de Boer and Bos, 1962; Patterson, 1976; Patterson and Henning, 1977). In notched-noise experiments, thresholds of a tone are measured in the presence of a noise masker with a spectral notch around the signal frequency as a function of the notch width.

Hall *et al.* (1983) measured the BMLD for both types of experiments, i.e. the notched-noise experiment and the bandwidening experiment. To account for the wider binaural critical bandwidth in the bandwidening experiment they suggested that the interaural difference cues in the dichotic condition are biased by the information from remote auditory filters indicating no interaural difference. According to their line of arguments, the larger bandwidth in the dichotic bandwidening experiment is accounted for by an increase in the strength of the detrimental effect as the masker bandwidth is increased.

In contrast to the bandwidening experiment, Hall *et al.* (1983) derived a similar critical bandwidth for the monaural and binaural system from the notched-noise data. They concluded that the two experiments measure different aspects of binaural processing. While the notched-noise experiment measures the binaural frequency selectivity, the bandwidening experiment reveals a process across frequency channels which depends upon the presence of noise in off-frequency filters. Obviously this cannot mean that the detrimental across-channel process is not affecting the notched-noise data since the no-notch condition of the notched-noise experiment is equivalent to a broadband condition for the bandwidening experiment. Hall *et al.* (1983) do not discuss explicitly how this detrimental across-channel process affects the BMLD in the notched-noise experiment. However, their comparison of the BMLD for a narrowband masker to the notched-noise data provides indirect information about the size of the effect and how it varies with notch width. According to Hall *et al.* (1983), level effects of the BMLD should be assessed using narrowband maskers centered at the signal frequency, since in this condition a negligible influence of the detrimental across-frequency effects could be assumed. Hall *et al.* (1983) reported a quantitative agreement between the threshold data in the notched-noise experiment and the 10-Hz bandwidth condition of the bandwidening experiment: Whenever the NoSo thresholds decreased by 20 dB, either due to a decrease in spectrum level of a narrowband masker or due to the introduction of a notch in a broadband noise reducing the excitation of the filter centered at the signal frequency, the corresponding NoSπ thresholds showed a decrease of about 13 dB. This comparison implicitly assumes that the magnitude of the BMLD reduction due to the detrimental across-channel process is determined by the difference between the BMLD for the narrowband masker and the broadband (no-notch) masker with the same spectrum level and does not vary with notch width.

Due to the relatively coarse sampling of level in the bandwidening experiment the comparison is limited to only a few data points. It is also somewhat unfortunate that Hall *et al.* (1983) showed only mean thresholds, since the BMLDs for narrowband maskers tend to show large individual differences (Bernstein *et al.*, 1998; Buss *et al.*, 2007). These individual differences may also hamper the comparison to other publications (e.g., Hall and Harvey, 1984; Buss *et al.*, 2003). If the hypothesis by Hall *et al.* (1983) is correct, a good correspondence between the notched-noise results and the level dependence of the BMLD for the narrowband masker should also be observed when compared individually. Such a comparison is not possible on the basis of the results of the previous studies.

In contrast to the detrimental across-channel process proposed by Hall *et al.* (1983), van de Par and Kohlrausch (1999) suggested a beneficial across-channel combination of information. Van de Par & Kohlrausch (1999) argued that when detecting a dichotic signal in the presence of a diotic narrowband masker, subjects might use information in filters adjacent to the peripheral filter centered at the signal frequency as an additional cue, since the filters have signal-to-noise ratios (SNRs) similar to the one in the filter centered at the signal frequency. This beneficial across-channel combination of information cannot be used in a diotic condition, because in this condition the fluctuations of the masker limit detection (Bos and de Boer, 1966) and these masker fluctuations are the same in the on- and off-frequency filters. For a broadband masker, the SNR is high in the filter centered at the signal frequency only. Thus, the auditory system cannot benefit from information in off-frequency filters neither in a diotic nor in a dichotic condition.

According to van de Par and Kohlrausch (1999), the apparently wider binaural bandwidth decreases with decreasing level, because of the reduced number of peripheral filters that are excited by the stimulus. Van de Par & Kohlrausch (1999) conclude that in a bandwidening experiment at a low masker level as well as in all broadband masking paradigms the binaural processor has to rely on the on-frequency filter and that, in these cases, a single-filter binaural model is sufficient to predict the thresholds. Breebaart *et al.* (2001b) showed that a model based on the hypothesis of van de Par and Kohlrausch (1999) can predict the wider binaural bandwidth observed in the bandwidening experiment.

A notched-noise experiment can be considered as a broadband masking situation. This has an implication on the change of the BMLD with notch width similar to those drawn in Hall *et al.* (1983). Whenever the NoSo thresholds decreased either due to a decrease in spectrum level of a broadband masker or due to the introduction of a notch in the noise masker reducing the excitation of the filter centered at the signal frequency, the corresponding change in BMLD should be the same. Thus the only difference between the two hypotheses is which bandwidth should be used for the comparison of the notched-noise data and the dependence of the BMLD on the masker level for a bandpass noise centered at the signal frequency. The masker should be narrowband for the hypothesis of a detrimental across-channel process and broadband for the hypothesis of a beneficial across-channel process.

The present study investigates which of the hypotheses can account for the notched-noise data. The dependence of the BMLD on the masker level is measured for a broadband and a narrowband masker and compared to results with notched-noise threshold data within the same subjects. To show all data sets within one figure, the dichotic thresholds are plotted as a function of the respective diotic thresholds. [2]

According to van de Par and Kohlrausch (1999), the BMLD in all broadband masking conditions including the notched-noise masking condition is solely determined by the information within the auditory filter centered at the signal frequency. Based on this hypothesis, the BMLD for the notched-noise masker and the broadband-noise masker should be the same for the same diotic threshold. Thus, the same threshold curves should be obtained for the threshold data for the notched-noise masker and for the broadband-noise masker when plotted as dichotic thresholds as a function of diotic thresholds (Verhey and Zerbs, 2001).

[2] This comparison is motivated by the discussion in Hall *et al.* (1983) on the similarity of the narrowband-noise data and notched-noise data. It implicitly assumes that the NoSo thresholds provide an estimate of the energy in the filter centered at the signal frequency. Such an assumption was the basis for the derivation of the filter characteristics, i.e. the energy in the filter centered at the signal frequency determines threshold (see, e.g., Fletcher, 1940; Patterson, 1976). Thus the thresholds on the abscissa can be regarded, to a first approximation, as an estimate of the energy in the auditory filter. A limitation of this interpretation is that thresholds are also influenced by the masker variability and envelope statistics (e.g. Verhey *et al.*, 2007). For the bandwidening experiment, Bos and de Boer (1966) showed that the masker variability decreases with the square root of the bandwidth. As a consequence, thresholds for narrowband signals are higher than for broadband signals with the same energy in the passband of the auditory filter centered at the signal frequency. For the notched-noise experiment, however, Patterson and Henning (1977) argued that, assuming an exponential filter shape, changes in notch width do not lead to changes in the variability of the decision statistics. Since a broadband masker is a special case of a notched-noise masker (i.e., a masker with no notch), the above prediction of the same threshold curves for notched-noise experiments and the broadband masker is also true if the masker variability is taken into account.

To test the hypothesis of a detrimental across-frequency process and its implication for the notched-noise experiment, more subjects and a higher level resolution than in Hall *et al.* (1983) were used in the present study to increase the accuracy of the estimated effect of level on the magnitude of the BMLD for narrowband maskers. According to Hall *et al.* (1983), the decrease in BMLD for the narrowband masker as the masker level decreases should be the same as observed in the notched-noise data for a comparable decrease in the diotic threshold. Thus, for the data representation chosen in the present study, the slope of the threshold curves for the narrowband experiment and the notched-noise experiment should be the same.

3.2. Methods

3.2.1. Apparatus and stimuli

Stimuli were generated digitally at a sampling rate of 44.1 kHz. A standard personal computer controlled stimulus generation and presentation and recorded results using a software package developed at the University of Oldenburg. Stimuli were D/A converted (RME ADI-8 DS, 32 bits), amplified (Tucker-Davis HB7), and presented via Sennheiser HD 580 headphones. Subjects were seated in a double-walled, sound-insulated booth.

The target signal was a sinusoid of 500 Hz that was either in phase (So) or antiphase (Sπ) between the two ears. Its duration was 300 ms including two 50 ms raised-cosine ramps at on- and offset, so that the steady state portion of the signal was 200 ms. The diotic masking noises (No) were generated in the frequency domain using a 2^{17}-point (0.34-Hz resolution) buffer. Their spectrum had a constant nonzero amplitude in the passband regions and a random phase. The noises were transformed to the time domain (inverse FFT) and restricted to the desired length of 127890 samples (i.e., a duration of 2.9 s). The noise masker was gated with 50 ms raised-cosine ramps at on- and offset.

For the notched-noise experiment, a constant spectrum level of 50 dB/Hz and six notch widths of 0, 50, 200, 400, 600, and 800 Hz were used. All notches were arithmetically centered at 500 Hz. The lower frequency limit was set to 30 Hz, the higher to 1 kHz. Stimuli and procedure were similar to those used by Hall *et al.* (1983).

In the experiment with a broadband noise, the masker spectrum level was varied from 0 to 50 dB/Hz in steps of 10 dB/Hz. Like in the notched-noise experiment, the lower and upper cut-off frequency of the masker were 30 and 1000 Hz, respectively. For the highest spectrum level the experimental condition was the same as in the notched-noise experiment with a notch width of 0 Hz. The thresholds for this spectrum level were taken from the notched-noise experiment.

In the experiment with a narrowband-noise masker, six different masker spectrum levels (10 to 60 dB/Hz in steps of 10 dB/Hz) were used. The masker was 10 Hz wide and arithmetically centered at the signal frequency.

3.2.2. Procedure

A three-interval forced-choice procedure with adaptive signal-level adjustment was used to determine detection thresholds in masking noise. Temporally centered in the masker, there were three intervals of 300 ms duration separated by 300 ms pauses. The intervals were indicated on the screen in front of the subject. One randomly chosen interval contained the signal. The subject's task was to indicate this interval. Responses were given by pressing the corresponding button 1, 2, or 3 on a computer keyboard. Trial-by-trial feedback was provided. On every trial a new sample of noise was generated.

Signal level was adjusted according to a one-up two-down rule tracking the 70.7% correct response level (Levitt, 1971). The initial step size of the signal level was 8 dB. The step size was halved after each second reversal of the level adjustment procedure until a step size of 1 dB was reached. After that the run continued for another six reversals. The mean value over these last six reversals was used as a threshold estimate.

Each subject did the experiments in the following order: Notched-noise experiment, broadband-noise experiment, and finally the narrowband-noise experiment. Runs with diotic and dichotic stimulus conditions were mixed in the notched-noise and broadband masking experiments. In the narrowband masking experiment, thresholds were first measured in the NoSo and then in the NoSπ condition because of the higher difficulty of this listening task compared to the other two experiments. [3] At least three threshold estimates were obtained and averaged for

[3]The sinusoidal signal and the narrowband-noise masker have both a clear pitch which is the same for the condition considered here, i.e. a narrowband masker centered at the signal frequency. In contrast, for the broadband maskers, only the signal has a clear pitch. Thus

each parameter value and subject.

3.2.3. Subjects

Eight normal-hearing subjects (4 male, 4 female, aged 19–30 years, mean 25 years) participated in all three experiments. Three of the subjects including the first author were members of the research group, the others were paid volunteers. All subjects had normal audiograms with hearing thresholds lower than or equal to 10 dB HL at the standard audiometric frequencies from 125 Hz to 1 kHz, i.e., the audiometric frequencies in the relevant frequency range. With the exception of subject 4 this also holds for the audiometric frequencies from 1.5 kHz to 8 kHz. Subject 4 had absolute thresholds up to 20 dB HL at 1.5 kHz and higher frequencies at the left ear and at 2 kHz and higher frequencies at the right ear.

3.3. Results

Fig. 3.2 shows the detection thresholds measured in the notched-noise, broadband, and narrowband experiment. NoSπ thresholds are plotted as a function of NoSo thresholds with triangles, squares, and diamonds, respectively. Using this data representation all threshold data can be plotted within one figure. The figure shows individual thresholds of eight subjects and the average thresholds over these subjects in the lower right panel. The dotted diagonal line denotes the same NoSo as NoSπ thresholds. The BMLD is the vertical distance between this line and a data point. The gray line is the narrowband threshold curve shifted such that its threshold at the masker spectrum level of 50 dB/Hz coincides with the threshold at the notch width of 0 Hz of the notched-noise experiment. The reason for plotting this shifted threshold curve is based on an analysis by Hall *et al.* (1983) (see Sec. 3.4.4). Error bars denote plus minus one intraindividual or interindividual standard deviation for the individual or for the mean thresholds, respectively.

due to the similarity of the subjective quality of masker and signal it is more difficult to detect the signal in narrowband noise than in broadband noise. In addition, even for subcritical bandwidths, the threshold of a sinusoidal signal in the presence of a signal-centered bandpass noise decreases as the bandwidth increases. The decrease is similar to the decrease observed for the difference limen of bandpass noise (e.g., Bos and de Boer, 1966). This decrease is likely to be due to level fluctuations of the masker which depend on the bandwidth (e.g., de Boer, 1966; Buus, 1990; Verhey, 2002). Thus, at the same signal-to-noise ratio it is harder to detect the diotic signal in narrowband noise than in broadband noise.

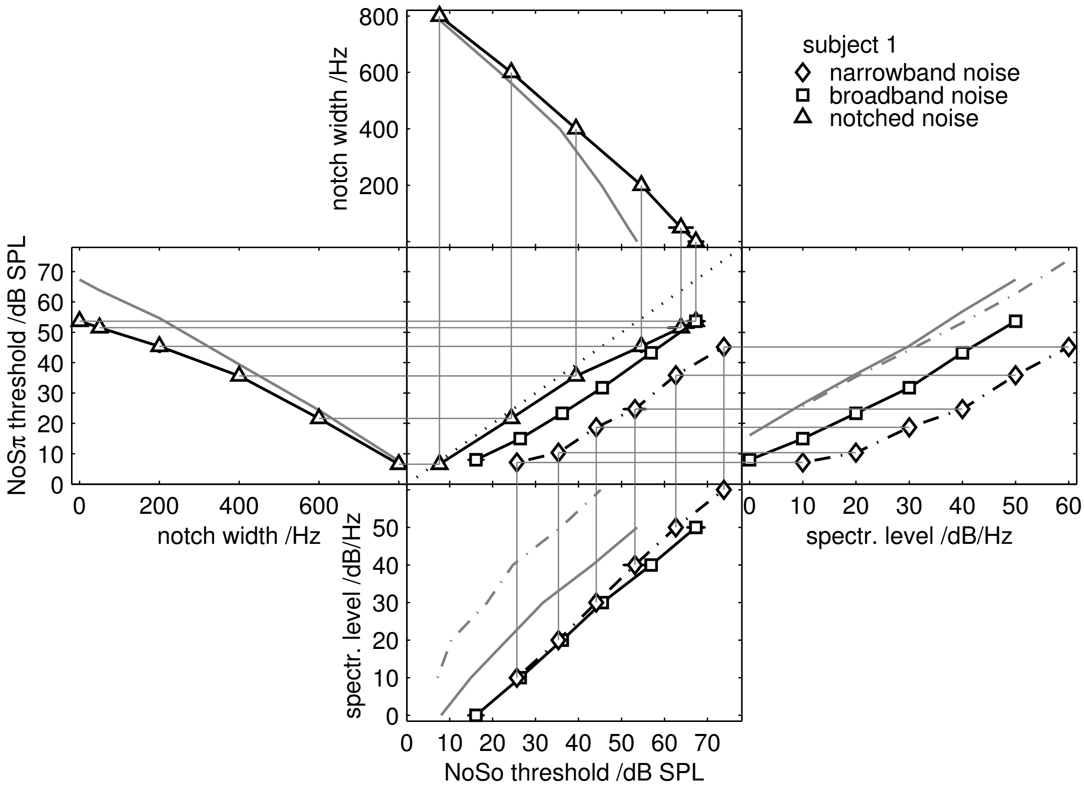

Figure 3.1.: Illustration of how the threshold data form the different experiments are plotted within one graph. This is the data representation used in Figs.3.2 and 3.3. As an example, the figure shows threshold data for subject 1. Thresholds of the notched-noise experiment are plotted in the left panel and in the upper panel. Thresholds of the broadband experiment (solid lines) and of the narrowband experiment (dash-dotted lines) are plotted in the right panel and in the lower panel. The symbols denote NoSo thresholds in the upper and lower panel and NoSπ thresholds in the left and right panel. The other thresholds (NoSo or NoSπ, respectively) are indicated by gray lines. The vertical gray lines connecting the upper and lower panel with the center panel denote the projection of NoSo thresholds to the center panel. The horizontal gray lines connecting the left and right panel with the center panel denote the projection of NoSπ thresholds to the center panel. Thus, the center panel shows the threshold data of the notched-noise experiment (triangles), broadband experiment (squares), and narrowband experiment (diamonds) in a representation where NoSπ thresholds are plotted as a function of NoSo thresholds. The dotted line in the center panel denotes the same NoSo and NoSπ thresholds.

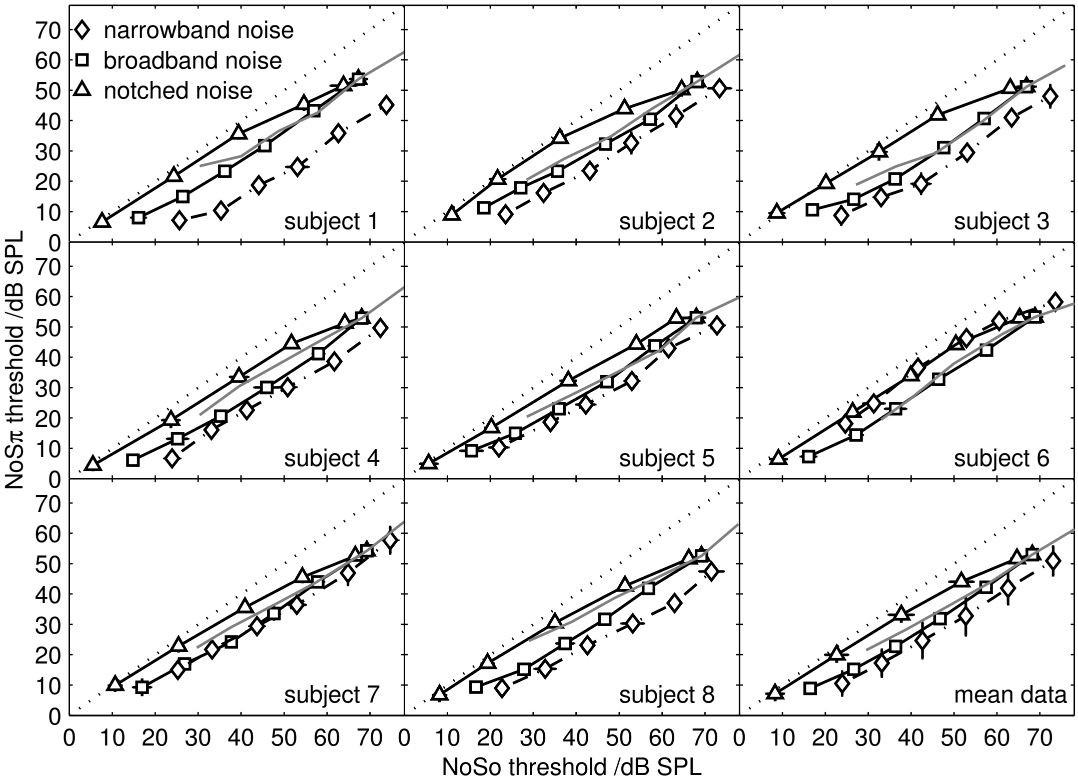

Figure 3.2.: Individual and mean (lower right panel) detection thresholds. The figure displays NoSπ thresholds as a function of NoSo thresholds as illustrated in Fig. 3.1. Thresholds of the notched-noise, broadband, and narrowband experiment are denoted with triangles, squares, and diamonds, respectively. The gray line is the narrowband threshold curve shifted such that its 50-dB/Hz threshold coincides with the threshold at the notch width of 0 Hz of the notched-noise experiment. The dotted diagonal line denotes the same NoSo and NoSπ thresholds. Error bars show the intraindividual standard deviations for the individual thresholds and the interindividual standard deviations for the mean thresholds. Standard deviations are not shown if they are below the size of the symbol.

3.3.1. Notched-noise

The highest threshold (no notch) of the notched-noise experiment is at the upper right end of each notched-noise threshold curve, the lowest (notch width of 800 Hz) at the lower left. For all subjects except for subject 6, the threshold data points of the notched-noise experiment exhibit the highest NoSπ thresholds for given NoSo thresholds.

For all subjects, NoSπ thresholds decrease with decreasing NoSo thresholds. This decrease is shallower for narrow than for large notch widths. Towards lower threshold the curve approaches the dotted diagonal line (i.e., the BMLD approaches 0 dB). The decrease of BMLD with increasing notch width differs interindividually: For the 600-Hz notch width, subjects 2 and 3 show almost no BMLD (smaller than 1 dB), whereas subjects 4, 5, and 6 still measure a BMLD of about 4 dB.

For the mean data, NoSo thresholds decrease with increasing notch width from 68 dB in a broadband noise without a notch to about 8 dB at a notch width of 800 Hz. Standard deviations are around 1 dB for notch widths up to 50 Hz, 2 dB for the largest notch width, and between 2 and 3 dB for intermediate notch widths. The large standard deviations for intermediate notch widths are due to individual differences in filter shape. Mean NoSπ thresholds decrease with increasing notch width from 53 dB in a broadband noise without a notch to 7 dB for a notch width of 800 Hz. Standard deviations as a function of notch width are similar to those of the diotic thresholds, except for values around 2 dB for intermediate notch widths. The mean BMLD decreases gradually with increase in notch width. It is about 15 dB in a broadband noise without a notch and reduces to a value clearly below the standard deviations of corresponding thresholds for the two largest notch widths.

3.3.2. Broadband noise

The highest threshold (at the spectrum level of 50 dB/Hz) of the broadband experiment is at the upper right end of each broadband threshold curve. It is the same as the highest threshold of the notched-noise experiment. Thresholds for lower spectrum levels are below the notched-noise threshold curve for all subjects. The lowest threshold (at the spectrum level of 0 dB/Hz) is at the lower left end of each broadband threshold curve.

Individual differences are small for the broadband-noise threshold data. They are found mainly in the decrease of BMLD towards low spectrum levels. Mean NoSo thresholds increase as a function of spectrum level from 16.5 dB at 0 dB/Hz to 68 dB at 50 dB/Hz. The standard deviation of the mean NoSo thresholds is mostly below 1 dB. The standard deviations of the mean NoSπ thresholds are below 1 dB at 50 dB/Hz as well, but increase towards lower spectrum levels to 1.7 dB at the spectrum level of 0 dB/Hz. Mean dichotic thresholds increase with increase in spectrum level from 9 dB at 0 dB/Hz to 53 dB at 50 dB/Hz. The mean BMLD increases with spectrum level from below 8 dB at 0 dB/Hz to 15 dB at 50 dB/Hz. The mean BMLD is clearly above at least twice the standard deviations of the corresponding thresholds even at the lowest spectrum level.

3.3.3. Narrowband noise

The highest threshold (at 60 dB/Hz) of the narrowband experiment is at the upper right end of each narrowband threshold curve, the lowest threshold (at 10 dB/Hz) is at the lower left end. The narrowband threshold curve is below the broadband threshold curve for most subjects (except for subjects 6 and 7).

The thresholds show large interindividual differences that also have been reported by Bernstein *et al.* (1998) and Buss *et al.* (2007). Individual diotic thresholds range from 22 to almost 26 dB at 10 dB/Hz and from 71.5 to almost 75 dB at 60 dB/Hz. Individual dichotic thresholds for the lowest spectrum level range from almost 7 to 18 dB, for the highest spectrum level they are in a range from 45 to 58 dB. Individual BMLDs range from almost 7 to 18.5 dB for the lowest and 15 to nearly 29 dB for the highest spectrum level. In particular, subject 6 apparently had problems with the dichotic stimulus condition and achieved, in contrast to all other subjects, a smaller BMLD than in the broadband masking experiment.

Mean NoSo thresholds in the narrowband experiment increase with increasing spectrum level from 24 dB at 10 dB/Hz to 73 dB at 60 dB/Hz. The interindividual standard deviations are around 1 dB for all spectrum levels for the NoSo thresholds, whereas they are in a range of 4 to above 6 dB for the NoSπ thresholds. Mean NoSπ thresholds are 10.5 dB and 51 dB for the spectrum levels of 10 and 60 dB/Hz, respectively. The BMLD of the mean thresholds increases with increasing spectrum level from above 13 dB at 10 dB/Hz to 22 dB at 60 dB/Hz.

3.4. Discussion

3.4.1. Comparison to previous studies

The bottom two panels of Fig. 3.3 show threshold data from previous studies related to the present study. In order to facilitate the comparison between the present data and the data in the literature, their results are plotted using the same data representation as in Fig. 3.2. The top left panel redraws the average thresholds of the present study, which were already shown in the bottom right panel of Fig. 3.2. The other panels show the threshold data of the present study with a gray curve without symbols. For comparison of the present data to previous studies, only a subset of the present data is shown which corresponds to the parameter range used in the respective study in the literature. To our knowledge, the study by Hall *et al.* (1983) was the only study measuring the BMLD for notched noise and the BMLD for a bandwidening experiment at different levels. Their threshold data are shown on the bottom left panel of Fig. 3.3.

Although the previous studies by Hall and coauthors track a different point on the psychometric functions than the present study, the data of the studies are similar. For the two smallest notch widths, i.e., the two highest NoSo thresholds, the thresholds of the present study and the thresholds of Hall *et al.* (1983) at the same spectrum level of 50 dB/Hz agree quantitatively.

For intermediate notch widths, NoSo thresholds tend to be lower in the study by Hall *et al.* (1983) than in the present study. This is presumably due to different average monaural auditory filter shape of the two groups of subjects. The best-fitting gammatone filter parameters for the mean diotic thresholds of the present study are a filter of sixth order and a width of 1.4 ERB (equivalent rectangular bandwidth, for the definition of ERB in Hz see, e.g., Glasberg and Moore, 1990; Kollmeier and Holube, 1992). The filter parameters were derived from the thresholds on the basis of a simple energy-detector model (Fletcher, 1940) with a gammatone filter using the filter implementation by Hohmann (2002). The diotic threshold data of Hall *et al.* (1983) for a spectrum level of 50 dB/Hz are best described by 1-ERB wide fourth-order gammatone filters (see also Zerbs, 2000). Thus, the filter parameters for the present data indicate a narrower filter with respect to filter tail and a broader filter with respect to the tip than those for the subjects participating in the experiment by Hall *et al.* (1983). Only for subject 3 of the present study a fourth-order gammatone filter with a bandwidth of

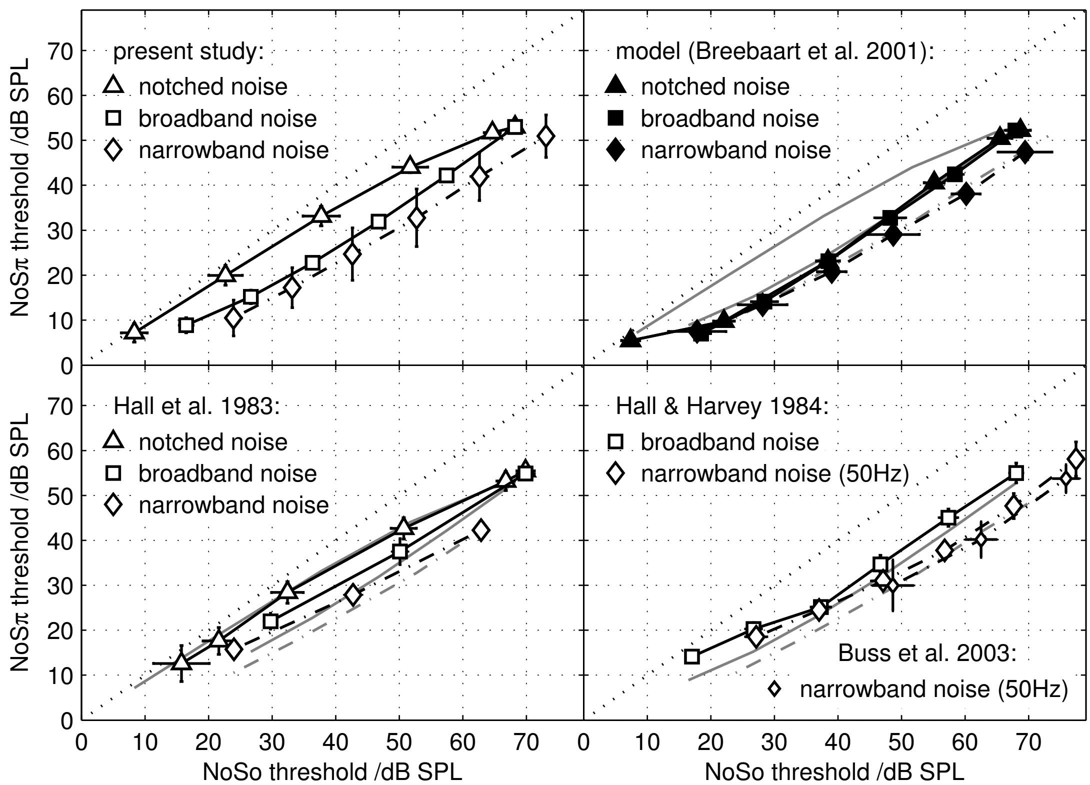

Figure 3.3.: Average detection thresholds of the present study (upper left panel and gray curves in the other panels) together with literature data (Hall *et al.*, 1983; Hall and Harvey, 1984; Buss *et al.*, 2003) and threshold predictions of the model by Breebaart *et al.* (2001a). The data representation is the same as in Fig. 3.2 as illustrated in Fig. 3.1.

1 ERB produces the best fit to the diotic thresholds. The NoSo thresholds of the other subjects indicate higher order of the gammatone filter and wider bandwidth. The diotic and dichotic threshold at the largest notch width is lower in the present study than in the study by Hall *et al.* (1983) indicating different absolute thresholds of the two groups of subjects.

Despite of the differences in diotic thresholds, the threshold curves for the notched-noise experiments of the two studies almost overlie one another, when plotted as dichotic thresholds as a function of diotic thresholds.

At the spectrum level of 50 dB/Hz, i.e., the highest diotic threshold, there is a quantitative agreement between the threshold data of Hall *et al.* (1983) and of the present study for the broadband masker and the narrowband masker. Towards lower NoSo thresholds the threshold curves for the two masker bandwidths are shallower in Hall *et al.* (1983) than in the present study. Thus, the decrease in BMLD as diotic thresholds decrease is faster than in the present data. For both maskers the difference is primarily due to higher NoSπ thresholds at the masker spectrum levels of 10 and 30 dB/Hz in the study by Hall *et al.* (1983). For the broadband masker, diotic and dichotic thresholds are both higher for these spectrum levels. The reason for this may be comparatively large individual differences at levels slightly above absolute threshold.

The shallower slope for the narrowband masker leads to the good correspondence of the change in BMLD between the notched-noise data and the data for the narrowband noise, which was already mentioned in the introduction. A slope of the threshold curve for the narrowband masker similar to the one in Hall *et al.* (1983) was found in Hall and Harvey (1984) for a masker bandwidth of 50 Hz (bottom right panel of Fig. 3.3). For spectrum levels of 40 dB/Hz (third threshold point from the right) and below, the BMLD decreases at a higher rate in Hall and Harvey (1984) than in the present study as spectrum level decreases. Recent experimental results by Buss *et al.* (2003) with the same masker bandwidth as used in Hall and Harvey (1984) show a quantitative agreement with the data in the present study, when plotted as dichotic thresholds as a function of diotic thresholds (small diamonds in the bottom right panel of Fig. 3.3).

For the broadband masker, Hall and Harvey (1984) measured an average threshold curve with a similar shape as the one of the present study. The BMLD was nearly constant for spectrum levels between 20 and 50 dB/Hz (four right threshold points). Below 20 dB/Hz, the BMLD decreased as spectrum level decreased.

The decrease was slightly larger in their study than in the present study: In the present study the BMLD was nearly 14 dB at a spectrum level of 20 dB/Hz and decreased down to almost 8 dB at a spectrum level of 0 dB/Hz. For the same range of spectrum levels the BMLD decreased from 12 dB to 3 dB in Hall and Harvey (1984).

In general, the data in the literature show the same tendency as found in the present study: For the data representation used in Fig. 3.3, all studies show the lowest threshold curve for the narrowband masker and the highest threshold curve for the notched-noise data. The slope of the threshold curves is usually different for the different masker types.

3.4.2. Possible role of beneficial across-frequency processing

A beneficial across-channel process is the basis of one hypothesis to account for the apparently wider bandwidth for the binaural system compared to the monaural frequency selectivity (van de Par and Kohlrausch, 1999, see Sec. 3.1). This beneficial across-channel process should increase the BMLD for narrowband maskers centered at the signal frequency. According to van de Par and Kohlrausch (1999) this beneficial across-channel process should have no effect in all broadband masking conditions including notched-noise masking, since in these cases the SNR is high only in the auditory filter centered at the signal frequency and for this reason combination of information across filters is unhelpful. Verhey and Zerbs (2001) argued that the hypothesis by van de Par and Kohlrausch (1999) would predict the same threshold curves for the notched-noise experiment and for the broadband experiment when plotted as dichotic thresholds as a function of diotic thresholds. A possibility to test this prediction is to use the model by Breebaart *et al.* (2001a) which included an implementation of the beneficial across-channel process proposed by van de Par and Kohlrausch (1999).

Breebaart *et al.* (2001a) developed a model of binaural auditory perception based on the monaural model by Dau *et al.* (1996) combined with an equalization-cancellation (EC) stage (Durlach, 1963) as first described by Holube *et al.* (1995) (see also Zerbs, 2000, for a slightly different implementation of the model). For the prediction of the present threshold data a filterbank with eight filters was used. The parameters of the auditory filters were adjusted to predict the diotic notched-noise threshold data, i.e., 1.4 ERB wide sixth-order gammatone filters (see Sec. 3.4.1). The spectral spacing was one filter per ERB. The level of the noise added after the filtering was set to 0.0 dB SPL as used in Zerbs (2000), since the predicted thresholds for the largest notch widths were too high when using a level of 9.4 dB SPL as in Breebaart *et al.* (2001a). The rest of the model parameters were the same as in Breebaart *et al.* (2001a). Stimuli and procedure were the same as in the respective psychoacoustic experiments.

Simulated thresholds are shown in the top right panel of Fig. 3.3. The effect of the beneficial across-frequency processing implemented in the model by Breebaart *et al.* (2001a) is reflected by the lower threshold curve for the narrowband masker than for the other two masker types. If instead of a filterbank a single filter centered at the signal frequency is used, the curves of predicted thresholds of all three masker types overlie one another (not shown). The beneficial across-channel effect results in a decrease of dichotic thresholds in narrowband of about 6 dB at the highest masker spectrum levels (see also Breebaart *et al.*, 2001b). For the broadband and for the narrowband maskers, there is a quantitative agreement between measurement and simulation in threshold curve (difference smaller than 3 dB).

As argued in Verhey and Zerbs (2001), based on the hypothesis of van de Par and Kohlrausch (1999), the same threshold curve is predicted for the notched-noise experiment and the broadband experiment. The NoSπ thresholds of the notched-noise experiment, however, are only predicted quantitatively at the notch widths of 0 and 800 Hz. For intermediate notch widths, the predicted NoSπ thresholds are about 10 dB too low. Thus, the model cannot predict the difference in threshold curve between the broadband masker and the notched-noise masker which is observed in the average and individual threshold data shown in Fig. 3.2.

For the thresholds measured in the present study, the difference of the BMLD between the two masker types for the same diotic threshold amounts to a maximum of 9.4 dB and a mean of 7.1 dB for the average data. The largest difference is obtained for subject 3, who shows a maximum difference of 12.6 dB and a mean of 9.3 dB. Subjects 5 to 7 show the smallest differences with a maximum distance of 8.5 dB and an average distance of 6.5 dB. A similar (though slightly smaller) difference is found when comparing the data for the different masker types of Hall *et al.* (1983) shown in the bottom left panel of Fig. 3.3 (5.4 dB maximum and 4.0 dB mean).

The comparison of model prediction with the measured data indicate that the beneficial across-channel process accounts for the apparently wider bandwidth for the binaural bandwidening experiment. However, a model with a realistic monaural filter width including only a beneficial across-frequency process can not predict the measured monotonic decrease in BMLD as the notch width increases. Thus, other processes are needed to account for this effect.

3.4.3. Role of envelope fluctuations

Recently, the possible role of masker envelope fluctuations was discussed in relation to the BMLD for narrowband maskers (Buss *et al.*, 2003, 2007). They compared the BMLD for a long signal with the BMLD for a short signal that was either placed in the minimum or in the maximum of the masker envelope. Fig. 3.4 shows, as an example, the data from Buss *et al.* (2007) for long (200 ms) and short (30 ms) sinusoids of 500 Hz. The noise spectrum level was 55 dB/Hz. The median is indicated with an open symbol, the span between the 25th and 75th percentiles with a box, the 10–90th percentile with bars, and the maximum and minimum with crosses. In agreement with the previous study (Buss *et al.*, 2003), Buss *et al.* (2007) found a similar median BMLD for the long signal and the short signal that was positioned in the dip of the masker envelope. The BMLD was reduced by about 5 dB for a short signal positioned at a peak of the masker envelope. The similarity of the BMLD for the dip position of the short signal and the long signal was interpreted as evidence for the ability of the subjects to listen into the dips of the masker when detecting the long signals. This interpretation will be referred to as the dip-listening hypothesis in the following. In the light of the dip-listening hypothesis, the decrease of the BMLD observed in the bandwidening experiment with increasing masker bandwidth may be interpreted as a result of a reduced effective duration of the dips as the masker bandwidth increases.

Fig. 3.4 shows, apart from the BMLDs measured by Buss *et al.* (2007), predictions (filled diamonds) of the model by Breebaart *et al.* (2001a) using the same parameters as described in the previous section. The model predicts the BMLD quantitatively for the long signals. The predicted BMLDs for the peak condition is within the 25th and 75th percentiles of the measured BMLDs. For the dip condition, the predicted BMLD is similar to the one for the peak condition and is between the 10th and 25th percentile of the BMLD measured by Buss *et al.* (2007). The model by Breebaart *et al.* (2001a) does not predict a similar median BMLD for short signals positioned in a masker-envelope dip and the long signal. This inability of the model may be interpreted as evidence for an inappropriate

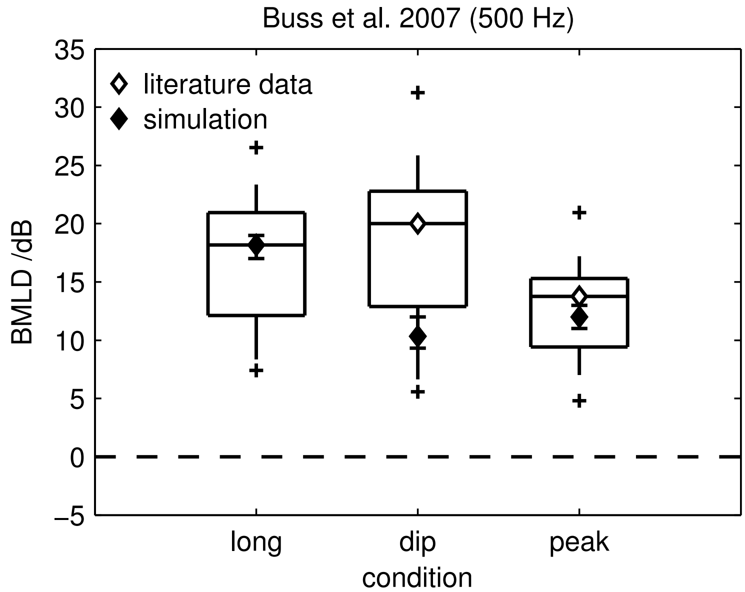

Figure 3.4.: Measured (open symbols) and simulated (filled symbols) BMLDs for an experiment by Buss *et al.* (2007) for three different conditions: long, where the signal was a 200-ms long sinusoid masked by the noise, peak, where a 30-ms sinusoid was positioned in a peak of the masker envelope and dip, where a 30-ms sinusoid was placed into a dip of the masker envelope. For the data measured by Buss *et al.* (2007), the median is indicated with an open symbol, the span between the 25th and 75th percentiles with a box, the 10–90th percentile with bars, and the maximum and minimum with crosses. For the simulation data, the median is indicated with a filled symbol; the error bars denote the quartiles. The dashed horizontal line denotes a BMLD of 0 dB.

cue used by the model to predict the different BMLD for the narrowband and broadband masker quantitatively. Note, however, that large individual differences are observed in the data by Buss *et al.* (2003, 2007) and that some subjects at some levels show a similar pattern of results as predicted by the model.

One may argue that the model is not able to predict the dichotic notched-noise threshold data, because it is not in agreement with the dip-listening hypothesis. This raises the question if the notched-noise data can be understood on the basis of this hypothesis. In order to answer this question the average envelope fluctuation rate for the notched-noise masker, here defined as the centroid of the envelope power spectrum, is calculated. For the calculations, the filtering properties of the outer, middle, and inner ear are accounted for by analyzing the Hilbert envelope after the masker has been preprocessed by an outer and middle ear filter as proposed in Breebaart *et al.* (2001a) and a 1.4 ERB wide sixth-order gammatone filter centered at the signal frequency. The average envelope fluctuation rate is about 44 Hz for a masker with no notch and increases as the notch width increases up to a maximum of 77 Hz for a notch width of 100 Hz. A further increase in notch width results in a decrease of the average envelope fluctuation rate. For the 10-Hz wide narrowband-noise masker used in the present study the average fluctuation rate is about 3 Hz. For the 50-Hz wide noise band used in Buss *et al.* (2007) the average envelope fluctuation rate is 15 Hz. [4] Thus the average envelope fluctuation rate for the notched noise is considerably higher (and thus the average dip duration shorter) than for the narrowband noise. The reduced dip duration implies that the dip listening cues are largely reduced for the notched-noise masker. This may account for the difference in the average BMLD between the notched-noise experiment and narrowband-noise experiment. It is, however, unlikely that dip listening is able to account for the difference in slope of the decrease in BMLD between the

[4] For small bandwidths, the average envelope fluctuation rate of bandpass noise is proportional to the bandwidth of the noise. The equation proposed in Rice (1954) which relates the average number of envelope maxima per second to the bandwidth of bandpass noise shows the same linear relation between these two quantities. Eddins and Wright (1994) used this equation to estimate the average envelope fluctuation rate of narrowband-noise maskers. This estimate results in slightly higher rates since a calculation based on the maxima of the envelope favours high fluctuation rates. Numerical simulation showed that the average envelope fluctuation rate was similar to the centroid if it is defined as half of the average rate of zero crossings of the ac-coupled envelope. The average rate of zero crossings (rather than the average rate of maxima) was also used in Carlyon *et al.* (1989) to estimate the average modulation rate of lowpass-noise modulators. Due to the auditory preprocessing all three definitions of the average envelope fluctuation rate predict hardly any change in rate for large bandwidths.

two studies. Assuming a monotonic relation between dip duration and reduction in the magnitude of BMLD, the BMLD in the notched-noise experiment should be smallest for the notch width of 100 Hz (i.e., for the smallest average dip duration). In contrast, a continuous decrease of the BMLD is observed, when the notch width is increased. This argues against an explanation of the difference between the notched-noise data and the narrowband-noise data solely on the basis of a dip-listening hypothesis. Another argument against a strong influence of dip-listening cues in the notched-noise data is the relatively small interindividual variability for the results of the notched-noise experiment. In contrast, the narrowband data for which the dip-listening hypothesis was hypothesized show a high inter-subject variability.

Although it is unlikely that cues based on the envelope fluctuations play an important role in the notched-noise experiment of the present study, modulation cues may be used in other binaural masking experiments. For example, Zwicker and Henning (1984) showed in a masking pattern experiment that the BMLD decreases rapidly when the signal is outside the bandwidth of the masker. This may reflect a difference in the ability of the monaural and binaural system to use modulation cues. Derleth and Dau (2000) showed that a model using a modulation filterbank to analyze the modulation predicts much steeper threshold curves than a simple energy-detector model. If the ability to use modulation cues is reduced in the binaural system, the threshold curve for the dichotic condition may be shallower than that for the monaural one, as found in the experimental data by Zwicker and Henning (1984). Further studies are needed to investigate the role of modulation cues in binaural detection tasks.

3.4.4. Possible role of detrimental across-frequency processing

For the results of Hall *et al.* (1983) shown in Fig. 3.3, the upper part of the notched-noise threshold data curve and the narrowband threshold data curve are parallel. This led Hall *et al.* (1983) to hypothesize that the BMLD in a notched noise is basically determined by the BMLD in a narrowband masking condition.

According to the hypothesis of Hall *et al.* (1983) the threshold curve for the notched-noise experiment should be an upward shifted version of the data for the narrowband-noise masker when plotted as dichotic thresholds as a function of diotic thresholds. Thus, the magnitude of the vertical shift reflects the constant reduction of the BMLD due to the detrimental across-frequency process (see

Sec. 3.1). [5]

In order to facilitate the comparison between the notched-noise data and the data for the narrowband noise in Fig. 3.2, a shifted version of the narrowband-noise data is shown with a gray line. Following the comparison strategy used by Hall *et al.* (1983), the data point for the narrowband noise at a spectrum level of 50 dB/Hz was aligned with the data point for the notched-noise experiment with no notch. For all subjects this alignment results in a shift towards higher NoSo and NoSπ thresholds, though there are large interindividual differences. On average, the threshold data shift on the abscissa is almost 6 dB and on the ordinate 11 dB. For the individual results the shifts on the abscissa range from above 3 to about 8 dB, shifts on the ordinate from about 1 (subject 6) to almost 18 dB (subject 1).

For two subjects (4 and 8) the shifted version of the narrowband-noise data is close to the notched-noise data. For all other subjects the data sets are still considerably different from one another (see Fig. 3.2). Note that for subject 6 the original narrowband threshold curve is close to the subject's notched-noise threshold curve, whereas the shifted version is not. Thus, only two out of eight subjects support the hypothesis of Hall *et al.* (1983) that the change in BMLD in the narrowband condition determines the change in BMLD in the notched-noise data. The reason for this discrepancy is unclear. It may be partly due to the very limited set of data points that were used in Hall *et al.* (1983) to compare the data for the two masker types. The relatively good correspondence between the two data sets for two of the eight subjects in the present study also indicates that it is partly due to a different set of subjects. The majority of the data of the present study shows that it is unlikely that a constant detrimental across-channel effect accounts for the BMLD in the notched-noise experiment. It is, however, possible to reconcile the hypothesis of a detrimental across-channel process with the notched-noise data, if it is assumed that the strength of the detrimental effect increases as the ratio between the level of the off-frequency components and the

[5] Note that the hypothesis of a detrimental across-channel process as proposed in Hall *et al.* (1983) does only assume a constant reduction for the notched-noise data at the same masker spectrum level. If the same reduction had been assumed for all masker spectrum levels, the same BMLD would be predicted for the same diotic thresholds. This is not in agreement with the data in Hall *et al.* (1983): For example, the BMLD is about 12 dB at a masker spectrum level of 30 dB/Hz and no notch, whereas it amounts to only about 8 dB at a masker spectrum level of 50 dB/Hz at a notch width of about 200 Hz, although both result in the same diotic thresholds. Thus, the notched-noise data in Hall *et al.* (1983) for the different spectrum levels indicate that the reduction of the BMLD due to the hypothesized across-channel process decreases as the masker spectrum level decreases.

level of the on-frequency components increases. This ratio increases as the notch width increases, i.e., according to this hypothesis the BMLD should decrease in agreement with the experimental results.

3.5. Summary and Conclusion

Diotic and dichotic detection thresholds of a sinusoidal signal were measured for a notched-noise masker with varying notch width and compared to threshold data for a broadband- and narrowband-noise masker with varying spectrum level. This comparison was motivated by the hypotheses of across-frequency processes to account for the apparently wider critical bandwidth in the bandwidening experiment in dichotic compared to monaural or diotic conditions. Both hypotheses predict that the level dependence of the BMLD for a masker centered at the signal frequency determines the decrease in BMLD as the notch width increases. The data of the present study indicate that, for the same diotic threshold, the BMLD is different in the notched-noise and broadband-noise experiment. In the notched-noise experiment, the BMLD decreases gradually with increasing notch width, whereas in the broadband masking experiment the BMLD is constant for most spectrum levels. In contrast to this finding, a model assuming a beneficial across-channel process to account for the large BMLD for a narrowband masker (van de Par and Kohlrausch, 1999) predicts the same BMLD for the broadband masker and the notched-noise masker if compared at the same diotic threshold for the two masker types. Thus, the hypothesis of a beneficial across-channel integration of information in the dichotic condition is not sufficient to account for both broadband-noise and notched-noise data. The model is also unable to predict recent experimental results (Buss *et al.*, 2007) relating to the temporal position of a short signal with respect to the masker envelope indicating a higher weight to masker envelope minima. However, a strategy based on the listening into the valleys is unlikely to account for the BMLD in the notched-noise experiment since the change in BMLD as the notch width increases is different from the change in the average duration of the masker dips. The measured threshold data are also not consistent with the hypothesis of Hall *et al.* (1983) that the change in BMLD in the notched-noise experiment is determined by the level dependence of the BMLD for a narrowband masker. According to this hypothesis, a decrease in the diotic threshold of the notched-noise experiment leads to the same decrease in BMLD as found for a narrowband masker if the masker level is decreased by the same amount. In contrast to this prediction the decrease in BMLD for the notched-noise experiment as the notch width increases is considerably faster than observed in the narrowband masking condition. Thus, the data is inconsistent with the predictions of both hypotheses. The notched-noise data may, however, be reconciled with the hypothesis of a detrimental across-channel process if it is assumed that the strength of the detrimental effect is determined by the level of the off-frequency components and its relation to the level of the on-frequency components.

Acknowledgments

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4. Notched-noise masking in NoSo and NoSπ condition at various center frequencies[1]

Abstract

Thresholds for homophasic (So) and antiphasic (Sπ) sinusoids masked by a diotic notched noise (No) were measured as a function of notch width. Signal frequency was 250, 500, 1000, or 2000 Hz. In addition, for the 500-Hz signal, the just-noticeable difference (JND) for interaural phase difference (IPD) was measured for all notch widths against a reference IPD of zero. For all signal frequencies, the difference between NoSo and NoSπ thresholds (binaural masking-level difference, BMLD) decreases continuously as the notch width increases. Based on these results a model is proposed that assumes a detrimental across-channel process by adding portions of the output of adjacent filters to the output of the on-frequency filter. A comparison between data and model predictions indicates that the detrimental effect may depend on the signal frequency being larger at 250 Hz than at the higher frequencies. The model also predicts a continuous increase in JND for the IPD as the notch width increases. The same decrease is found in the measured data. For the signal frequency of 500 Hz, it is shown that the decrease in BMLD with increasing notch width can neither be explained by interaurally asymmetric nor by nonlinear auditory filters.

[1]Preliminary results of this paper were presented at the 2007 meeting of the Deutsche Gesellschaft für Akustik (Nitschmann and Verhey, 2007).

4.1. Introduction

One of the main characteristics of the auditory system is its frequency selectivity. The aim of the present study is to investigate the frequency selectivity of the binaural auditory system at different signal frequencies and how it relates to the monaural frequency selectivity.

Several experimental paradigms have been proposed to estimate the frequency selectivity of the auditory system. A classical paradigm is the bandwidening experiment proposed by Fletcher (1940). In the bandwidening experiment, thresholds are measured for a sinusoidal signal masked by a bandpass-filtered noise spectrally centered at the signal frequency. For a constant masker spectrum level, thresholds first increase as the masker bandwidth increases. Beyond a certain "critical" bandwidth, however, thresholds do not vary with masker bandwidth. This critical bandwidth was considered as a measure of the width of the auditory filter centered at the signal frequency (e.g., Fletcher, 1940).

The bandwidening paradigm was not only used to measure monaural frequency selectivity, but also to estimate the binaural critical bandwidth using masking conditions where interaural disparities are used as an additional cue for signal detection (e.g., Bourbon and Jeffress, 1965; Sever and Small, 1979). In these binaural experiments, a sinusoid with an interaural phase difference (IPD) of zero (So) or 180 degrees (Sπ) is masked by a diotic noise masker (No). The result of these bandwidening experiments indicate a wider critical bandwidth for the dichotic (NoSπ) condition than for the diotic (NoSo) condition [2].

Another experimental paradigm to assess the frequency selectivity of the auditory system is the notched-noise experiment (de Boer and Bos, 1962; Patterson, 1976). The advantage of the notched-noise experiment is that the dynamic range of thresholds is larger and the experiment is less affected by changes in the masker variability than the bandwidening experiment (de Boer, 1962; Patterson and Henning, 1977). Due to the larger dynamic range, it is possible not only to derive a bandwidth of the auditory filter, but also to estimate the attenuation characteristics or shape of the auditory filters. Presumably because of these advantages the notched-noise experiment is now the standard experiment to derive the parameters

[2] The NoSo condition is regarded as a good estimate of the monaural frequency selectivity since the bandwidth derived from a monaural condition NmSm does not differ significantly from that observed in an NoSo condition (Sever and Small, 1979). Thus, the bandwidth derived from the NoSo thresholds will be referred to as the monaural bandwidth in the following.

of monaural auditory filter parameters from a psychoacoustical experiment (e.g., Weber, 1977; Patterson and Nimmo-Smith, 1980; Moore *et al.*, 1990; Glasberg and Moore, 2000; Baker and Rosen, 2006).

Although the notched-noise experiment is widely used for the assessment of the monaural frequency selectivity, there is little data on the binaural frequency selectivity using this experimental paradigm. To our knowledge the only study comparing monaural and binaural frequency selectivity using the notched-noise experiment (and also the bandwidening experiment) was presented by Hall *et al.* (1983). For the bandwidening experiment, they used the bandwidth where threshold had dropped by 3 dB compared to the threshold at the largest masker bandwidth to estimate the critical bandwidth (see also Sever and Small, 1979). For the notched-noise experiment, they used the notch width where the threshold had dropped by 3 dB relative to the condition without notch. This definition of bandwidth will be referred to as the 3-dB bandwidth in the following. Hall *et al.* (1983) measured binaural 3-dB bandwidths in the bandwidening experiment that were considerably larger than the monaural 3-dB bandwidths. At the highest masker spectrum level of 50 dB/Hz, the binaural 3-dB bandwidth was larger than four times the monaural. The difference decreased with spectrum level; the binaural 3-dB bandwidth was about twice as large as the monaural at the spectrum level of 30 dB/Hz. For the notched-noise experiment, Hall *et al.* (1983) found also slightly larger 3-dB bandwidths for the dichotic experiment compared to the diotic thresholds but the difference was considerably smaller than that for the bandwidening experiment: The largest difference was measured at the highest spectrum level where the binaural 3-dB bandwidth was 1.25 times the monaural.

To reconcile the contradicting results from the two experiments, Hall *et al.* (1983) suggested a detrimental across-channel process raising the thresholds in some of the dichotic masking conditions: In dichotic conditions with broadband maskers the auditory system receives binaural information from more than the (monaural) critical band centered at the signal frequency. According to this hypothesis, this information is detrimental for signal detection, since the signal-to-noise ratio (SNR) in filters remote from the signal frequency is low. Increasing the bandwidth in the bandwidening experiment changes the number of critical bands excited by the masker and thus increases the strength of the detrimental effect on thresholds. Thus, dichotic thresholds in the bandwidening experiment start to decrease at larger bandwidths than diotic thresholds.

The curve of the dichotic thresholds in the notched-noise experiment shows a slightly shallower decrease than that of the diotic thresholds. Hall *et al.* (1983) argued that this shallower decrease reflects the level dependence of benefit of binaural cues as measured with a narrowband masker centered at the signal frequency, i.e. a masker without a detrimental across-channel effect.

The hypothesis of a detrimental across-channel effect to account for the wider binaural bandwidth in the bandwidening experiment has been challenged by van de Par and Kohlrausch (1999). They argued that the large difference between monaural and binaural filter bandwidth estimates observed in the bandwidening experiment is due to a beneficial across-channel effect lowering the thresholds in some dichotic conditions: For narrowband maskers, the auditory system is able to use information from off-frequency filters where the SNR is comparable to the one in the filter centered at the signal frequency. As the bandwidth of the masker increases, the SNR in off-frequency filters decreases reducing the effect of the beneficial across-frequency process. For all conditions where a tonal signal is used together with a broadband masker, van de Par and Kohlrausch (1999) hypothesized that the binaural processor has to rely on the on-frequency filter alone since all other filters contain no interaural differences. For the notched-noise paradigm, the hypothesis by van de Par and Kohlrausch (1999) would predict that the binaural masking-level difference (BMLD), i.e. the difference between diotic and dichotic thresholds, should be accounted for by the level-dependent BMLD for broadband maskers without notch.

Nitschmann *et al.* (2009) tested the two hypotheses measuring the BMLD in the notched-noise experiment and comparing it to the level-dependent BMLD for broadband and narrowband maskers. All experiments had in common that the same subjects participated in all three experiments and the signal was a 500-Hz sinusoid which was either in phase (NoSo condition) or in antiphase (NoSπ condition). Nitschmann *et al.* (2009) showed that the decrease in BMLD as the notch width increases can neither be accounted for by the level-dependent BMLD for broadband nor by the level-dependent BMLD for narrowband-noise maskers. Nitschmann *et al.* (2009) also showed a difference between model predictions and notched-noise data in a model (Breebaart *et al.*, 2001a) incorporating the beneficial across-channel process suggested by van de Par and Kohlrausch (1999). Thus, the predictions of the two hypotheses seem not to account for the threshold data in the notched-noise experiment.

Recently, Buss *et al.* (2003) argued that the BMLD is determined by the portions of the signal falling into the minima of the masker envelope. This hypothesis may account for the difference in BMLD between narrowband and broadband maskers. The duration of the minima in masker envelope increases as the bandwidth of the masker decreases leading to a larger BMLD for narrowband maskers. It is, however unlikely that such a mechanism can account for the decrease in BMLD as the notch width increases since the masker variations do hardly change with notch width (Patterson and Henning, 1977).

So far, binaural notched-noise data are restricted to a signal frequency of 500 Hz. The present study investigates the influence of notch width on the BMLD for various signal frequencies. A conceptual model is proposed, that can account for the diotic and dichotic notched-noise data at 500 Hz. The model assumes a detrimental across-channel effect to account for the decrease in BMLD as the notch width is increased. As a reference model, a model version is used that does not include the across-frequency process. The validity of the model assumption is then tested with the data at the other frequencies.

The detrimental process reduces the accuracy in the representation of IPDs. In order to test how realistic the IPD representation is, the just-noticeable IPD is measured for the signal frequency of 500 Hz for various notch widths and compared to model predictions. To investigate if interaural differences in auditory filter shape yield a sufficient explanation for the difference in frequency selectivity observed in binaural experiments in comparison to monaural experiments, thresholds for a 500-Hz sinusoid in notched noise are also measured for the left and right ear separately. The filter parameters derived from these thresholds are used for individually and interaurally different preprocessing in the model.

4.2. Methods

4.2.1. Apparatus and stimuli

Stimuli were generated digitally at a sampling rate of 44.1 kHz. A standard personal computer controlled stimulus generation and presentation and recorded results using a software package developed at the University of Oldenburg. Stimuli were D/A converted (RME ADI-8 DS, 32 bits), amplified (Tucker-Davis HB7), and presented via Sennheiser HD 580 headphones. Subjects were seated in a double-walled, sound-insulated booth.

The masking noises (No) were generated in the frequency domain using a 2^{15}-point (1.35-Hz resolution) buffer. Their spectrum had a constant nonzero amplitude in the passband regions and a random phase. The lower masker frequency limit was 30 Hz for the signal frequencies of 250 and 500 Hz. It was set to 60 and 120 Hz for the signal frequencies of 1 and 2 kHz, respectively. The upper cut-off frequency of the masker was always set to twice the signal frequency. The noises were transformed to the time domain (inverse FFT) and restricted to the desired length of 26460 samples (i.e., 600 ms) for one noise interval. The noise intervals were gated using 50 ms raised-cosine ramps at on- and offset.

The noise maskers had a constant spectrum level of 30 dB/Hz. At this spectrum level auditory filters can be assumed to be approximately symmetric on a linear frequency scale (Glasberg and Moore, 1990; Wright, 1996). Besides a condition without notch, notch widths were 0.1, 0.2, 0.4, 0.8, and 1.6 times the signal frequency. The notch was symmetric, i.e., the arithmetic center frequency of the notch was equal to the signal frequency.

In the diotic and dichotic notched-noise detection experiment, the target signal was a sinusoid of 250, 500, 1000, or 2000 Hz that was either in phase (So) or antiphase (Sπ) between the two ears. To control effects of absolute threshold, there was also a measurement condition without a noise masker.

In the monaural left and right notched-noise detection experiment, the signal frequency was 500 Hz. A noise of a spectrum level of -20 dB/Hz ranging from 30 to 1000 Hz was presented to the contralateral ear to prevent detection by this ear via bone conduction.

In the IPD discrimination experiment in notched noise, the signal frequency was 500 Hz. The just-noticeable difference (JND) in signal IPD (just-noticeable IPD, jnIPD) was measured for the notch widths used in the detection experiments. A diotic signal (IPD of zero) was used as a reference. The level of the signal was set to a value 3 dB above the individual threshold in the diotic notched-noise experiment. These levels are given in Tab. 4.1.

Signal duration was 300 ms including 50 ms raised-cosine ramps at on- and offset, so that the steady state portion of the signal was 200 ms. Signals were always temporally centered in the masker intervals.

$\Delta f/f_{\mathrm{sig}}$	S 2	S 5	S 6	S 7
0.0	48.3	50.4	49.8	47.2
0.1	45.7	47.7	46.8	43.8
0.2	42.3	42.7	42.5	38.1
0.4	33.3	31.0	33.4	26.5
0.8	22.4	18.0	19.3	14.9
1.6	7.6	1.4	6.2	6.3

Table 4.1.: Signal levels used in the discrimination experiment for each of the four subjects S 2, S 5, S 6, and S 7 of the discrimination experiment and every relative notch width $\Delta f/f_{\mathrm{sig}}$. The levels are given in dB SPL.

4.2.2. Procedure

A three-interval forced-choice procedure with adaptive signal-parameter adjustment was used to determine thresholds. The three masker intervals (each of 600-ms duration) were separated by 300-ms pauses. The masker intervals were indicated on the screen in front of the subject. The subject's task was to indicate the interval containing a sinusoid (detection experiments) or containing a nonzero IPD in the sinusoid (discrimination experiments). Responses were given by pressing the corresponding button 1, 2, or 3 on a computer keyboard. Trial-by-trial feedback was provided.

In the detection experiments, one randomly chosen masker interval contained the signal. Signal level was adjusted according to a one-up two-down rule tracking the 70.7% correct response level (Levitt, 1971). The initial step size of the signal level was 8 dB. The step size was halved after each second reversal of the level adjustment procedure until a step size of 1 dB was reached. Using this step size the run continued for another six reversals. The mean over these last six reversals was used as a threshold estimate.

In the discrimination experiment, each of the three masker intervals contained a signal. In contrast to the detection experiment, all three masker intervals of one trial were the same to exclude effects of differences in the random phase of the masker intervals. One randomly chosen interval contained a nonzero IPD in the signal implemented such that a positive phase angle was added to the right ear sinusoid while the left ear sinusoid remained unchanged. The signal in the two reference intervals had an IPD of zero. The parameter of adjustment was the phase angle added to the right ear signal. The target signal IPD started at π

(i.e., an Sπ sinusoid), the maximum possible difference. The decadic logarithm of the IPD was used as tracking variable (Saberi, 1995). It was adjusted according to a one-up two-down rule. The initial step size was 0.2. It was halved after each lower reversal to 0.1 and 0.05. Using this final step size, the run continued for another eight reversals. The mean over these eight reversals was used as a threshold estimate.

The measurement procedure stopped if the subject chose a wrong interval three times successively at the maximum IPD of π. This occurred almost exclusively at the largest notch width and faintest signal level. In this case additional runs were necessary to obtain a total of at least three valid threshold estimates. To obtain three valid threshold estimates at the relative notch width of 1.6, subject 2, 5, 6, and 7 needed 10, 5, 22, and 8 runs, respectively. For the relative notch width of 0.8, subject 7 needed four runs to obtain three valid threshold estimates. The averages of the valid threshold estimates were used as a final threshold estimate.

The experiments were conducted in the following order of signal frequencies for every subject: 500 Hz, 250 Hz, 1000 Hz, 2000 Hz. Runs with diotic and dichotic stimulus conditions were mixed within every signal frequency. The monaural threshold and IPD discrimination data were gathered after the subjects had finished the diotic and dichotic notched-noise experiments. At least three threshold estimates were obtained and averaged for each parameter value and subject (see below for details).

Three criteria for a valid threshold measurement were imposed on the data in the detection experiments: (i) The standard deviation of each single threshold estimate had to be below 3 dB. If a single threshold estimate had a standard deviation above 3 dB, it was discarded and remeasured. (ii) If the second threshold estimate in a certain masking condition was more than 2 dB below the first and the third was below the second plus 20% the difference of first minus second, this was regarded as a learning effect. In this case all the thresholds of the respective interaural condition (diotic or dichotic) of this run were remeasured once. The results of the first run of this interaural condition were discarded. This was the most frequent reason for remeasurement. (iii) Three threshold estimates were obtained and averaged for each parameter value and subject. The standard deviation of the mean over these threshold estimates had to be below 3 dB. If it was above 3 dB, more threshold estimates for the respective parameter values were obtained and the previous ones discarded. This applied to eight of the threshold estimates.

Mostly, this occurred as a consequence of a learning effect, so that all thresholds of the respective interaural condition were remeasured as described above.

Rarely learning effects occurred, but the subjects were not able to reproduce as low threshold estimates as in the second and third run in the remeasurement. For this reason the standard deviations of four individual average thresholds are slightly above 3 dB: Absolute threshold at 2 kHz in Sπ condition for subject 4 and 6, and the two thresholds for the 800-Hz notch width at the 2-kHz signal frequency experiment of subject 7.

4.2.3. Subjects

Eight subjects (4 male, 4 female, aged 20–38 years, mean 29 years) participated in the experiments. Three subjects including the first author were members of the research group, the others were paid volunteers. All subjects had normal audiograms with hearing thresholds lower than or equal to 10 dB HL at the standard audiometric frequencies from 125 Hz to 4 kHz, i.e., the audiometric frequencies in the relevant frequency range.

For most subjects, thresholds for 6 and 8 kHz were also lower than or equal to 10 dB HL. However, subject 2 had an absolute threshold of 20 dB HL on the right ear at 6 kHz, subject 5 had an absolute threshold of 15 dB HL on the left ear at 6 kHz, subject 6 had an absolute threshold of 20 dB HL on the left ear at 8 kHz and subject 7 had an absolute threshold of 20 and 15 dB HL on the left ear at 6 and 8 kHz, respectively, and 20 dB HL on the right ear at 8 kHz.

All subjects participated in the diotic and dichotic detection experiments. Only subjects 2, 5, 6, and 7 participated in the monaural detection experiments and the discrimination experiment.

4.3. Results and discussion

4.3.1. Detection experiments

Fig. 4.1 shows detection thresholds averaged over the individual results of eight subjects as a function of relative notch width, i.e., notch width Δf divided by signal frequency f_{sig}. The four panels of Fig. 4.1 show the results of the four different signal frequencies. Circles and triangles denote the signal IPD of zero (So) and 180 degrees (Sπ), respectively. Thresholds masked by a diotic notched noise

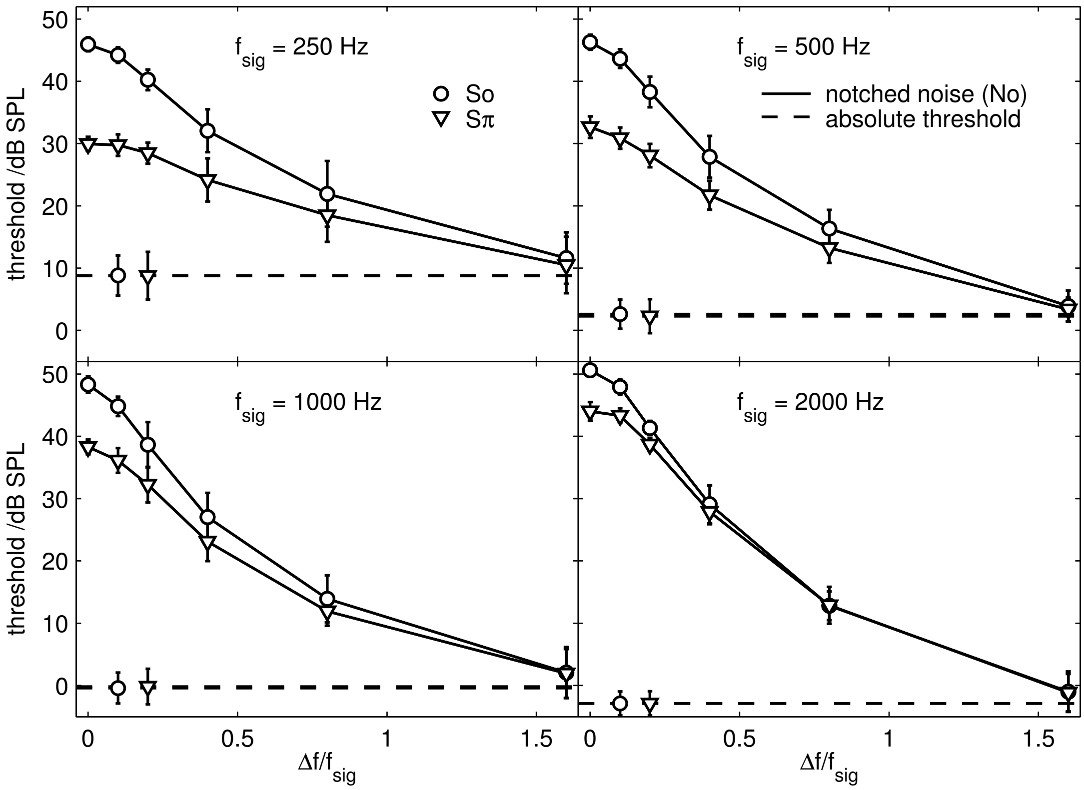

Figure 4.1.: Mean detection thresholds for a signal frequency of 250 (upper left panel), 500 (upper right panel), 1000 (lower left panel), and 2000 Hz (lower right panel) as a function of notch width Δf relative to signal frequency f_{sig} (solid lines). Circles and triangles denote So and Sπ thresholds, respectively. The dashed, horizontal lines denote absolute thresholds for the respective signal frequency. Error bars denote plus minus one interindividual standard deviation. They are only shown when they exceed the size of the symbols. The thresholds are also given in Tab. 4.2.

f_{sig} = $\Delta f/f_{sig}$	250 Hz So	250 Hz Sπ	500 Hz So	500 Hz Sπ	1 kHz So	1 kHz Sπ	2 kHz So	2 kHz Sπ
0.0	45.9	29.9	46.3	32.6	48.3	38.3	50.6	44.0
0.1	44.2	29.8	43.6	30.9	44.8	36.1	47.9	43.3
0.2	40.2	28.5	38.3	28.1	38.7	32.2	41.3	38.7
0.4	32.1	24.2	27.9	21.7	27.0	23.1	29.1	27.9
0.8	21.9	18.5	16.3	13.3	13.9	11.9	12.8	12.9
1.6	11.6	10.5	3.9	3.4	2.1	1.9	-1.0	-1.1
abs.	8.8	8.8	2.6	2.3	-0.4	-0.2	-2.9	-2.9

Table 4.2.: Average So and Sπ thresholds for a sinusoid in diotic notched noise as a function of relative notch width $\Delta f/f_{sig}$. The abbreviation abs. denotes absolute thresholds. The threshold data are shown in Fig. 4.1. All thresholds are given in dB SPL. The BMLDs are given in Tab. 4.3.

f_{sig} = $\Delta f/f_{sig}$	250 Hz	500 Hz	1 kHz	2 kHz
0.0	16.0	13.6	10.0	6.6
0.1	14.4	12.8	8.7	4.6
0.2	11.8	10.2	6.4	2.6
0.4	7.9	6.2	3.9	1.2
0.8	3.4	3.1	2.0	-0.1
1.6	1.1	0.5	0.2	0.1
abs.	0.0	0.3	-0.2	0.0

Table 4.3.: Average BMLDs for a sinusoid in diotic notched noise as a function of relative notch width $\Delta f/f_{sig}$. The abbreviation abs. denotes absolute thresholds. All BMLDs are given in dB.

(No) are denoted by solid lines; dashed lines denote absolute thresholds. Error bars denote plus minus one interindividual standard deviation. The interindividual standard deviations are around 1 dB in a broadband masker without notch and increase with increasing notch width due to individual differences in filter shape and absolute threshold. At the largest notch widths, the interindividual standard deviations are mainly between 3 and 5 dB. Tab. 4.2 provides an overview of the thresholds shown in Fig. 4.1.

At the signal frequencies of 250, 500, 1000, and 2000 Hz, average absolute thresholds are about 9, 2.5, 0, and -3 dB SPL, respectively. The same absolute thresholds are obtained for the So and the Sπ signal (absolute value of the difference below 1 dB). Averaged over four subjects, Diercks and Jeffress (1962) found a small BMLD of about 1 dB for 250-Hz sinusoids. Since individual BMLDs at this signal frequency range from almost -1 dB to 2 dB in the present study, the difference to Diercks and Jeffress (1962) might be due to different subjects. Suzuki and Takeshima (2004) compiled absolute threshold data from a lot of studies. The mean diotic absolute thresholds of the present study are about 2 dB below the averages of the experimental data given by Suzuki and Takeshima (2004).

For all signal frequencies, diotic and dichotic masked thresholds decrease with increasing notch width. The decrease of diotic thresholds is larger than the decrease of dichotic thresholds so that the BMLD (given in Tab. 4.3) decreases with increase in notch width.

Signal frequency 250 Hz

The upper left panel of Fig. 4.1 shows thresholds for a 250-Hz sinusoid. Diotic thresholds decrease with increase in notch width from 46 dB SPL [3] in a broadband masker to about 12 dB at a relative notch width of 1.6. Dichotic thresholds decrease from 30 dB in a broadband masker to 10.5 dB at a relative notch width of 1.6. The BMLD decreases with increasing notch width from 16 dB at a relative notch width of 0.0 to a value of 1 dB at a relative notch width of 1.6. The latter BMLD is well below the standard deviations of the thresholds. The BMLD at the relative notch width of 0.4 is the largest notch width where the size of the BMLD (8 dB) exceeds the standard deviations of the thresholds.

For the signal frequency of 250 Hz, thresholds for So and Sπ sinusoids in broad-

[3] In the rest of the present study, all detection thresholds will be given in dB SPL, i.e., dB *re* 0.00002 Pa.

band noise have been measured by van de Par and Kohlrausch (1999). In contrast to the present study, they used a spectrum level of 43 dB/Hz. Assuming a linear dependence of thresholds and masker spectrum level for broadband maskers without notch (Hall and Harvey, 1984), their diotic and dichotic thresholds for the largest bandwidth are in good agreement with the present data at a notch width of zero: Both diotic and dichotic threshold of van de Par and Kohlrausch (1999) are about 1 dB lower than the corresponding thresholds of the present study.

Signal frequency 500 Hz

The upper right panel of Fig. 4.1 shows thresholds for a 500-Hz sinusoid. Diotic thresholds decrease with increase in notch width from about 46 dB in a broadband masker to 4 dB at a relative notch width of 1.6. Dichotic thresholds decrease from about 33 dB in a broadband masker to about 3 dB at a relative notch width of 1.6. The BMLD decreases with increasing notch width from almost 14 dB in a broadband masker to a value below 1 dB. The BMLD is below the standard deviations of the corresponding thresholds for relative notch widths larger than 0.4 as for the 250-Hz signal. Hall *et al.* (1983) conducted an experiment similar to the present one for the signal frequency of 500 Hz. In general, the shape of the threshold curves agrees with their results. Both show a decrease in threshold as the notch width increases which is larger in the diotic condition than in the dichotic condition. In general, the thresholds in Hall *et al.* (1983) are 2–4 dB higher than in the present study. This is probably due to differences in the procedure. They used a three-interval forced-choice procedure with a 1-up 3-down rule whereas the present study used a 1-up 2-down rule.

NoSo and NoSπ thresholds in a broadband masker for the same masker spectrum level as in the present study were obtained by, e.g., Sever and Small (1979) and Hall and Harvey (1984). Their results are in good agreement with the threshold data of the present study: The differences to the thresholds of the present study do not exceed 2 dB. Since the dichotic thresholds obtained by both Sever and Small (1979) and Hall and Harvey (1984) are higher and the diotic threshold is lower in Sever and Small (1979), their BMLD is smaller than in the present study. When the difference in masker spectrum level is taken into account, the diotic thresholds of the present study agree well with the thresholds in broadband noise reported by Bernstein and Trahiotis (1999) and van de Par and Kohlrausch (1999). In contrast to Sever and Small (1979) and Hall and Harvey (1984) the dichotic thresholds of the studies by Bernstein and Trahiotis (1999) and van de Par and Kohlrausch (1999) are about 2 dB lower than those of the present study which is probably indicating a small effect of the difference in the spectrum level used in the experiments even at spectrum levels of 30 dB/Hz and above.

Signal frequency 1000 Hz

The lower left panel of Fig. 4.1 shows thresholds for a 1-kHz sinusoid. Diotic and dichotic thresholds decrease from 48 and 38 dB, respectively, in a broadband masker to 2 dB at a relative notch width of 1.6. The BMLD decreases from 10 dB in a broadband masker to 0 dB at the relative notch width of 1.6. For 0.2 and larger relative notch widths the BMLD is of the same size as the standard deviations of the corresponding thresholds or below.

Weber (1977) measured thresholds for a diotic 1-kHz signal in a diotic notched-noise masker at different spectrum levels. Taking into account that he used the 75%-correct points as threshold estimates, his thresholds coincide well with the average thresholds of the present study. The largest difference between the thresholds is found at the notch width of 100 Hz where the threshold given by Weber (1977) is about 5 dB above the threshold of the present study; the other thresholds are between 1 and about 4 dB above.

Thresholds for a 1-kHz sinusoid masked by a broadband noise in NoSo and NoSπ condition were measured by van de Par and Kohlrausch (1999) at a comparable spectrum level of 37 dB/Hz. Converted to threshold estimates at 30 dB/Hz, they are in very good agreement with the average broadband thresholds of the present study (difference below 1 dB).

Signal frequency 2000 Hz

The lower right panel of Fig. 4.1 shows thresholds for a 2-kHz sinusoid. Diotic and dichotic thresholds decrease from about 51 and 44 dB, respectively, in a broadband noise masker to -1 dB at a relative notch width of 1.6. The BMLD is 6.6 dB in a broadband masker and decreases with increasing notch width to 0 dB at the relative notch widths of 0.8 and 1.6. As for the signal frequency of 1 kHz, the BMLD is smaller than the standard deviations of the corresponding thresholds for all relative notch widths larger than 0.2.

Threshold data of a notched noise of the same spectrum level masking a sinusoid of 2 kHz have been published, e.g., by Weber (1977) and Moore *et al.* (1995). In the latter study, monaural stimuli were used. The threshold data measured by Weber (1977) and Moore *et al.* (1995) are in reasonable agreement with the data of the present study. At a relative notch width of 0.8 (1.6 kHz), 2-kHz thresholds from these notched-noise studies are higher than the highest individual thresholds at this notch width of the present study. Slightly higher thresholds might result from the 79%-correct level that was tracked in the study by Moore *et al.* (1995). Higher thresholds at larger notch widths might be a result of individual differences of the subjects since in most studies there was only a small number of subjects. In contrast to generating the notch in the noise masker by using a filter, the effectively steeper filtering by generation in the frequency domain used in the present study might lead to less noise remaining in the notch and hence lower thresholds.

NoSo and NoSπ thresholds of a 2-kHz sinusoid in broadband noise have been measured, e.g., by Sever and Small (1979) and van de Par and Kohlrausch (1999). Sever and Small (1979) used the same spectrum level as in the present study; the threshold data of van de Par and Kohlrausch (1999) were converted to this spectrum level assuming a roughly constant BMLD over spectrum levels. In the diotic condition, the thresholds obtained by Sever and Small (1979) and van de Par and Kohlrausch (1999) are less than 2 dB below the average threshold of the present study. The dichotic thresholds are up to 1 dB above the average threshold of the present study. Thus, the BMLD estimate is 2–3 dB smaller than in the present study.

Filter parameters

Tab. 4.4 displays auditory filter width estimates derived from the mean diotic and dichotic thresholds (Fig. 4.1, Tab. 4.2) in notched noise. The 3-dB bandwidth as defined in Sec. 4.1 is denoted by $n_{3\mathrm{dB}}$. The parameters were derived in a linear interpolation between the thresholds. A similar filter width estimate was used by Hall *et al.* (1983). This filter width estimate is independent of the assumption of a particular attenuation characteristic of the auditory filter; however, the parameters $n_{3\mathrm{dB}}$ rely only on the thresholds in the region of a 3-dB decrease compared to the condition without notch, not on all thresholds. B denotes the width of third-order gammatone filters (implementation by Hohmann, 2002) fitted to the threshold curves using a power-spectrum model [4]. Filter parameters were derived from the

[4] Before the gammatone filtering the stimuli were filtered using a first-order band-pass filter with cutoff frequencies at 500 Hz and 5.3 kHz as a combined outer and middle ear filter (see

f_{sig} /Hz	250	500	1000	2000
$n_{3\mathrm{dB}}$(NoSo) /Hz	33	53	86	210
$n_{3\mathrm{dB}}$(NoSπ) /Hz	68	72	121	300
$r(n_{3\mathrm{dB}})$	2.0	1.4	1.4	1.4
B(NoSo) /ERB	1.07	1.05	1.08	0.98
B(NoSπ) /ERB	2.54	2.03	1.78	1.28
$r(B)$	2.4	1.9	1.6	1.3

Table 4.4.: Auditory filter parameters derived from the mean NoSo and NoSπ thresholds in a notched-noise masker. $n_{3\mathrm{dB}}$(NoSo) and $n_{3\mathrm{dB}}$(NoSπ) denote the notch widths where the diotic and dichotic thresholds, respectively, have decreased by 3 dB compared to a broadband masker, interpolated in a linear fit to the threshold data. B(NoSo) and B(NoSπ) denote the equivalent rectangular bandwidth (ERB) of third-order gammatone filters (Hohmann, 2002) fitted to the diotic and dichotic threshold data, respectively. $r(n_{3\mathrm{dB}})$ and $r(B)$ denote the ratio of binaural bandwidth measure divided by the corresponding monaural bandwidth measure.

NoSo and NoSπ thresholds. r denotes the ratio of the corresponding parameters for NoSπ and NoSo thresholds.

Concerning the 3-dB bandwidth $n_{3\mathrm{dB}}$, the largest difference between diotic and dichotic parameters can be found at the signal frequency of 250 Hz where the dichotic value is twice the size of the diotic. For the other signal frequencies, the dichotic 3-dB bandwidth is below one and a half times the diotic value. The smallest difference can be found for the signal frequency of 500 Hz: The 3-dB notch widths are 53 and 72 Hz in the diotic and dichotic condition, respectively. Hall *et al.* (1983) conducted a similar notched-noise experiment and obtained 3-dB bandwidths of 51 and 62 Hz in the same conditions. So, except for a slightly larger dichotic value in the present study, the derived parameters are in good agreement. For the signal frequency of 2 kHz, Patterson and Nimmo-Smith (1980) measured a 3-dB bandwidth of 220 Hz in the diotic condition which is in good agreement with the 210 Hz of the present study.

The bandwidth B of the best fit of third-order gammatone filters fitted to the diotic thresholds is around 1.0 ERB (equivalent rectangular bandwidth, see Glasberg and Moore, 1990; Kollmeier and Holube, 1992) for all signal frequencies. When fitted to the dichotic thresholds, the bandwidth of third-order gammatone

Sec. 4.4.1).

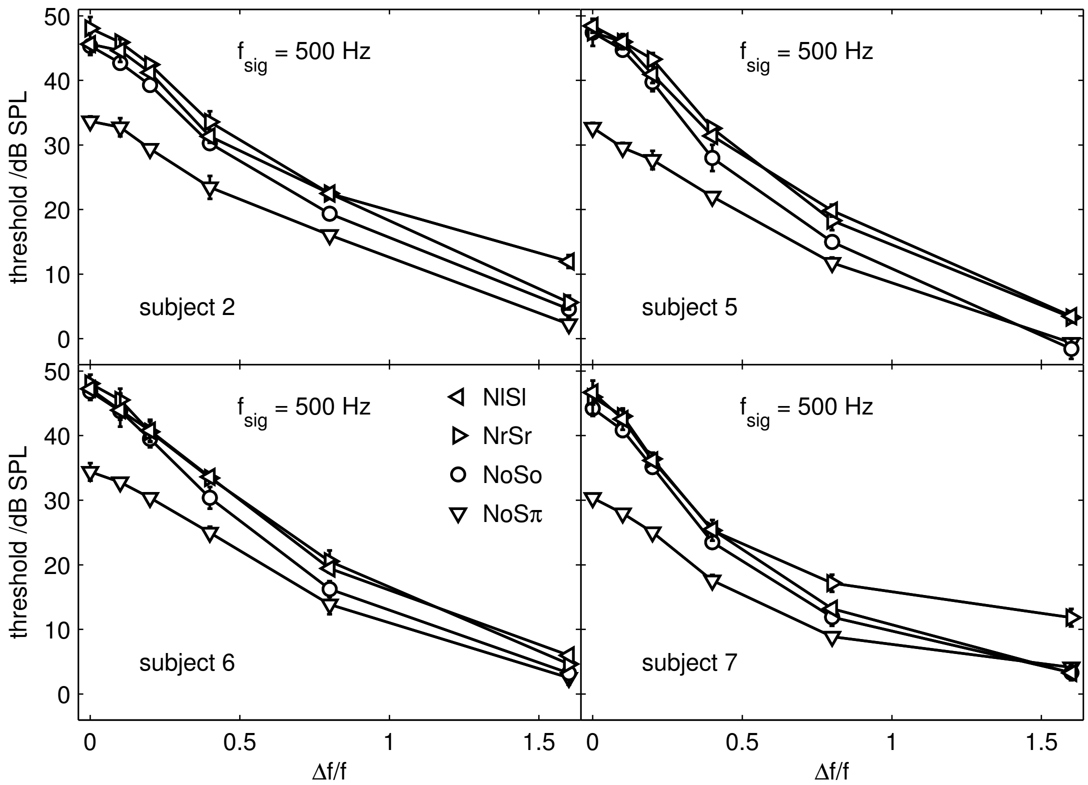

Figure 4.2.: Detection thresholds for a 500-Hz sinusoid as a function of notch width for subjects 2, 5, 6, and 7. Monaural left (NlSl) and right (NrSr) thresholds are denoted with triangles left and right, respectively. Diotic thresholds (NoSo) are denoted with circles, dichotic thresholds (NoSπ) with triangles down. Error bars denote intraindividual standard deviations. They are only shown when they exceed the size of the symbols.

filters is strictly monotonically decreasing with increase in signal frequency, showing that the difference between monaural and binaural filters is most prominent at 250 Hz and smaller at 2 kHz.

Monaural detection experiments

Fig. 4.2 shows individual detection thresholds of subjects 2, 5, 6, and 7 for a 500-Hz sinusoid as a function of notch width. Monaural left (NlSl), monaural right (NrSr), diotic, and dichotic thresholds are denoted with triangles left, triangles right, circles, and triangles down, respectively. Tab. 4.5 gives auditory filter parameters derived from the individual NlSl, NrSr, and NoSo thresholds using gammatone

condition	S 2	S 5	S 6	S 7
NlSl	2/0.88	3/1.01	3/1.23	2/0.51
NrSr	3/1.17	3/1.02	3/1.11	2/0.70
NoSo	3/1.26	3/0.85	3/1.03	2/0.50

Table 4.5.: Auditory filter parameters (gammatone filter order/filter bandwidth in ERB) derived from detection thresholds in notched noise in a power-spectrum model. The stimuli were presented monaurally left (NlSl), right (NrSr), or diotically (NoSo).

filters in a power-spectrum model.

The individual diotic and dichotic thresholds of Fig. 4.2 are generally similar to the mean thresholds (Fig. 4.1, upper right panel). Monaural thresholds of Fig. 4.2 are above or equal to the diotic thresholds for all notch widths and subjects. Due to interaural differences in absolute thresholds, subjects 2 and 7 show differences in monaural masked thresholds at large notch widths of up to 8 dB. Interaural differences in monaural masked thresholds are below 3 dB in subjects 5 and 6. Larger interaural differences im monaural masked thresholds are also reflected in larger differences in filter parameters (Tab. 4.5). Generally, the shape of the diotic thresholds corresponds to the lower monaural thresholds (i.e., to the "better" ear). However, diotic thresholds are lower than the corresponding lower monaural thresholds, particularly for subjects 5 and 6 at large notch widths. The maximum difference (subject 5, relative notch width 1.6) amounts to almost 5 dB. Averaged over subjects, the difference increases with relative notch width from 1 to almost 4 dB. For 250-Hz absolute thresholds, Diercks and Jeffress (1962) reported a difference between monaural threshold at the better ear and diotic threshold that ranged individually from above 1 to almost 4 dB. The mean difference of 2.8 dB given by Diercks and Jeffress (1962) is above the mean difference at the largest notch width of the present study (1.8 dB).

The interaural differences in monaural masked thresholds of the present study are well within the variation found across subjects as, e.g., in Patterson *et al.* (1982). The two younger listeners (aged 29 and 42 years) of the 500-Hz condition in their study show interaural differences that are between those of subject 6 and 2 (both aged 33 years) of the present study.

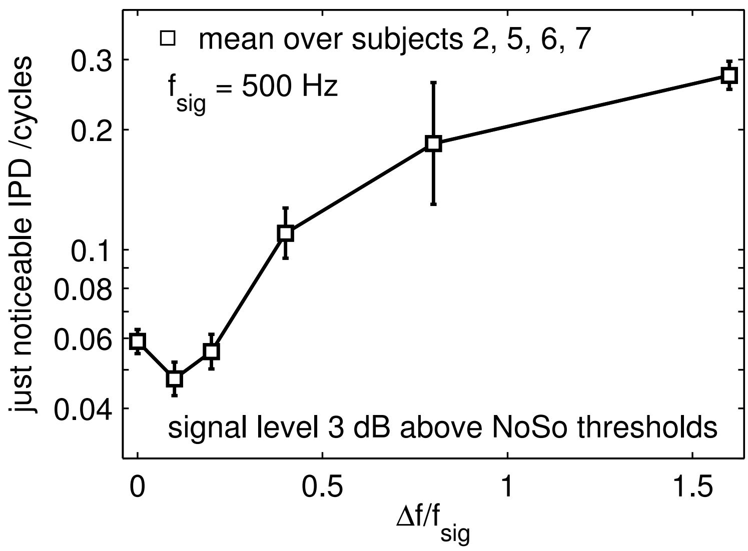

Figure 4.3.: Mean just-noticeable difference in IPD (jnIPD) for a 500-Hz signal as a function of notch width of a diotic noise masker. The reference IPD was zero. The level of the sinusoid was kept constant 3 dB above the NoSo threshold of the respective subject at the respective notch width. The levels are given in Tab. 4.1. Error bars denote plus minus one interindividual standard deviation. The figure shows jnIPDs averaged over subjects 2, 5, 6, and 7.

4.3.2. Discrimination experiment

Fig. 4.3 shows jnIPDs as a function of notch width averaged over subjects 2, 5, 6, and 7. The levels of the sinusoids were fixed 3 dB above the level of the individual diotic threshold in the detection experiment. The sinusoid levels used are given in Tab. 4.1. In a broadband masker without notch, the jnIPD is about 0.06 cycles (i.e., 21 degree). It is slightly smaller at the notch width of 50 Hz. For higher notch widths, it increases monotonically reaching a value of 0.27 cycles (99 degree) at a notch width of 800 Hz.

For the notch widths up to 100 Hz, the intraindividual error bars of the jnIPD estimates are overlapping; nevertheless the estimates decrease from the condition without notch to the 50-Hz notch condition for all four subjects. Since measurement runs often stopped in the condition with the largest notch width (see Sec. 4.2.2), this jnIPD estimate might be biased towards low values.

One way to understand these jnIPD threshold data is to think of detectablility rather than discrimination: The So reference sinusoids were all equally detectable since they were presented at a level 3 dB above individual diotic threshold at the respective notch width. The target sinusoids were presented at the same level, but their detectability generally was higher due to the nonzero IPD. The maximum advantage in detection is given by the notch-width dependent BMLD for the 500-Hz sinusoid (Fig. 4.1, upper right panel). This maximum advantage is in effect at the beginning of every threshold run of the discrimination experiment. The adaptive decrease in IPD reduces this advantage.

Assuming a linear dependence of the BMLD on the IPD with its maximum at 0.5 cycles (Sπ) and no BMLD at 0.0 cycles (So), a "BMLD at threshold jnIPD" can be computed from BMLD and jnIPD average over subjects 2, 5, 6, and 7. This measure is almost 1.6 dB in the condition without notch and decreases to 1.1 dB at the relative notch width of 0.8. Since it does not show a large change with increase in notch width, one may assume that the jnIPD threshold data in Fig. 4.3 are primarily determined by the notch-width dependence of the BMLD. At the largest notch width, a value of 0.2 dB clearly lower than the other measures hints towards a bias to lower jnIPDs.

4.3.3. BMLD formula

There is a gradual decrease in BMLD in the measured threshold data. The average BMLD is half the size it is in a condition without notch at the relative notch widths of 0.40, 0.35, 0.29, and 0.33 at the signal frequencies of 250, 500, 1000, and 2000 Hz, respectively.

A simple and yet reasonable equation to describe the dependence of BMLD on relative notch width and signal frequency is possible using a maximum BMLD of 20 dB and two terms with an exponential decay:

$$\begin{aligned} &\mathrm{BMLD}(f_{\mathrm{sig}}, \Delta f) = \\ &\exp(-f_{\mathrm{sig}}/1500\,\mathrm{Hz})\,\exp(-2\Delta f/f_{\mathrm{sig}})\,20\,\mathrm{dB}. \end{aligned} \tag{4.1}$$

The two terms with exponential decay describe the decrease of BMLD with increase in signal frequency and relative notch width. Eq. 4.1 is depicted in Fig. 4.4. For the 2-kHz BMLDs, Eq. 4.1 is not in good agreement with the measured thresholds. At low signal frequencies and the two smallest notch widths, the measured decrease in BMLD is smaller than that predicted by the equation.

For the range of frequencies used in the present study, the exponential decay

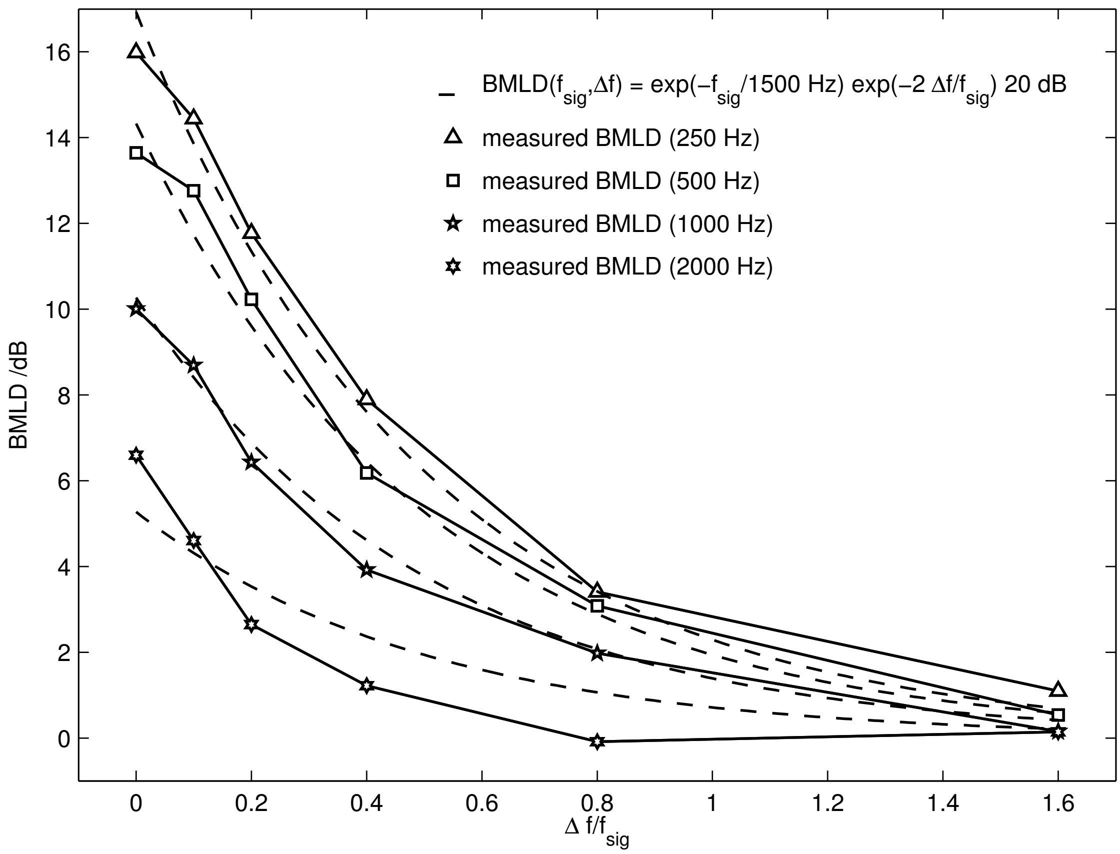

Figure 4.4.: Average BMLDs as a function of relative notch width for the signal frequencies of 250, 500, 1000, and 2000 Hz denoted with triangles, squares, pentagrams, and hexagrams, respectively. The dashed lines depict the fit given by the formula.

describing the decrease of BMLD with increase in signal frequency yields a fit of similar goodness as

$$\mathrm{BMLD}(f_{\mathrm{sig}}) = \log_{10}\left(\frac{k+1}{k-1}\right) 10\,\mathrm{dB} \tag{4.2}$$

with $k = (1+\sigma_\epsilon^2)\exp((2\pi f_{\mathrm{sig}}\sigma_\delta)^2)$ given by Durlach (1972) (see also Kohlrausch, 1988). For the prediction of the BMLDs in a masker without notch measured in the present study, best parameters are $\sigma_\epsilon = 0.22$ and $\sigma_\delta = 57$ µs. Kohlrausch (1988) reports $\sigma_\epsilon = 0.13$ and $\sigma_\delta = 80$ µs as a median fitted to BMLDs for frequencies between 200 and 800 Hz.

Since Eq. 4.2 yields a curve with a shallow slope for small values of f_{sig}, it appears to be appropriate to describe the decrease of BMLD with increase in notch width: For small notch widths the BMLD does not drop exponentially (see Fig. 4.4). However a multiplication of two equations like Eq. 4.2 to form an equation like Eq. 4.1 results in two more parameters than Eq. 4.1 and yields a less accurate fit to the BMLD data of the present study.

4.4. Modeling

4.4.1. Model structure

The model used in the present study is based on the "effective" monaural model proposed by Dau *et al.* (1996) and its extension to a binaural model by Zerbs (2000) using the equalization-cancellation (EC) principle (Durlach, 1963). The model consists of several stages of processing that are assumed to occur in human auditory processing. It acts as an artificial observer in the same experimental procedures as conducted with the subjects. To analyze the effects of critical model stages with respect to the frequency selectivity, different model versions were used as described below. Except for the DRNL-filter model version, they all use the same monaural model part, but there are differences in the implementation of the binaural model part.

The initial stage of the model is a Butterworth band-pass filter of first order with cutoff frequencies at 500 Hz and 5.3 kHz that is thought to reflect the combined transfer function of the outer and middle ear. The filtering on the cochlea is modeled by a linear gammatone filterbank (Hohmann, 2002) in all model versions but one. The filters are of third order and 1 ERB wide. One of the filters is centered at the signal frequency. In one model version a dual resonance non-linear filter (DRNL, Lopez-Poveda and Meddis, 2001) is used. This version is referred to as the *DRNL-filter model* [5]. After cochlear filtering a white noise is added in every frequency channel of the filterbank to account for absolute threshold effects. The noise is independent in the filterbank channels and uncorrelated between left and right channels. The level of the noise is 7 dB SPL in the model versions with linear auditory filtering and 18 dB SPL in the DRNL-filter model. The following stage of processing is a half-wave rectification and a low-pass filtering at 1 kHz.

In the binaural part of the model version referred to as the *seven-filter model* in the following, a weighted addition of peripheral filters takes places after the half-wave rectification and low-pass filtering: The outputs of the filters centered 1, 2, and 3 ERB below and above the filter centered at the signal frequency are multiplied by 0.05 and added to the on-frequency filter. The basic model version using the same gammatone filter for the simulation of diotic and dichotic thresholds is referred to as the *single-filter model*. In the binaural part of all model versions the absolute value of a white noise with a level of 2 dB SPL is added subsequently to the half-wave rectification and low-pass filtering. In the seven-filter model, this addition of noise occurs after the weighted addition of filters.

The next stage of the model contains five consecutive nonlinear feedback loops (Dau *et al.*, 1996), also referred to as adaptation loops to account for adaptation and compression in the auditory system.

In the binaural model part, the subsequent processing stage comprises the comparison between preprocessed left and right ear signals. It is based on the EC principle (Durlach, 1963). The implementation of the present model is that of Zerbs (2000).

In the binaural part of the model version referred to as the *phase-shift model*

[5]Each DRNL filter consists of two processing pathways: One linear pathway and one nonlinear pathway. The linear pathway consists of a gammatone filter and a low-pass filter; center and cut-off frequency of both filters are somewhat below the center frequency of the combined DRNL filter. The nonlinear pathway consists of a gammatone filter, a broken-stick nonlinearity, another gammatone filter, and a gain. Both gammatone filters are centered at the center frequency of the combined DRNL filter. The DRNL filter parameters used for the simulation shown in Fig. 4.8 are: The gammatone filters of the nonlinear pathway were of second and fourth order. A gammatone filter of fourth order was used in the linear pathway. The low-pass filter was of eighth order. The slope in the low-level region of the nonlinearity was 0.78, in the upper compressive part it was 0.16.

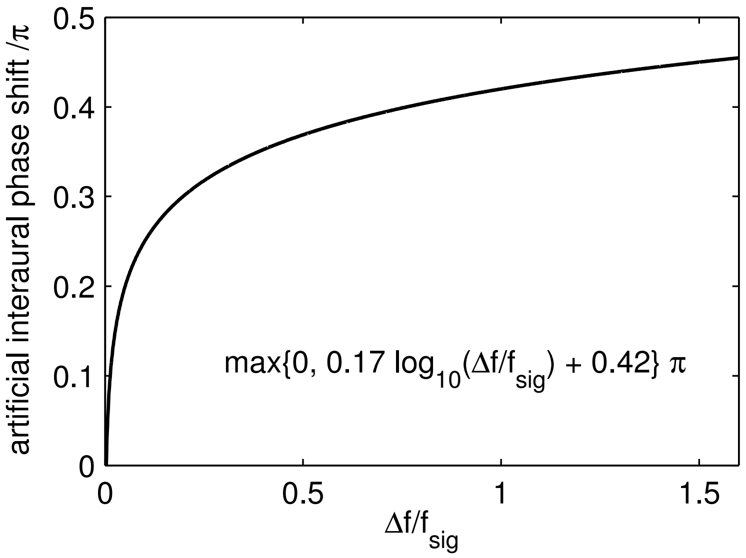

Figure 4.5.: Artificial interaural phase shift as a function of relative notch width. This phase shift is used in the phase-shift model. It is applied to the right preprocessed channel immediately before the EC processing stage to reduce its effectiveness in a notch-width dependent way.

in the following, a phase shift is applied to the right preprocessed channel immediately before the EC processing stage to reduce the effectiveness of the EC processing. The phase shift depends only on the relative notch width with no phase shift at the notch width of zero. Fig. 4.5 shows the interaural phase shift as a function of relative notch width.

The processing of both the monaural and binaural model parts concludes with a first-order low-pass with a cutoff frequency of 8 Hz after the adaptation loops and the EC stage, respectively. The output of these auditory processing stages is termed the internal representation of the corresponding stimulus.

An optimal detector (Dau *et al.*, 1996) is used as the decision device of the model. It combines the information across time of the monaural and binaural model part and chooses the lower threshold prediction of both parts. In the decision process, a stored temporal representation of the signal to be detected (the *template*) is compared to the actual internal representation by calculating the unnormalized cross correlation between the two temporal patterns. This is comparable to a "matched filtering" process. The template is derived once at a clearly suprathreshold (20 dB above the respective measured threshold in the detection experiments) signal level [6]. The idea is that at the beginning of an experiment the signal is usually presented at a highly detectable level where the subject is assumed to be able to get an "image" of the signal. The performance of the optimal detector is limited by internal noise. A detailed description of most stages of the model is given in Dau *et al.* (1996)

Changes of the monaural part of the model compared to the model by Dau *et al.* (1996) concern the simulation of absolute thresholds: The model by Dau *et al.* (1996) contained a minimum input value to the adaptation loops to account for absolute threshold. The models by Zerbs (2000) and also by Breebaart *et al.* (2001a) replaced this by a filtering before and the addition of white noise after the auditory filterbank.

Differences to the binaural model proposed by Zerbs (2000) include: The effects of the outer and middle ear were modeled using a first-order band-pass filter with cutoff frequencies of 500 Hz and 5.3 kHz instead of the original first-order high-pass filter with a cutoff frequency of 1 kHz. The new filter parameters resulted in a better correspondence between measured and simulated absolute thresholds. Besides the band-pass filter parameters are similar to those proposed by Puria *et al.* (1997) who derived middle-ear parameters from human-cadaver ears and suggested a pass-band between 400 Hz and 4 kHz with slopes of 4 dB/octave below and -8 dB/octave above. The pass-band of this outer and middle ear filter is wider than the first-order band-pass filter with cutoff frequencies at 1 and 4 kHz used by Breebaart *et al.* (2001a). The level of the noise added after the auditory filterbank was 7 dB SPL. This noise level was 0 and 9.4 dB SPL in the models of Zerbs (2000) and Breebaart *et al.* (2001a), respectively. The reason for these changes was a better correspondence between measurement and simulation relating to absolute thresholds. The parameters of the gammatone filters were fitted to the diotic thresholds using a power-spectrum model (Tab. 4.4). 1 ERB wide third-order gammatone filters yielded good results for most diotic mean thresholds [7]. The same filter parameters were used by Breebaart *et al.* (2001a) whereas Zerbs (2000) used gammatone filters of fourth order. The addition of the absolute value of a white noise of 2 dB SPL in the binaural model part was necessary for the

[6]In the discrimination experiments, the template is derived at the (constant) signal level 3 dB above the (mean) diotic threshold.

[7]For the signal frequency of 2 kHz, fourth-order filters of a bandwidth larger than 1 ERB would yield a better fit. However, to keep the number of adjusted parameters small, the same filter parameters were used for all signal frequencies accepting not very good correspondence between measurement and simulation results in particular for the 2-kHz signal frequency.

quantitative prediction of dichotic thresholds at large notch widths.

Unless stated otherwise, all model parameters were kept constant. The simulated mean thresholds (Fig. 4.6 and Figs. 4.8–4.11) were averaged over 24 simulated runs for each thresholds (i.e., 8 subjects times 3 repetitions like in the measurement). The simulated individual thresholds (Fig. 4.7) were averaged over 3 simulated runs for each threshold like in the measurement. The error bars of the simulated thresholds denote the standard deviations. They are only shown when they exceed the size of the symbols.

4.4.2. Detection experiments

Fig. 4.6 shows the measured threshold data as in Fig. 4.1 (open symbols) and simulated thresholds (filled symbols) as predicted by the single-filter model described above as a function of relative notch width. The dashed lines denote absolute thresholds.

Simulated diotic and dichotic absolute thresholds correspond well with the measured thresholds except for the signal frequency of 2 kHz where the predicted thresholds are 1.5 dB higher than measured.

The auditory filter parameters were fitted to the diotic thresholds in notched noise. For this reason there is a good correspondence between measured and simulated thresholds. The differences are below 3 dB. The largest differences can be found at small notch widths at the signal frequencies of 250 and 2000 Hz. The decrease of diotic thresholds is apparently slightly shallower than predicted by the gammatone filter. For the signal frequency of 2 kHz different gammatone filter parameters would yield a better fit (see footnote above in Sec. 4.4.1). For the signal frequency of 250 Hz a higher variance of internal noise would have improved the correspondence between measurement and simulation.

Simulated dichotic thresholds in broadband noise without notch agree very well with the measured thresholds. With increasing notch width simulated thresholds decrease earlier than measured. The model predicts a constant BMLD as large as in the condition without notch whereas the BMLD decreases continuously in the measured threshold data. For the relative notch widths of 0.8 and 1.6, the predicted BMLD decreases primarily due to the noise added in the binaural part of the model. Without addition of noise a predicted BMLD of 0 dB as measured for the largest notch width would not have been possible. Instead, the predicted BMLDs for the signal frequencies of 250, 500, and 1000 Hz would have been above

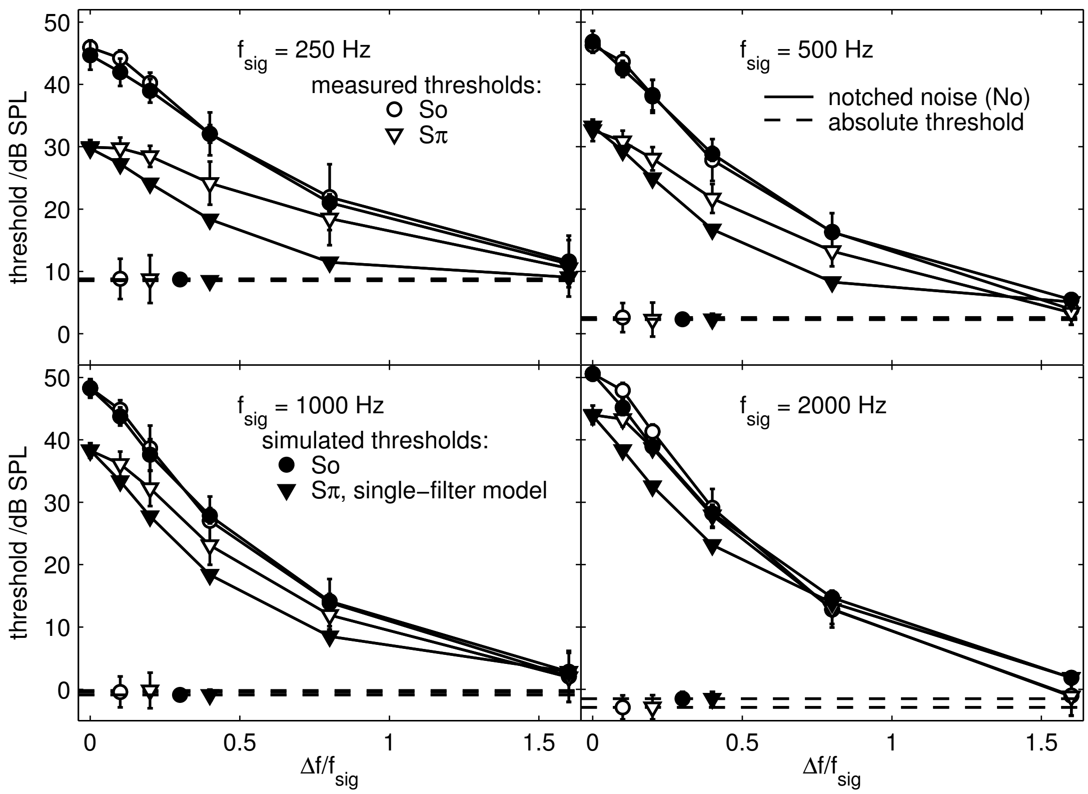

Figure 4.6.: Measured (open symbols, as in Fig. 4.1) and simulated (filled symbols) thresholds for a diotic (circles) or dichotic (Sπ, triangles) sinusoid. Thresholds as a function of notch width of a diotic noise masker and absolute thresholds are denoted by solid and dashed lines, respectively. The parameters of the gammatone filter were fitted to the diotic thresholds. The same filter parameters were used to predict the dichotic thresholds. Error bars of the simulated thresholds denote the standard deviations. They are only shown when they exceed the size of the symbols.

8, almost 7, and 4 dB, respectively (data not shown).

Among the first ideas to overcome the deficiencies of the binaural model part of the single-filter model (Fig. 4.6) is the simulation of a "natural" asymmetry in auditory filtering by determining filter parameters from left and right notched-noise experiments separately. Another idea is to test if more physiological non-linear auditory filtering (Lopez-Poveda and Meddis, 2001) yields dichotic threshold predictions in better correspondence with the measured thresholds. The results of these simulations are depicted in Figs. 4.7 and 4.8.

Fig. 4.7 shows individual diotic and dichotic thresholds for a 500-Hz sinusoid in notched noise for subject 2, 5, 6, and 7 (open symbols). Filled symbols denote simulated diotic thresholds (circles) and simulated dichotic thresholds using the filter parameters derived from the diotic thresholds (squares) and from the left and right monaural notched-noise thresholds (diamonds). The filter parameters used for the simulation are given in Tab. 4.5.

The shapes of the curve of simulated diotic thresholds are in reasonable agreement with the measured data. There might, however, be an offset to higher (subject 2) or lower (subject 5) thresholds since only the filter parameters, not the variance of the internal noise was fitted individually. Absolute thresholds were not fitted individually either. Since the four subjects of this experiment showed lower absolute thresholds at 500 Hz than the average of all eight subjects and the masked threshold for the relative notch width of 1.6 is largely determined by the absolute threshold, threshold predictions for this notch width are too high.

The simulated dichotic thresholds using the filter parameters derived from the diotic thresholds show the same trend for individual data as the upper right panel of Fig. 4.6 shows for average data: The correspondence between simulation and measurement is good for the notch width of zero and worsens with increase in notch width, since the model assumes a constant BMLD for dichotic thresholds above about 10 dB SPL.

A binaural model version with interaurally asymmetric auditory filter parameters fitted to monaural left and right notched-noise thresholds improves the correspondence with the measured dichotic thresholds. For subject 2 (upper left panel in Fig. 4.7) this model version yields threshold predictions in very good agreement with the measured thresholds except for the largest notch width. For subject 5 (upper right panel) interaurally asymmetic in contrast to symmetric auditory filtering results in an increase of simulated dichotic thresholds at intermediate notch

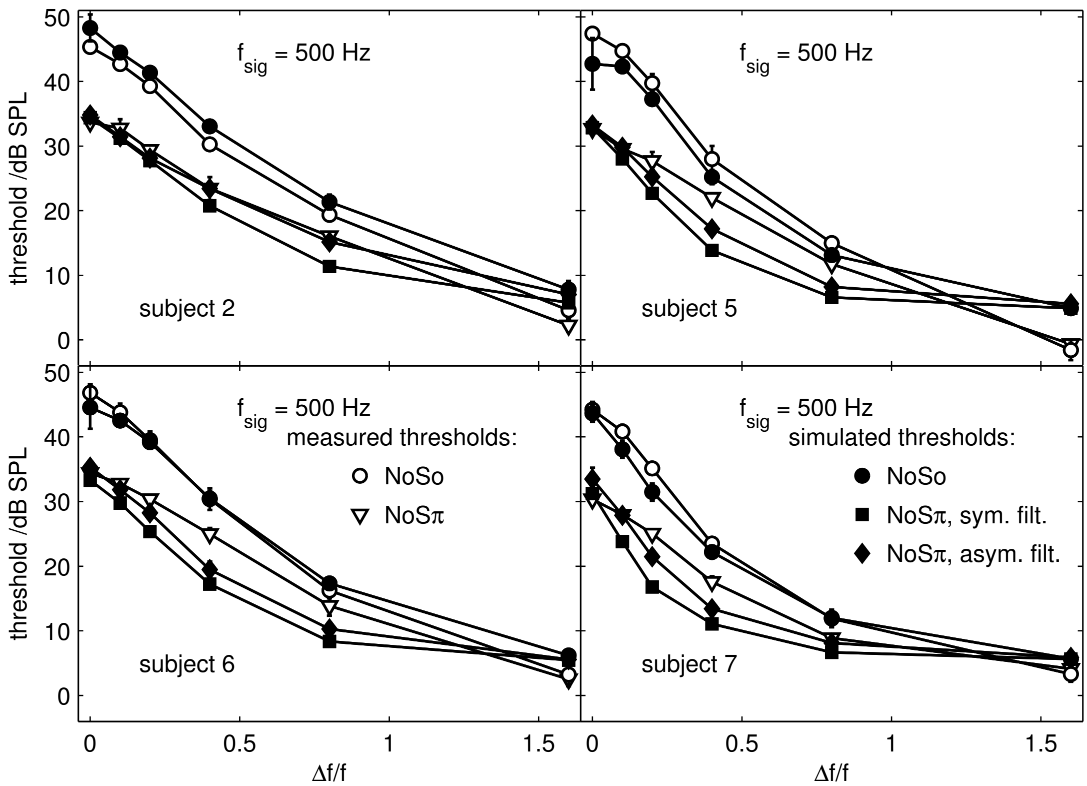

Figure 4.7.: Individual measured (open symbols) and simulated (filled symbols) thresholds for a diotic (circles) and dichotic (other symbols) 500-Hz sinusoid as a function of notch width. The individually fitted filter parameters are given in Tab. 4.5. Filled squares denote simulated dichotic thresholds using the filter parameters derived from the measured diotic thresholds. Filled diamonds denote simulated dichotic thresholds using the filter parameters obtained from the NlSl and NrSr thresholds for the processing of the left and right channel of the stimulus, respectively. Only the filter parameters were fitted to the individual threshold data. Error bars denote the standard deviations. They are only shown when they exceed the size of the symbols.

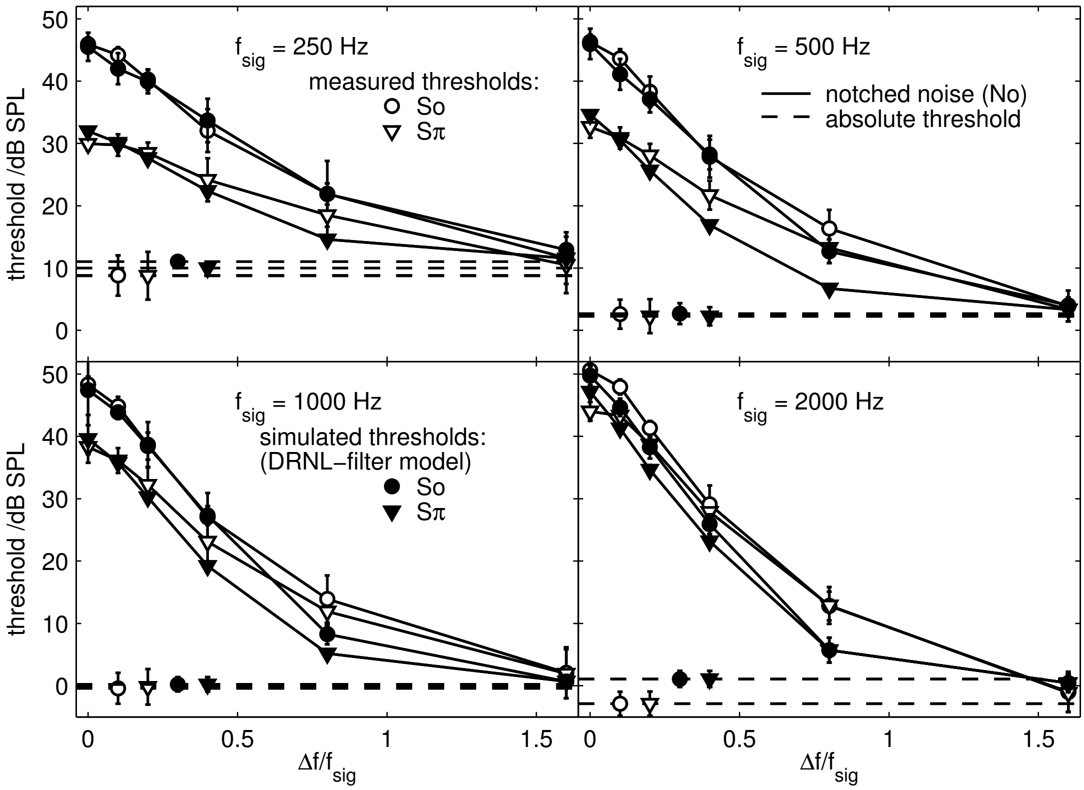

Figure 4.8.: Similar to Fig. 4.6, but non-linear filters were used for all threshold simulations *(DRNL-filter model)*. For details see text.

widths of up to 3 dB. This increase is not enough to yield a good correspondence between measured and simulated dichotic thresholds. For subject 6 (lower left panel) asymmetric filtering leads to an elevation of the curve of simulated dichotic thresholds of about 2 dB. For the relative notch width of 0.4 this is still more than 5 dB lower than the measured dichotic threshold. For subject 7 (lower right panel) also the whole curve of simulated dichotic thresholds is elevated using asymmetric filtering. The curves of simulated dichotic thresholds using asymmetric filtering do not correspond with the curve of measured thresholds for subjects 5, 6, and 7, even when neglecting the thresholds at the largest notch width.

Thus, though apparently explaining the dichotic thresholds of subject 2, in general interaurally asymmetric auditory filters are not the key to an understanding of binaural frequency selectivity. Another hint to this fact is that subject 5 does not show an interaural difference in filter parameters at all (see Tab. 4.5).

Fig. 4.8 shows the measured threshold data as in Fig. 4.1 (open symbols) and simulated thresholds (filled symbols) as predicted by the DRNL-filter model described above as a function of relative notch width. The dashed lines denote absolute thresholds.

DRNL-filter parameters and the level of the white noise added after auditory filtering were fitted to the diotic thresholds. The effect of the suppression inherent in the DRNL filters can be observed at the simulated thresholds for the relative notch width of 0.8: A high masker level below and above the signal frequency suppresses the masker at the signal frequency which leads to lower thresholds for the signal. The suppression effect increases with increasing signal frequency (Dubno and Ahlstrom, 2001).

Similar to the single-filter model using linear gammatone filters (Fig. 4.6) this model version also predicts a constant BMLD over most notch widths in contrast to the decreasing BMLD in the measured thresholds. For this reason merely non-linear filtering with the same parameters for diotic and dichotic threshold simulations cannot account for the measured threshold data.

Fig. 4.9 shows the measured threshold data as in Fig. 4.1 (open symbols) and simulated thresholds (filled symbols) as predicted by the seven-filter model described above as a function of relative notch width. The dashed lines denote absolute thresholds. The simulated diotic thresholds are the same as in Fig. 4.6 since the changes in the model concern only the binaural part.

Simulated absolute thresholds are in good agreement with the measured thresholds. In fact, except for the 250-Hz threshold, absolute thresholds are the same as in the single-filter model (Fig. 4.6) since the detector chooses the lower of the diotic and the dichotic threshold and the addition of adjacent filters in the binaural model part leads to increased dichotic thresholds.

Generally, the addition of adjacent filters in the seven-filter model improved the correspondence between measured and simulated dichotic thresholds compared to the single-filter model. Yet predicted dichotic thresholds are still lower than measured for intermediate notch widths: The largest difference occurs for the relative notch width of 0.2: Simulated dichotic thresholds are about 3, less than 2, 3, and 5 dB below the measured thresholds at the signal frequencies of 250, 500, 1000, and 2000 Hz, respectively. The curve of simulated 250-Hz thresholds is below the measured threshold curves for most notch widths, whereas there is a better agreement for the signal frequencies of 500 and 1000 Hz. For small notch widths, all curves of simulated dichotic thresholds show a steeper slope than measured.

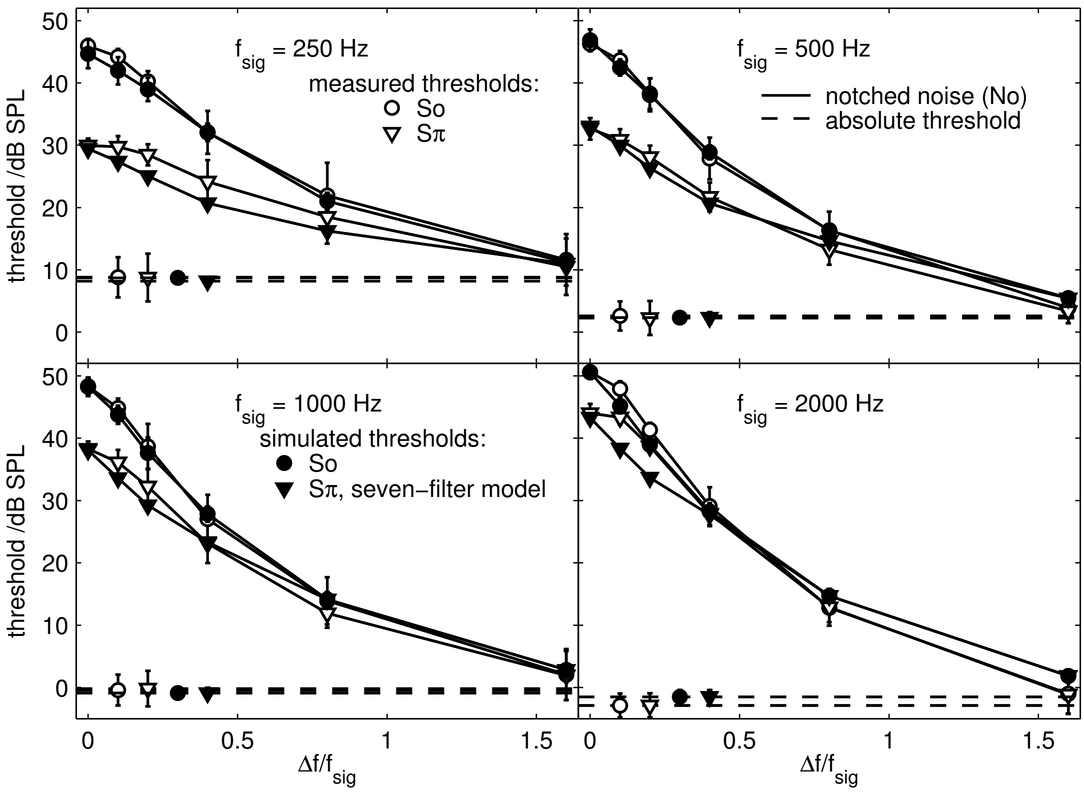

Figure 4.9.: Similar to Fig. 4.6, but the dichotic thresholds were predicted using an effectively wider auditory filter obtained by weighted addition of seven filters *(seven-filter model)*. For details see text.

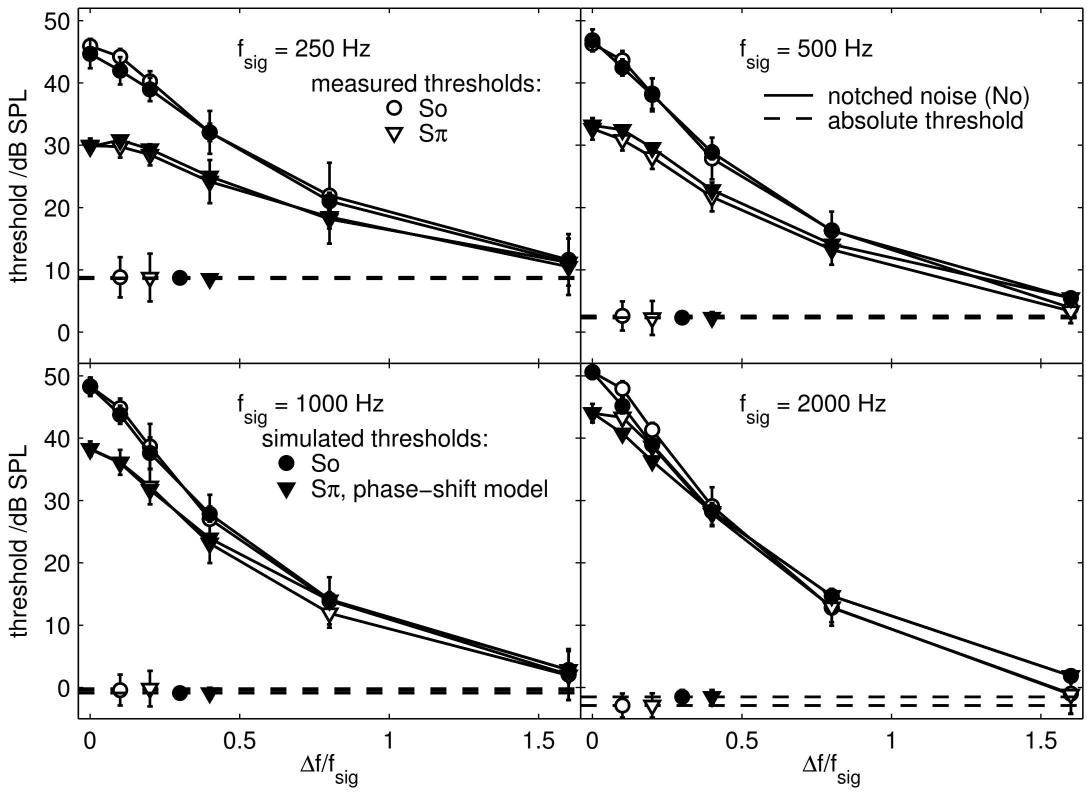

Figure 4.10.: Similar to Fig. 4.6, but the EC process was hampered by an interaural phase shift depending only on the relative notch width *(phase-shift model)*. For details see Fig. 4.5 and text.

Fig. 4.10 shows the measured threshold data as in Fig. 4.1 (open symbols) and simulated thresholds (filled symbols) as predicted by the phase-shift model described above as a function of relative notch width. The dashed lines denote absolute thresholds. The simulated diotic thresholds are the same as in Fig. 4.6 since the changes in the model concern only the binaural part.

This model version leads to predicted dichotic thresholds that agree very well with the measured thresholds: Except for the 2-kHz signal frequency, simulated thresholds are hardly below the measured thresholds; the largest difference is 2 dB at the signal frequency of 1 kHz and a relative notch width of 0.8. For the 2-kHz signal frequency, the size of the BMLD is predicted to an accuracy of 1 dB though dichotic (and diotic) thresholds are 2–3 dB lower than measured for relative notch widths of 0.1 and 0.2.

This model version is an implementation of the idea that there is a continuum from a large BMLD in a broadband masker without notch to a negligible BMLD for tones without masker. It starts with the large BMLD in broadband and hampers EC processing more and more with increasing relative notch width (Fig. 4.5), i.e., with the relative spectral distance between signal and the nearest edge of the noise masker. The phase-shift model yields the best results in the detection experiment, it is unclear, however, how it might be realized physiologically.

4.4.3. Discrimination experiment

In all four panels, Fig. 4.11 shows the mean jnIPDs (open symbols) as in Fig. 4.3 together with predicted jnIPDs by the single-filter model (upper left panel), DRNL-filter model (upper right panel), seven-filter model (lower left panel), and phase-shift model (lower right panel) as a function of relative notch width. Like in the measurement process (see Sec. 4.2.2) the simulation run stopped if a wrong interval was chosen three times successively at the maximum IPD of π. This constraint results in no valid threshold estimates at all for the largest notch width in the DRNL-filter model and the phase-shift model.

The single-filter model and the DRNL-filter model underestimate the effect of notch width on the jnIPD; they show a shallower increase in simulated jnIPDs than measured. The threshold curves predicted by the seven-filter model and by the phase-shift model show a better correspondence to the curve of measured thresholds; the phase-shift model, however, predicts jnIPDs that are between 1.2 (no notch) and about twice (relative notch width 0.2) as large as measured. The

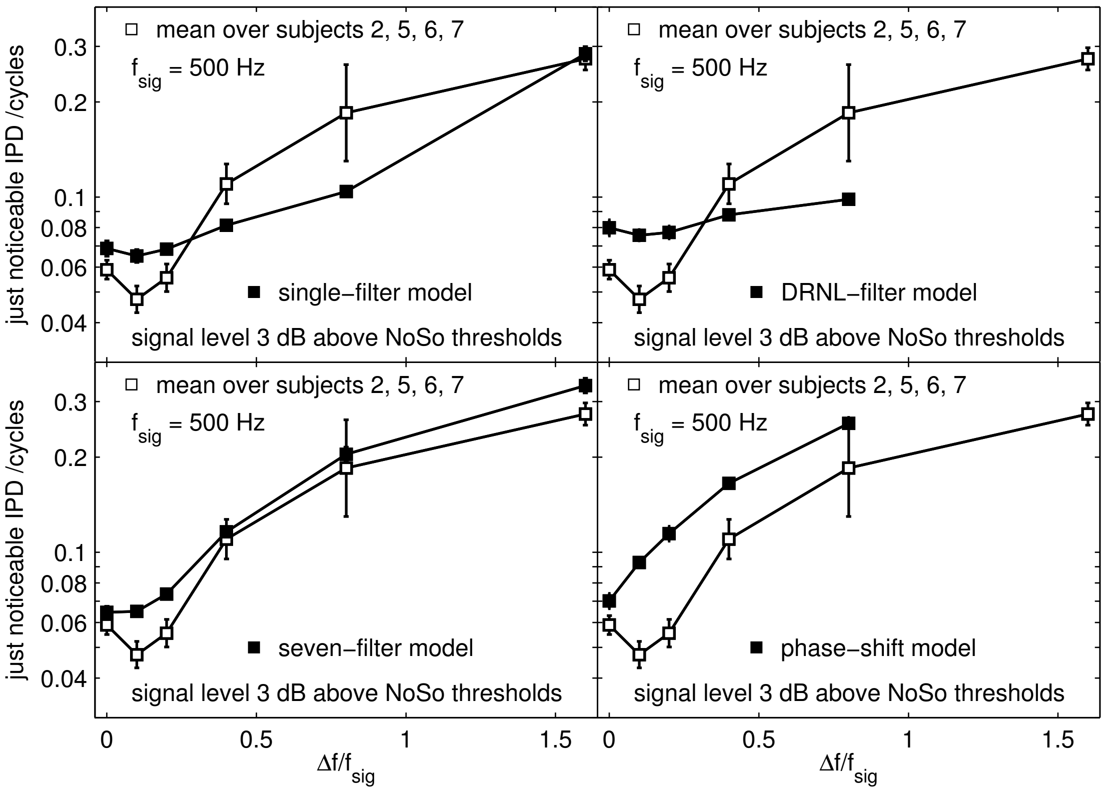

Figure 4.11.: Measured (open squares as in Fig. 4.3) and simulated (filled squares) just-noticeable IPDs for a 500-Hz sinusoid as a function of relative notch width. The panels show thresholds predicted by the four model versions used for the predictions shown in Figs. 4.6 (upper left), 4.8 (upper right), 4.9 (lower left), and 4.10 (lower right).

seven-filter model yields the simulation results in best agreement with the measured jnIPD.

As discussed in Sec. 4.3.2 for the measured thresholds, also the simulation results might reflect detectability rather than discrimination: For the signal frequency of 500 Hz used in the discrimination experiment, the single-filter model (Fig. 4.6) and the DRNL-filter model (Fig. 4.8) simulations show lower dichotic thresholds than measured particularly at the intermediate relative notch widths of 0.4 and 0.8. At these notch widths lower jnIPDs than measured are predicted by these two model versions. There is good agreement between measured and predicted detection (Fig. 4.9, upper right panel) and discrimination thresholds for the seven-filter model. The 500-Hz dichotic detection thresholds predicted by the phase-shift model (Fig. 4.10) slightly exceed the measured thresholds for all notch widths. The largest deviation occurs at the relative notch widths of 0.1 and 0.2, and just at these notch widths the deviation of the predicted jnIPD from the measured jnIPD is largest.

4.5. General discussion

The aim of the present study is to highlight differences in monaural and binaural auditory filter bandwidth after the huge difference observed in the bandwidening experiment has been largely explained by van de Par and Kohlrausch (1999) as an across-channel effect.

The decrease of BMLD with increasing notch width (Fig. 4.1) is not merely an effect of noise masker level since the BMLD is constant over a large range of masker levels if the masker does not contain a notch at the signal frequency (Hall and Harvey, 1984; Nitschmann *et al.*, 2009). This can also be observed in hearing-impaired subjects (Nitschmann *et al.*, 2010).

Consequently, effective models of binaural perception (Zerbs, 2000; Breebaart *et al.*, 2001a) that were designed to predict NoSπ thresholds in a broadband masker without notch fail to predict diotic *and* dichotic thresholds in a notched-noise masker when using the same auditory filter parameters for both conditions (Zerbs, 2000). They predict rather a constant BMLD as observed in a broadband masker without notch (see also Fig. 4.6). Breebaart *et al.* (2001b) might not have noticed that because they do not show diotic threshold data for the notched-noise experiment.

Interaural asymmetry of auditory filters as a key to understand the huge difference observed in the bandwidening experiment was investigated by Staffel *et al.* (1990). They conclude that their data measured for a signal frequency of 500 Hz do not support a strong association between monaural critical band asymmetry and the width of the NoSπ critical band. The difference in auditory filter bandwidth observed in the notched-noise experiment is smaller, but yet cannot be explained by individual interaural differences in auditory filters.

Predicted dichotic detection thresholds in reasonable agreement with the measured threshold data were obtained using the seven-filter model (Fig. 4.9) or the phase-shift model (Fig. 4.10), both featuring a processing stage that hampers binaural detection by adding portions of the output of adjacent filters to the output of the on-frequency filter or by applying a phase shift to the right preprocessed channel, respectively. Due to the low weighting (0.05) of the six filters adjacent to the on-frequency filter, the ERB of the combined "binaural" auditory filter of the seven-filter model is only 1.2 times the value of the monaural filter. Of course, a different monaural and binaural frequency selectivity is not a feature of the auditory filtering on the basilar membrane, but a retrocochlear process. The seven-filter model and the phase-shift model offer an early (immediately after the half-wave rectification and low-pass filtering, i.e. the haircell stage) and a late (immediately before the EC processing) way of hampering binaural auditory processing, respectively. However, both are effective processing models and do not aim at exactly describing physiology. The seven-filter model can be regarded as a possible realization of the detrimental across-channel process hypothesized by Hall *et al.* (1983).

Within the present study, all spectral notches were arithmetically centered at the signal frequency. Glasberg and Moore (1990) point out that even from symmetric notched-noise data it is possible to derive asymmetric filter estimates taking into account the filtering of the outer and middle ear and allowing for off-frequency listening by shifting the center frequency of the filter. However, Glasberg and Moore (1990) recommend against trying to derive the asymmetry of the auditory filter from symmetric notched-noise data. Since the aim of the present study was to highlight the differences in principle between filter width estimates derived from diotic and dichotic notched-noise threshold data, no effort was made to assess auditory filter asymmetry. The asymmetry and level dependence of the "binaural" auditory filters measured in a notched-noise experiment in NoSπ condition might be of future interest similar as it was for the diotic notched-noise experiment.

4.6. Summary

- In a diotic and symmetric notched-noise masker, the BMLD decreases gradually as a function of notch width.
- Model simulations with a linear auditory filter fitted to the diotic threshold data indicate that the dichotic thresholds cannot be predicted by a model that only processes the information within the filter centered at the signal frequency.
- Neither the extension of the model by incorporating suppression nor by accounting for individual interaural differences in filter shape can reconcile the model predictions with the experimental data.
- Simulations with a model assuming a detrimental across-channel process show, in general, a good agreement between the measured and predicted BMLD.
- The extended model also predicts the reduction in accuracy in detecting an interaural phase difference of a 500-Hz signal as the notch width increases.
- The difference between monaural and binaural auditory filter bandwidth derived by fitting gammatone filters to the diotic and dichotic threshold curves increases with decrease in signal frequency.

Acknowledgments

Advise and help of Helge Lüddemann and Helmut Riedel concerning the discrimination experiment and Stephan Ernst and Stefan Klockgether concerning the DRNL filters are gratefully acknowledged. This study was supported by the Deutsche Forschungsgemeinschaft (DFG GRK 591/3 and SFB tr31), the HearCom project, and the Audiologie-Initiative Niedersachsen.

5. Monaural and binaural frequency selectivity in hearing-impaired subjects [1]

Abstract

Sensorineurally hearing-impaired (HI) subjects often report difficulties in complex acoustical environments. To investigate whether these problems arise from specific deficits in the frequency selectivity in binaural listening conditions, thresholds were measured for a 500-Hz sinusoid in phase (So) or antiphase (Sπ) masked by a diotic notched noise (No). The equivalent rectangular bandwidth (ERB) for filters derived from diotic (NoSo) and dichotic (NoSπ) threshold curves is larger for the HI subjects than for the normal-hearing (NH) subjects. However, the ratio of binaural to monaural ERB is the same. The data indicate that there is no additional retrocochlear impairment reducing the binaural frequency selectivity of HI subjects. A specific binaural impairment was also tested by measuring the perception of binaural pitch (Huggins' pitch). Two out of eight HI subjects failed to perceive this pitch, although in the masking experiment they obtained a binaural masking-level difference of up to 10 dB. The current data therefore provide no clear evidence for a specific binaural impairment factor in hearing impairment that deteriorates several aspects of binaural processing in a similar way.

[1] Parts of this study have been presented at the "35. Erlanger Kolloquium" in Erlangen, Germany (Nitschmann, 2008a), at the "11. Jahrestagung der Deutschen Gesellschaft für Audiologie" in Kiel, Germany (Nitschmann *et al.*, 2008b), and at the joint ASA-EAA conference in Paris, France (Nitschmann *et al.*, 2008c). Reprinted with permission from Nitschmann *et al.* (2010). Copyright 2010, International Journal of Audiology.

5.1. Introduction

Hearing-impaired (HI) people often have difficulties in complex listening situations (Bronkhorst and Plomp, 1992; Peissig and Kollmeier, 1997). One reason for this might be that HI subjects often show a reduced frequency selectivity (e.g., Glasberg and Moore, 1986; Peters and Moore, 1992; Leek and Summers, 1993) compared to normal-hearing (NH) subjects. However, in HI subjects the binaural processing may also be affected by the hearing impairment: HI subjects show a high variability in specific binaural tasks and a general decrease of binaural abilities with increasing hearing loss (Holube, 1993; Wagener, 2003). Also recent data on discrimination and melody recognition of binaural-pitch stimuli (Santurette and Dau, 2007) indicate a binaural deficit in HI subjects.

Santurette and Dau (2007) found a reduced ability of HI subjects to perform this task which seemed to be related to a reduced frequency selectivity. However, the correlation between the performance in the melody recognition task and the frequency selectivity of the HI subjects was not significant. This weak correlation might result from the fact that Santurette and Dau (2007) measured the monaural frequency selectivity. In a recent study, Nitschmann *et al.* (2009) showed that the filter widths derived from data for signals with interaural disparities (dichotic condition) are usually larger than those derived from listening conditions where the same stimuli were presented to both ears (diotic condition). [2] Hence the question of the present study is if a specific binaural impairment factor exists in the sense that the binaural frequency selectivity is reduced in HI listeners. Such a specific binaural impairment factor may then also account for the reduced ability of some HI subjects to perform the melody recognition task used in Santurette and Dau (2007).

In order to test this hypothesis, the subjects' ability to perceive Huggins' pitch (Cramer and Huggins, 1958) is tested in the frequency region around 500Hz. In addition, the monaural and binaural frequency selectivity is measured at the same frequency for HI subjects and compared to the results for NH subjects using the same experimental paradigm. This comparison is performed at the same masker level as used for the NH subjects (Nitschmann *et al.*, 2009) and at the same

[2] The frequency selectivity derived from diotic thresholds is very similar to that derived from monaural thresholds since in a diotic presentation no information can be gained from comparing the stimuli to both ears. Hence, for frequency selectivity derived from diotic thresholds the term "monaural" will be used. Frequency selectivity derived from dichotic thresholds will be called "binaural".

loudness.

The present study uses the notched-noise experiment, a common paradigm in psychoacoustics to assess frequency selectivity. In a notched-noise experiment thresholds for a sinusoidal signal are measured in the presence of a noise masker that contains a spectral notch around the signal frequency (de Boer and Bos, 1962; Patterson, 1976).

In order to determine the monaural and binaural frequency selectivity, thresholds are measured with a diotic masker (No) and a sinusoidal signal which was presented either diotically (So) or with an interaural phase difference of π (Sπ, dichotic condition). A similar paradigm was already used in Hall *et al.* (1983) to determine the monaural and binaural frequency selectivity in NH subjects. Hall *et al.* (1983) argued that thresholds for the dichotic notched-noise experiment might be influenced by the level dependence of the binaural masking-level difference (BMLD), i.e. the threshold difference between the diotic and dichotic condition. Thus, in addition to the notched-noise experiment the level dependence of the BMLD is measured for each subject. As a masker a broadband noise is used; this experiment will be referred to as the broadband masking experiment in the following. The use of a broadband noise masker is due to a hypothesis by van de Par and Kohlrausch (1999) who argued that in all broadband masking conditions (including notched-noise masking) the same detection strategy is used.

5.2. Methods

5.2.1. Apparatus

Subjects were seated in a double-walled, sound-insulated booth. Stimuli were generated digitally at a sampling rate of 44.1 kHz. A standard personal computer controlled stimulus generation and presentation and recorded results using a software package developed at the University of Oldenburg. Stimuli were D/A converted (RME ADI-8 DS, 32 bits), amplified (Tucker-Davis HB7), and presented via Sennheiser HD 580 headphones.

5.2.2. Procedure and stimuli

Masking experiments

For the masking experiments, a three-interval forced-choice procedure with adaptive signal-level adjustment was used to determine masked thresholds. Each trial was 2,9 s long. The masker was presented for the whole duration of the trial. Temporally centered in the masker, there were three intervals of 300-ms duration separated by 300-ms pauses. Thus the masker was switched on 700 ms before the first interval and switched off 700 ms after the third interval including two 50-ms raised-cosine ramps at on- and offset. The intervals were indicated on the screen in front of the subject. One randomly chosen interval contained the signal. The signal was an So or $S\pi$ sinusoid of 500 Hz. It had a duration of 300 ms including 50 ms raised-cosine ramps at on- and offset. The task of the subject was to indicate this signal interval after each trial. Responses were given by pressing the corresponding button (1, 2, or 3) on a computer keyboard. Trial-by-trial feedback was provided. Signal level was adjusted according to a one-up two-down rule tracking the 70.7% correct response level (Levitt, 1971). The initial step size of the signal level was 8 dB. The step size was halved after each second reversal of the level-adjustment procedure until a step size of 1 dB was reached. With this minimum step size of 1 dB the run continued for another six reversals. The mean over these last six reversals was used as a threshold estimate.

The same noise masker was presented to both ears (diotic presentation). The maskers were generated in the frequency domain using a 2^{17}-point (0.34-Hz resolution) buffer. Their spectrum had a constant nonzero amplitude in the passband regions and a random phase. The lower frequency limit was always set to 30 Hz, the higher to 1 kHz. The noise maskers were transformed to the time domain (inverse FFT) and restricted to the desired length of 127890 samples (2.9s).

For the notched-noise experiment, the notch width was either 0, 50, 200, 400, or 600 Hz. The notch was arithmetically centered at the signal frequency. Stimuli and procedure were similar to those used by Hall *et al.* (1983). The masker spectrum level was 50dB/Hz. Nitschmann *et al.* (2009) measured thresholds for NH subjects for this spectrum level.

For the broadband masking experiment, a bandpass-noise masker with no notch was used. In general, the masker spectrum level was 10, 20, 30, 40, or 50 dB/Hz. For the highest spectrum level, the experimental condition was the same as in the notched-noise masking experiment with a notch width of 0 Hz. Thus, to reduce measuring time, the threshold for this spectrum level was taken from the notched-noise experiment.

For five HI subjects (1, 2, 4, 6, and 8), these two masking experiments were also performed with a spectrum level that was adjusted to elicit the same loudness as for the NH subjects. For this purpose, loudness functions of third-octave bands geometrically centered at 125, 250, 500, and 1000Hz were estimated for each HI subject using the method of adaptive categorical loudness scaling (ACALOS, Brand and Hohmann, 2002). From the loudness functions the spectrum level was estimated which produces the same specific loudness at these frequencies as for NH subjects. For intermediate frequencies, the spectrum levels were interpolated from the values for the measured frequencies. Due to the differences in the individual loudness functions the resulting spectrum level was an individually different function of frequency. A similar procedure was used in Verhey *et al.* (2006) to ensure the audibility of all frequency components in an experiment on spectral loudness summation in HI subjects. In the following, the experiments using the same spectrum level as in the NH study will be referred to as the equal-masker-level condition, while those measured at the same specific loudness will be referred to as equal-masker-loudness condition. Note that the same specific loudness does not necessarily imply the same overall loudness since spectral loudness summation is usually smaller for HI than for NH subjects (e.g., Verhey *et al.*, 2006).

Runs with diotic and dichotic stimulus conditions were mixed in the notched-noise and broadband masking experiments. At least three threshold estimates were obtained and averaged for each parameter value and subject. [3] In addition to the masked thresholds, the threshold in quiet was measured for a diotic 500-Hz sinusoid using the same forced-choice procedure as for the masking experiments.

Three criteria had to be fulfilled for a threshold measurement in order to be considered as valid: (i) The standard deviation of each single threshold estimate calculated from six turning points had to be below 3 dB. If the standard deviation of a single threshold estimate was above 3 dB, it was discarded and remeasured. This applied to a total of three thresholds of the notched-noise experiment. (ii) If the second threshold estimate in a certain masking condition was more than 2 dB below the first and the third was lower than the second or not more than 20% of

[3] Subject 2 did not finish the experiments for the equal-masker-loudness condition. Since the intraindividual standard deviations of the obtained thresholds are small, the thresholds are nevertheless shown here.

the difference of first minus second higher than the second threshold estimate, this was regarded as a learning effect. In this case the thresholds were remeasured and the first threshold estimates were discarded. This applied to two diotic thresholds of the broadband masking experiment. (iii) In total, three threshold estimates were obtained and averaged for each parameter value and subject. The standard deviation of the mean over these threshold estimates had to be below 3 dB. If it was above 3 dB, more threshold estimates for the respective parameter values were obtained and the previous ones discarded. This did not occur in the experiments of the present study.

Pitch experiment

The ability of the subject to perceive Huggins' pitch (Cramer and Huggins, 1958) was tested in a way similar to Santurette and Dau (2007): Ten noise intervals, each of 1 s duration including two 50-ms raised-cosine ramps at on- and offset, were presented to the subject at a level of 80 dB SPL. The noise was generated in the frequency domain as described for the masking experiment. In contrast to the masking experiment, a 2^{16}-point buffer was used because of the shorter stimulus duration. The noise was broadband (30 to 1000 Hz) with random phases.

Noise intervals 1 and 10 contained diotic noise. Noise intervals 2 to 9 contained a major scale in Huggins' pitch. Huggins' pitch was introduced by a linear transition of the interaural phase difference from 0 to 2π in a narrow frequency band. The width of the Huggins-pitch band was 16% of its center frequency. Culling *et al.* (1998) showed that an interaural-phase transition bandwidth of this size ensures a good perceptibility of the Huggins' pitch. The major scale was in twelve-tone equal temperament and geometrically centered at 500 Hz, i.e., the center frequency of the lowest and highest Huggins' pitch were 353.6 and 707.1 Hz, respectively.

Subjects who did not report the percept of a scale or something increasing in pitch after two presentations of the Huggins-pitch scale were given a forced-choice task with two stimuli of different Huggins-pitch center frequency. In this forced-choice task, the center frequencies of the bands with an interaural phase difference other than 0 or 2π were fixed at 594.6 and 420.4 Hz, i.e., a frequency ratio of $\sqrt{2}$:1, geometrically centered at 500Hz. If Huggins' pitch is perceived, this difference should be clearly audible since the pitch of these two center frequencies is in a frequency region where most HI subjects participating in the study by Santurette and Dau (2007) showed a good frequency discrimination. The spectrum level of

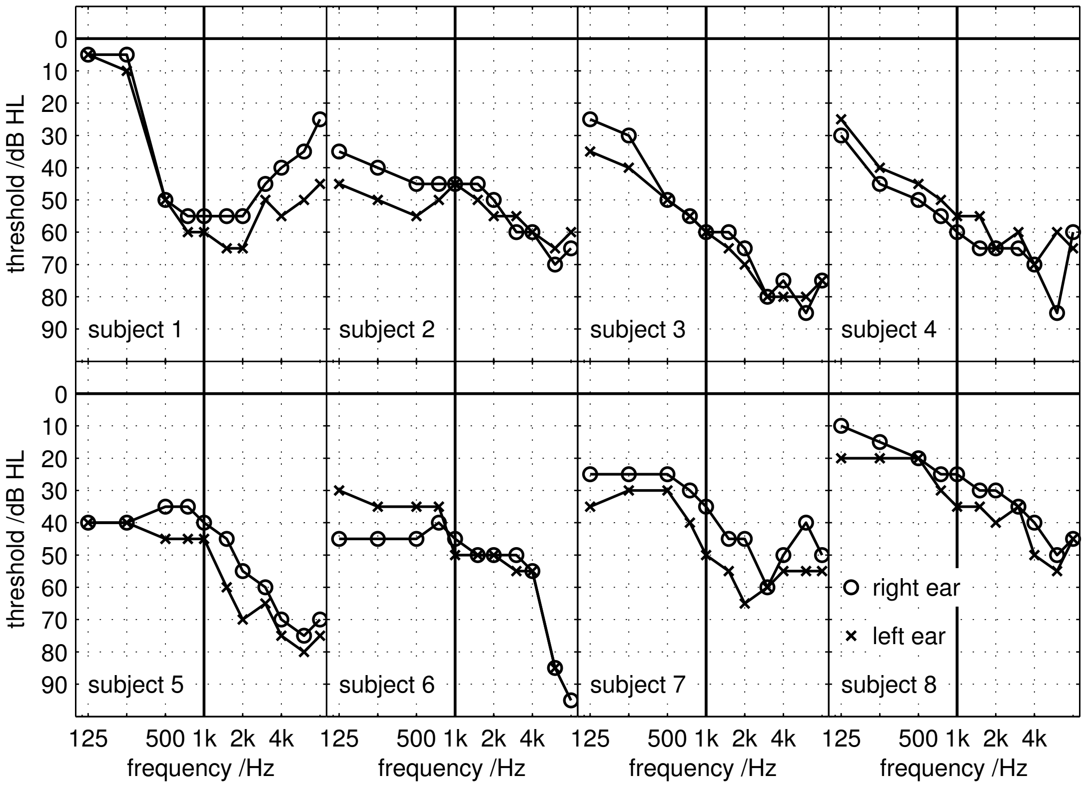

Figure 5.1.: Audiograms for the left (crosses) and right (circles) ears of the eight HI subjects who participated in the study. The audiograms are arranged according to decreasing threshold at 500 Hz measured diotically in a forced-choice procedure.

the noise was 50 dB/Hz. The Huggins-pitch stimuli were presented in a three-interval forced-choice procedure. Each stimulus interval had a duration of 600 ms including two 50-ms raised-cosine ramps at on- and offset. The intervals were separated by 300-ms silence intervals. One randomly chosen stimulus interval contained the Huggins-pitch stimulus with the lower pitch, the other two intervals contained the stimulus with the higher pitch. The subject's task was to indicate the interval with the lower pitch. A run consisted of 21 trials. The number of correct responses was counted. The measurement was stopped if there was a run without a wrong answer or, if no improvement over runs could be observed, after three runs.

5.2.3. Subjects

Eight HI subjects [4] (6 female, 2 male, aged 22–81 years, mean 58 years) participated in the experiments. They were all paid volunteers. All subjects had participated in various other listening experiments at the University of Oldenburg before. The experiments were approved by the University of Oldenburg Research Ethics Committee.

Fig. 5.1 shows the audiograms of the eight subjects. The audiograms are arranged according to decreasing threshold at 500 Hz measured in a forced-choice procedure. In the masking experiments the highest noise masker frequency was 1 kHz. For this reason absolute thresholds for frequencies below 1 kHz are most important for the present study. Since stimuli were always presented to both ears, the interaural difference in thresholds in the frequency region up to 1 kHz had to be small. At 500 Hz three of the subjects show no interaural difference in thresholds, two subjects show a difference of 5, and three show a difference of 10 dB. [5]

All but one (subject 6) had a pure sensorineural hearing loss. Subject 6 had partly artificial ossicles in both ears (stapedectomy) after treatment of otosclerosis. At 500 Hz, the air-bone gap amounted to 0 and 10 dB for the left and right ear, respectively. It was similar for the other frequencies within the spectral range used in the experiments of the present study for the right ear. For the left ear, it increased up to 15 dB at 1 kHz. In general, the subjects use hearing aids bilaterally. Subject 3 uses only one hearing aid in the right ear. Hearing aids were not used during the experiments.

[4] The results of two additional subjects had to be discarded due to the following reasons: One subject did not have the time to finish the experiments, the other subject did not produce reliable thresholds, probably due to medication. Using the criteria described at the end of Sec. 5.2.2, at least 70% of the mean thresholds of every experiment for this subject had to be discarded. A remeasurement of the notched-noise experiment did not improve the results.

[5] McFadden (1968) showed that a difference of 10 dB in masker spectrum level hardly changes the BMLD. That this can also be assumed to apply to interaural differences due to a hearing loss is supported by Humes *et al.* (1988) who modeled hearing loss by noise.

5.3. Results

5.3.1. Masking experiments

Notched-noise experiment

Fig. 5.2 shows the NoSo (circles) and NoSπ (triangles) thresholds for a 500-Hz sinusoid as a function of notch width. Thresholds for the equal-masker-level and equal-masker-loudness condition are denoted by black solid and dashed lines, respectively. For comparison, thresholds averaged over the individual data from eight NH subjects (Nitschmann *et al.*, 2009) are shown with gray symbols connected with gray lines. In addition to the masked thresholds, the individual absolute thresholds are shown (dotted lines), which were measured with the same procedure as used in the masking experiments. Error bars denote intraindividual standard deviations from the mean for the HI subjects and interindividual standard deviations for the NH threshold data. Standard deviations are only shown when they exceed the size of the symbols.

In general, thresholds for the diotic as well as for the dichotic signal decrease with increasing notch width. The slope of decrease is shallower for HI than for NH subjects. Thus the difference between corresponding thresholds of HI and NH subjects increases with notch width.

For the diotic signal and a masker without a notch, thresholds measured in the equal-masker-level condition (solid black lines) range from 69 to 73 dB SPL. They show a small intersubject variability and their mean is about 2 dB above the corresponding average diotic threshold for the NH subjects. In the corresponding dichotic condition, individual differences of thresholds are larger than for the diotic condition. At a notch width of 0 Hz, individual dichotic thresholds range from 55 to 68 dB SPL and the BMLDs range from 5 dB (subject 2) to 14 dB (subjects 6 and 8). In general, at the same masker level, HI subjects tend to have smaller BMLDs than NH subjects. As for NH subjects, the BMLD decreases with increasing notch width until it is below the size of the corresponding standard deviations for all subjects. The decrease of BMLD with increasing notch width depends on the subject. For example, at a notch width of 200 Hz, subjects 2, 3, 4, and 7 show a BMLD of more than 50% of their maximum BMLD while subjects 5 and 6 show a relative BMLD of less than 30% and 40%, respectively. At the notch width of 400 Hz only subject 7 shows a BMLD that is more than twice the size of the

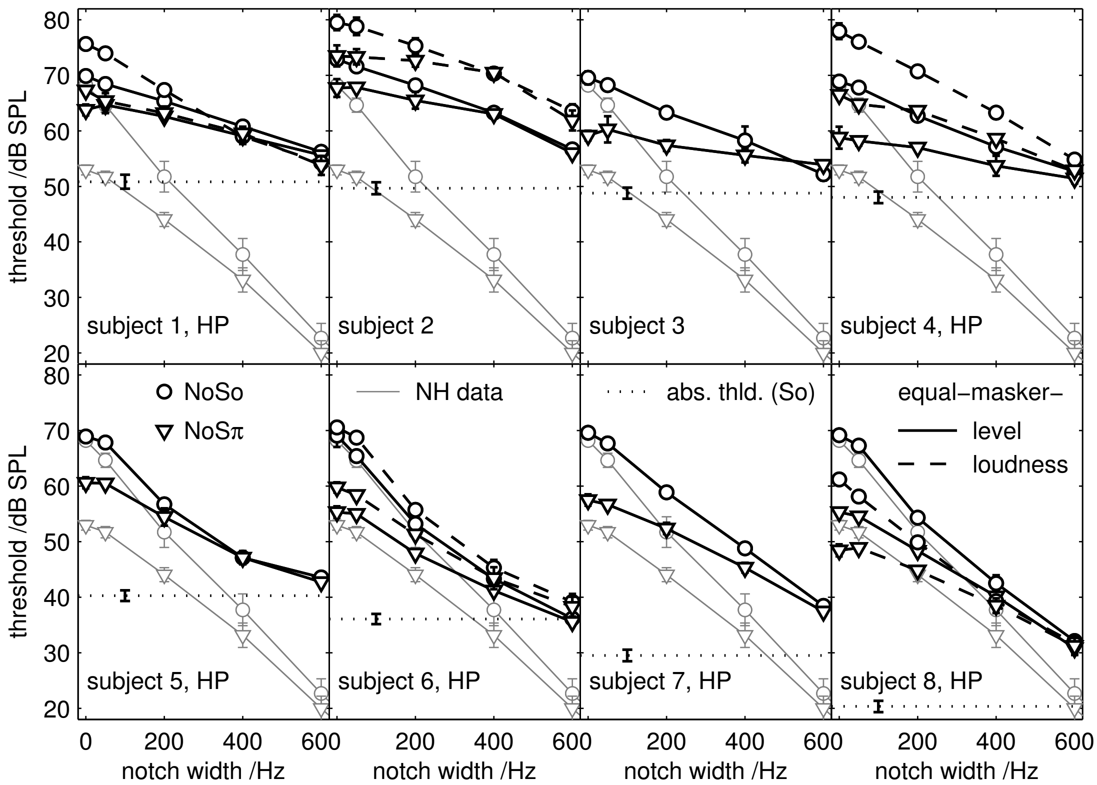

Figure 5.2.: Masked NoSo (circles) and NoSπ (triangles) detection thresholds for a 500-Hz sinusoid as a function of notch width. Black solid and dashed lines denote the thresholds measured in the equal-masker-level and equal-masker-loudness condition, respectively. The black dotted line denotes the absolute threshold of the subject. The thresholds plotted in gray are thresholds averaged over eight NH subjects in the same experiment. The abbreviation HP in a panel indicates that this HI subject is able to perceive Huggins' pitch. Error bars indicate intraindividual and interindividual standard deviations for the thresholds of the HI and NH subjects, respectively.

corresponding standard deviations. For all subjects, the BMLD diminishes for the largest notch width of 600 Hz. The diotic threshold at the largest notch width of 600 Hz is 0 (subject 6) to 12 dB (subject 8) higher than absolute threshold.

In the equal-masker-loudness condition, threshold curves (dashed lines) are similar in shape to those in the equal-masker-level conditon (solid black lines). However, they show a large intersubject variability in the position of the threshold curves. Four of the five threshold curves of the equal-masker-loudness condition are shifted to higher values while one subject (subject 8) showed lower thresholds.

Auditory filter shape

For an estimate of filter characteristics, different definitions of the bandwidth and assumptions of the filter shape were used. On the one hand, bandwidth is estimated directly from the data by a linear fit to the thresholds in dB. This is the 3-dB down notch width $n_{3\mathrm{dB}}$, i.e. the notch width where thresholds have declined by 3 dB compared to the masker without a notch. The 3-dB down notch widths are shown in the second and third row of Tabs. 5.1 and 5.2. The 3-dB down notch width was also used by Hall *et al.* (1983) to analyze their threshold data. On the other hand, filters are characterized on the basis of a commonly used filter shape, a linear fourth-order gammatone filter (Patterson *et al.*, 1995; Irino and Patterson, 2001; Patterson *et al.*, 2003). The bandwidths of the filters were determined using a power-spectrum model. They are given in the fifth and sixth row of Tabs. 5.1 and 5.2. The attenuation characteristics of the gammatone filters (implementation by Hohmann, 2002) are shown in Fig. 5.4.

Tabs. 5.1 and 5.2 show the filter parameters for the equal-masker-level and equal-masker-loudness condition, respectively. In addition to the filter-width estimates, the ratios r of binaural and monaural filter-width estimates are given.

For the HI subjects, monaural 3-dB down notch widths range from 40 to 126 Hz in the equal-masker-level condition and from 48 to 150 Hz in the equal-masker-loudness condition. For the same subjects, binaural 3-dB down notch widths range from 104 to 274 Hz in the equal-masker-level condition and from 84 to almost 400 Hz in the equal-masker-loudness condition. The ratio $r(n_{3\mathrm{dB}})$ of binaural divided by monaural 3-dB down notch widths is between 1.6 and 2.6 (average 2.1) in the equal-masker-level condition and between 1.3 and 3.3 (average 2.3) in the equal-masker-loudness condition. The standard deviation of the latter average is 0.8 and about double the size as that of the former.

Subject	1	2	3	4	5	6	7	8	NH
$n_{3\mathrm{dB}}$(NoSo) /Hz	126	126	101	106	76	40	68	63	42
$n_{3\mathrm{dB}}$(NoSπ) /Hz	253	253	210	274	122	106	126	104	84
$r(n_{3\mathrm{dB}})$	2.0	2.0	2.1	2.6	1.6	2.6	1.8	1.7	2.0
ERB(NoSo) /Hz	326	285	260	271	162	130	141	108	82
ERB(NoSπ) /Hz	441	356	671	485	237	231	231	186	125
r(ERB)	1.3	1.3	2.6	1.8	1.5	1.8	1.6	1.7	1.5
Huggins' pitch	+	−	−	+	+	+	+	+	+

Table 5.1.: Auditory filter parameters fitted to the notched-noise data of the HI subjects. The table contains parameters derived from threshold data of the equal-masker-level condition. $n_{3\mathrm{dB}}$ is the notch width where the diotic or dichotic threshold has decreased by 3 dB relative to the notch width of 0 Hz, derived from a linear fit to the threshold data. ERB is the equivalent rectangular bandwidth of a gammatone filter of fourth order fitted to the diotic or dichotic threshold data. r is the ratio of the binaural divided by the monaural parameter for $n_{3\mathrm{dB}}$ and ERB. In the bottom row, the subject's ability to perceive Huggins' pitch is denoted by a +. The rightmost column contains parameters averaged over NH subjects.

Fig. 5.5 shows the predictions on the basis of the gammatone filter (black lines) together with the measured thresholds (open symbols). The equivalent rectangular bandwidths (ERBs) of the gammatone filters fitted to the individual threshold data of the equal-masker-level condition range from 108 to 326 Hz in the diotic case. For the dichotic thresholds, they range from 186 to 671 Hz. For the equal-masker-loudness condition, individual ERBs range from 116 to 246 Hz for the diotic and from 194 to 465 Hz for the dichotic thresholds. For every subject and condition, the Euclidean distance between measured thresholds and the corresponding data points of the fit was smaller than 6 dB (average 2 dB). Averaged over subjects, the ratio r(ERB) ranges between 1.7 and 1.6 in the equal-masker-level and equal-masker-loudness condition, respectively.

Any of the binaural filter bandwidth estimates is wider than the corresponding monaural filter bandwidth estimate.

Broadband masking experiment

Fig. 5.3 shows NoSo (circles) and NoSπ (triangles) thresholds for a 500-Hz sinusoid as a function of spectrum level of a broadband-noise masker. Diotic and dichotic

Subject	1	2	4	6	8	NH
$n_{3\mathrm{dB}}$(NoSo) /Hz	79	150	81	64	48	42
$n_{3\mathrm{dB}}$(NoSπ) /Hz	125	398	206	84	160	84
$r(n_{3\mathrm{dB}})$	1.6	2.7	2.5	1.3	3.3	2.0
ERB(NoSo) /Hz	246	221	210	121	116	82
ERB(NoSπ) /Hz	465	277	335	194	204	125
r(ERB)	1.9	1.3	1.6	1.6	1.8	1.5
Huggins' pitch	+	−	+	+	+	+

Table 5.2.: As in Tab. 5.1, but the parameters were derived from threshold data measured in the equal-masker-loudness condition.

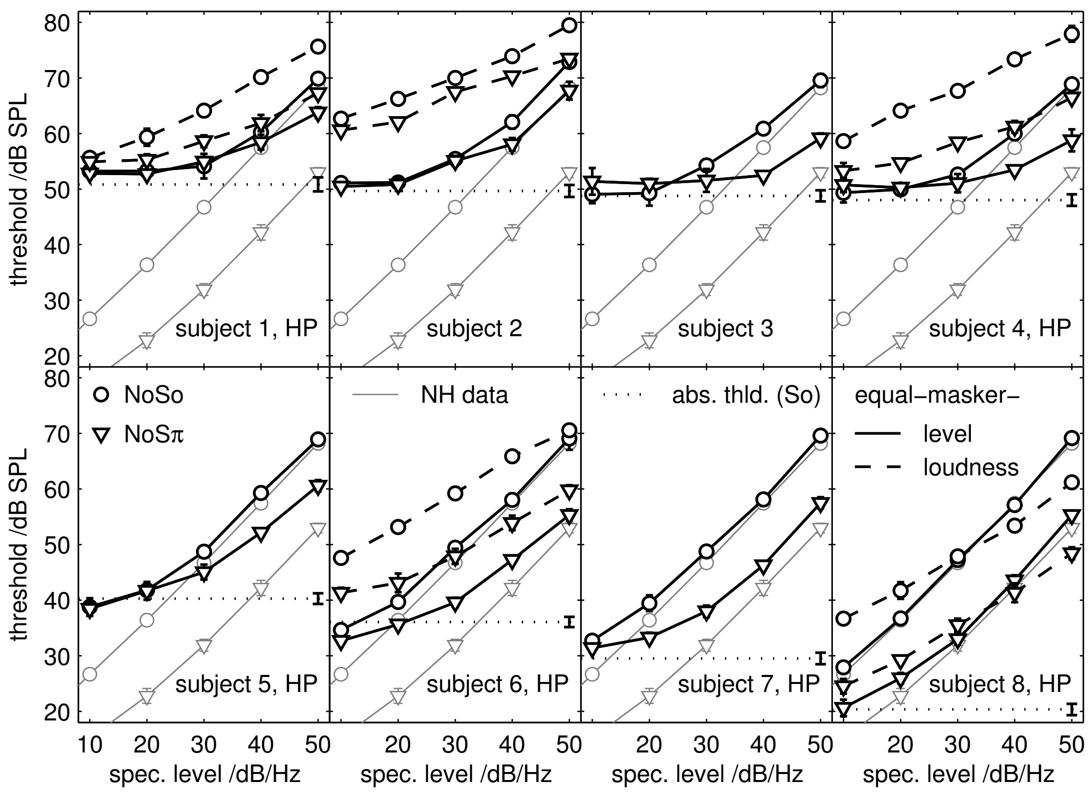

Figure 5.3.: Masked detection thresholds for a 500-Hz sinusoid as a function of spectrum level of a broadband masker. The same symbols and line styles are used as in Fig. 5.2. The spectrum level given on the abcissa is the spectrum level used in the equal-masker-level condition. In the equal-masker-loudness condition, it indicates the masker level that elicited the same loudness impression in the NH subjects (for details see text).

thresholds increase with increase in masker spectrum level, as expected.

In the equal-masker-level condition (black solid lines), the dependence of masker spectrum level is linear for all masker spectrum levels at least about 10 dB above absolute threshold. Near absolute threshold, the slope of the threshold curves becomes shallower starting with the lower dichotic thresholds. Consequently, the BMLD decreases and finally vanishes for thresholds close to absolute threshold. In the equal-masker-loudness condition, spectrum levels were fitted individually to the result of a categorical loudness scaling (see Sec. 5.2.2). For this reason spectrum levels were different from the spectrum levels given on the abcissa, different for every subject, and frequency dependent. In general, the masker spectrum levels in the equal-masker-loudness condition were increased; particularly the low spectrum levels were higher than in the equal-masker-level condition. This is also reflected in the data (dashed lines). The general shapes of the threshold curves and the BMLD are similar to those for the equal-masker-level condition. However, the threshold curves are slightly shallower than in the equal-masker-level condition, which presumably reflects the recruitment of the subjects.

5.3.2. Huggins' pitch

The letters "HP" added to the subject number in Figs. 5.2, 5.3, and 5.5 denote that this subject is able to perceive Huggins' pitch. This information is also given in the bottom row of Tabs. 5.1 and 5.2. Most subjects showed no difficulities in perceiving Huggins' pitch. However, subjects 2, 3, and 4 did not report the percept of a musical scale. These subjects performed the forced-choice experiment with two Huggins' pitches of different center frequency as described in Sec. 5.2.2. Subject 4 made only two mistakes in the 42 presentations of the stimuli, always chose the correct interval from the 7th presentation onwards and thus did not choose a wrong interval in the second run. Hence, it is very likely that subject 4 perceives Huggins' pitch. Subjects 2 and 3 made 22 (35%) and 20 (32%) correct responses out of 63 presentations of the three runs. These percentages are close to the probability of guessing the correct answer (33%). So, in all probability, subjects 2 and 3 are not able to perceive Huggins' pitch.

5.4. Discussion

5.4.1. Monaural frequency selectivity

For all HI subjects, the monaural frequency selectivity was broader than for the NH subjects. The size of the difference depends on the subject and - to a lesser extent - on the method to estimate the filter characteristics. The variability in filter shape is larger for the HI subjects than for the NH subjects. As an example, Fig. 5.4 shows auditory filter shapes fitted to the NoSo (left panels) and NoSπ (right panels) notched-noise threshold data of HI (upper panels) and NH (lower panels) subjects using fourth-order gammatone filters.

The fourth-order gammatone filter yielded a better fit to the threshold data for the HI than for the NH subjects indicating that, for the NH subjects, another filter order could improve the fit. The filter width estimates $n_{3\mathrm{dB}}$ and ERB show a high correlation (0.95) in the equal-masker-level condition; in equal-masker-loudness condition, there is a correlation of 0.6 between them. The gammatone filter fit uses all thresholds and leads to a smooth curve of predicted thresholds (see Fig. 5.5). Though the 3-dB down notch widths are independent of a specified filter shape (like fourth-order gammatone filters), they mainly depend on the thresholds around the signal level 3 dB below the signal level at 0-Hz notch width. Thus, less thresholds determine the bandwidth estimate. This can be observed comparing equal-masker-level and equal-masker-loudness condition: For the gammatone filter fit, monaural bandwidth estimates decreased for all HI subjects except for subject 8 in the equal-masker-loudness condition compared to the equal-masker-level condition. For subject 8 the opposite occurred, but subject 8 was the only subject where the masker spectrum level was reduced in the equal-masker-loudness condition compared to the equal-masker-level condition. Using the 3-dB down notch widths, subjects 2 and 6 showed a larger, and subjects 1, 4, and 8 a narrower bandwidth estimate in the equal-masker-loudness condition compared to the equal-masker-level condition. Thus, the ERB is a more consistent filter bandwidth estimate than the 3-dB down notch width if the specified filter shape is in good agreement with the threshold data.

Glasberg and Moore (1986) measured auditory filter shapes in unilaterally HI subjects using a notched-noise experiment similar to the equal-masker-level condition of the present study. Their ERB for the normal ears ranged from 85 to 105 Hz which is somewhat above the NH mean of 82 Hz, but below all ERBs of

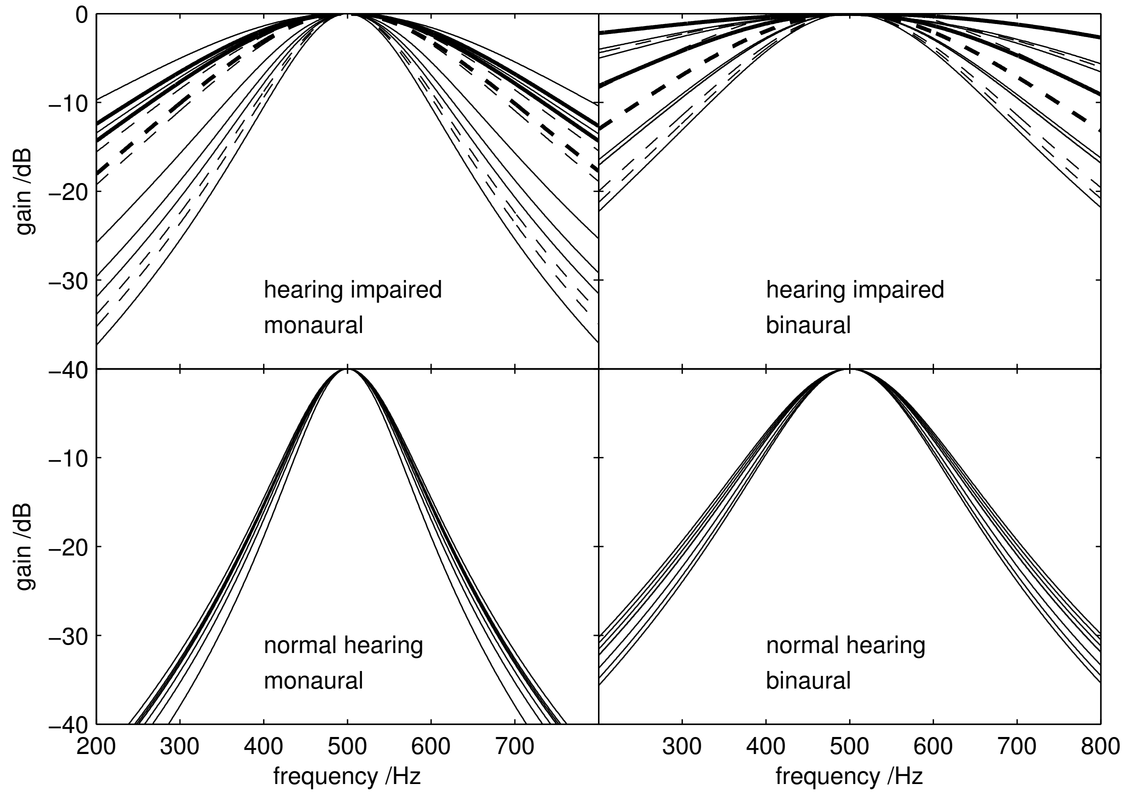

Figure 5.4.: Auditory filter shapes fitted to the NoSo (left panels) and NoSπ (right panels) threshold data of the notched-noise experiment of HI (upper panels) and NH (lower panels) subjects. Thresholds were fitted with a linear gammatone filter of fourth order. For the HI subjects, solid and dashed lines denote filter shapes fitted to threshold data obtained in the equal-masker-level and equal-masker-loudness condition, respectively. Thin lines denote subjects who were able to perceive Huggins' pitch, bold lines subjects who were not.

the HI subjects of the present study. For the impaired ears, Glasberg and Moore (1986) obtained ERBs between 140 and above 650 Hz. Except for subject 8 who has a comparatively mild hearing loss, all ERBs derived from the thresholds of the equal-masker-level condition of the present study are between the minimum and maximum value of Glasberg and Moore (1986)'s study. Patterson *et al.* (1982) conducted a notched-noise experiment at 500 Hz at a 10 dB lower spectrum level. They had subjects of different age whose ERB ranged from 98 to 361 Hz, increasing with age. Peters and Moore (1992) derived auditory filter parameters from diotic notched-noise thresholds measured in young and elderly HI subjects. The signal frequency was 400 Hz. The mean ERBs were 144 and 180 Hz for the young and elderly HI subjects, respectively, whereas for the average NH subject it was 88 Hz. The ERB of 82 Hz of the average NH data from Nitschmann *et al.* (2009) is in good agreement with the 79 Hz, which result from the formula provided in Glasberg and Moore (1990): $\mathrm{ERB} = 24.7(4.37f + 1)$, where frequency f is expressed in kHz.

Baker and Rosen (2002) showed that auditory filter nonlinearity is reduced even for hearing losses of only 20 dB HL and reported that for this reason filter shapes that do not change with level can be fitted almost as well to the threshold data as level-dependent filter shapes. For the same reason filter shapes derived from a notched-noise experiment where the probe tone level is fixed will yield similar results as if the masker level is fixed. This is not the case for NH subjects (Rosen *et al.*, 1998).

5.4.2. Binaural frequency selectivity and the role of the level-dependent BMLD

For all HI subjects, the binaural filter width was larger than the monaural. This is due to the shallower slope of the dichotic notched-noise threshold curve compared to the one in the diotic condition. Since the notched-noise thresholds cover a large range of levels, it is likely that at least part of this effect is due to the level-dependent BMLD. In order to evaluate if the shallower slope is solely due to this effect, dichotic thresholds for the notched-noise experiment were estimated from the thresholds of the broadband masking experiment. These estimates are shown in Fig. 5.5 with filled symbols. Error bars denote the intraindividual standard deviation for the open symbols. For the filled symbols, error bars denote the square root of the sum of the variances of the corresponding diotic and dichotic thresholds except for the notch width of 0 Hz where the thresholds of the notched-noise and broadband masking experiment are the same. For most notch widths larger than zero, there is a significant difference between the predicted and the measured dichotic data. In general, the interpolated threshold curves show a steeper decrease than the dichotic thresholds of the notched-noise experiment. This is a result of the persistence of BMLD from 50 dB/Hz to masker levels close to absolute threshold in the broadband masking experiment, whereas the BMLD gradually decreases with increasing notch width in the notched-noise experiment. So, at the same diotic threshold (i.e., at the same excitation in the auditory filter) there is a different BMLD in the notched-noise and in the broadband masking experiment for intermediate notch widths. The result is more prominent in subjects with a mild hearing loss. This difference between notched-noise masking and broadband masking is at odds with van de Par and Kohlrausch (1999) who hypothesized the same level dependence of the BMLD in all broadband masking conditions including notched-noise masking. A similar conclusion was drawn in Nitschmann *et al.* (2009) for NH subjects.

In Tabs. 5.1 and 5.2 the filter bandwidths of Fig. 5.4 are given together with a ratio r(ERB) of binaural divided by monaural auditory filter bandwidth. For the equal-masker-level condition of the HI subjects' data, this ratio is on average 1.7 with a standard deviation of 0.4. For the thresholds measured in the equal-masker-loudness condition, the mean is 1.6 with a standard deviation of 0.2. The average of the ratios [6] of the NH subjects is 1.6 with a standard deviation of 0.1. Thus, both NH and HI subjects show wider filters in the dichotic notched-noise experiment, however, the ratio r(ERB) is similar between NH and HI subjects.

An increased ratio r(ERB) could be caused by processing deficits both before (i.e., more peripheral) or after (i.e., more central than) the first physiological binaural interaction on the brainstem level. A possible reason for the former case might be that the temporal accuracy of the neural response in monaural stages preceding the binaural stage could be impaired due to hearing impairment. Such an impairment might not lead to larger monaural bandwidths, but could have a detrimental effect on binaural processing which relies on synchronicity of the input from both sides and might therefore lead to a larger binaural bandwidth. However, the similar ratio r(ERB) for NH and HI subjects indicates that there is

[6] The ratio 1.5 in Tabs. 5.1 and 5.2 is that for the NH mean thresholds.

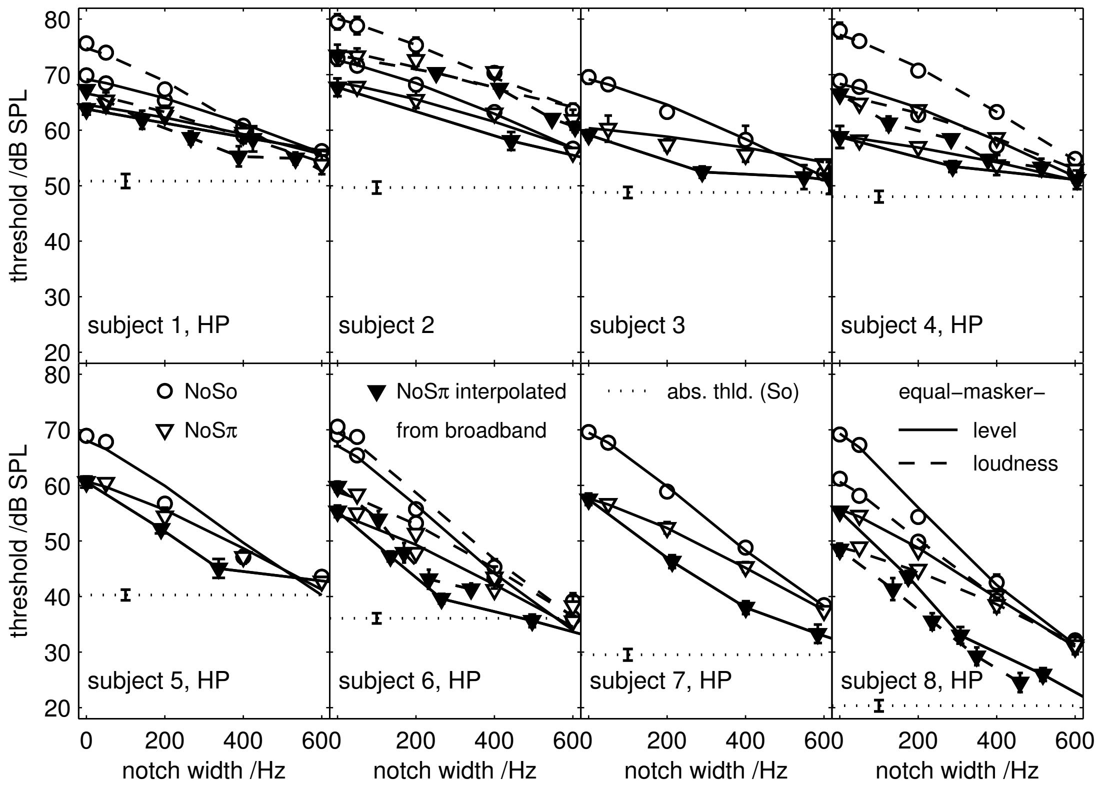

Figure 5.5.: Similar to Fig. 5.2, but now only the open symbols indicate the measured thresholds, while the solid and dashed lines show the predictions of an energy detector model using a fourth-order gammatone filter whose parameters were fitted to the individual thresholds of the equal-masker-level and equal-masker-loudness condition, respectively. Filled symbols denote NoSπ thresholds predicted for the broadband masking condition shown in Fig. 5.3.

neither an impairment of the specific binaural, centrally located processing that effectively increases the auditory filter width in dichotic listening situations in NH subjects nor in the aspects of the function of the preceding peripheral (or monaural) processes which could have caused an increased ratio r(ERB) in HI subjects.

The gammatone filter fit is slightly better for the dichotic than for the diotic thresholds in equal-masker-level and equal-masker-loudness condition. As for the filter bandwidth estimates obtained from the diotic thresholds, binaural filter width estimates are more consistent between equal-masker-level and equal-masker-loudness condition when using the gammatone filter: Subjects 2, 4, and 6 show a narrower bandwidth estimate in the equal-masker-loudness condition compared to the equal-masker-level condition, whereas subjects 1 and 8 showed a wider bandwidth estimate. Using the gammatone filter fits, there is only one subject (subject 1) who shows an opposite change in monaural and binaural bandwidth estimate between equal-masker-loudness and equal-masker-level condition; using the 3-dB down notch width, there are two (subjects 6 and 8).

For both 3-dB down notch widths and gammatone filters, the ratio r (see Tabs. 5.1 and 5.2) is clearly above 1. The correlation between the ratios derived from the two methods to estimate the filter bandwidth, however, is low. Nevertheless, as for the estimates based on the gammatone filters the ratios are also similar between the data for NH and HI subjects: The ratios of the 3-dB down notch widths for the HI subjects is 2.1 (standard deviation 0.4) in the equal-masker-level condition and 2.3 (standard deviation 0.8) in the equal-masker-loudness condition, and the ratio for the NH subjects is 2.0 (standard deviation 0.6).

5.4.3. Relation between Huggins' pitch and frequency selectivity

Subjects 2 and 3 were not able to perceive Huggins' pitch. Interestingly, both subjects show a BMLD (see Figs. 5.2 and 5.3). The broadband noise without a notch at a spectrum level of 50 dB/Hz corresponds well to the stimulus used in the Huggins-pitch experiment in spectrum as well as in level. In this condition and at this spectrum level, subjects 2 and 3 show a BMLD of above 5 and above 10 dB, respectively. So they are able to benefit from an interaural phase difference of masked sinusoids whereas they cannot benefit from interaural phase differences in a noise of similar level.

According to the gammatone filters fitted to the thresholds of the notched-noise experiment (see Tabs. 5.1 and 5.2) subjects 2 and 3 are among the subjects exhibiting the widest auditory filters (bold lines in Fig. 5.4). So, for these two subjects, the relative portion of the frequency band containing the transition of interaural phase that generates the Huggins' pitch is narrower; the Huggins' pitch may be kind of diluted by diotic noise. However, subjects 1 and 4 show comparable filter bandwidths and both are able to perceive Huggins' pitch, though subject 4 did not perceive Huggins' pitch immediately. Subject 1's ability to perceive Huggins' pitch might be due to the subject's kind of hearing loss: Subject 1 is NH at 125 and 250 Hz, and has a hearing loss of 50 dB HL and more in the frequency region between 0.5 and 2 kHz. For this reason the forced-choice experiment with Huggins' pitches was conducted with subject 1 varying the center frequency of the Huggins' pitch. The ratio of the two Huggins' pitches was maintained: $\sqrt{2}$:1, geometrically centered around the center frequency. At the center frequencies of 250, 353.6, 500, and 707.1 Hz, subject 1 made 70%, 78%, 57%, and 76% correct responses, respectively. Though subject 1 did not arrive at a perfect performance, the percentages are clearly above chance level and for this reason it is very likely that subject 1 can perceive Huggins' pitch at all of these frequencies. Additionally, there might be an effect of age since subject 3 was the oldest subject participating in the experiment, whereas subject 1 was the youngest.

5.4.4. Binaural impairment factor

The question if a specific binaural impairment can be detected for sensorineural HI subjects as an independent factor (in addition to, e.g., the audiogram, age, general loss in intensity resolution ability, and temporal or spectral resolution) has been addressed by several authors in the past. Several "battery approach" studies that used both monaural and binaural tests with the same set of NH and HI subjects (such as, e.g., Häusler *et al.*, 1983; Kinkel *et al.*, 1991; Kinkel and Kollmeier, 1992; Koehnke *et al.*, 1995; Holube and Kollmeier, 1996; Wagener, 2003) found that in general binaural functions (such as, e.g., BMLD, interaural time and level discrimination, binaural intelligibility level difference) decrease with increasing hearing loss, but also the variability of the specific binaural performance increases. Kollmeier (1999) therefore postulated a common factor underlying several binaural functions that indicates the degradation in HI subjects independent from other primary auditory factors (such as, e.g., loss in audibility, loss in dynamic range, and increase of the "internal noise").

Further support for such a general ability or disability to perform binaural psychoacoustical tasks was given by Santurette and Dau (2007) who could separate their subjects into a group that was able to perceive Huggins' pitch and another subgroup that was not able to do so. An argument *against* such a common binaural impairment factor was made by Beutelmann and Brand (2006) who measured and predicted binaural intelligibility level differences (i.e., the advantage measured as the speech reception thresholds for listening with both ears in a dichotic situation as opposed to listening with the "better" ear): They could model the data for HI subjects to a large degree purely on the basis of the individual audiogram (raised absolute threshold modeled as uncorrelated noise) without having to assume a specific binaural impairment factor.

The existence of such a binaural impairment factor cannot be supported from the present study: On the one hand, the ratio between binaural and monaural frequency bandwidth is on average very similar for the HI and NH subjects employed here. Moreover, a decrease in one binaural performance parameter (such as, e.g., the ability to detect a Huggins' pitch) is not strictly linked to the deterioration of another binaural performance (e.g., the BMLD). Hence, these two different kinds of binaural performance are either controlled by separate binaural impairment factors or an underlying, not yet characterized common factor exists that influences both binaural-performance measures in a different way. In any case, it is reasonable to state that the current data do not support the hypothesis of a single binaural impairment factor that could characterize the loss in binaural-hearing capabilities in a simple and concise way.

5.5. Summary and Conclusion

- As for the NH subjects, the bandwidth of auditory filters estimated from notched-noise experiments is wider for HI subjects when instead of NoSo thresholds NoSπ thresholds are used.

- The wider binaural filter width cannot be accounted for by the level dependence of the BMLD alone.

- The ratio of binaural to monaural bandwidth estimates is similar for NH and HI subjects. This indicates that, despite of a generally poorer monaural frequency selectivity in HI subjects, the processes responsible for the apparently wider binaural bandwidth are unaltered in HI subjects.

- Two HI subjects were unable to perceive Huggins' pitch. These subjects had broad auditory filters. However, subjects with filters of similar width perceived Huggins' pitch. This indicates that broad filters might be a prerequisite but are not sufficient to account for the failure to perceive a binaural pitch.

- The HI subjects that were unable to perceive Huggins' pitch were still able to take advantage of an NoSπ versus an NoSo masking condition. They showed a BMLD of up to 10 dB. The ratio of the monaural and the binaural filter width was similar to that of the other subjects at least for one of these two subjects. Thus it is unlikely that the inability to detect Huggins' pitch is due to a general impairment of the binaural system.

- The current data therefore provide no clear evidence for a specific binaural impairment factor in hearing impairment that deteriorates several aspects of binaural processing in a similar way.

Acknowledgments

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6. Summary and general conclusions

The present thesis investigated the frequency selectivity of the human auditory system with respect to binaural masking conditions.

In the beginning was the measurement of Bourbon and Jeffress (1965) who found a striking difference between diotic and dichotic bandwidening experiments with the bandwidth of the binaural filter being twice as large as that of the monaural.

After several other researchers had repeated and varied this experimental paradigm, Hall *et al.* (1983) combined the bandwidening experiment with a notched-noise experiment, its spectral counterpart, and proposed a hypothesis to analyze their data: For a dichotic signal in a diotic masker, all auditory filters contribute to the detection of the signal, however, the effect of auditory filters remote from the signal frequency is detrimental since their signal-to-noise ratio (SNR) is low. In the bandwidening experiment, NoSπ thresholds improve over a large range of bandwidths because of less detrimental off-frequency information with decreasing bandwidth. Hall *et al.* (1983) concluded that the "true" level dependence of the BMLD should be measured using a signal-centered narrowband masker since in this case there is no detrimental off-frequency information. They assumed the same level dependence of the BMLD in the notched-noise experiment as in a narrowband-noise experiment when a constant offset due to the detrimental across-channel process that has no effect for a sufficiently narrow masker is subtracted.

An alternative hypothesis was proposed by van de Par and Kohlrausch (1999): For a dichotic signal in a diotic narrowband masker, there is a beneficial across-frequency integration of information since the SNR is high in several auditory filters centered at or near the signal frequency. With increasing masker bandwidth the SNR in off-frequency filters decreases and there finally is no advantage in detection in using other auditory filters than the on-frequency filter anymore. Van de Par & Kohlrausch (1999) concluded that in all conditions where a tonal signal is used together with a broadband masker, regardless whether it is a notched noise or a noise without notch, a single-filter binaural model is adequate and an operational binaural critical bandwidth should be measured that is similar to the monaural critical bandwidth.

The present study tested both hypotheses in the same psychoacoustic experimental procedure and in the same subjects by contrasting NoSo and NoSπ detection thresholds for a 500-Hz sinusoid masked by a notched noise to those masked by a narrowband and broadband noise without notch.

Hall *et al.* (1983) supported their conclusion by their averaged notched-noise thresholds and three pairs of diotic and dichotic thresholds of the 10-Hz bandwidth condition of the bandwidening experiment. Their conclusion is in contradiction to the findings of the present study: The very fact that the BMLD in narrowband noise exhibits greater individual differences than in notched noise gives a hint that this conclusion might have to be rejected. The threshold data of the present study comparing six pairs of diotic and dichotic thresholds and individual thresholds provide evidence for that.

Certainly, in all broadband masking conditions including notched-noise masking, the SNR is highest in one auditory filter centered at or near the signal frequency. Thus, the beneficial across-frequency process hypothesized by van de Par and Kohlrausch (1999) does not yield an advantage in signal detection. However, this does not mean that the level dependence of the BMLD is the same in notched noise and broadband noise without notch as concluded by van de Par and Kohlrausch (1999). The present study demonstrated this using the model by Breebaart *et al.* (2001a) that implements the across-frequency process hypothesized by van de Par and Kohlrausch (1999) with its filter parameters fitted to the measured diotic mean thresholds of the notched-noise experiment: The model predicts the thresholds in broadband noise (and, of course, the diotic notched-noise thresholds) in good agreement to the measurement, but it is not able to predict the dichotic thresholds of the notched-noise experiment. Instead and in accordance with the conclusion of van de Par and Kohlrausch (1999), the model of Breebaart *et al.* (2001a) predicts the same level dependence of the BMLD for all broadband maskers with and without notch, and this results in predicted thresholds lower than measured for intermediate notch widths. Thus, while the beneficial across-channel process suggested by van de Par and Kohlrausch (1999) works well as an explanation of dichotic bandwidening thresholds, their conclusion concerning all broadband maskers has to be rejected.

To investigate whether this difference in level dependence of the BMLD is a result of nonlinear auditory filtering, the notched-noise experiment and the experiment with a broadband masker without notch were repeated with sensorineurally hearing-impaired (HI) subjects, who exhibit less auditory filter nonlinearity (Baker and Rosen, 2002). Except for generally smaller BMLDs the thresholds of HI subjects showed the same difference between the notched-noise experiment and a broadband masker without notch: A continuously decreasing BMLD over notch widths and a rather constant BMLD over spectrum levels, respectively. This provides evidence that the difference in level dependence of the BMLD between notched-noise experiment and broadband experiment is not an effect of the nonlinear auditory filtering.

Auditory filter parameters were obtained from the diotic and dichotic notched-noise thresholds and compared to thresholds measured in the same experiment in normal-hearing (NH) subjects. The filters fitted to the dichotic thresholds were wider than those fitted to the diotic thresholds. The filters fitted to the thresholds of HI subjects were wider than those fitted to the thresholds of NH subjects. The ratio of dichotic divided by diotic equivalent rectangular bandwidth, however, was similar for NH and HI subjects. This is a sign of no additional retrocochlear impairment in HI subjects compared to NH subjects.

In addition, as a second test of binaural processing in HI subjects, the ability to perceive Huggins' pitch, a binaural pitch based on interaural phase differences in a small frequency band of a broadband masker, was tested. Two out of eight HI subjects were not able to perceive Huggins' pitch. Nevertheless, these two subjects showed a BMLD for a 500-Hz sinusoid in a broadband noise of the same level. This indicates that not a single binaural impairment factor is responsible for both BMLD and for the binaural spectral correlation processing that yields the Huggins' pitch.

To investigate the dependence of NoSo and NoSπ thresholds in notched noise on the signal frequency, the notched-noise experiment was conducted in NH subjects at signal frequencies of 250, 500, 1000, and 2000 Hz. Analysis of the diotic and dichotic threshold data using a power-spectrum model revealed an increasing difference between monaural and binaural auditory filter bandwidth towards lower signal frequencies.

The results were simulated using different modifications of the effective model by Zerbs (2000) that combines a monaural model (Dau *et al.*, 1996) with the equalization-cancellation principle (Durlach, 1963). Though different in details, the basis of the models by Zerbs (2000) and Breebaart *et al.* (2001a) is the same, in particular, both implement the beneficial across-channel process hypothesized by van de Par and Kohlrausch (1999).

The threshold data measured in the notched-noise experiments show a continuous decrease of the BMLD. In contrast to the measurement, the model by Zerbs (2000) with filter parameters fitted to the diotic thresholds (i.e., 1 ERB wide gammatone filters of third order) predicts a rather constant BMLD as would be expected in a broadband masker without notch. This prediction is in line with the beneficial across-channel process hypothesized by van de Par and Kohlrausch (1999) and the prediction of the model by Breebaart *et al.* (2001a) discussed above.

The idea that interaurally different auditory filters could be the reason for the different filter parameters derived from the diotic and dichotic notched-noise thresholds was explored by measuring monaural left and right thresholds in notched noise for the signal frequency of 500 Hz. The simulation using interaurally different individual filter parameters derived from these thresholds yielded predicted thresholds in better agreement with those measured compared to the simulation with interaurally symmetric filter parameters. However, for most of the subjects the predicted dichotic thresholds for intermediate notch widths were still lower than meaured. Hence, interaurally different auditory filters are not the reason for the difference between diotic and dichotic thresholds observed in the notched-noise experiment. For this reason the other modifications to the model by Zerbs (2000) all use interaurally symmetric filter parameters.

The mere use of nonlinear auditory filters (Lopez-Poveda and Meddis, 2001) fitted to the diotic thresholds does not explain the dichotic notched-noise thresholds. Adding portions of the outputs of lower and higher filters adjacent to the on-frequency filter yields simulated dichotic notched-noise thresholds in reasonable agreement with the measured thresholds. This can be considered as a realization of the detrimental across-channel process hypothesized by Hall *et al.* (1983). The increasing difference between diotic and dichotic filter parameters with decreasing signal frequency is a problem that remains in this model.

In conclusion, this thesis demonstrated the challenges and limits of understanding binaural spectral processing in NH and HI subjects by means of quantitative processing models. While current models (Zerbs, 2000; Breebaart *et al.*, 2001a) are unable to correctly predict the level dependence of the BMLD in broadband maskers with a spectral notch at the signal frequency, the present study provides a lot of particularly dichotic notched-noise threshold data and shows ways to simulate these data in better agreement with the measurement than before. This was achieved by combining ideas of the beneficial (van de Par and Kohlrausch, 1999) and detrimental (Hall *et al.*, 1983) across-channel processes while rejecting the conclusions the authors drew from their hypotheses on the basis of the measured threshold data. The currently best model for explaining the experimental data observed here assumes an "effective" widening of the binaural critical band due to small contributions of adjacent filters (with less favourable SNR) in the broadband condition that have no effect in diotic or monaural conditions.

A. Additional material

This chapter contains parts that were omitted in Chapters 3, 4, and 5 to keep them concise.

Sec. A.1 contains the individual NoSo and NoSπ detection thresholds of Fig. 3.2 in Chapter 3 displayed in the traditional way as a function of the experimental parameter varied. Sec. A.2 contains individual threshold data to the mean threshold data reported in Chapter 4. Sec. A.3 contains further considerations concerning the modeling of the thresholds measured in the notched-noise experiment at different signal frequencies of Chapter 4. Sec. A.4 describes how the parameters derived from the categorical loudness scaling were used to generate stimuli of the same loudness for the experiments of Chapter 5.

A.1. Individual detection thresholds in notched, broadband, and narrowband noise

This section shows the threshold data of Fig. 3.2 in Chapter 3 in the traditional way as a function of the parameter of variation.

A.1.1. Notched noise

Fig. A.1 shows NoSo (circles) and NoSπ (triangles) thresholds for a 500-Hz sinusoid as a function of notch width. Diotic and dichotic thresholds decrease with increase in notch width. In general the slope of the NoSπ threshold curve is shallower than that of the NoSo threshold curve. For this reason the BMLD decreases with increase in notch width. Individual NoSo thresholds in broadband noise without a notch vary between 67 (subject 3) and 69 dB (subjects 7 and 8). Individual differences increase with increase in notch width. At a notch width of 800 Hz, NoSo thresholds are in a range from below 6 (subjects 4 and 5) to 11 dB (subject 2). The trend is similar for individual NoSπ thresholds: If the masker does not contain

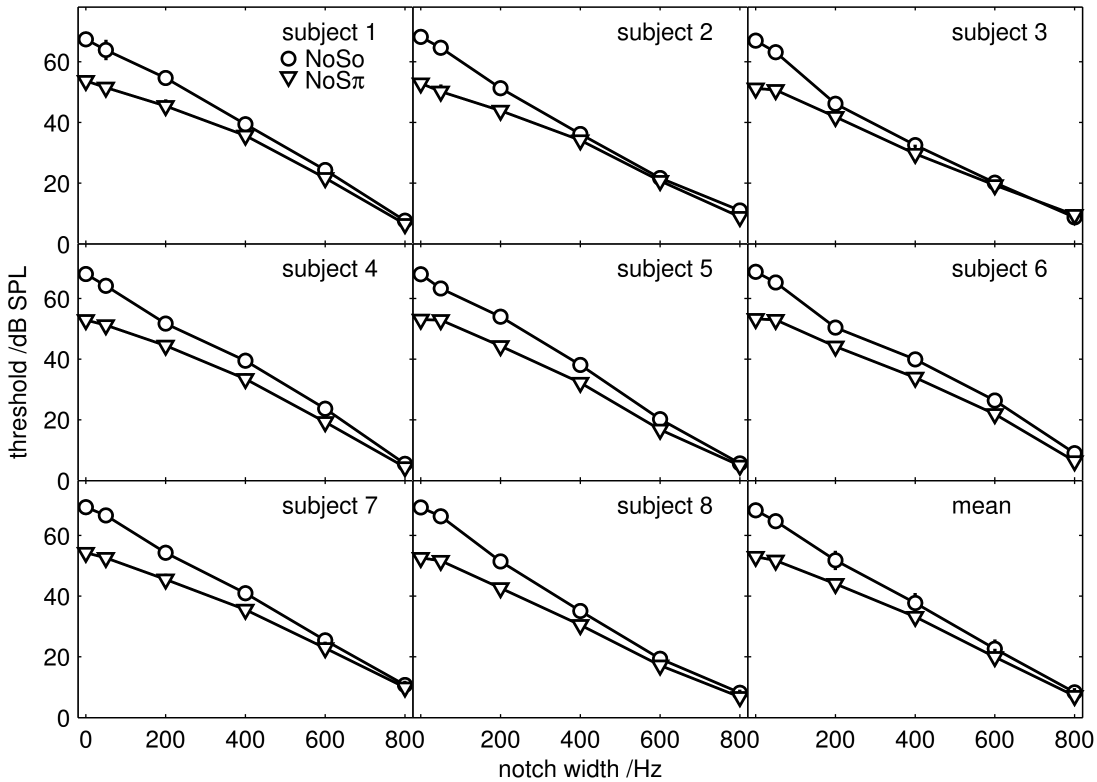

Figure A.1.: Detection thresholds for 500-Hz sinusoids in phase (So, circles) or antiphase (Sπ, triangles) as a function of notch width of a diotic noise masker (No). Masker spectrum level was 50 dB/Hz. The lower right panel shows average thresholds. Error bars denote plus minus one intraindividual standard deviation for the individual thresholds and plus minus one interindividual standard deviation for the average thresholds. They are only shown when they exceed the size of the symbols.

a notch, thresholds range from 51 (subject 3) to 54 dB (subject 7). They range from 4 (subject 4) to 10 dB (subject 7) at the largest notch width. BMLDs at a notch width of 0 Hz vary individually from almost 14 (subject 1) to almost 17 dB (subject 8). At the largest notch width, all individual BMLDs are about the size as the standard deviations of the corresponding thresholds. When individual filter parameters are derived from the thresholds using a gammatone filter in a power-spectrum model, subject 3 is the only subject who shows a 1 ERB wide gammatone filter of fourth order as a best fit to the NoSo thresholds. For the other subjects, wider gammatone filters of a higher filter order (i.e., a wider tip region and narrower filter tails) yield better fits. Auditory filter parameters of the individual subjects fitted to the threshold data in a power spectrum model are given in Tabs. A.1 (fixed gammatone filter order) and A.2 (bandwidth and filter order fit to the threshold data). Mean NoSo threshold decreases from 68 dB at a notch width of 0 Hz to 8 dB at a notch width of 800 Hz. Mean as well as some individual diotic thresholds show a linear dependence on notch width. Such a relation was already reported by Patterson *et al.* (1982). Mean dichotic thresholds show a roughly linear dependence on notch width as well. Mean dichotic thresholds are 53 and 7 dB at the notch widths of 0 and 800 Hz, respectively. Mean BMLD is 15 dB in the masker without a notch and decreases to a value clearly below the standard deviations of the corresponding thresholds at the largest notch width.

Auditory filter parameters

Tabs. A.1 and A.2 display one-parameter and two-parameter fits estimating the width of the auditory filters derived from the individual notched-noise thresholds of Fig. A.1, respectively. Tab. A.1 displays 3-dB down notch widths $n_{3\mathrm{dB}}$ that do not depend on assumptions of the filter shape and the bandwidth of gammatone filters of fourth order fitted to the threshold data using a power spectrum model. The parameters given in Tab. A.1 correspond to those of Tabs. 5.1 and 5.2 in Chapter 5. Tab. A.2 shows parameters of gammatone filters fitted to the diotic and dichotic individual threshold curves in a power spectrum model without fixing the filter order. The rightmost columns in both tables show parameters derived from the average threshold data.

For the gammatone filter fit of Tab. A.1, the Euclidean distance between thresholds and fit is below 10 dB for the diotic and below 8 dB for the dichotic thresholds for every subject. For the gammatone filter fit of Tab. A.2, the Euclidean distance

Subject	1	2	3	4	5	6	7	8	mean
$n_{3\mathrm{dB}}$(NoSo) /Hz	59	42	40	38	32	42	54	51	42
$n_{3\mathrm{dB}}$(NoSπ) /Hz	87	58	93	79	100	96	78	85	84
$r(n_{3\mathrm{dB}})$	1.5	1.4	2.3	2.1	3.1	2.3	1.5	1.7	2.0
ERB(NoSo) /Hz	83	82	76	82	79	86	83	70	82
ERB(NoSπ) /Hz	128	135	131	122	114	128	138	117	125
r(ERB)	1.6	1.6	1.7	1.5	1.4	1.5	1.7	1.7	1.5

Table A.1.: Auditory filter parameters fitted to the threshold data depicted in Fig. A.1. $n_{3\mathrm{dB}}$ denotes the notch widths where the diotic or dichotic threshold has decreased by 3 dB relative to the notch width of 0 Hz, derived from a piecewise linear fit to the threshold data. ERB is the equivalent rectangular bandwidth of a gammatone filter of fourth order fitted to the diotic or dichotic threshold data. r is the ratio of the binaural divided by the monaural parameter for $n_{3\mathrm{dB}}$ and ERB.

Subject	1	2	3	4	5	6	7	8	mean
G(NoSo)	9	5	4	9	8	6	7	5	6
B(NoSo) /ERB	1.79	1.24	0.97	1.75	1.60	1.49	1.64	1.12	1.43
G(NoSπ)	13	9	5	11	9	8	8	6	7
B(NoSπ) /ERB	2.51	2.41	1.87	2.33	2.13	2.22	2.34	1.89	2.11

Table A.2.: Gammatone filter parameters fitted to the threshold data depicted in Fig. A.1. In contrast to Tab. A.1, the filter order G was not fixed at four. B denotes the bandwidth of the gammatone filter in ERB.

between thresholds and fit is below 6 dB for the diotic and below 3 dB for the dichotic thresholds for every subject; the fit for the diotic thresholds is below 3 dB for all subjects except for subjects 4 and 6.

The equivalent rectangular bandwidths (ERB, for ERB see, e.g., Glasberg and Moore, 1990; Kollmeier and Holube, 1992) in Hz as given in Tab. A.1 can be computed from the value in ERB used in Tab. A.2 using the formula (Glasberg and Moore, 1990): ERB $= f/9.265 + 24.7$ Hz.

The 3-dB down notch widths $n_{3\mathrm{dB}}$ of the subjects are between 32 and 59 Hz in the monaural and between 58 and 100 Hz in the binaural case. For the average thresholds, this filter width estimate is twice as large in the binaural as in the monaural case. There are, however, large intersubject differences in this ratio. The bandwidths derived from the diotic and dichotic thresholds using gammatone filters of fourth order are around 80 Hz and about 127 Hz, respectively. [1]. The ratio r (ERB) of binaural divided by monaural filter bandwidths ranges from 1.4 to 1.7.

In each of the auditory filter bandwidth estimates of Tab. A.1, the parameter derived from the dichotic thresholds stands for an increased filter bandwidth, i.e., a reduced frequency selectivity compared to the parameters derived from the diotic thresholds.

For a comparison to literature data, monaural threshold data for the two ears of the subjects of the study by Patterson *et al.* (1982) were averaged and gammatone filters of fourth order were fitted to these individual threshold data in the same way as in the present study. The result were ERBs of 98, 109, 127, and 361 Hz for the subjects JM 29, CS 42, MS 60, and AH 72, respectively. Compared to the average ERB of 80 Hz in Tab. A.1, all subjects in Patterson *et al.* (1982) show wider filters. However, a tendency in the filter parameters of Tab. 4.5 in Chapter 4 can be observed that filter parameters derived from diotic thresholds might reflect a little narrower filters than those derived from monaural thresholds. The 3-dB down notch widths derived by Hall *et al.* (1983) in the corresponding condition of their notched-noise experiment were 51 Hz in the monaural and 64 Hz in the

[1]Note that using a power spectrum model for the dichotic thresholds leads to an overestimation of filter bandwidth. A more realistic model of auditory processing, e.g., of the equalization-cancellation (EC, Durlach, 1963) type (Zerbs, 2000; Breebaart *et al.*, 2001a) uses somewhat narrower filters since the EC processing effectively acts as a broadening of filters. Nevertheless, also for the models the parameters of filters to predict dichotic notched-noise thresholds represent wider filters than those to predict diotic notched-noise thresholds. See Sec. A.3 below.

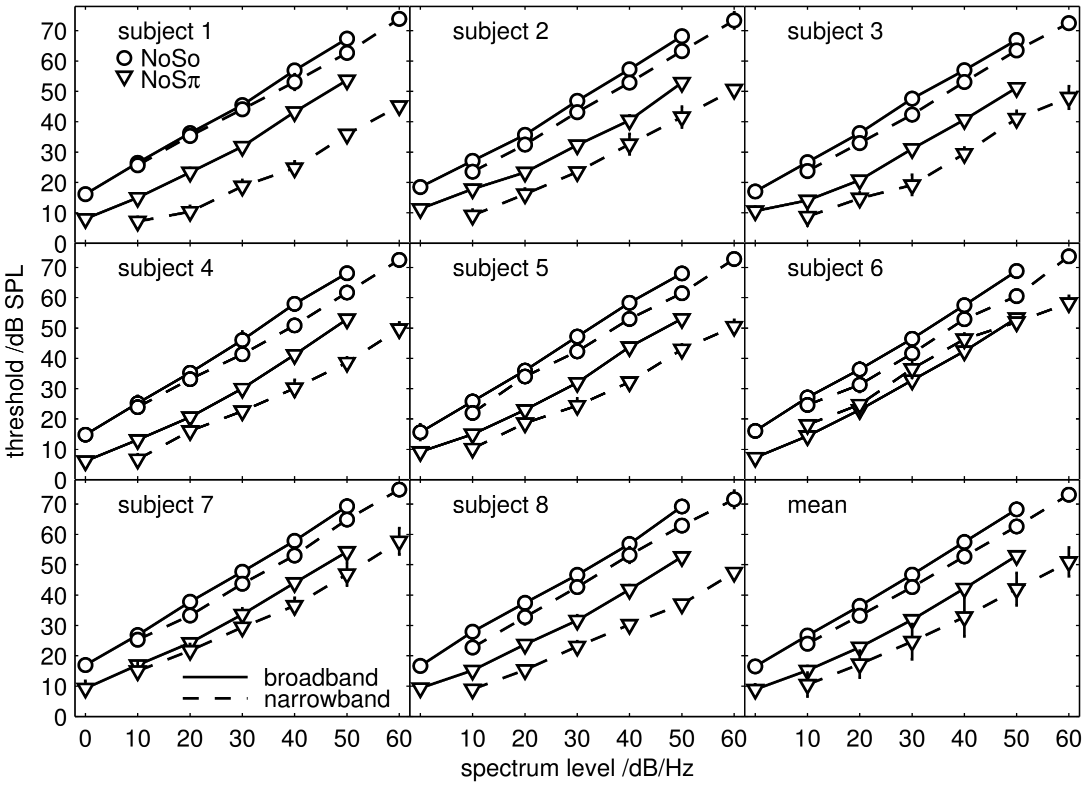

Figure A.2.: Detection thresholds for 500-Hz sinusoids in phase (So, circles) or antiphase (Sπ, triangles) as a function of spectrum level of a diotic broadband (970 Hz, solid line) or narrowband (10 Hz, dashed line) masker. The lower right panel shows average thresholds. Error bars denote plus minus one intraindividual standard deviation for the individual thresholds and plus minus one interindividual standard deviation for the average thresholds. They are only shown when they exceed the size of the symbols.

binaural case. The value for the monaural case is well in line with those of the present study. Except for subject 2, binaural 3-dB down notch widths are larger in the present study than in that of Hall *et al.* (1983). Reasons for this might be intersubject differences in thresholds or the small differences in method between both experiments.

A.1.2. Broadband and narrowband noise

Fig. A.2 shows NoSo (circles) and NoSπ (triangles) thresholds for a 500-Hz sinusoid as a function of masker spectrum level. The masker is either a broadband noise (solid lines) or a 10-Hz wide narrowband noise (dashed lines) arithmetically centered at the signal frequency. Thresholds increase with increasing masker spectrum level. The BMLD is roughly constant, though somewhat smaller at small masker spectrum levels. In general, the BMLD is larger for the narrowband than for the broadband masker.

The thresholds of the broadband experiment at the highest spectrum level are the same as in the notched-noise experiment (Fig. A.1). Individual NoSo thresholds in broadband noise vary between 15 (subject 4) and almost 19 dB (subject 2) at the lowest spectrum level. The slope of the NoSo threshold curves is rather exactly 1 dB per dB/Hz for all subjects; only subjects 2 and 8 show a different slope at low spectrum levels. NoSπ thresholds range between 6 (subject 4) and 11 dB (subject 2) at the lowest spectrum level. Individual BMLDs at this spectrum level are in a range from below 7 (subjects 3 and 5) to almost 9 dB (subject 6) and increase with spectrum level. This increase in BMLD shows interindividual differences, but for spectrum levels above 20 or 30 dB/Hz there is almost no further increase in BMLD with spectrum level. At the lowest spectrum level, mean NoSo threshold is 16.5 dB. The diotic mean thresholds increase 10 dB with 10 dB/Hz increase in spectrum level. The mean NoSπ thresholds at the lowest spectrum level is 9 dB. The slope of the NoSπ threshold curve is monotonically decreasing with increase in spectrum level. Mean NoSπ threshold is 15 and 23 dB at the masker spectrum levels of 10 and 20 dB/Hz, respectively. Towards higher spectrum levels, the increase of NoSπ thresholds is roughly 10 dB with 10 dB/Hz increase in spectrum level. The mean BMLD is below 8 dB at the lowest spectrum level. It is monotonically increasing up to the spectrum level of 30 dB/Hz. From this spectrum level on, it is constant at 15 dB.

Detection thresholds in a 10-Hz wide masker centered at the signal frequency show a larger interindividual variability than the thresholds measured in a broadband masker. This larger variability can be found primarily in the dichotic thresholds, but also the diotic thresholds show more intersubject variability than in broadband masking. Individual NoSo thresholds range between 22 (subject 5) and 26 dB (subject 1) at the lowest spectrum level of 10 dB/Hz. Thresholds increase with spectrum level to values between above 71 (subject 8) and almost 75 dB (subject 7) at the highest spectrum level of 60 dB/Hz. NoSo thresholds increase roughly 10 dB if spectrum level is increased by 10 dB/Hz. NoSπ thresholds show large interindividual differences. At the lowest spectrum level, thresholds are in a range from 7 (subject 1 and 4) to 18 dB (subject 6). Subject 6's NoSπ thresholds were the highest of all subjects at all spectrum levels. For most spectrum levels they were above the NoSπ thresholds of the same subject in broadband noise of the same spectrum level. At the highest spectrum level, individual dichotic thresholds vary from 45 (subject 1) to 58 dB (subject 6). At all spectrum levels, subject 1 and 6 show the largest and smallest BMLDs, respectively. Individual BMLDs range from below 7 to above 18 dB at the lowest spectrum level; at the highest spectrum level, individual BMLDs take values between 15 and almost 29 dB. Mean NoSo thresholds increase from 24 at the lowest to 73 dB at the highest spectrum level. Mean NoSπ thresholds increase from below 11 at the lowest to 51 dB at the highest spectrum level. Mean BMLD increases monotonically with spectrum level. It is above 13 and 22 dB at the lowest and highest spectrum level, respectively.

A.2. Individual thresholds in notched noise of various center frequencies

Since there were no striking interindividual differences in the thresholds, only average thresholds are reported in Chapter 4. Individual results are reported in this section.

Figs. A.3–A.6 show detection thresholds for sinusoids in a diotic notched-noise masker as a function of notch width. The figures show individual thresholds and the average over these thresholds in the lower right panel. Sinusoids were either interaurally in phase (So, denoted by circles) or antiphase (Sπ, denoted by triangles). Masker spectrum level was 30 dB/Hz. Dashed lines denote absolute thresholds. Error bars denote plus minus one intraindividual or interindividual standard deviation for the individual or average thresholds, respectively. For further details on stimulus generation see Chapter 4. Auditory filter parameters derived from the thresholds of the notched-noise experiment are given in Tabs. A.2.5 and A.4 below.

Three of the subjects participated in both studies reported in Chapter 3 and 4: Subjects 1, 3, and 8 of the experiments reported in in Chapter 3 were subjects 6, 7, and 4 of the experiments reported in Chapter 4 and this section, respectively.

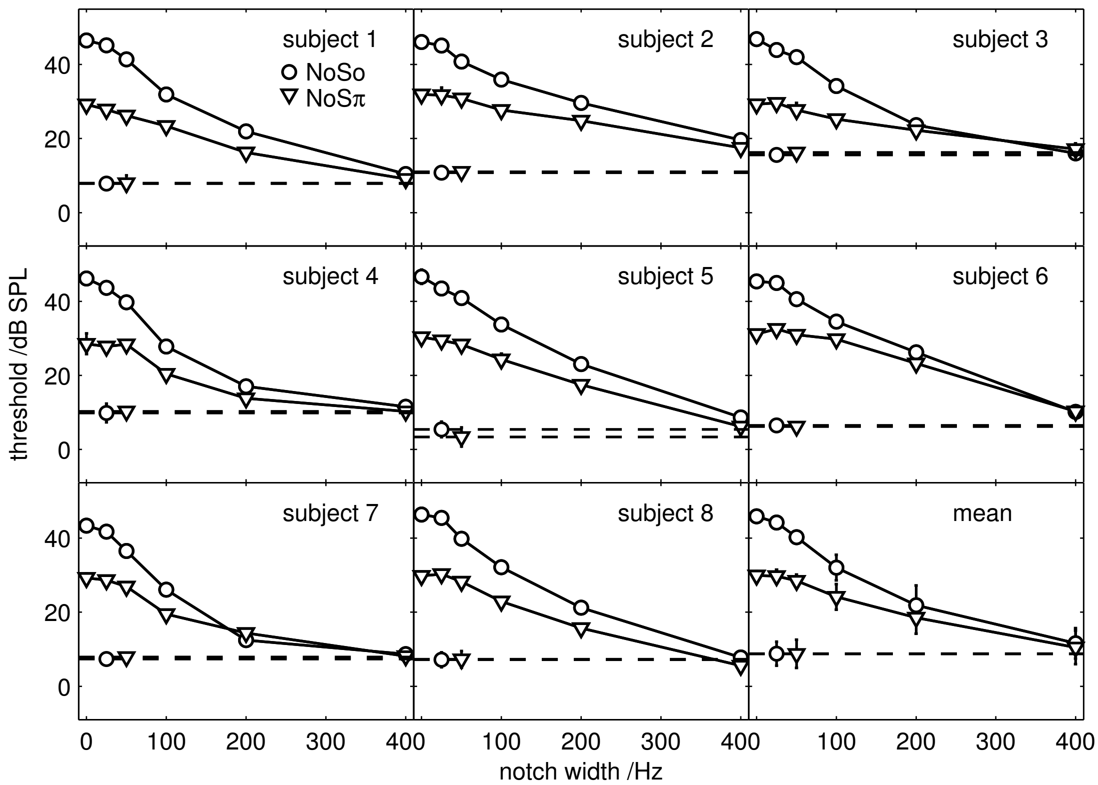

Figure A.3.: Detection thresholds for 250-Hz sinusoids in phase (So) or antiphase (Sπ) as a function of notch width of a diotic noise masker (No). Masker spectrum level was 30 dB/Hz. Dashed lines denote absolute thresholds. The lower right panel shows average thresholds. Error bars denote plus minus one intraindividual standard deviation for the individual thresholds and plus minus one interindividual standard deviation for the average thresholds. They are only shown when they exceed the size of the symbols.

A.2.1. Signal frequency 250 Hz

Fig. A.3 shows NoSo and NoSπ thresholds for a 250-Hz sinusoid as a function of notch width. Dashed lines denote absolute thresholds for So and Sπ sinusoids. Individual absolute thresholds are in a range from 3 dB (subject 5) to 16 dB SPL (subject 3). The BMLD of the absolute thresholds ranges individually from almost -1 to +2 dB, but the standard deviations of the corresponding thresholds exceeds twice the absolute value of the BMLD for every subject. Hence, absolute thresholds do not show a dependence on IPD. Diercks and Jeffress (1962) measured absolute thresholds for So and Sπ sinusoids of 250 Hz. For a 250-Hz sinusoid, they obtained absolute thresholds in a range between 25 to 30 dB SPL. Individual BMLDs ranged from 0.5 to 1.4 dB, i.e., they were within the range of BMLDs observed in the present study. In contrast to the present study, the individual BMLDs in Diercks and Jeffress (1962) were all positive resulting in an average BMLD of 0.9 dB compared to 0.0 dB in the present study.

Thresholds masked by a broadband masker without a notch show only small interindividual differences. Diotic thresholds are in a range from about 43 (subject 7) to 47 dB (subjects 3 and 5); dichotic thresholds range from below 29 (subject 4) to 32 dB (subject 2). With increasing notch width individual differences in thresholds increase: At the notch width of 400 Hz, diotic and dichotic thresholds range from 8 and 5.5 dB (subject 8) to 20 and 17.5 dB (subject 2), respectively. For all subjects except for subject 2, the 400-Hz threshold is close above absolute threshold. The difference of the NoSo threshold to absolute threshold for subject 2 is almost 9 dB.

In broadband noise without a notch, the BMLD varies individually between 14 (subject 2) and almost 18 dB (subjects 3 and 4). It decreases with increase in notch width and takes values that are about the size of the standard deviations of the corresponding thresholds (subject 8) or clearly below at a notch width of 400 Hz. The average BMLD is half the value of the BMLD in broadband noise at a notch width of 100 Hz already. Individual BMLDs at that notch width range from 5 (subject 6) to 9 dB (subjects 5, 8, and 3). The decay of BMLD with increasing notch width exhibits individual differences: At a notch width of 200 Hz, all individual subjects except for subject 3 and 7 show a BMLD above the size of the standard deviations of the corresponding thresholds.

Subject 2 whose thresholds at a notch width of 400 Hz were at least 6 dB above absolute threshold (NoSπ data) turned out to have the greatest auditory filter bandwidth: Best fitting parameters for the gammatone filter implementation by Hohmann (2002) were a filter order of two at a bandwidth of at least 1 ERB. Depending on the outer and middle ear filtering assumed for the power spectrum model used to derive the filter parameters (see Chapter 4, Sec. 4.3.1), the bandwidth might be 1.2 ERB as well. Other subjects also having a gammatone filter of second order as a best fit had filter bandwidths between 0.4 and 0.8 ERB. On the other hand, subject 2's diotic threshold data show that high thresholds at large notch widths do not necessarily have to mean high absolute thresholds, but merely wider auditory filters. Subject 3 not only had the highest absolute thresholds in the forced-choice measurement, but was the only subject with 10 dB HL on both ears in the audiogram, so this subject's hearing at this frequency was worse than the other subjects', who mostly had thresholds around 0 dB HL at 250 Hz.

Baker and Rosen (2006) measured NmSm thresholds in a notched-noise experiment to determine auditory filter shapes at different levels and frequencies. They used the threshold data for further analysis and showed only example data of one subject. In a broadband noise of 30 dB/Hz spectrum level this subject's NmSm threshold is in good agreement with the average NoSo threshold in a broadband masker of the present study. With increasing notch width, his thresholds tend to be higher than the average diotic thresholds of the present study, however they are in reasonable agreement with subject 2's diotic threshold data. Baker and Rosen (2006) estimated their subject's absolute threshold in the fitting procedure for the filter shapes and came to an estimate of 29 dB SPL for this subject. This is more than 12 dB above the highest absolute threshold at 250 Hz measured in the present study, but well in line with the absolute thresholds obtained by Diercks and Jeffress (1962).

A.2.2. Signal frequency 500 Hz

Fig. A.4 shows NoSo and NoSπ thresholds for a 500-Hz sinusoid as a function of notch width. Dashed lines denote absolute thresholds for So and Sπ sinusoids. Individual absolute thresholds are in a range from -3 (subject 5) to +6 dB SPL (subject 4). The BMLD of the absolute thresholds ranges individually from almost -0.5 to 1.4 dB, but the standard deviations of the corresponding thresholds exceeds the absolute value of the BMLD for every subject. Hence, absolute thresholds do not show a dependence on IPD. The BMLD for absolute thresholds of subject 5 is the largest of the eight subjects; the corresponding standard deviations are about the same size.

In a broadband masker without a notch, individual diotic thresholds vary between 44 (subject 7) and 47.5 dB (subject 4), dichotic thresholds are in a range from 30 (subjects 3 and 7) to 35 dB (subject 8). Diotic as well as dichotic thresholds in the 800-Hz notch width condition range from about -1 (subject 5) to 6 dB (diotic thresholds of subject 1 and 3). All thresholds at 800-Hz notch width are close to or close above absolute threshold.

The BMLD in a broadband masker varies from 12 (subject 2) to 16 dB (subject 4) and decreases with increasing notch width. The BMLD of most subjects

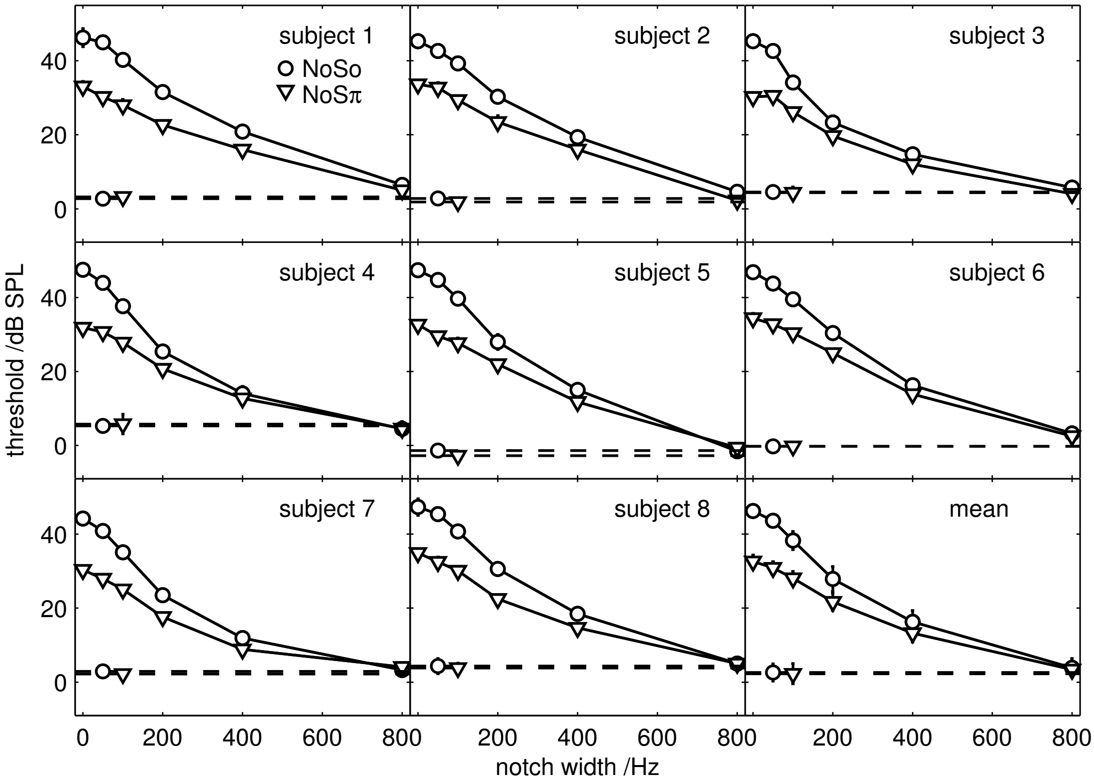

Figure A.4.: As in Fig. A.3, but for a signal frequency of 500 Hz

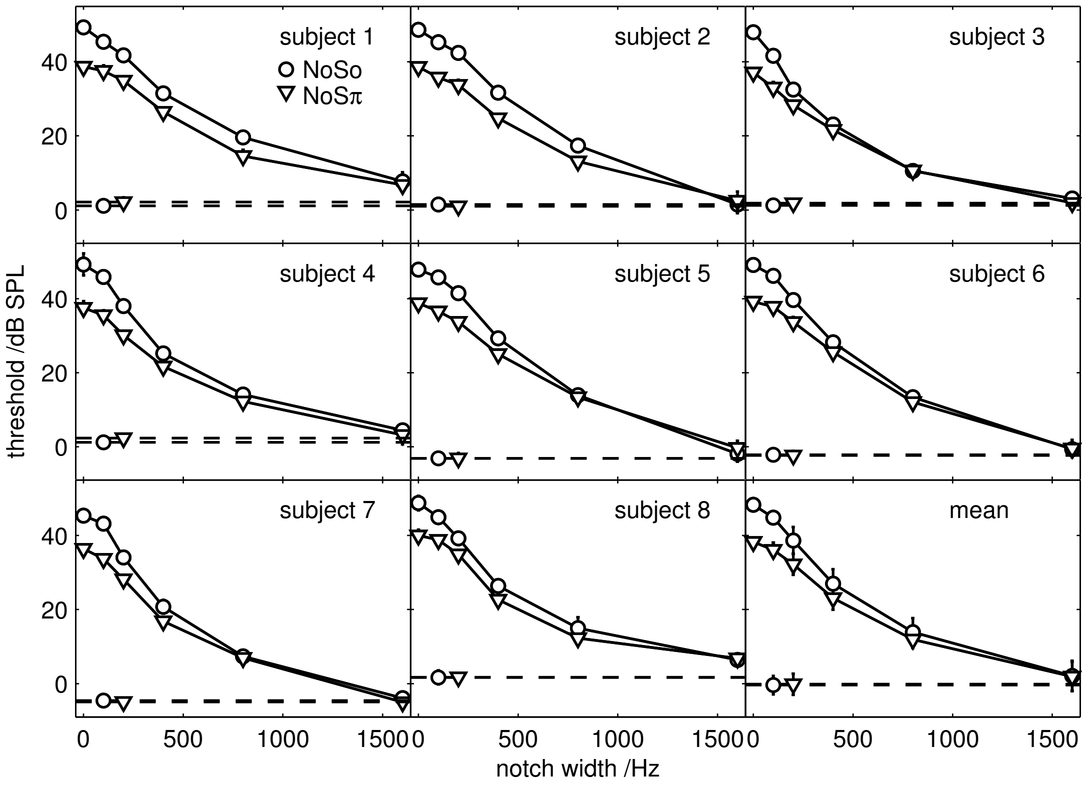

Figure A.5.: As in Fig. A.3, but for a signal frequency of 1000 Hz

is below half its size in broadband at a notch width of 200 Hz already. Subject 1, 2, and 8, however, show a BMLD larger than half the BMLD in broadband at a notch width of 200 Hz. Except for subjects 4 and 6, all subjects show a BMLD larger than the standard deviations of the corresponding thresholds at a notch width of 400 Hz. At 800-Hz notch width, finally, no individual BMLD exceeds the standard deviations of the corresponding thresholds.

A.2.3. Signal frequency 1000 Hz

Fig. A.5 shows NoSo and NoSπ thresholds for a 1000-Hz sinusoid as a function of notch width. Dashed lines denote absolute thresholds for So and Sπ sinusoids. Individual absolute thresholds are in a range from -5 (subject 7) to +2 dB SPL (subjects 1 and 4). The BMLD of the absolute thresholds ranges individually from almost -1 to +0.5 dB, but the standard deviations of the corresponding thresholds are at least about twice the absolute value of the BMLD for every subject. Hence, absolute thresholds do not show a dependence on IPD.

In a broadband masker without a notch, individual diotic thresholds are in a range from about 45 (subject 7) to 49 dB (subjects 1, 4, and 6); dichotic thresholds vary from about 36 (subject 7) to 40 dB (subject 8). At the largest notch width of 1.6 kHz, individual diotic and dichotic thresholds range from -5 (subject 7) to almost 8 dB (subject 1). The differences between individual diotic and dichotic thresholds are below the size of the respective standard deviations. The thresholds at this notch width are at or close above (up to 6 dB for subject 1) absolute threshold. At a fixed gammatone filter order of three, subject 1's filter-bandwidth estimate derived from the NoSo thresholds in a power spectrum model is 1.4 ERB. The next subjects in filter bandwidth are subjects 2 and 8 with 1.2 ERB wide gammatone filters of third order. Individual auditory filter bandwidths are given in Tabs. A.2.5 and A.4 below.

Individual BMLDs range from 9 (subjects 5, 7, and 8) to almost 12 dB (subject 4) in broadband noise. At a notch width of 400 Hz, subject 3 is the only one to show a BMLD below the standard deviations of the corresponding thresholds. At 800-Hz notch width, only subjects 1 and 2 show a BMLD larger than the standard deviations of the corresponding thresholds. At 1.6-kHz notch width, finally, all individual BMLDs are below the standard deviations of the corresponding thresholds.

A.2.4. Signal frequency 2000 Hz

Fig. A.6 shows NoSo and NoSπ thresholds for a 2000-Hz sinusoid as a function of notch width. Dashed lines denote absolute thresholds for So and Sπ sinusoids. Individual absolute thresholds are in a range from about -6 (subject 7) to 0 dB SPL (subjects 2 and 6). The BMLD of the absolute thresholds ranges individually from almost -1 to +2 dB, but the standard deviations of the corresponding thresholds at least exceed the absolute value of the BMLD for every subject. Hence, absolute thresholds do not show a dependence on IPD.

In a broadband masker without a notch, individual diotic thresholds are in a range from 50 (subjects 1 and 2) to 52 dB (subject 8); dichotic thresholds vary from about 42 (subjects 3 and 4) to 47 dB (subject 8). At a notch width of 3.2 kHz individual diotic and dichotic thresholds vary in a range between -7 (subject 7) and 3 dB (subject 2). The thresholds at this notch width are at or close above absolute threshold.

Individual BMLDs in broadband noise range from 5 (subjects 7 and 8) to 9 dB

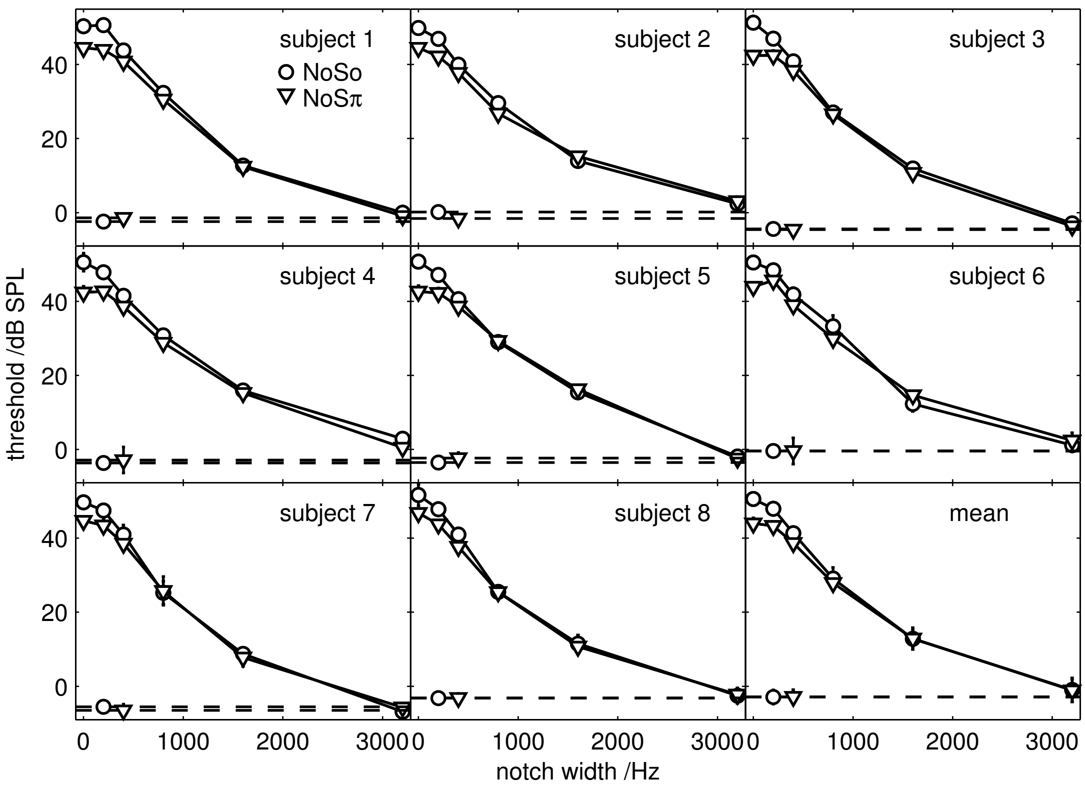

Figure A.6.: As in Fig. A.3, but for a signal frequency of 2000 Hz

Subject	1	2	3	4	5	6	7	8	mean
250 Hz, $n_{3\mathrm{dB}}$(NoSo) /Hz	36	37	25	28	24	40	32	34	33
250 Hz, $n_{3\mathrm{dB}}$(NoSπ) /Hz	50	81	72	68	63	103	55	59	68
250 Hz, $r(n_{3\mathrm{dB}})$	1.4	2.2	2.8	2.4	2.6	2.6	1.7	1.7	2.0
500 Hz, $n_{3\mathrm{dB}}$(NoSo) /Hz	68	55	52	42	53	49	44	61	53
500 Hz, $n_{3\mathrm{dB}}$(NoSπ) /Hz	54	81	85	82	48	79	61	63	72
500 Hz, $r(n_{3\mathrm{dB}})$	0.8	1.5	1.6	1.9	0.9	1.6	1.4	1.0	1.4
1 kHz, $n_{3\mathrm{dB}}$(NoSo) /Hz	77	90	47	89	121	101	109	78	86
1 kHz, $n_{3\mathrm{dB}}$(NoSπ) /Hz	170	108	74	119	129	139	106	147	121
1 kHz, $r(n_{3\mathrm{dB}})$	2.2	1.2	1.6	1.3	1.1	1.4	1.0	1.9	1.4
2 kHz, $n_{3\mathrm{dB}}$(NoSo) /Hz	288	201	140	208	166	228	225	156	210
2 kHz, $n_{3\mathrm{dB}}$(NoSπ) /Hz	357	232	346	348	344	290	270	199	300
2 kHz, $r(n_{3\mathrm{dB}})$	1.2	1.2	2.5	1.7	2.1	1.3	1.2	1.3	1.4

Table A.3.: 3-dB down notch widths $n_{3\mathrm{dB}}$ derived from the individual diotic and dichotic threshold curves in a piecewise linear fit. The rightmost column shows data derived from the average thresholds. $r(n_{3\mathrm{dB}})$ denotes the ratio of the dichotic divided by the corresponding diotic parameter.

(subject 3). All individual BMLDs are above the size of the standard deviations of the corresponding thresholds in the broadband and 200-Hz notch condition. At 400-Hz notch width, all subjects except for subject 5 and 7 show BMLDs above the size of the standard deviations of the corresponding thresholds. At 800-Hz notch width, only subjects 2 and 4 show BMLDs above the size of the standard deviations of the corresponding thresholds.

A.2.5. Auditory filter parameters

Tab. A.2.5 gives the notch widths $n_{3\mathrm{dB}}$ at which individual diotic or dichotic threshold has dropped 3 dB relative to the masker without a notch. The parameters were determined by a piecewise linear fit to the threshold data. $n_{3\mathrm{dB}}$ is independent of the assumption of any particular filter shape; however, this parameter depends only on the thresholds in the region about 3 dB down from the threshold in a broadband masker without a notch, not on all thresholds. $r(n_{3\mathrm{dB}})$ denotes the ratio of binaural divided by monaural filter-width estimate. Tab. A.4 gives the ERBs of gammatone filters of third order fitted to the individual diotic and dichotic thresholds using a power spectrum model. Before the auditory filtering a Butterworth band-pass filter of first order with cutoff frequencies at 500 Hz

Subject	1	2	3	4	5	6	7	8	mean
250 Hz, B(NoSo) /ERB	1.01	1.74	1.29	0.95	1.00	1.15	0.90	0.90	1.07
250 Hz, B(NoSπ) /ERB	2.43	3.00	3.00	2.53	1.97	2.47	2.22	1.86	2.54
250 Hz, r(ERB)	2.4	1.7	2.3	2.7	2.0	2.1	2.5	2.1	2.4
500 Hz, B(NoSo) /ERB	1.23	1.26	1.14	0.95	0.85	1.03	1.06	1.05	1.05
500 Hz, B(NoSπ) /ERB	2.36	1.92	2.33	2.30	1.83	1.80	2.26	1.97	2.03
500 Hz, r(ERB)	1.9	1.5	2.0	2.4	2.2	1.7	2.1	1.9	1.9
1 kHz, B(NoSo) /ERB	1.42	1.15	1.10	1.04	0.98	0.97	0.87	1.22	1.08
1 kHz, B(NoSπ) /ERB	2.02	1.78	1.95	1.98	1.63	1.53	1.34	1.79	1.78
1 kHz, r(ERB)	1.4	1.5	1.8	1.9	1.7	1.6	1.5	1.5	1.6
2 kHz, B(NoSo) /ERB	1.00	1.12	0.88	1.13	1.03	1.04	0.80	0.83	0.98
2 kHz, B(NoSπ) /ERB	1.27	1.51	1.24	1.49	1.46	1.42	1.01	1.09	1.28
2 kHz, r(ERB)	1.3	1.3	1.4	1.3	1.4	1.4	1.3	1.3	1.3

Table A.4.: Auditory filter bandwidths B derived from the individual diotic and dichotic threshold curves using a gammatone filter of third order in a power spectrum model. To facilitate a comparison across signal frequencies, filter bandwidths are given in ERB. The rightmost column shows data derived from the average thresholds. r(ERB) denotes the ratio of the dichotic divided by the corresponding diotic parameter.

and 5.3 kHz was applied as a simulation of outer and middle ear filtering. For details see Chapter 4, Sec. 4.4.1. For the gammatone filter fit of Tab. A.4, the Euclidean distance between individual thresholds and fit is below 10 dB for every subject.

The filter parameters derived from the average thresholds are discussed in Chapter 4, Sec. 4.3.1. Only the individual data will be discussed in the following beginning with the lowest signal frequency. Monaural and binaural 3-dB down notch widths $n_{3\mathrm{dB}}$ for the signal frequency of 250 Hz range from 24 to 40 Hz and 50 to 103 Hz, respectively. The smallest difference between monaural and binaural $n_{3\mathrm{dB}}$ is found in subject 1 with values of 36 and 50 Hz, i.e., a ratio of 1.4. The ratio averaged over subjects is 2.2 at a standard deviation of 0.5. For the same signal frequency, monaural and binaural gammatone filter bandwidths B range from 0.90 to 1.74 ERB and 1.86 to 3.00 ERB, respectively. For this auditory filter-width estimate, the smallest difference between monaural and binaural values is found in subject 2 with a ratio of 1.7. The ratio r(ERB) for subject 1 who showed the smallest difference in $n_{3\mathrm{dB}}$ is above the average for r(ERB) over subjects of 2.2 at a standard deviation of 0.3. This difference in the parameters derived from the same thresholds is due to the fact that $n_{3\text{dB}}$ relies on the thresholds about 3 dB below the threshold in broadband without a notch, whereas B reflects the whole threshold curve. Monaural and binaural 3-dB down notch widths $n_{3\text{dB}}$ for the signal frequency of 500 Hz range from 42 to 68 Hz and 48 to 85 Hz, respectively. Three subjects show monaural and binaural $n_{3\text{dB}}$ of the same size (subject 8) or even a smaller binaural than monaural $n_{3\text{dB}}$ (subjects 1 and 5). This is due to parallel curves of diotic and dichotic thresholds at narrow notch widths. $r(n_{3\text{dB}})$ below 1.0 are only found at this signal frequency and only for the 3-dB down notch widths. The average $r(n_{3\text{dB}})$ over subjects for 500 Hz is 1.3 at a standard deviation of 0.4. For the same signal frequency, monaural and binaural gammatone filter bandwidths B range from 0.85 to 1.26 ERB and 1.80 to 2.36 ERB, respectively. The smallest difference between binaural and monaural B is found in subject 2 with a ratio $r(\text{ERB})$ of 1.5. The average $r(\text{ERB})$ over subjects is 2.0 at a standard deviation of 0.3. Monaural and binaural 3-dB down notch widths $n_{3\text{dB}}$ for the signal frequency of 1000 Hz range from 47 Hz (due to a steep decrease of thresholds in subject 3) to 121 Hz and 74 to 170 Hz, respectively. Subject 7 shows comparable monaural and binaural $n_{3\text{dB}}$. The average $r(n_{3\text{dB}})$ over subjects is 1.5 at a standard deviation of 0.4. For the same signal frequency, monaural and binaural gammatone filter bandwidths B range from 0.87 to 1.42 ERB and 1.34 to 2.02 ERB, respectively. Subject 1 shows the smallest difference between monaural and binaural B with a ratio $r(\text{ERB})$ of 1.4. The average $r(\text{ERB})$ over subjects is 1.6 at a standard deviation of 0.2. Monaural and binaural 3-dB down notch widths $n_{3\text{dB}}$ for the signal frequency of 2000 Hz range from 140 Hz (subject 3 as for the 1-kHz signal frequency) to 288 Hz and 199 to 357 Hz, respectively. The average $r(n_{3\text{dB}})$ over subjects is 1.5 at a standard deviation of 0.5. For the same signal frequency, monaural and binaural gammatone filter bandwidths B range from 0.80 to 1.13 ERB and 1.01 to 1.51 ERB, respectively. As for the 1-kHz signal frequency, the ranges of individual monaural and binaural filter bandwidths B are overlapping which did not occur in the data for the lower signal frequencies. The average $r(\text{ERB})$ over subjects for 2 kHz is 1.3 at a standard deviation of 0.1. The standard deviation of the r average over subjects is smaller for $r(\text{ERB})$ than for $r(n_{3\text{dB}})$ for all signal frequencies. All individual ratios $r(\text{ERB})$ except for those of subject 5 decrease with increase in signal frequency. This trend is not found in the individual ratios $r(n_{3\text{dB}})$.

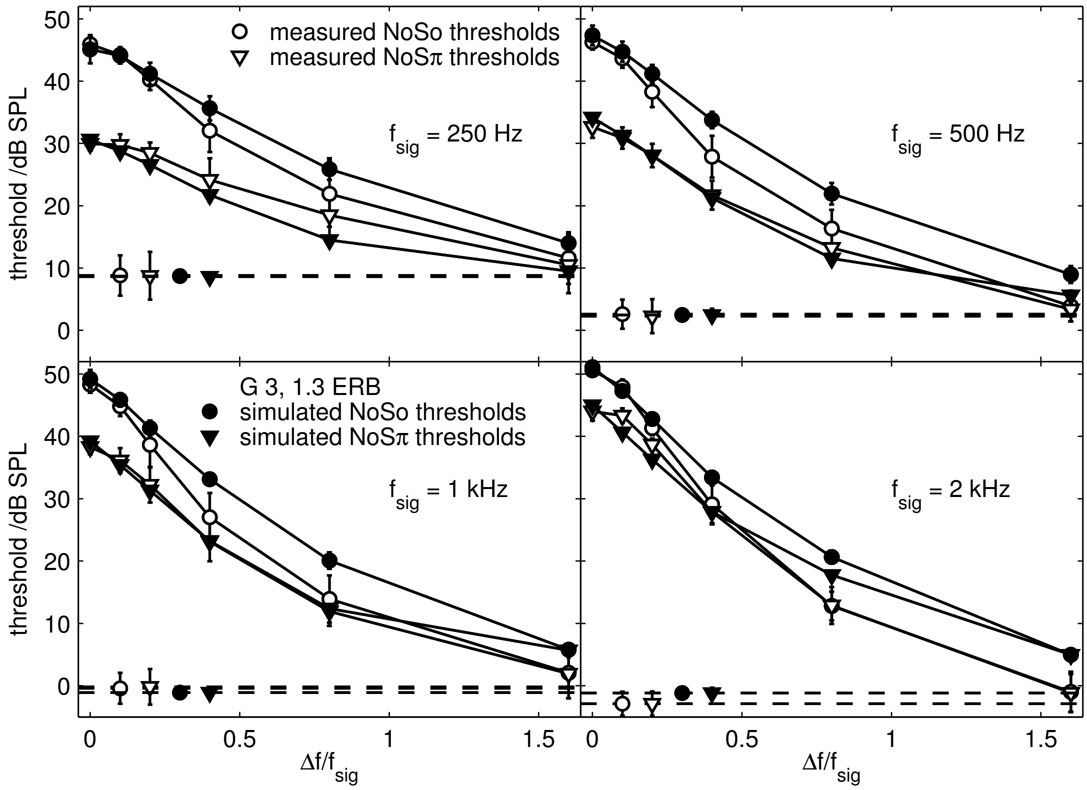

Figure A.7.: Measured thresholds as in Fig. 4.1. This model version used the same auditory filter bandwidth for diotic and dichotic simulations; gammatone filter bandwidth was fitted to obtain simulation results in good agreement with the measured *dichotic* thresholds. Error bars of the simulated thresholds denote plus minus one standard deviation of the predicted mean threshold. They are only shown when they exceed the size of the symbols.

A.3. Further model results for dichotic notched-noise masking

A.3.1. Filter parameters fit to dichotic thresholds

Fig. A.7 shows diotic (circles) and dichotic (triangles) simulated (filled symbols) and measured (open symbols) thresholds as functions of relative notch width. As in Fig. 4.6, linear gammatone filters were used for the simulation. Except for the bandwidth of the filters, all simulation parameters were the same. In contrast to Fig. 4.6, the gammatone filter bandwidth was made to fit the *dichotic* thresholds.

The same filter bandwidth was used to predict the diotic thresholds.

It was not possible to achieve reasonable predictions for all signal frequencies with the same gammatone filter bandwidth. The filters finally chosen were 1.3 ERB wide gammatone filters or third order, i.e., the filters were 0.3 ERB wider than those used for the simulation data shown in Fig. 4.6. Using these parameters most predicted dichotic thresholds of the signal frequencies 500 and 1000 Hz are in good correspondence with the measurement. The level of 2 dB of white noise added in the binaural model part seems to be too high since the predicted thresholds at the largest notch widths are about 2 and 4 dB higher than measured. Using the 1.3 ERB wide filter most dichotic threshold predictions are lower than measured for the 250-Hz signal frequency. For the dichotic thresholds at this signal frequency, 1.7 ERB wide gammatone filters of third order would yield a prediction in very good agreement with the measured thresholds. Hence, the binaurally increased filter width is more prominent for low signal frequencies.

As in the simulations shown in Figs. 4.6 and 4.8, the predicted BMLD is constant for all notch widths as long as thresholds are clearly above absolute threshold.

A.3.2. Filter parameters fit separately for every signal frequency

Fig. A.8 is presented to demonstrate that almost perfect fit is possible if the portions of the output of filters adjacent to the on-frequency filter may depend on the signal frequency. Note that the weight and the number of adjacent filters added to the on-frequency filter decreases with increasing signal frequency.

A.4. Spectrum levels of same loudness

Due to their hearing loss hearing-impaired (HI) subjects perceive stimuli differently to normal hearing. For this reason an attempt of this study was to present the stimuli at the same loudness as for normal-hearing subjects. This was achieved by evaluating the data of a categorical loudness scaling.

All HI subjects did a categorical loudness scaling (Brand and Hohmann, 2002). Third-octave bands centered at 125, 250, 500, and 1000 Hz were used. The noises were presented diotically via Sennheiser HDA 200 headphones.

In a first step the categorical loudness of the third-octave bands at spectrum

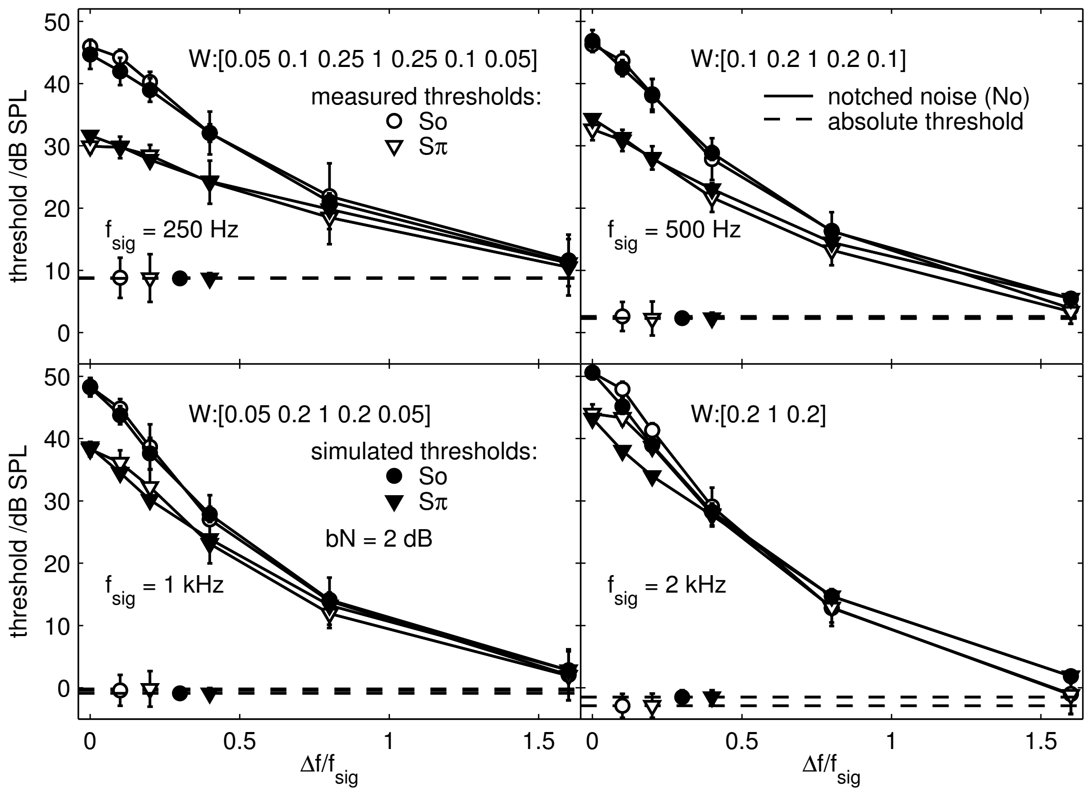

Figure A.8.: Measured thresholds as in Fig. 4.1. This model version used different weightings of the adjacent filters for every signal frequency. The parameters used are given in every panel. Error bars of the simulated thresholds denote plus minus one standard deviation of the predicted mean threshold. They are only shown when they exceed the size of the symbols.

levels of 10, 20, 30, 40, and 50 dB/Hz was estimated from norm data (normal-hearing average) of the loudness scaling. The spectrum levels of the noise maskers for each HI subject were changed so that the stimuli were of the same categorical loudness as for normal-hearing subjects. For the frequencies of 125, 250, 500, and 1000 Hz, the spectrum levels that produce the same loudness were gathered from the categorical loudness scaling. The values can be found in Tab. A.5. The normal-hearing (NH) data are given as a proof of concept: The procedure generating spectrum levels of the same loudness as for normal-hearing subjects should yield the same spectrum levels as those put into it. This is roughly the case with largest differences at the spectrum level of 10 dB/Hz. Between these four data points the spectrum level of same loudness was interpolated using a cubic spline interpolation. Below 125 Hz the same spline was used to extrapolate the data. A notch was applied into the noise spectrum after this procedure if desired.

Generally, the effective spectrum level was increased, especially for the low spectrum levels. However subject 8 had a smaller spectrum level of same loudness in the notched-noise experiment as a result of this subject's categorical loudness scaling.

The individual loudness fit was done with third-octave bands and not with the real masking noises, because normal-hearing loudness data were available without measurement for third-octave bands (and the third-octave band stimuli were already part of the categorical loudness scaling software).

All subjects did a categorical loudness scaling, but only five of them did a forced-choice measurement with individually fitted masker spectrum levels.

S 1	125 Hz	250 Hz	500 Hz	1000 Hz	S 2	125 Hz	250 Hz	500 Hz	1000 Hz
10	-19.2	7.1	35.8	39.9	10	49.3	41.4	39.3	33.3
20	-4.3	18.0	40.9	44.1	20	53.3	45.5	43.5	37.8
30	9.7	28.6	46.1	48.1	30	57.0	49.5	47.8	42.1
40	23.6	38.5	51.2	52.0	40	60.7	53.2	51.9	46.2
50	37.5	48.6	56.5	56.6	50	64.5	57.0	56.0	51.1
S 4	125 Hz	250 Hz	500 Hz	1000 Hz	S 6	125 Hz	250 Hz	500 Hz	1000 Hz
10	35.7	38.1	40.2	43.3	10	33.0	30.0	27.7	36.8
20	41.5	43.8	44.6	47.7	20	38.9	36.8	33.7	42.1
30	47.1	49.3	49.2	51.9	30	44.4	43.4	39.8	47.1
40	52.5	54.4	53.5	55.7	40	49.8	49.6	45.7	51.6
50	58.0	59.7	57.8	59.9	50	55.3	56.0	51.5	56.8
S 8	125 Hz	250 Hz	500 Hz	1000 Hz	NH 1	125 Hz	250 Hz	500 Hz	1000 Hz
10	19.6	18.7	18.9	23.3	10	6.2	14.5	10.3	10.2
20	28.1	26.9	24.5	30.1	20	16.6	23.7	20.2	20.6
30	36.0	34.8	30.3	36.4	30	26.4	32.6	30.3	30.3
40	43.9	42.2	35.9	42.2	40	36.0	41.0	40.0	39.2
50	51.8	49.8	41.6	48.6	50	45.8	49.6	49.3	49.2

Table A.5.: Spectrum levels of individually fitted loudness. All quantities without unit are spectrum levels in dB/Hz. The numbers 10 to 50 in the left columns are the spectrum levels used in the equal-masker-level condition of the experiment, the other numbers are the spectrum levels interpolated to achieve the same loudness as for normal-hearing subjects. As a proof of concept data of a normal-hearing subject are given at the bottom of the table.

B. Binaural masking patterns[1]

As seen in the NoSo and NoSπ thresholds in the notched-noise experiment, the BMLD starts to decrease when the signal frequency is located outside the spectrum of the masking noise. Aside from the notched-noise experiment psychoacoustic masking patterns are another masking experiment in which the spectral position of signal and masker is such that in some conditions the signal lies within the masker spectrum and in others it lies outside.

The history of masking patterns began as a “masked audiogram” when Wegel and Lane (1924) measured thresholds for pure tones of various frequencies in the presence of a tonal masker of a fixed frequency. The result of such an experiment was called a masking pattern or masked audiogram because of the similarity in measurement to an audiogramm. Various interactions between the tonal signal and the tonal masker lead to thresholds for the signal that depend rather on the tones’ frequency ratio or difference than display the excitation by these two tones only. For this reason Fletcher and Munson (1937) used narrowband noise instead of a tone as a masker. Egan and Hake (1950) present masking patterns for a tonal masker as well as for a narrowband noise masker.

The aim of the present study was to remasure some conditions of the binaural masking patterns by Zwicker and Henning (1984) using an adaptive forced-choice paradigm instead of a Békésy tracking procedure.

B.1. Methods

Apparatus and procedure were the same as described in Chapter 3 unless otherwise stated. The noise masker was generated in the frequency domain. Its spectrum level was 50 dB/Hz. The noise masker was centered either at 250 or 500 Hz.

[1] Three of the four experiments of this chapter were part of a bachelor thesis (Yango, 2007) co-supervised by the author.

[2] Noise masker bandwidths were either 10 or 100 Hz. For the masker center frequency of 250 Hz, the target signal frequency was varied between 160 and 340 Hz in steps of 30 Hz. For the masker center frequency of 500 Hz, the target signal frequency was varied between 410 and 590 Hz in steps of 30 Hz.

The experiments in which the masker was centered at 250 Hz and the experiment with the 10-Hz wide masker centered at 500 Hz were part of a bachelor thesis (Yango, 2007). The experiment with the 100-Hz wide masker centered at 500 Hz was conducted after this bachelor thesis had been completed. In addition, some remeasurements were conducted to fulfill the requirements given in Sec. 5.2.2. Subjects ar, ay, and sg of Yango (2007) participated in the present study. Two additional new subjects participated as well. Three of the five subjects were female. The subjects were aged between 18 and 30 years (mean 24 years). They were all paid volunteers including the student who conducted the experiments. All subjects had normal audiograms with hearing thresholds lower than or equal to 10 dB HL at the standard audiometric frequencies at least in the frequency range relevant for the experiments.

B.2. Results and Discussion

Fig. B.1 shows diotic (circles) and dichotic (triangles) masked thresholds for a sinusoidal signal as a function of its frequency. The diotic masking noise was arithmetically centered at 250 Hz (left panels) or 500 Hz (right panels). Masker bandwidth was 10 Hz (upper panels) or 100 Hz (lower panels). The edges of the maskers are denoted by the dotted vertical lines. Error bars denote plus minus one interindividual standard deviation. They are only shown when they exceed the size of the symbol. The gray dashed lines denote the mean of threshold data at the spectrum levels of 40 and 60 dB/Hz measured by Zwicker and Henning (1984) at the corresponding masker bandwidths.

The threshold data in Fig. B.1 are similar to those measured by Zwicker and Henning (1984): A large BMLD is measured when the signal lies within the spectrum of the masker; The BMLD drops rapidly, particularly in the 10-Hz wide masker, when the signal is outside the masker spectrum. Except for the 10-Hz

[2]The measurement by Zwicker and Henning (1984) was only for a masker center frequency of 250 Hz, but two masker spectrum levels (40 and 60 dB/Hz), three noise masker bandwidths (10, 31.6, and 100 Hz), and one more interaural condition (NπSo).

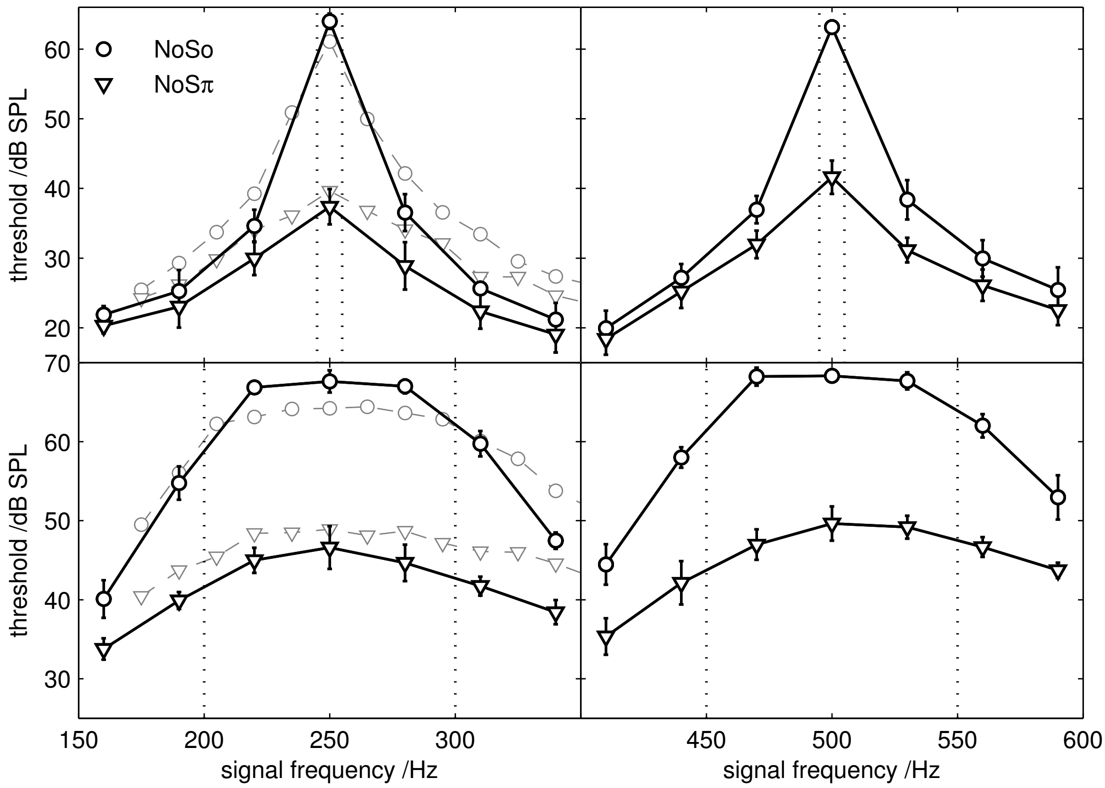

Figure B.1.: Masked detection thresholds for sinusoids as a function of sinusoid frequency. The IPD of the signal was zero (So, circles) or 180 degree (Sπ, triangles). The masker was centered at 250 Hz (left panels) or 500 Hz (right panels). Masker bandwidth was 10 Hz (upper panels) or 100 Hz (lower panels). The edges of the maskers are denoted by the dotted vertical lines. Error bars denote plus minus one interindividual standard deviation. They are only shown when they exceed the size of the symbol. The gray dashed lines denote threshold data derived from the thresholds measured by Zwicker and Henning (1984).

wide masker centered at 250 Hz the threshold data curves exhibit a smaller decrease towards higher than towards lower signal frequencies. This is probably due to the “upward spread of masking” that increases with increase in masker level. For monaural stimuli, this effect was already observed by, e.g., Egan and Hake (1950) (for a possible explanation see Moore and Glasberg, 1983, 1987).

The diotic thresholds for the signals at the noise center frequency show a larger dependence on masker bandwidth than on noise center frequency; at the noise bandwidth of 10 Hz, they are 63 and 64 dB. The corresponding diotic thresholds in the 100 Hz wide masker are around 68 dB. The BMLD is larger for the narrower noise-masker bandwidth and for the lower signal frequencies. The largest BMLD of almost 27 dB is measured at 250 Hz in the 10 Hz wide masker. The BMLDs at 250 Hz in the 100 Hz wide masker and at 500 Hz in the 10 Hz wide masker are of the same size, about 21 dB. The smallest BMLD of almost 19 dB is measured at 500 Hz in the 100 Hz wide masker. This is still larger than the 15 dB measured at 500 Hz in a broadband masker of the same spectrum level (Chapter 3). As a result of a 3 dB higher diotic and a 2 dB lower dichotic threshold the BMLDs at 250 Hz measured in the present study exceed those from the data interpolated from Zwicker and Henning (1984) by at least 5 dB. The differences might result from the different detection cue in diotic and dichotic masking condition in combination with a Békésy tracking procedure (Zwicker and Henning, 1984) in contrast to a forced-choice experiment in the present study.

Diotic and dichotic thresholds decrease when the signal frequency is outside the noise masker spectrum. Due to the steeper decrease in diotic thresholds the BMLD diminishs. In the experiment with the 10 Hz wide masker centered at 250 Hz, the BMLD is above the size of the standard deviations of the corresponding thresholds only for the signal frequencies of 250 and 280 Hz. At the signal frequencies of 220 and 310 Hz, the BMLD is about the size of the standard deviations; for the remaining signal frequencies, it is clearly below. In the experiment with the 10 Hz wide masker centered at 500 Hz, the BMLD is above the size of the standard deviations of the corresponding thresholds only at the signal frequencies of 470, 500, and 530 Hz. The BMLD always exceeds the size of the standard deviations of the corresponding thresholds in the 100 Hz wide masker.

The single-filter model and seven-filter model described in Chapter 4 both yield dichotic thresholds in resonable agreement with the measured thresholds. The difference between the predicted thresholds of single-filter model and seven-filter model is small. Both model versions underestimate the decline of thresholds outside the 10 Hz wide masker. Despite of the use of a gammatone filterbank the model seems not to be able to predict the asymmetry in threshold curves attributed to the upward spread of masking. This is probably due to the linear, level-independent auditory filtering. The steep decrease of diotic thresholds outside the noise-masker spectrum can be modeled using a modulation filterbank (Dau *et al.*, 1997) as shown by Derleth and Dau (2000).

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Erklärung

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbständig verfasst und nur die angegebenen Hilfsmittel verwendet habe.

Magdeburg, 2. Juni 2010

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Marc Nitschmann