Zur Homepage der Dissertation

Towards a neurophysiological correlate of the precedence effect: from psychoacoustics to electroencephalography

Vom Institut für Physik der Universität Oldenburg

zur Erlangung des Grades eines

Doktors der Naturwissenschaften (Dr. rer. nat.)

angenommene Dissertation

Jörg Damaschke

geb. am 29. November 1973

in Delmenhorst

Erstreferent: Prof. Dr. Dr. Birger Kollmeier

Korreferent: Prof. Dr. Volker Mellert

Tag der Disputation: 28. April 2004

Contents

1 General introduction **1**

2 Adaptation of the precedence effect **7**

2.1 Introduction 8

2.2 Methods 12

2.2.1 Apparatus 12

2.2.2 Subjects 12

2.2.3 Stimuli and paradigms 12

2.3 Results 19

2.3.1 Further analysis 23

2.4 Discussion 28

2.4.1 Adaptation processes of the precedence effect 29

2.4.2 Speed-accuracy trade-off 31

2.4.3 3-AFC versus 'pick-out' paradigm 32

2.4.4 Theoretical approach 34

2.5 Conclusions 36

3 Lateralization and discrimination **39**

3.1 Introduction 40

3.2 Methods 43

3.2.1 Apparatus 43
3.2.2 Subjects 43
3.2.3 Paradigms and stimuli 43
3.2.4 Experiment I and II, the adaptive 1-up-2-down 3-I 6-AFC procedure 45
3.2.5 Experiment III, the 'pick-out' procedure 47
3.3 Results 49
3.4 Discussion 57
3.4.1 The relation between discrimination and lateralization thresholds 58
3.4.2 The usage of monaural and binaural cues in the discrimination task of chapter 2 60
3.4.3 Adaptation effects 61
3.5 Conclusions 63

4 Neural correlates of the precedence effect **65**

4.1 Introduction 66
4.2 Methods 70
4.2.1 Apparatus 70
4.2.2 Subjects 71
4.2.3 Paradigm and stimuli 71
4.2.4 Data analysis 73
4.3 Results 74
4.3.1 Results of ABR recordings 74
4.3.2 Results of CAEP recordings 79
4.3.3 Relation between MMN components and performance in discrimination tasks 84

4.4 Discussion 88

4.4.1 Relation between ABRs and the precedence effect 88

4.4.2 Relation between CAEP and the precedence effect 92

4.5 Conclusions 94

5 Summary and outlook 97

Bibliography 105

Chapter 1

General introduction

Most of our time we spend in reverberant environments. Sound which is emitted in these environments not only reaches our two ears on the direct path but is reflected by walls, ceilings or furnishings and, therefore, reaches our ears from several additional directions. Hence, interaural parameters, e.g., the interaural time difference (ITD) and interaural level difference (ILD) of the direct sound differs from these parts of the indirectly received sound. Despite these contradictory directional information, our auditory system manages very well to localize sound sources in reverberant spaces. This ability is thought to be assisted by the *precedence effect* (Wallach et al., 1949) which is a well known term in the scope of psychoacoustics. The precedence effect groups together several phenomena which have in common that the perception of directional information provided by an indirect sound is strongly influenced by the presence of the direct sound. Hence, the precedence effect is a fundamental phenomenon in the scope of auditory grouping. For this reason, investigating the precedence effect sheds light on the formation of spatial auditory objects on the bases of binaural sound features and helps to characterize the ability to localize auditory objects in complex auditory scenes. The current thesis therefore investigates the precedence effect using the objective method of auditory evoked potentials (AEP).

Since sounds of our daily environment are too complex for a systematic investigation of the influence of various stimulus parameters, dependencies between direct sounds and their respective reflections are investigated in laboratories with simplified sounds. This is mostly done by using brief tone pulses for the direct sound which will in this thesis be referred to as the 'lead' stimulus. Commonly, reflections are also modelled as brief tone pulses with the same intensity as the lead click. In this thesis, a single reflection of equal intensity as the direct sound is considered and is referred to as the 'lag' stimulus.

In general, Wallach et al.'s finding has been confirmed in many subsequent studies that can be separated in several groups according to the tasks which was assigned to the subjects and the different perceptual phenomena, respectively. The precedence effect itself splits up in at least three different subgroups which was, e.g., described by Litovsky et al. (1999):

- *fusion:* in experiments where the aspect of fusion is considered, subjects are commonly asked to indicate whether they perceived one or two auditory events. Thus, these kind of experiments determine the *echo threshold*, i.e., the lead-lag delay where subjects begin to perceive the lag as a second auditory event (echo). For transient stimuli, lead and lag are perceived as a single auditory event if the lead-lag delay is shorter than 2 ms. Lead and lag contribute their directional information equally to the compound auditory object. Such experiments were, e.g., performed by Freyman et al. (1991) or Krumbholz and Nobbe (2002). Situations where a fused object splits up into two auditory events by changing the roles of lead and lag were described by Clifton (1987).

- *localization dominance:* localization dominance refers to the fact that the position of the lead dominates the perceived location of the compound stimulus of lead and lag. For lead-lag delays from 2 ms to 5 ms lead and lag still fuse to a single auditory event and the compound stimulus is perceived at or near the position of the lead. Subjects in experiments that refer to localization dominance are commonly asked to localize/lateralize stimuli with lead-lag delays below the echo threshold. Such results were, e.g., obtained by Shinn-Cunningham et al. (1993), Shinn-Cunningham et al. (1995), Tollin and Henning (1998) and Tollin and Henning (1999).

- *discrimination suppression:* for lead-lag delays from 2 ms to 5 ms changes in the lag are more difficult to perceive as similar changes in the lead. Experiments where the aspect of discrimination suppression is addressed, subjects are usually asked to discriminate positions of the lagging sound. These kind of measurements were performed, among others, by Saberi and Perrott (1990), Litovsky and Macmillan (1994) or Yang and Grantham (1997).

Relations among these three phenomena were described, e.g., by Litovsky and Shinn-Cunningham (2001).

In recent physiological studies researchers investigated response patterns of neurons of the auditory pathways in several animals (e.g., barn owl, Keller and Takahashi (1996), rabbit, Fitzpatrick et al. (1995) and cat, Litovsky (1998); Litovsky and Yin (1998); Litovsky and Delgutte (2002); Yin (1994)). For spatially separated sounds they found neurons that show precedence-like response patterns, i.e., for lead-lag delays shorter than the recovery time of the neurons, a response to the lead stimulus is observable whereas the response to the lag is suppressed (depending on the spatial separation of both stimuli). For increasing lead-lag delays the neurons show a gradually increasing response to the lag stimulus.

Previous neurophysiological studies that investigated the processing of spatial sound features in the human auditory system made use of AEP, i.e., recording the electroencephalogram while presenting acoustical stimuli. Due to their latency range AEPs can be divided into three groups: auditory brainstem responses (ABRs) cover the first 10 ms after stimulus onset whereas middle latency responses cover the time interval from 10 ms to 50 ms after stimulus onset. Cortical auditory evoked potentials (CAEP) cover the time interval from 50 ms after stimulus onset.

Several researchers showed that the mismatch negativity (MMN) which is a component of the CAEP is a useful tool to elucidate the processing of directional information by the auditory system (see, e.g., Paavilainen et al., 1989; Schröger, 1996; Schröger and Eimer, 1996; Schröger et al., 1997; Schröger and Wolff, 1996; Damaschke et al., 2000). The MMN is elicited if any infrequent discriminable change in a sequence of repetitive auditory stimuli occurs. This component was first described by Näätänen et al. (1978). For a comprehensive overview see, e.g., Lang et al. (1995); Csepe and Molnar (1997); Näätänen (1995); Näätänen and Alho (1997). Commonly, the MMN is obtained by subtracting the recorded potential of a frequently presented stimulus (reference) from that of an infrequent and randomly presented stimulus (deviant). This definition is shown to be reasonable, although different definitions are conceivable (see, e.g., Damaschke et al., 1998).

So far, to the best knowledge of the author, no neurophysiological investigations of the precedence effect in humans have been published. Hence, the aim of this thesis is to find a neurophysiological correlate of the precedence effect in humans using AEPs. In order to locate the generation of the precedence effect within ascending levels of the human auditory pathway, different latency ranges of the AEP are considered.

In general, if one wants to find a neurophysiological correlate of a psychoacoustical effect one first has to investigate the perception of this effect in psychoacoustical experiments using the same stimuli and paradigms as employed in neurophysiological measurements. In order to improve the significance of the comparison between results of the subjective (psychoacoustical) and objective (AEP) measurements of this thesis, stimulus presentations of both types of measurements had to be equalized.

Chapter 2 and chapter 3 investigate the perception of stimuli that evoke the precedence effect under conditions of continuous stimulation. Common psychophysical methods are not adapted to the comparison with electroencephalographical data because only a few stimuli are presented prior to the subjects' decision about his/her perception. In contrast, in most EEG studies stimuli are presented continuously and periodically in order to obtain a sufficient signal-to-noise ratio of the stimulus-related auditory evoked potentials that are usually very small (about one microvolt) in comparison with the EEG noise, i.e., the stimulus-unrelated brain activity.

To the best knowledge of the author, nothing is known about the perception of stimuli that evoke the precedence effect under conditions of continuous stimulation, i.e., under conditions of AEP recordings. Therefore, chapter 2 deals with adaptation processes caused by continuous stimulation. This is done by performing several discrimination tasks, i.e., subjects had to separate dichotic stimuli (lag-ITD $\neq$ 0 μs) from diotic stimuli (lag-ITD = 0 μs), that vary from single presentation to continuous presentation mode. Additionally, the stimulus timing uncertainty is varied which includes the introduction of the 'pick-out' paradigm that is adapted from the stimulus presentation during EEG recordings. Although presenting clicks that only do carry ITDs and no ILDs is an artificial situation for the auditory system most experimenters use such artificial clicks for the sake of simplicity. In real life an interaural time delay is always accompanied by an interaural level difference due to the shadowing effect of the listener's head. However, applying simplified artificial stimuli, interaural parameters as well as the lead-lag delay can be adjusted very easily. This would be more difficult using more realistic stimuli. Nevertheless, experimenters begin to use more realistic stimuli in order to quantify influences exerted by the lead on the lag and vice versa (see, e.g., Otten, 2001).

In chapter 2 subjects were asked to indicate *any* perceived difference between the stimuli. Hence, *discrimination* thresholds were determined. In chapter 3, however, subjects were asked to indicate whether differing stimuli were perceived on the left or right hand side so that *lateralization* thresholds were determined. In other words, measurements of chapter 2 determine just noticeable difference in the perceived cues of a stimulus and measurements of chapter 3 determine just noticeable differences that are sufficient to be interpreted as a directional cue. By combining the results of chapter 2 and chapter 3, the extent can be quantitatively assessed in which directional (binaural) and other cues, e.g., spectral cues (monaural), are used in discrimination tasks.

In chapter 4 ABRs and CAEPs are recorded and analyzed applying stimuli that evoked the precedence effect in the psychoacoustical experiments. CAEP were determined according to the paradigm of the MMN. In order to find a neurophysiological correlate of the precedence effect, psychoacoustical data obtained in chapters 2 and 3 were compared with the neurophysiological data obtained in chapter 4.

Finally, chapter 5 summarizes all results and gives an outlook of what will be done in future experiments.

Chapter 2

Adaptation mechanisms of the precedence effect in situations with multiple reference presentations

ABSTRACT

In order to examine adaptation mechanisms in the precedence effect, the influence of multiple presented reference stimuli as well as the influence of continuous stimulation on the discrimination thresholds for a lag-ITD were determined as a function of adaptation to the reference stimulus. Therefore, double click-pairs were presented where the first click-pair (lead) was presented diotically (leag-ITD = 0 μs) and the second click-pair was presented either diotically (lag-ITD = 0 μs, reference) or dichotically (lag-ITD $\neq$ 0 μs). The lead-lag delay was varied from 0 ms to 20 ms and the subjects had to indicate stimuli deviating from the reference condition.

Several experiments were performed that vary in timing and number of presented reference stimuli. In the non-continuous mode, an increasing number of reference stimuli are presented. Results indicate that discrimination thresholds *decrease* with increasing number of reference stimuli presented before the deviant in a non-continuous presentation mode. In contrast, *increased* discrimination thresholds were obtained

using continuous stimulation. The results provide evidence for a more distinct internal representation of the reference condition with repeated stimuli that is overruled by timing uncertainties in the continuous stimulation mode.

2.1 Introduction

If a sound is emitted in a reverberant environment, it reaches a listener's ear on the direct path and, additionally, on several longer indirect paths that include reflections from one or more surfaces. Despite the fact that ambiguous directional information is provided at the listener's ears by the direct sound and the reflections, the ability to localize the sound source is in general not disturbed. Usually, our auditory system manages very well to localize the sound source by extracting the directional information contained in the direct sound and to ignore similar information provided by the reflections.

More than 50 years ago Wallach et al. (1949) established the term 'precedence effect' which is also known as the 'Haas effect', 'law of the first wavefront' or 'echo suppression'. It refers to a group of auditory phenomena in (simulated) spatial listening conditions that relate to the fact that the direct sound (lead) dominates the directional information provided by the reflections (lags). More precisely, if two successive sounds are presented with a short delay ($<$ 5 ms) the compound stimulus of lead and lag is perceived as a single auditory event. For lead-lag delays up to 2 ms lead and lag contribute their directional information equally to the perceived location (fusion) and for lead-lag delays from 2 ms to 5 ms the perceived location is dominated by the directional information provided by the first arriving sound whereas the directional information of the second sound is suppressed (localization dominance). Since then, several experimenters investigated the relation between the information which is provided by the lead and the lag which is used to localize a sound. This has either been done in free-field studies (see, e.g., Clifton, 1987; Freyman et al., 1991; Shinn-Cunningham et al., 1993; Litovsky and Macmillan, 1994) or in headphone studies (see, e.g., Saberi and Perrott, 1990; Tollin and Henning, 1998, 1999). Some recent publications also use virtual acoustics to investigate aspects of the precedence effect (Otten, 2001).

A large number of studies on different aspects of the precedence effect confirm that directional information of the lag seems to be suppressed by the presence of the lead. Further studies showed that subjects do not have difficulties to discriminate a single click-pair from a double click-pair even if the double click-pair is perceived as a single auditory event due to a very short lead-lag delay. Features like timbre and the extent of the auditory object are still influenced by the presence of the lag (see, e.g., Blauert, 1997; Litovsky et al., 1999) indicating that only the directional information and not most of the other features of a double-click pair are influenced by the precedence effect.

In order to determine discrimination, lateralization or echo thresholds many researchers employed either adaptive runs (see, e.g., Saberi and Perrott, 1990; Litovsky and Macmillan, 1994; Yang and Grantham, 1997; Tollin and Henning, 1998; Krumbholz and Nobbe, 2002) or they determined psychometric functions by applying several fixed ITDs (see, e.g., Zurek, 1980; Gaskell, 1983; Yost and Soderquist, 1984; Perrott et al., 1989; Freyman et al., 1991; Shinn-Cunningham et al., 1993; Stellmack et al., 1999). For example, in their recent study, Tollin and Henning (1998) determined 'ITD thresholds'. They employed a lateralization task using a two-interval setup, where each interval contains one double click-pair. The first interval contained either a positive or negative (probability 0.5) lag-ITD and the second interval contained the time-inverted signal of the first interval. Subjects had to indicate which of both intervals they perceived farthest to the left. In this way, Tollin and Henning determined lag-ITD values that yield a reliable lateralization as a function of the lead-lag delay.
However, all the above mentioned procedures have in common, that the stimulation is stopped after a few presentations (mostly one or two intervals containing one or two click-pairs) and subjects are asked for their response. In contrast, in real-life conditions, spatially localized sound sources are received continuously by our auditory system. This is also similar in EEG experiments using the MMN where a

reference stimulus is presented continuously (randomly interrupted by a deviant). To our knowledge, however, it is unclear whether the precedence effect also occurs under such conditions of continuous stimulation or what kind of influence on the discrimination threshold of a lag-ITD is exerted by continuous stimulation.

Indeed, in the scope of the precedence effect the so-called buildup effect occurs if multiple click-pairs are presented and the subjects are asked to indicate whether they perceived one or two auditory events. The buildup effect then leads to a strengthened fused image, i.e., the lag is perceived as fading off with repeated presentations (Litovsky et al., 1999). Due to this adaptation effect, the *echo threshold* which is commonly defined as the lead-lag delay where the lag is perceivable as a second auditory event, is increased in a multiple reference stimulation mode compared to a single reference presentation mode (see, e.g., Krumbholz and Nobbe, 2002). In another study Freyman et al. (1991) determined echo thresholds as a function of the number of click-pairs preceding the test click-pair. In order to indicate the test click-pair, it was presented after a 750 ms break after a train of reference clicks. Subjects were asked whether they perceived an echo in the test click. As a result, the echo threshold was increased if a click train preceded the test click. Up to nine clicks led to an increase of the echo threshold independent of the click rate or duration of the preceding click train. In addition, using a procedure similar to Freyman et al., studies performed by Djelani (2001) revealed that the buildup effect is specific for one direction and is not affected by the presentation of a single stimulus from another direction. Furthermore, Djelani determined a mean value of 4.5 ms for the half-life of the buildup effect by varying the duration of the temporal gap between the preceding conditioning click-train and the target click.

In order to investigate what kind of adaptation processes in the precedence effect occur if the stimulus presentation is adapted towards real-life conditions, discrimination thresholds of a lag-ITD are determined as a function of the lead-lag delay in several experiments. In all experiments performed here lag-ITD values are determined where subjects were able to discriminate reliably sounds with (deviant stimulus) from sounds without inserted lag-ITD (reference stimulus). The stimulation was adapted towards real-life conditions in two senses: first, the stimulation is varied from solitary to continuous presentation because in real-life our auditory system also receives sounds continuously. Thereby, a continuous presentation mode may influence the discrimination thresholds in at least two ways: on the one hand as subjects are forced to respond very quickly compared to a solitary presentation mode, a kind of speed-accuracy trade-off is conceivable which may lead to increased discrimination thresholds. On the other hand as more information about the reference stimulus is provided if it is presented repeatedly, a continuous presentation may also lead to decreased discrimination thresholds. Different experiments were performed in order to be able to distinguish between these two opposite effects. Second, procedures differ due to their stimulus timing uncertainty. This accounts for the fact that in real-life abrupt changes of the location of a sound source may not always be predictable for the auditory system. Discrimination threshold are expected to depend on this stimulus timing uncertainty because the predictability of the occurrence of reference stimuli may enable a build up of a precise internal representation which is expected to facilitate the discrimination task yielding lower thresholds.

Inserting an ITD in the lag is a change of an interaural parameter. Nevertheless, subjects in this study were, unlike to other studies, not asked to discriminate perceived lateralizations[1]. Instead, they were asked to indicate *any* difference between double click-pairs with or without inserted lag-ITD. This task is more general as commonly used in the literature where mostly subjects were asked to discriminate directions.

Obviously, discrimination judgements obtained here are not necessarily based on lateralization cues only but may as well be based on *any* cue like timbre or changes of the spatial extent. At least the general discrimination task of the current experiments may therefore be easier for the subjects to perform as they do not have to distinguish between several sound features such as timbre, spaciousness or lateralization at the same time but they can concentrate on indicating any deviation.

[1] Unlike the localization of a sound at an external position of the head which occurs in a free-field arrangement, hearing via headphones leads to a perception of a position within the head which is commonly called lateralization.

2.2 Methods

2.2.1 Apparatus

All psychophysical experiments were performed in a double-walled sound proof booth (IAC 1203A). Signal generation and presentation were controlled by a personal computer using a software package for matlab which was developed at the University of Oldenburg. Stimuli were generated digitally with the matlab software at a sampling rate of 96 kHz, transformed by an D/A converter (type SEK'D 2496 DSP) amplified by a preamplifier (type Behringer HA 4400) and presented via headphones (type AKG K 501) at a level of 40 dB HL (hearing level). The subjects sat in front of the monitor of the personal computer and gave their responses by pressing predetermined buttons on the keyboard.

2.2.2 Subjects

Overall, eight subjects (2 female, 6 male) participated in this study. Six of them were members of the research group 'Medizinische Physik' of the University of Oldenburg. They were aged between 18 and 38 and all normal hearing according to their audiogramm (hearing loss $<$ 20 dB between 0.125 kHz and 8 kHz). Four of the subjects had intensive experience in psychoacoustical measurement tasks. The remaining four had only little prior experience with psychoacoustical measurements but had several practice runs until the actual data collection began. In particular, attention was paid to the subjects' vigilance. Most subjects performed about five measurements in a row (net measuring time about 20 minutes) until they reported fatigue.

2.2.3 Stimuli and paradigms

Figure 2.1 illustrates the two basic types of stimuli employed in this study: the basic component of the stimuli was a pulse of about 50 μs in duration (five samples with a value of one at a sampling frequency of 96 kHz). The acoustic pulse was therefore

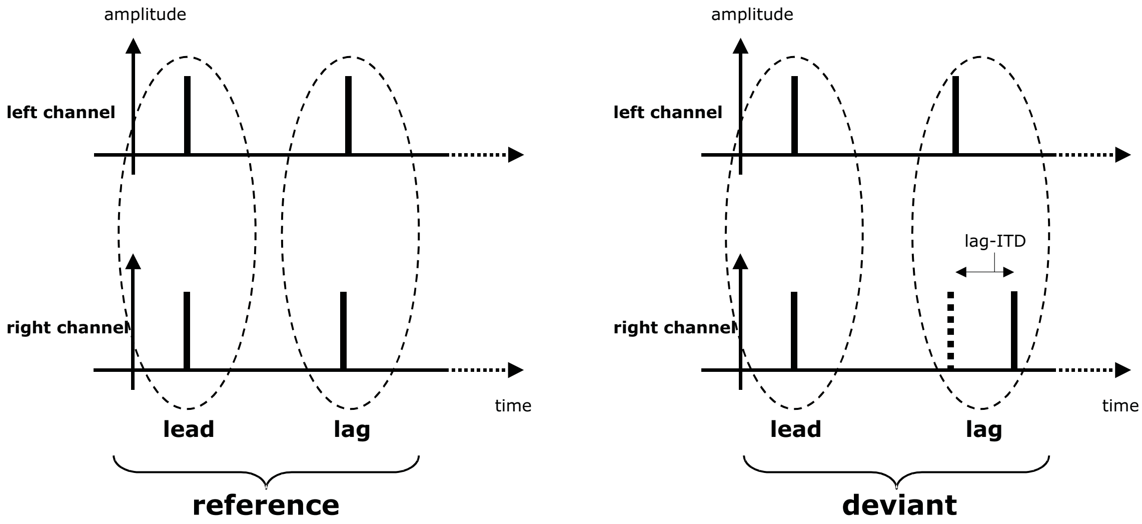


Fig. 2.1: Illustration of a reference (left panel) and a deviant (right panel) lead-lag click-pair. Stimuli with an inserted ITD in the lag click were deviants whereas reference stimuli had no lag-ITD. The lead ITD of both stimuli was zero.

approximately the impulse response of the earphones (AKG 501). The measured impulse response of the headphones had a duration of about 1 ms.

The left panel of Fig. 2.1 shows a reference stimulus which consisted of two click-pairs, the first click-pair which is referred to as the lead and a second click-pair which is referred to as the lag. The right panel of Fig. 2.1 shows a deviant where the lag-click of the right channel is delayed, i.e., an ITD was inserted. The lag-ITD was varied in each respective experimental condition as the independent variable. Additionally, during all five experiments the lead-lag delay was varied as a parameter, i.e., the lead-lag delay was fixed during one experimental run, but was varied across runs.

Overall, five experiments were performed which had different properties that are introduced in the following. All experiments determined the individual discrimination threshold of a lag-ITD, i.e., the discrimination threshold of an ITD in the presence of a preceding click (the lead). Table 2.1 summarizes the properties of the five experiments.

- *gated/continuous:* In the gated stimulus presentation mode the stimulation is

Experiment	gated/cont.	adaptive/fixed	ratio std./dev.
I. '3-AFC'	gated	adaptive	2/1
II. '3-AFC pre-signal'	gated	fixed	5/1
III. '3-AFC continuous'	continuous	fixed	5/1
IV. '3-AFC train'	gated	adaptive	11/1
V. 'pick-out'	continuous	fixed	about 180/30

Tab. 2.1: Parameter combinations employed in the five experiments. The stimulus presentation could either be gated or continuous. Discrimination thresholds were either determined by an adaptive forced choice procedure or by applying fixed lag-ITDs. Additionally, the ratio between standards and deviant within one trial is shown.

stopped in each trial until the subject depresses the response button. In the continuous stimulation mode the presentation of the subsequent stimulus starts immediately without interruption. Hence, the subject is forced to respond quickly while the stimulation continues.

- *adaptive/fixed:* In the *adaptive* data collection mode the lag-ITD was increased after each incorrect response and decreased after two successive correct responses. Additionally, the step-size was varied during one measurement. The starting lag-ITD in the adaptive paradigms was 430 μs [2]. The initial step-size was 42 μs (8 samples). It was halved from 42 to 21 μs (4 samples) after the first upper reversal and from 21 to 10 μs (1 sample) after the second (lower) reversal. In the subsequent measurement phase the 70.7 percent correct performance was obtained as a mean across the ITD-values of six reversals before the measurement terminated. Each subject received a detailed introduction to the paradigm which contained some training sequences. After the introduction three repetitions were run for each lead-lag delay. In the *fixed* data collection mode the psychometric function was determined by employing

[2] This corresponds to a lateralization of approximately half the way between the center of the head and the left ear

runs with lag-ITDs of 150, 300, 450, 600, 750 and 900 μs, respectively. The 70.7 percent correct performance was interpolated by fitting a psychometric function according to equation

$$f(x) = \frac{1}{1 + e^{(a+bx)}} \tag{2.1}$$

to the individual data set where a determines the horizontal shift and b the slope of the function. Feedback was provided for the subjects after each trial in all adaptive experiments. In contrast, no feedback was given in the experiments with fixed lag-ITDs.

- *ratio standard/deviant:* While only one deviant is presented in each trial in all AFC experiments, the number of additionally presented reference stimuli is an experimental variable that varies between two and eleven.

In order to clarify each experimental condition, Fig. 2.2 shows examples of the respective time signals presented in Experiments I to IV. Figure 2.3 shows a sketch of the stimulus sequence applied in Experiment V. In all experiments all lead-ITDs were zero and all interclick intervals were 500 ms yielding a stimulus repetition rate of 2 Hz. In the 3-AFC procedures subjects had to indicate the interval containing the deviant. Response buttons were enlightened when the corresponding interval was presented. In the 'pick-out' procedure subjects had to indicate any perceived deviant by pressing any key on the keyboard. Note: subjects were encouraged to use *any* sound feature for their discrimination task.

In the following all experiments are described briefly:

Experiment I: '3-AFC': In Experiment I a gated, adaptive 1-up 2-down 3-AFC paradigm was applied. One double click-pair was presented per interval whereof one was a deviant (lag-ITD $\neq 0$). Subjects received a feedback whether their respective response was correct. Values of the lead-lag delay were 0, 1, 2, 3, 5, 7, 10 to 20 ms which were presented in randomized order. During one measurement the lead-lag delay was kept constant.

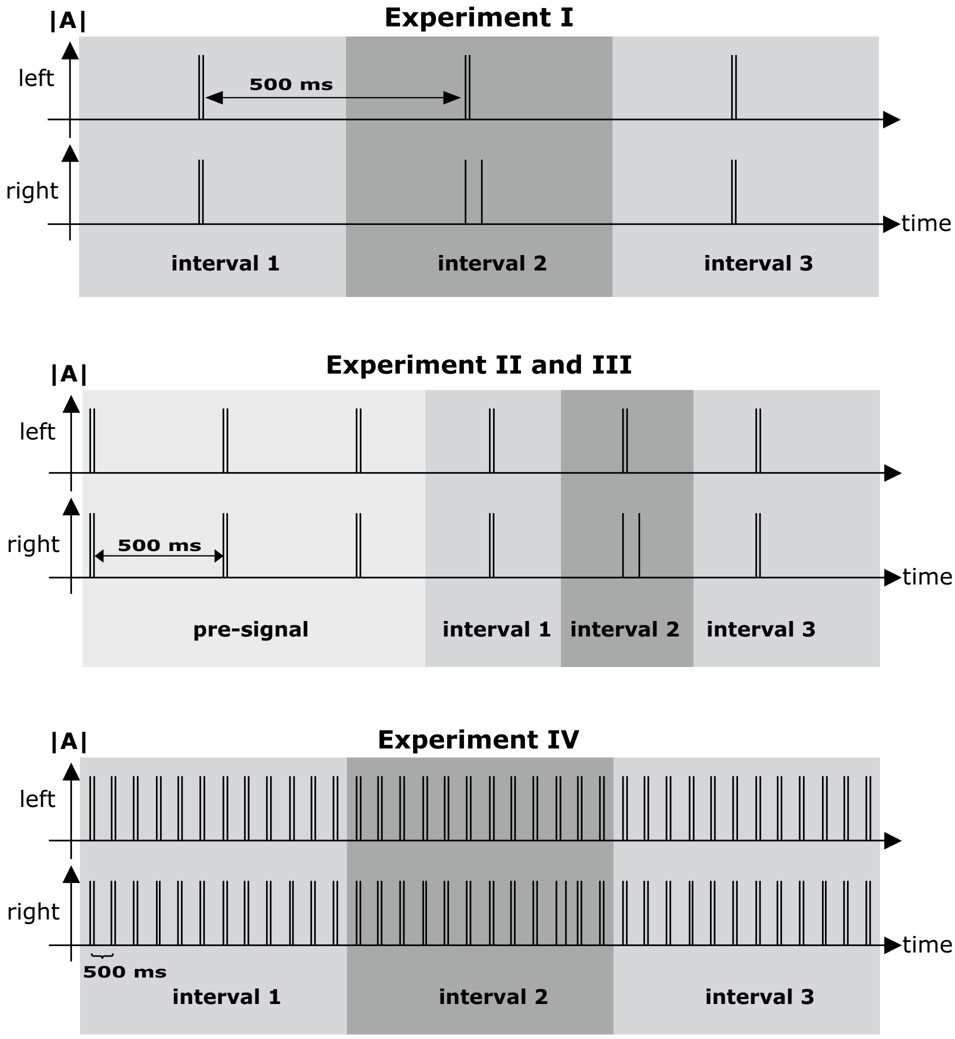


Fig. 2.2: Examples of the time signals of Experiments I to IV. A time signal of Experiment I ('3-AFC') is shown in the upper panel where the second interval contains the deviant. The middle panel shows a time signal of Experiments II and III where three additional reference stimuli precede the three intervals. The lag-ITD is embedded in the second interval whereas the first and third interval contain reference stimuli. The lower panel shows a signal as used in Experiment IV ('3-AFC train'). Interval I and III contain reference stimuli, interval II contains the deviant stimulus (lag-ITD in the tenth click-pair). Unlike Experiment I each interval contains twelve double click-pairs. All interclick intervals are 500 ms.

Experiment II: '3-AFC pre-signal': In Experiment II a gated procedure with fixed lag-ITDs was employed. A trial consisted of a pre-signal containing three reference stimuli followed by three intervals each containing a double click-pair whereof one was a deviant. Hence, three more reference stimuli were presented than in Experiment I in each trial and a deviant could appear on position 4, 5 or 6.

Experiment III: '3-AFC continuous': Experiment III is similar to Experiment II but employs a continuous instead of a gated stimulus presentation. Subjects had to respond within the pre-signal of the following trial so that the response is treated as a hit.

Experiment IV: '3-AFC train': Experiment IV is similar to Experiment I with the only difference that each interval contained twelve instead of one double click-pair. The position of the deviant was equally distributed from position four to twelve within one of the three intervals. As the measuring time was twelve times longer in the '3-AFC train' experiment (Experiment IV) the discrimination threshold was only determined for lead-lag delays of 1, 5 and 20 ms (presented in randomized order).

Experiment V: 'pick-out': In Experiment V a procedure with fixed lag-ITDs and a continuous stimulation mode was applied. Therefore, stimulus sequences of frequent reference stimuli (about 180) and rare deviants (30) as sketched in Fig. 2.3 were presented to the subjects. Each stimulus sequence had a duration close to two minutes.

At randomly chosen positions of the sequence deviants with one of the fixed lag-ITDs from 150 μs up to 900 μs in steps of 150 μs appeared. Each of the six different lag-ITDs was installed 5 times in each sequence in shuffled order on condition that at least three standards follow (precede) a deviant. The lead-lag delay was varied as a parameter over the sequences but was constant within each sequence. Lead-lag delays of 0, 1, 2, 3, 5, 7, 10 and 20 ms were applied so that a total of 48 different sequences (6 sequences per lead-lag delay) were presented.

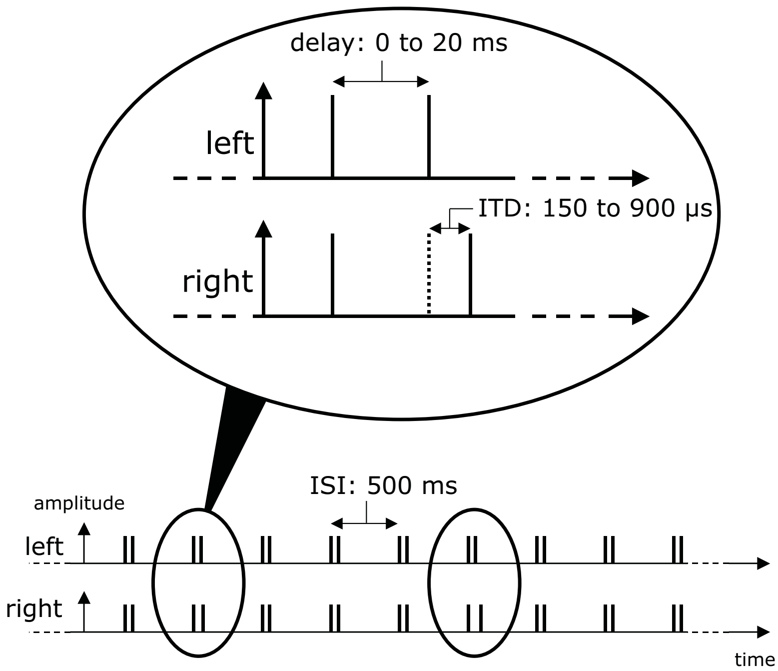


Fig. 2.3: Sketch of the stimulus sequence used in Experiment V ('pick-out'). The sequence overall consisted of about 210 lead-lag click-pairs (about 180 reference stimuli and 30 deviants). The interaural time difference of the lag click of the deviant, see enlarged cut-out, was varied from 0 μs up to 900 μs in steps of 150 μs. The lead-lag delay was varied from 0 ms up to 20 ms. Within one sequence the lead-lag delay is kept constant.

Subjects were asked to hit a button on the keyboard as fast as possible after they detected a deviant stimulus. A subjects' response was treated as a hit in Experiment V ('pick-out') if any button on the keyboard was pressed within one second after the presentation of the deviant. In doing so, the attention was turned strongly to the stimulus sequence. An analysis of the key-press statistic revealed that subjects managed well to press a button just after they perceived a deviant, i.e., in most cases (more than 87 percent) they pressed the response button even before the next standard was presented (reaction time $<$ 500 ms). In a few cases (less than 10 percent) the subject's reaction was delayed so that one standard was presented between the deviant and the subject's reaction. Reactions with delays larger than one second were treated as false alarms which occurred very rarely (less than 3 percent).

The subjects received no feedback during the 'pick-out' measurement.

2.3 Results

The following three plots show values of lag-ITDs that yield 70.7 percent correct performances as a function of the lead-lag delay.

Figure 2.4 shows discrimination thresholds obtained by the '3-AFC' experiment

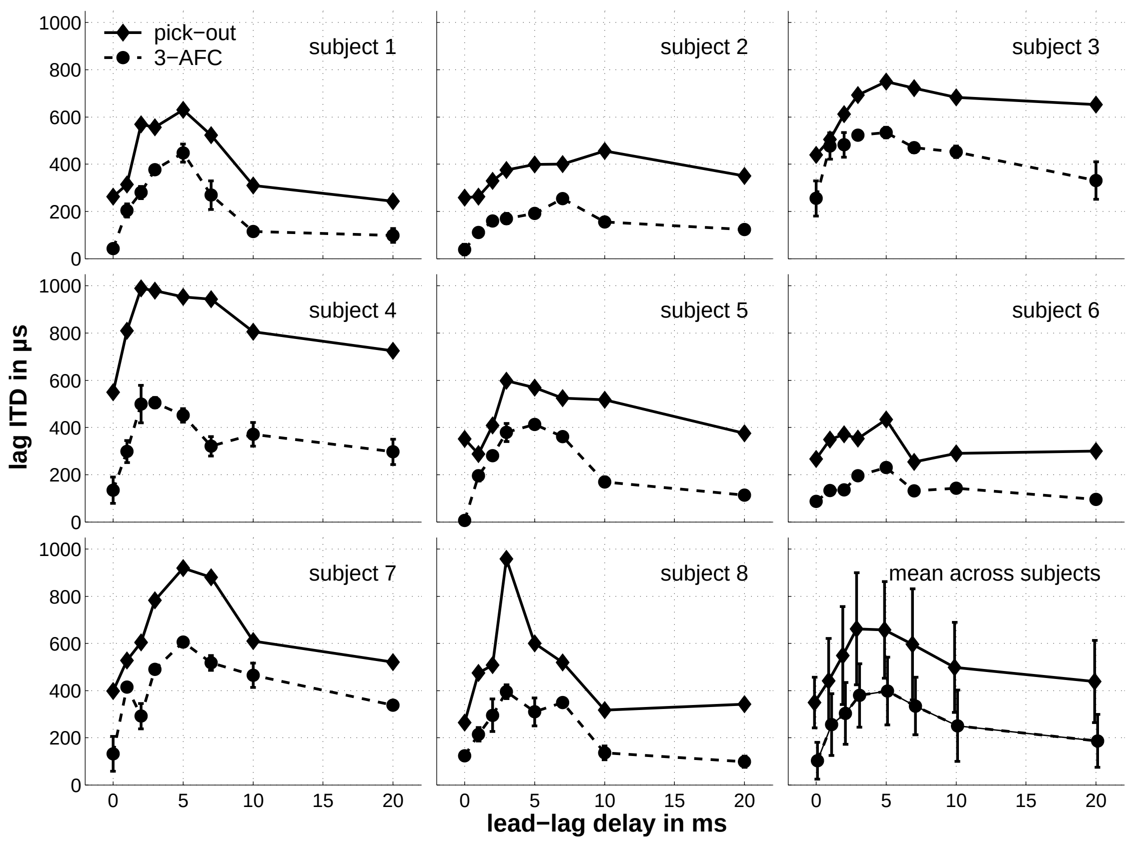


Fig. 2.4: Discrimination thresholds of eight subjects obtained by two different conditions. Plotted are lag-ITD values that yield 70.7 percent correct performance over the lead-lag delay from 0 ms to 20 ms. The diamonds represent the values of the 'pick-out' condition and the circles those of the '3-AFC' condition. Intraindividual standard deviations for the '3-AFC' condition are very small, for the 'pick-out' condition there are no intraindividual standard deviations. The lower right panel shows the average across all subjects as well as interindividual standard deviations.

(Experiment I) which were plotted as circles and discrimination thresholds of the 'pick-out' experiment (Experiment V) which were plotted as diamonds. Displayed are values of single subjects as well as the grand mean averaged across all eight subjects. Errorbars in panels of single subjects indicate intraindividual standard deviations which are mostly fairly small. In the lower right panel errorbars show the interindividual standard deviation for each threshold value. Grand mean discrimination threshold values of both experiments show the same characteristic in dependence of the lead-lag delay. Both thresholds increase up to a lead-lag delay around 4 ms and decrease again for lead-lag delays up to 20 ms. However, lag-ITDs obtained in the '3-AFC' experiment are about 250 μs smaller than those obtained by the 'pick-out' experiment for all lead-lag delays. This difference is significant for all conditions according to Wilcoxon ranksum tests ($p < 0.05$).

Although discrimination threshold values of both experiments differ significantly for each lead-lag delay, interindividual standard deviations as plotted in Fig. 2.4 seem to be quite large with values exceeding 100 μs. However, results of single subjects as shown in the other panels indicate that the main difference of the individual thresholds is due to a constant vertical shift. Except for this vertical shift, characteristics of the individual threshold values for most subjects are similar to the characteristic of the mean values. However, subjects can be separated into two groups that differ with respect to the shape of their discrimination threshold: subjects of the first group (subjects 1, 4, 7 and 8, respectively) manage to decrease their threshold values again for lead-lag delays larger than 5 ms whereas the second group (subjects 2, 3, 5 and 6, respectively) cannot benefit as clearly from an increasing lead-lag delay. This holds for the threshold values of the 'pick-out' experiment and the '3-AFC' experiment.

Figure 2.5 shows discrimination threshold values of single subjects of the '3-AFC continuous' experiment (Experiment II) as down-pointing triangles, the '3-AFC presignal' experiment (Experiment III) as squares and the '3-AFC train' experiment (Experiment IV) as up-pointing triangles. The lower right panel shows the respective values averaged across all five subjects. In these experiments lag-ITD discrimination thresholds were determined for lead-lag delays of 1, 5 and 20 ms, respectively (see section 2.2). Errorbars in panels of single subjects indicate intraindividual standard errors whereas errorbars in the lower right panel indicate interindividual standard deviations of the mean values.

Obviously, discrimination threshold values obtained by these experiments lead to the same characteristic as described above, i.e., thresholds for a lead-lag delay of 5 ms are higher than those for lead-lag delays of 1 ms or 20 ms, respectively. This characteristic is also observable for discrimination threshold values of Experiment I and V (see Fig. 2.4).

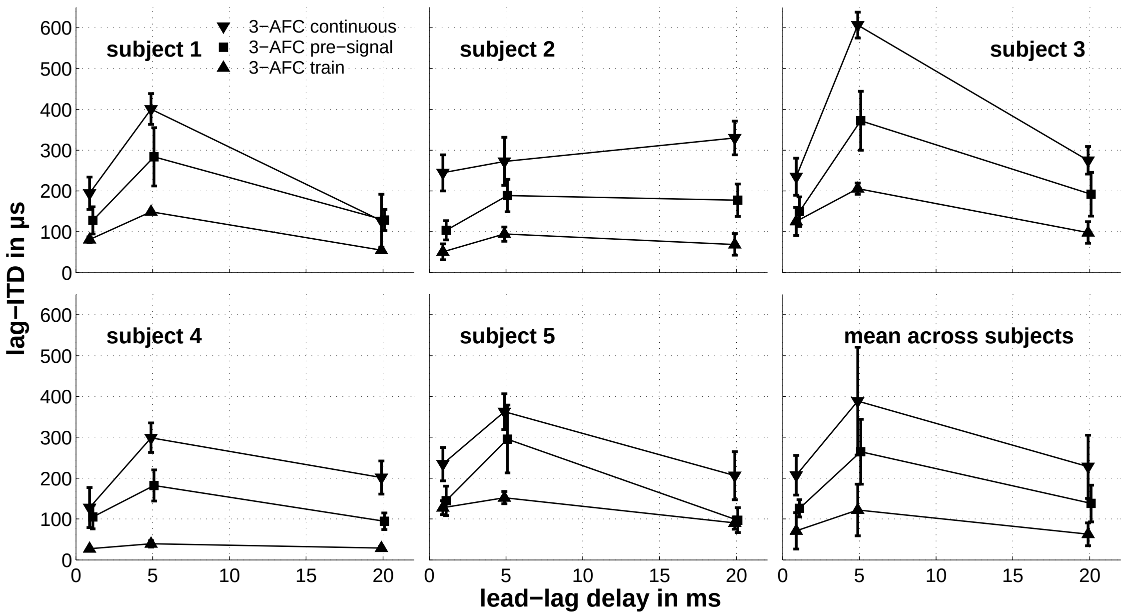


Fig. 2.5: Discrimination thresholds of single subjects as well as the grand mean averaged across all subjects obtained by three different experiments. Plotted are lag-ITD values that yield 70.7 percent correct performance as a function of the lead-lag delay. The down-pointing triangles represent values of the '3-AFC continuous' experiment (Experiment III), the squares those of the '3-AFC pre-signal' experiment (Experiment II) and the up-pointing triangles represent lag-ITD values of the '3-AFC train' experiment (Experiment IV). Errorbars show the intraindividual standard deviation of single subjects and the interindividual standard deviation for the mean values, respectively. For clarity, lead-lag delays were partly slightly shifted.

In Fig. 2.5 highest thresholds were obtained in the '3-AFC continuous' experiment which differ significantly ($p < 0.05$) from the smallest values in the '3-AFC train' experiment. Values of the '3-AFC pre-signal' experiment lie in-between.

A comparison of the discrimination threshold values obtained by all five experiments are shown in Fig. 2.6. For clarity, errorbars were omitted in this plot. The same symbols as in Fig. 2.4 and 2.5 represent the results of Experiments I to V. All threshold values were averaged across those five subjects that participated in all five experiments. Obviously, each experiment leads to different discrimination threshold values. Overall, the highest thresholds were obtained in the 'pick-out' experiment whereas the lowest thresholds were obtained in the '3-AFC train' experiment. The spread of discrimination threshold values between these two extremes is very large.

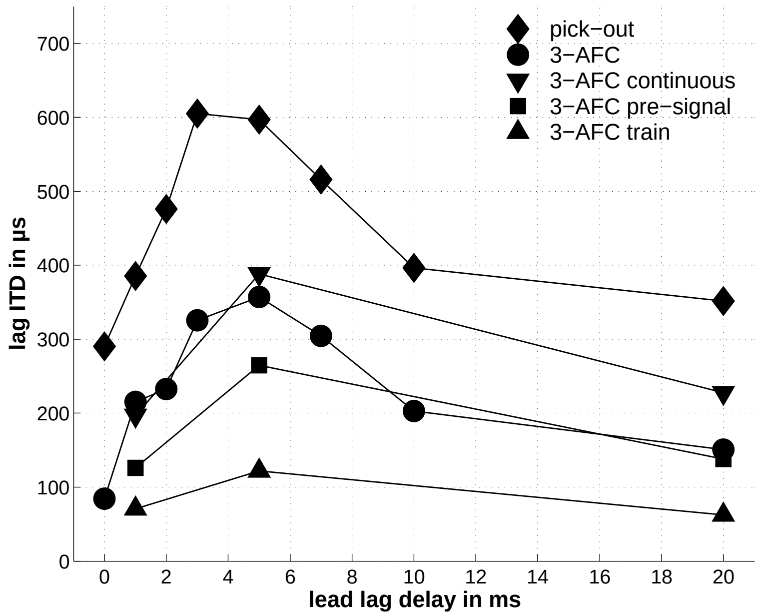


Fig. 2.6: Comparison of discrimination thresholds of all five experiments. The same symbols as in Fig. 2.4 and 2.5 represent the results of Experiment I to V. For clarity, errorbars were omitted in this plot and results of each experiment were connected. Note: All thresholds were averaged across those five subjects that took part in all five experiments. Hence, values of the 'pick-out' and the '3-AFC' experiments (Experiments V and I) are not identical to those shown in Fig. 2.4.

For a lead-lag delay of 5 ms the '3-AFC train' experiment yielded a lag-ITD of about 120 μs whereas the 'pick-out' experiment yielded a lag-ITD of about 660 μs. Thus, a range of more than 500 μs is covered by the results of these five experiments. For lead-lag delays of 1 ms and 20 ms respectively, the range is only slightly smaller (400 μs).

2.3.1 Further analysis

Influence of the number of reference stimuli presented before the deviant on the discrimination threshold in the 'pick-out' experiment

In order to test the hypothesis that the number of reference stimuli presented prior to the deviants influences the discrimination threshold, discrimination performances were analyzed with respect to that effect for the 'pick-out' experiment. Figure 2.7 shows the percent correct discrimination performances of the 'pick-out' experiment as a function of the number of reference stimuli preceding the deviant. As mentioned in section 2.2, sequences were designed with the constraint that at least three and at maximum ten reference stimuli preceded (followed) a deviant. Plotted are the mean discrimination performances averaged over eight subjects and averaged over all lead-lag delays. The six curves represent the discrimination performances for the six fixed lag-ITDs from 150 μs up to 900 μs. As in no sequence eight reference stimuli preceded the deviant having a lag-ITD of 150 μs this data point could not be calculated. Obviously, discrimination performances increase with increasing lag-ITD. However, there is no consistent dependence between the number of reference stimuli presented before the deviant and the discrimination performance. This indicates that discrimination threshold values for deviants that where preceded by only a few reference stimuli equal those where up to ten reference stimuli preceded the deviant.

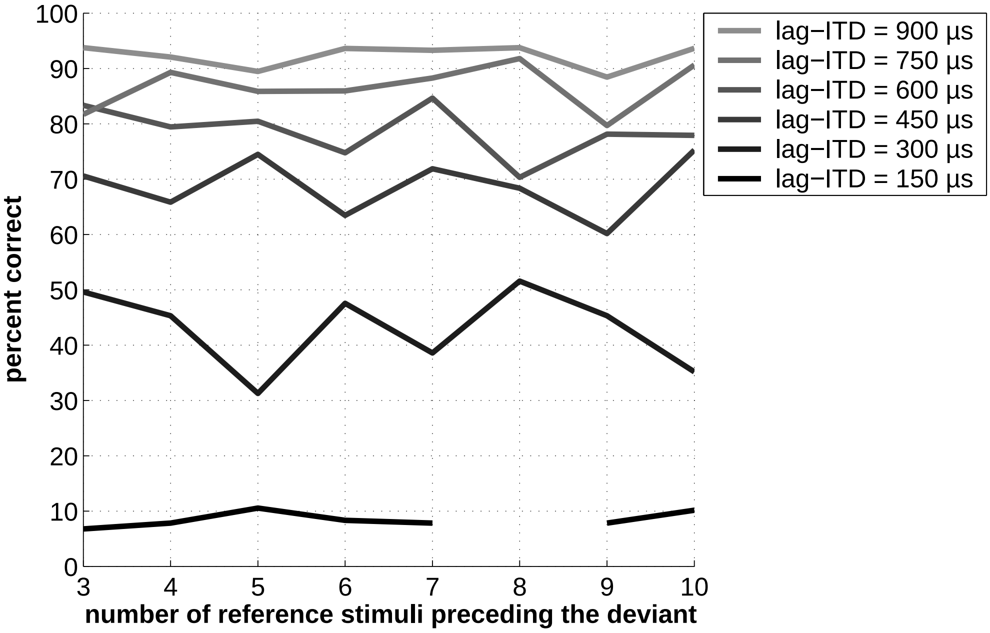


Fig. 2.7: Percent correct performances in dependence of the number of reference stimuli presented before the deviants for the 'pick-out' paradigm. Plotted is the mean over eight subjects. The six curves represent the discrimination performance for the six fixed lag-ITDs from 150 μs up to 900 μs.

Spectral dissimilarity as a rough predictor of the discrimination threshold

The increase of the discrimination thresholds for increasing lead-lag delays from 0 ms to 5 ms as shown in Fig. 2.4 may be qualitatively modelled by the spectral dissimilarity of reference and deviant stimulus. This dissimilarity can to a first approximation be expressed by the frequency difference between corresponding spectral notches as follows: due to comb filter effects certain frequencies of the spectrum of a double click-pair cancel. These notch frequencies f_c can be calculated for the reference stimulus as:

$$f_{c,ref} = \frac{2 \cdot n - 1}{2d_{ll}} \tag{2.2}$$

where n is the order of the cancelled frequency and d_{ll} the lead-lag delay.
The notch frequencies of the deviant can be computed as:

$$f_{c,dev} = \frac{2 \cdot n - 1}{2(d_{ll} + d_{ITD})} \tag{2.3}$$

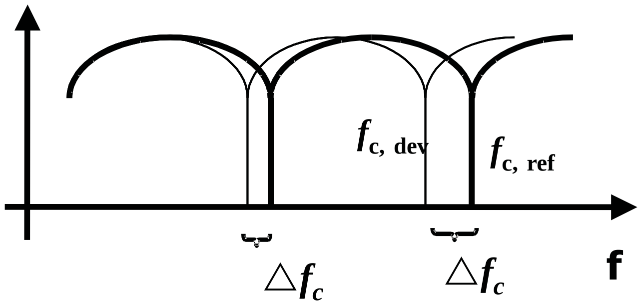


Fig. 2.8: Illustration of the spectra of reference (thick line) and deviant (thin line). Due to comb filter effects frequencies $f_{c,std}$ cancel in the spectrum of the reference and frequencies $f_{c,dev}$ cancel in the spectrum of the deviant in dependence of the lead-lag delay and the lag-ITD. In addition, differences Δf_c between the notch frequencies in the spectra of reference and deviant stimulus are indicated.

where d_{ITD} is the lag-ITD. Figure 2.8 sketches the spectra of reference and deviant stimuli and the frequencies that cancel. Furthermore, frequency differences Δf_c between the cancelled frequencies of reference and deviant are indicated. A rough measure of the difference between both spectra is the difference between the corresponding notch frequencies. This frequency difference may be expressed as:

$$\Delta f_c = \frac{2 \cdot n - 1}{\frac{2d_{ll}}{d_{ITD}} + 2d_{ll}} \tag{2.4}$$

Figure 2.9 illustrates the difference Δf_c between the cancelled frequencies of both spectra in a 3-D plot. The four panels represent four different lead-lag delays d_{ll} (1,2,3 and 5 ms). In each panel Δf_c is plotted as a function of the lag-ITD d_{ITD} and the cancelled frequency of the reference stimulus. The upper panels show the resulting Δf_c for lead-lag delays of 1 ms (left panel) and 2 ms (right panel), the lower panels show the resulting Δf_c for lead-lag delays of 3 ms (left panel) and 5 ms (right panel), respectively.

Obviously, the exerted influence of the lag-ITD on the resulting Δf_c is larger the smaller the lead-lag delays are for a given notch frequency. In other words, the slope of the Δf_c-grid in dependence on the lag-ITD is steeper for short lead-lag delays.

This fact is illustrated in Fig. 2.10. Plotted is the difference between the Δf_c values obtained with a lag-ITD of 1000 μs and 0 μs versus the cancelled frequency of the

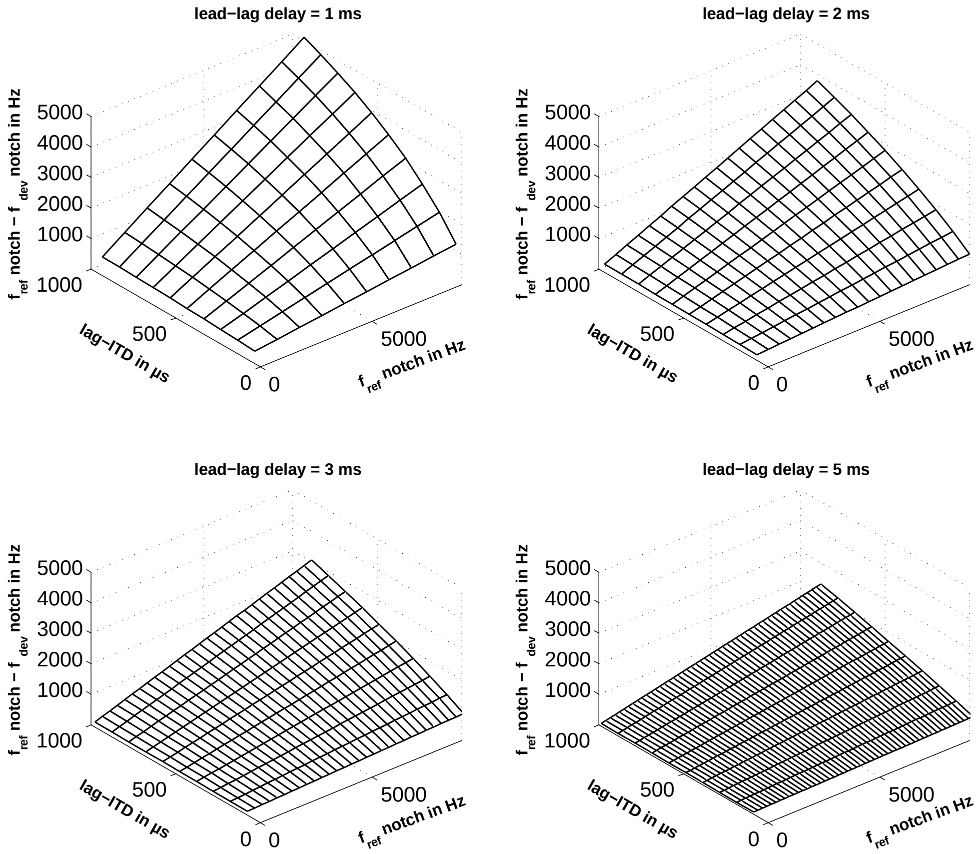


Fig. 2.9: Illustration of the differences Δf_c between the cancelled frequencies in the spectra of reference and deviant stimuli. Due to comb filter effects certain frequencies in the spectrum of the deviant and reference cancel in dependence of the lag-ITD and the lead-lag delay. The upper panels show the resulting Δf_c of lead-lag delays of 1 ms (left panel) and 2 ms (right panel), the lower panels show the resulting Δf_c of lead-lag delays of 3 ms (left panel) and 5 ms (right panel), respectively.

reference stimulus. Triangles, squares, diamonds and circles represent lead-lag delays of 1, 2, 3 and 5 ms, respectively. Figure 2.10 shows that the larger the lead-lag delay, the smaller the resulting differences between the $\Delta f_c s$ obtained with a lag-ITD of 1000 μs and 0 μs. However, the larger the lead-lag delay the more frequency notches occur in a given frequency region.

This simple analytical model shows that differences between the monaural spectra

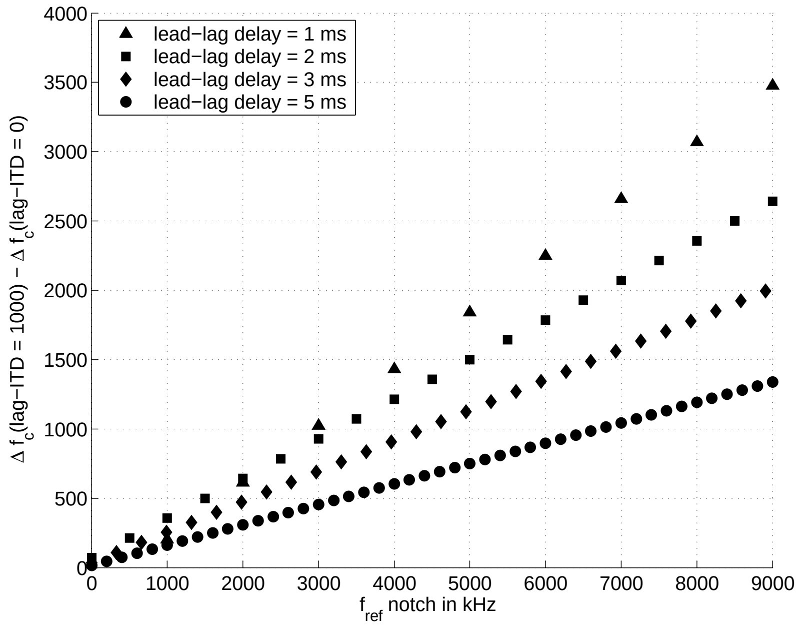


Fig. 2.10: Plot of the difference between the Δf_cs obtained with a lag-ITD of 1000 μs and 0 μs versus the cancelled frequency of the reference stimulus. Triangles, squares, diamonds and circles represent lead-lag delays of 1, 2, 3 and 5 ms, respectively.

of reference and deviant stimuli could explain the discrimination thresholds for lead-lag delays from 0 ms up to 5 ms. Generally, a necessary constraint in order that the auditory system could perceive a deviation is that both spectra differ.

However, differences between the spectra of reference and deviant are a necessary but not necessarily a sufficient condition for the auditory system to perceive a difference between both signals. For this reason, a perception model was employed that evaluates the differences between both signals on the bases of their internal representations in the auditory system. The internal representations were calculated according to the perception model by Huber (2003). This auditory processing model calculates internal representations of the reference and the deviant and determines a perceptual similarity measure (PSM) which varies between zero (no similarity at all) and one (total similarity). The left panel of Fig. 2.11 shows the PSM between internal representations of reference and deviant as a function of the lead-lag delay for different lag-ITDs. PSMs increase for lead-lag delays from 0 ms to 5 ms. All curves, each representing one lag-ITD from 100 μs to 700 μs in steps of 200 μs, show an asymptotical characteristic. However, the larger the lag-ITD the smaller the asymptotic value is reached for large lead-lag delays, i.e., not all curves reach a PSM of one for large lead-lag delays. The right panel of Fig. 2.11 shows the lag-ITD values for a constant PSM of 0.998. The characteristic of the discrimination threshold for lead-lag delays from 1 ms to 5 ms can be simulated quite well, i.e., lag-ITD increase with increasing lead-lag delay. Thereby, absolute lag-ITD values are dependent on the chosen PSM value. However, for lead-lag delays larger than 5 ms simulated lag-ITD values still increase while discrimination thresholds as obtained from the behavioral tasks decrease again.

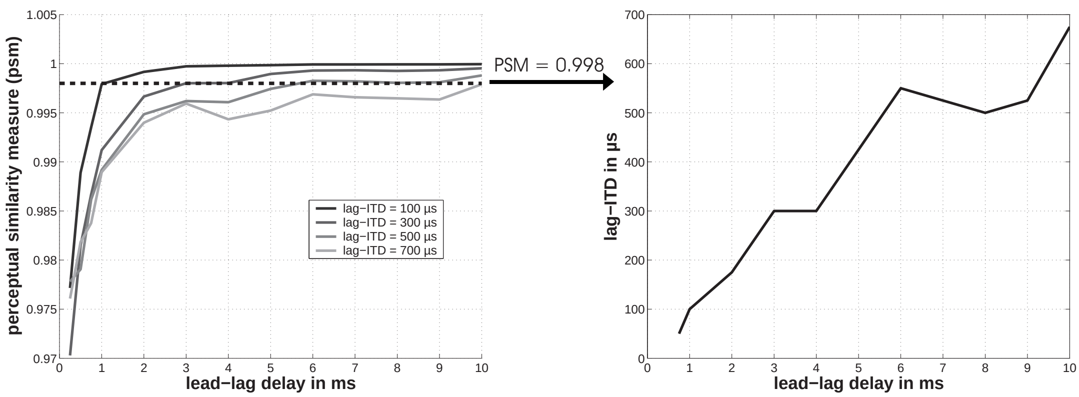


Fig. 2.11: **Left panel:** *Plot of the perceptual similarity measure (PSM) for different lag-ITDs as a function of the lead-lag delay.* **Right panel:** *Plot of the lag-ITD for a constant PSM of 0.998.*

2.4 Discussion

In order to investigate adaptation processes of the precedence effect evoked by multiple presentation of the reference stimuli or continuous stimulation, five experiments were performed that differ in timing and number of presented reference stimuli. It was shown that discrimination thresholds of lag-ITDs vary considerably between different experiments. Figure 2.12 gives an overview about the effects that could explain the differences between the discrimination thresholds obtained by the five experiments.

2.4.1 Adaptation processes of the precedence effect

In Experiment I lag-ITD discrimination thresholds were determined in a 3-AFC paradigm where two reference stimuli and one deviant were presented in random order. Discrimination thresholds were shown to be dependent on the lead-lag delay. Mean values vary between 80 μs and 360 μs for a lead-lag delay around 5 ms.

Generally, lag-ITD *discrimination* values found in Experiment I are in agreement with lag-ITD *lateralization* values found in a recent study by Tollin and Henning (1998). One of the stimuli they used was a double click-pair containing a lag-ITD that was applied for lead-lag delays from 0.1 ms up to 25.6 ms. Three of their four subjects show increased threshold ITDs as the lead-lag delays increase from 1 ms to 12.8 ms.

There are several similarities between the results of both studies: firstly, thresholds of all subjects in both studies seem to be rather individual, i.e., results vary a lot over subjects. Lag-ITD lateralization thresholds found by Tollin and Henning (1998) vary between 200 μs and 650 μs for a lead-lag delay of 2 ms, while discrimination thresholds of the present study vary from 330 μs to 990 μs. Mean values of both studies are within the same order of magnitude. This might be surprising as the subjects in this study were asked to indicate *any* perceived difference and hence lower thresholds are expected than those ITD thresholds found by Tollin and Henning (1998) obtained with a lateralization task.

Secondly, even though the tasks of both studies are different, the range of lead-lag delays where the lead affects the lag-ITD threshold is similar in both studies. However, Tollin and Henning obtained highest thresholds for three subjects for lead-lag delays of 1 ms or 2 ms (ITD thresholds of subject number four were at maximum at around 200 μs) whereas highest lag-ITD discrimination thresholds in the present study were obtained for lead-lag delays around 5 ms.

Finally, thresholds for the largest lead-lag delay of both studies do not reach the low values of the shortest lead-lag delay. The largest lead-lag delay Tollin and Henning applied was 25.6 ms where they obtained ITD thresholds that were increased by a factor around 1.5 (for two subjects) or 3 (for one subject) compared to the threshold at a lead-lag delay of 0.1 ms. In the present study, the discrimination threshold of the largest lead-lag delay (20 ms) is increased on the average by a factor around 2. In conclusion, the presence of the lead in both studies leads to similar influences on the perception of the lag.

Due to only a few presentations of the reference stimulus in Experiment I, adaptation processes are unlikely to occur. In Experiment II ('3-AFC pre-signal') between 3 and 5 reference stimuli precede the deviant as the pre-signal contains three reference stimuli and in Experiment IV between 3 and 35 reference stimuli precede the deviant as each interval contains 12 double click-pairs. Hence, due to an increasing number of presented reference stimuli adaptation processes are more likely to appear in these conditions. As shown in Fig. 2.6 discrimination thresholds obtained in this study decrease with increasing number of reference stimuli preceding the deviant: thresholds obtained in the '3-AFC pre-signal' condition (Experiment II) were lower than those of the '3-AFC' condition (Experiment I) and thresholds obtained in the '3-AFC train' condition (Experiment IV) were the lowest (see Fig. 2.5 and Fig. 2.6). Hence, there is a high correlation between the ratio of presented reference and deviant stimuli and the discrimination threshold. Therefore, it is reasonable to assume that the discrimination threshold decreases if the accuracy of the internal representation is increased. The more reference stimuli precede the deviant, the more precise the internal representation and the easier the discrimination task. This means that the adaptation process supports the detection of any deviating sound feature rather than suppresses any information. Noticeably, during the 'pick-out' experiment such dependencies between the number of presented reference stimuli before a deviant and the discrimination threshold were not found (see Fig. 2.7). Percent correct performances are similar for numbers of reference stimuli from 3 to 10 and were only dependent on the lag-ITD. This may be explained by assuming that during the 'pick-out' measurement the auditory system remains in the adapted state throughout the whole sequence without being disrupted from this adaptation

by a deviant. Hence, the systematically larger thresholds obtained for the 'pick-out' paradigm are most likely not due to a lack of adaptation to the reference stimulus. Instead, the difference has to be attributed to cognitive processes associated with timing uncertainty of the stimulus to be detected.
The finding of decreasing discrimination thresholds with increasing adaptation to the reference presented so far seems to contradict with findings of an increased echo threshold with increasing adaptation: Freyman et al. (1991) or more recently Krumbholz and Nobbe (2002) have shown that the *echo threshold* is increased as multiple repetitions of the reference lead-lag click-pair were presented prior to the test click-pair. Freyman et al. (1991) asked subjects in their study whether they perceived an echo, Krumbholz and Nobbe (2002) asked their subjects whether they perceived one or two auditory events. Thus, in both studies subjects were asked to indicate the number of perceived events. The *echo threshold* usually is defined as the lead-lag delay where subjects tend to perceive the second click as a separate event. Unlike these studies, subjects in the present study had to indicate *any* difference between click-pairs with or without lag-ITD.

Taking the results of Freyman et al., Krumbholz and Nobbe and the present experiments into account, it can be concluded that although lead and lag might fuse to one auditory event, a lag-ITD can still be detected due to subtle changes in the perceived properties of the auditory event. Therefore, the results of the present study do not contradict previous findings.

2.4.2 Speed-accuracy trade-off

Procedures of the '3-AFC continuous' (Experiment III) and the 'pick-out' experiment (Experiment V) make use of continuous stimulus presentation. In these two experiments sequences of more than 200 stimuli were presented without any break for the subjects. Hence, the perception of double click-pairs during continuous stimulation is determined. Subjects had to respond very quickly while already listening to the next stimuli. In contrast to that, during the '3-AFC' (Experiment I), the '3-AFC pre-signal' (Experiment II) and the '3-AFC train' experiment (Experiment IV) the stimulus presentation stopped after the third interval and the subjects were not forced to respond as quickly. The next trial was not presented until the subjects responded. The resulting break may be used by the subjects to compare the three intervals with the established internal representation of the reference stimulus. Furthermore, they may compare the three intervals among each other without any temporal restrictions. This facilitates the detection of the deviant and may therefore be the primary reason for the lower discrimination thresholds found here.

The influence of forcing the subjects to respond very quickly, can be derived quantitatively by comparing the discrimination threshold values obtained by the '3-AFC pre-signal' experiment (Experiment II) and the '3-AFC continuous' experiment (Experiment III). The only difference between these two experiments is that in the '3-AFC pre-signal' experiment the stimulation stops after the third interval whereas in the '3-AFC continuous' experiment it does not. As Fig. 2.5 indicates, discrimination threshold values of the '3-AFC continuous' experiment are larger for all lead-lag delays than those of the '3-AFC pre-signal' experiment. This difference can be explained by a speed-accuracy trade-off mechanism. However, this does not explain the even larger differences between both continuous presentation modes, i.e., '3-AFC continuous' and 'pick-out' paradigm.

2.4.3 3-AFC versus 'pick-out' paradigm

As described in section 2.2 four different 3-AFC and one 'pick-out' paradigm were employed in order to determine discrimination thresholds for a lag-ITD. Although the subject's task in each of the five experiments was to discriminate a deviation from a reference stimulus, the paradigm applied in each experiment plays an important role.

In the '3-AFC' (Experiment I) and the '3-AFC train' (Experiment IV) experiments an *adaptive* procedure was used, in the '3-AFC pre-signal' (Experiment II) and the '3-AFC continuous' (Experiment III) experiments the 70.7 percent correct performance was interpolated between several sampling points of a psychometric function. Both procedures should yield the same results. In order to assure this, a control

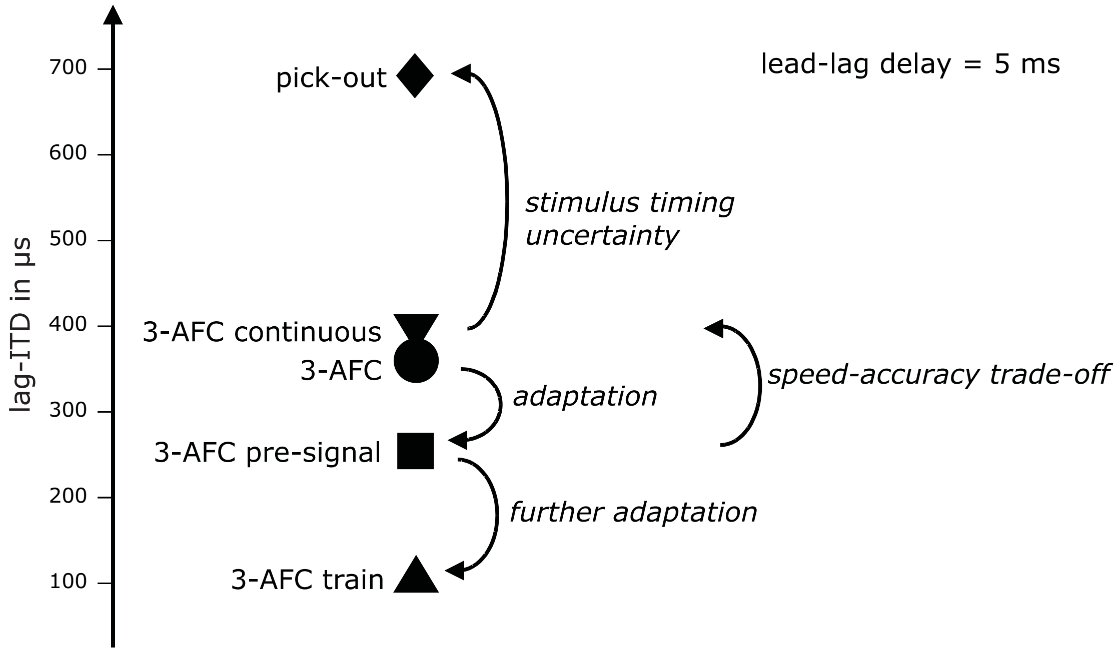


Fig. 2.12: Overview of the various effects that could explain the differences between the discrimination performances of the five experiments. Plotted are discrimination performances averaged across five subjects obtained at a lead-lag delay of 5 ms.

experiment was conducted using the 3-AFC paradigm with the fixed lag-ITD procedure. As expected, the adaptive as well as the non-adaptive procedure yields the same thresholds.

Although the stimulus presentation of the '3-AFC continuous' (Experiment III) and the 'pick-out' experiments (Experiment V) were continuous, the discrimination threshold values obtained by these two experiments differ significantly. The main difference between both paradigms is the stimulus timing uncertainty: in the '3-AFC' paradigm the subjects know exactly when a deviant may occur as the pre-signal as well as the three intervals are marked. Additionally, the subjects knew that the pre-signal only consisted of reference stimuli. Therefore, they could establish a precise internal representation of this stimulus. In contrast to that, in the 'pick-out' paradigm, the subjects did not know what kind of stimulus will be next because there is no pre-signal and no marking of any interval. It is likely that while performing the 'pick-out' task subjects evaluate each double click-pair more separately. In contrast to that, while performing the '3-AFC' task, it is reasonable to assume that subjects compare the established internal representation with the current double click-pair. Moreover, in the 3-AFC paradigm, intervals that may contain a deviant are marked and the subject only has to choose between three different intervals. This is not the case in the 'pick-out' paradigm. There, no interval is marked which also makes the 'pick-out' task more difficult. Hence, the stimulus timing uncertainty seems to have a considerable effect on the discrimination threshold.

This assumption is supported by previous studies performed by Watson et al. (1975, 1976) and Leek and Watson (1984) which revealed that the uncertainty about the stimulus has a significant effect on the discrimination performance. Although the stimulus uncertainty described in these studies refers to the uncertainty about the change of the stimulus (one of ten tone components is altered), these studies show that discrimination thresholds depend critically on the subjects' expectation of the presented stimuli. Furthermore, terms like 'Temporal Uncertainty' and 'Interval of Time Uncertainty' as described by Green and Swets (1988) and Egan et al. (1961), respectively, refer to the same effect as found in the present study because they describe the influence of the uncertainty about the occurrence of the target stimulus. Egan et al. (1961) performed detection experiments in which a noise was presented continuously and, in certain time intervals which were marked by a light, a target signal (1 kHz sinusoid which is 500 ms in duration) may be presented. Results reveal that even a small increase of the timing uncertainty, i.e., a small extension of the interval in which the signal may appear, exerts a significant influence on the detectability of the target signal. Moreover, a further increase of the timing uncertainty leads to a steady decrease of the detectability. It is reasonable to assume that a similar effect appears in the present study by applying the 'pick-out' paradigm in which no information is provided to the subjects about when a deviant is likely to occur.

2.4.4 Theoretical approach

Several researchers have already noted that the overall spectrum of a lead-lag click-pair changes as a function of the lead-lag delay and the lag-ITD (see, e.g., Tollin and Henning, 1999). These considerations mostly cover lead-lag delays up to 1 ms or 2 ms. In section 2.3 of the present study, a spectral dissimilarity approach was introduced that shows the influence of the lag on the lead for larger lead-lag delays. Furthermore, a perception model was employed in order to calculate differences of the internal representations of the stimuli. According to both of these approaches the behavior of the discrimination threshold in the range from 0 ms to 5 ms can be explained as follows: as illustrated in Fig.2.9 the differences between the spectra of the reference and the deviant stimulus can be described as the differences of the notch frequencies that result from comb filter effects. These differences Δf_c which are displayed as a function of the applied lag-ITD and the cancelled frequency of the reference stimulus are shown for four different lead-lag delays (1, 2, 3 and 5 ms). Obviously, the inserted lag-ITD leads to a much larger difference if the lead-lag delay is short. This means that for short lead-lag delays a small change of the lag-ITD leads to a large difference in the spectral domain at certain frequencies, whereas for larger lead-lag delays a change of the lag-ITD does not lead to such big differences. Therefore, if compared at the same discrimination performance level, lag-ITDs for smaller lead-lag delays may be much smaller than those for larger lead-lag delays.

However, in this analytical approach only the shift of corresponding frequency notches is considered. The perceptual relevance of such a criterion is not clear at all: for example, a frequency notch of the 14. order in the reference spectrum may be closer to the frequency notch of the 13. order of the deviant spectrum. In addition, the auditory system is expected to evaluate the energy and the envelope fluctuations in certain frequency bands rather than to detect shifts in corresponding frequency notches. In order to better assess the perceptual relevance of the monaural cues available to the subjects to discriminate between the reference and the deviant stimulus, a perception model was employed. The comparison of the internal representations according to the perception model yields a dependence on the lead-lag delay similar to the simple analytical approach. Specifically, for a constant lag-ITD, differences between the reference and the deviant spectrum increase with increasing lead-lag delay. This finding is in partial agreement with the discrimination thresholds obtained from the psychoacoustical measurements, i.e., only for the initial portion of the discrimination performance (i.e., for lead-lag delays up to 5 ms) monaural cues seem to dominate performance as a function of the lead-lag delay. As the lead-lag delay increases above 5 ms, the observed performance stays stable and improves again which cannot be predicted from monaural cues. Since binaural cues are available in this configuration, the observed decrease in threshold reflects the usage of the binaural cues. This is comparable with echo thresholds as, e.g., listed in the review paper by Litovsky et al. (1999).

2.5 Conclusions

In the present study five experiments were performed in order to evaluate adaptation processes in discrimination tasks of lag-ITDs in dependence of prior stimulus presentation and the applied paradigm. The following conclusions can be drawn from the results:

- In non-continuous presentation modes adaptation processes during the presentation of multiple references increase the accuracy of the internal representation and yield lower discrimination thresholds of a lag-ITD.
- Due to a speed-accuracy trade-off mechanism, a continuous presentation mode leads to higher discrimination thresholds than those obtained from a non-continuous presentation mode.
- In continuous presentation modes, the stimulus timing uncertainty has a considerable effect on the discrimination thresholds. In the 'pick-out' paradigm stimulus timing uncertainty is very high which makes the buildup of an internal representation of the reference stimulus more difficult. In contrast, in the 3-AFC paradigm having a low stimulus timing uncertainty the buildup of the internal representation is considerably easier which leads to much lower discrimination thresholds.
- The the decrease of the discrimination performance for lead-lag delays from 0 ms to 5 ms could be explained by comparing the spectra of both stimuli (an-

alytical approach) as well as by the comparison of the internal representations of the stimuli (perception model). As these models evaluate monaural cues this finding suggests that monaural cues dominate the discrimination thresholds for lead-lag delays up to 5 ms whereas binaural cues seem to be suppressed due to the precedence effect. For larger lead-lag delays the predictions of both the analytical and the perception model do not agree with the discrimination performances of the psychoacoustical measurements which suggests that for these delays binaural cues are not suppressed and therefore available for the auditory system yielding lower thresholds than predicted by the models.

Chapter 3

Lateralization and discrimination of precedence-effect-type stimuli and the role of adaptation

ABSTRACT

Experiments performed in this chapter investigate the suppression of directional information provided by an interaural time difference (ITD) of a lagging click (lag) which is preceded by a leading click (lead) as a function of the lead-lag delay. Additionally, adaptation effects of multiple reference presentations and continuous stimulation were evaluated. Three experiments were performed that differ in the number of presented reference stimuli (lag-ITD = 0 μs) per trial as well as with respect to the stimulus timing uncertainty. Subjects were asked to indicate any deviant (lag-ITD $\neq$ 0 μs) and, in addition, to assign it to the left or right hand side. Results of the present study are compared with previously collected discrimination thresholds obtained from the same group of subjects. The comparison reveals that directional information is suppressed to a larger extent than other cues, i.e., suppression of direction occurs for a larger range of lead-lag delays than the suppression of discrimination. Moreover, multiple reference presentations and continuous stimulation exert similar influences on both discrimination and lateralization thresholds, i.e., if the reference stimulus is presented repeatedly its internal representation becomes

more distinct yielding lower thresholds than using solitary presented reference stimuli. In contrast, a continuous presentation mode yields higher thresholds than in the case of solitary stimulation due to speed-accuracy trade-off and stimulus timing uncertainty effects. In the non-adaptive continuous presentation mode, significant 'anomalous' lateralizations where observed, i.e., subjects lateralized stimuli consistently on the opposite side as expected. Hence, directional information was consistently misinterpreted by the auditory system.

3.1 Introduction

The ability of the auditory system to sort out the direction of the direct sound and to ignore the directional information that is provided by the reflections has been termed the *precedence effect* (Wallach et al., 1949). It is defined as the suppression of directional information provided by the lag in presence of the lead (see chapter 2). Many researchers performed experiments in the scope of the precedence effect where mostly two pairs of clicks are used to simplify the studies. The first click-pair is commonly referred to as the *lead* and the second click-pair is referred to as the *lag*. An important parameter of this stimulus arrangement is the lead-lag delay. In most studies, an interaural time difference (ITD) in either the lead and/or the lag is embedded and subjects are asked to describe the perceived location of the compound stimulus.

Researchers determined several thresholds related to the precedence effect depending on the experimental setup and the task assigned to the subjects. For example, *lateralization*[1] *thresholds* were determined by Tollin and Henning (1998) who applied a two interval paradigm where the lag-ITD of the first interval was either positive or negative and the second interval contained the same lag-ITD but with opposite sign. They asked their subjects which of the two intervals they perceived farthest to the left. Lateralization thresholds were also obtained by Gaskell (1983) or Saberi

[1] Unlike the localization of a sound at an external position of the head which occurs in a free field arrangement, hearing via headphones leads to a perception of a position within the head which is commonly called lateralization.

and Perrott (1990). Saberi and Perrott applied a two interval paradigm where the first interval contained a diotic double click-pair and the second interval contained a double click-pair with an inserted lag-ITD. Their subjects had to indicate whether they perceived the second interval to the left or right side of the first interval. *Echo thresholds* (see, e.g., Freyman et al., 1991; Litovsky et al., 1999; Krumbholz and Nobbe, 2002) usually determine the lead-lag delay where subjects tend to perceive lead and lag as two separate auditory events rather than a single fused auditory object.

Generally, if one inserts an ITD in the lag click-pair not only directional features (binaural cues) of the compound stimulus are changed but also features like timbre (monaural cues) and spaciousness of the auditory object. Hence, in order to determine the influence of the precedence effect, i.e., the suppression of directional information, one has to distinguish carefully between changes of different stimuli features that are affected by a lag-ITD. It is unclear whether the directional information of the lag is suppressed or contributes its information to the total spectrum of lead and lag. The change of spectral features due to the change of the lag-ITD has so far been described theoretically by experimenters like Gaskell (1983) or Tollin and Henning (1999) but was not separated yet from directional features in psychophysical tasks. Indeed, in non of the before mentioned studies perceived lateralizations provided by a lag-ITD were related to the discrimination performances, i.e., asking subjects not to lateralize stimuli with lag-ITD (deviants), but 'only' to discriminate them from stimuli without lag-ITD (reference).

In chapter 2 discrimination thresholds were determined for the same group of subjects for a lag-ITD in a lead lag stimulus arrangement as a function of the the lead-lag delay using several stimulation modes. Different stimulus presentation modes were applied in order to investigate adaptation processes that occur if the stimulation is adapted to real-life conditions, i.e., continuous stimulation was applied and the stimulus timing uncertainty was varied. Thereby, in all experiments of chapter 2, subjects had the chance to use *any* sound feature (monaural and binaural) to discriminate deviant from reference stimuli. Results of chapter 2 show, that discrimination thresholds depend on both the lead-lag delay and the presentation mode, i.e., a

repeated reference stimulus leads to lower thresholds (compared to those obtained by solitary stimulation of the reference) as its internal representation becomes more distinct. In contrast, continuous stimulation exerts an opposite effect, i.e., due to speed-accuracy trade-off and stimulus timing uncertainty effects higher thresholds are obtained compared to gated stimulation (stimulation is stopped after one trial). Similar effects are expected to be found for the *lateralization threshold* which is addressed in this chapter.
Additionally, discrimination thresholds for lead-lag delays up to about 5 ms as obtained in chapter 2 could be simulated using both an analytical and a perception model that evaluate monaural stimulus parameters. This suggests, that mainly monaural cues are used to perform the discrimination task for these lead-lag delays while binaural cues were suppressed due to the precedence effect. For lead-lag delays larger than about 5 ms both models fail at predicting the discrimination performance which indicates that the precedence effect does not operate for these lead-lag delays and binaural cues help to improve discrimination performance significantly.

The aim of the current study is to separate the detectability of directional cues from other detected changes by comparing lateralization thresholds for a lag-ITD with the previously obtained discrimination thresholds. As in the current experiments several presentation modes similar to those of chapter 2 were employed, i.e., stimulations which were also adapted to real-life conditions, thresholds of both chapters can be compared in order to determine whether the adaption of the stimulation to real-life conditions exerts similar influences on both the discrimination and the lateralization thresholds. Furthermore, the determination of the lateralization thresholds allows to test the assumption which arose from the comparison of the simulated and the behavioral data of chapter 2, i.e., binaural cues help to improve the discrimination performance. If this is the case, lateralization thresholds are expected to be similar to discrimination thresholds for lead-lag delays larger than about 5 ms. For lead-lag delays smaller than 5 ms lateralization performance is expected to be worse than the discrimination performance because of the suppression of directional information due to the precedence effect.

3.2 Methods

3.2.1 Apparatus

All psychophysical experiments took place in a double-walled sound proof booth (IAC 1203A). Signal generation and presentation were controlled by a personal computer using a software package for matlab which was developed at the University of Oldenburg. Stimuli were generated digitally with the matlab software at a sampling rate of 96 kHz, transformed by an D/A converter (type SEK'D 2496 DSP) amplified by a preamplifier (type Behringer HA 4400) and presented via headphones (type AKG K 501) at a level of 40 dB HL (hearing level). The subjects sat in front of the monitor of the personal computer and gave their responses pressing predetermined buttons on the keyboard.

3.2.2 Subjects

Eight subjects (all male) participated in this study. All subjects are members of the research group 'Medizinische Physik' of the University of Oldenburg. They were aged between 23 and 38 and all normal hearing according to their audiogram (hearing loss $<$ 20 dB between 0.125 kHz and 8 kHz). Three of the subjects had intensive experience in psychophysical measurement tasks, three subjects had little experience and two of them were rather inexperienced. All subjects that took part in experiments of the present chapter also participated in experiments of chapter 2.

3.2.3 Paradigms and stimuli

In all experiments double click-pairs were used where the first click is referred to as the *lead* and the second click is referred to as the *lag*. The time interval between the two clicks is called the lead-lag delay. Lead-lag click-pairs split up into two types: reference stimuli and deviants (see Fig. 3.1). Reference stimuli consist of two diotic clicks, i.e., no ITD is embedded neither in the lead nor in the lag click. In contrast to that, an ITD was embedded in the lag click of a deviant stimulus. This ITD was

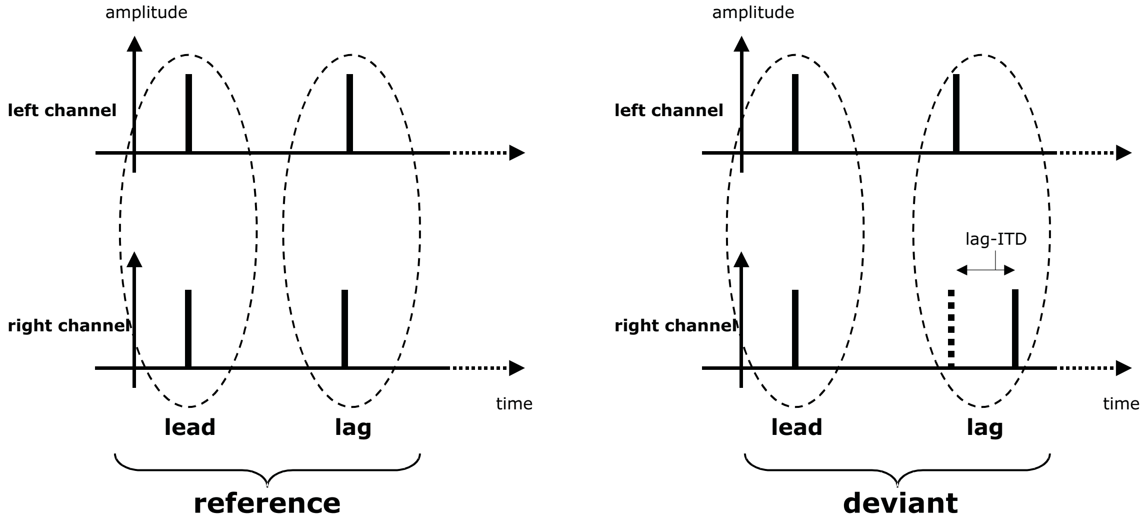


Fig. 3.1: Illustration of a reference stimulus (left panel) and a deviant (right panel) lead-lag click-pair. Stimuli with an inserted ITD in the lag click were deviants whereas reference stimuli had no lag-ITD. The lead-ITD of both stimuli was zero.

either positive or negative yielding lateralizations to the either the left or right hand side, respectively (a positive ITD delayed the lag click of the right channel which yielded a lateralization to the left side).
The lateralization threshold was determined in three different experiments which can be described in short as follows:

Experiment I: Adaptive 3-interval 6-alternative-forced-choice 1-up-2-down experiment where each interval contains one lead-lag click-pair ('3-I 6-AFC single').

Experiment II: Adaptive 3-interval 6-alternative-forced-choice 1-up-2-down experiment where each interval contains twelve lead-lag click-pairs ('3-I 6-AFC train').

Experiment III: 'Pick-out' experiment where a two minute lasting sequence is presented continuously ('pick-out').

All experiments are described in detail in the following:

3.2.4 Experiment I and II, the adaptive 1-up-2-down 3-I 6-AFC procedure

In Experiment I and II, in each trial three intervals were presented whereof one contained the deviant. Subjects were asked to identify the interval containing the deviant and, in addition, to assign the lag click to either the left or right hand side. Therefore, six response buttons, two for each interval, were available for the

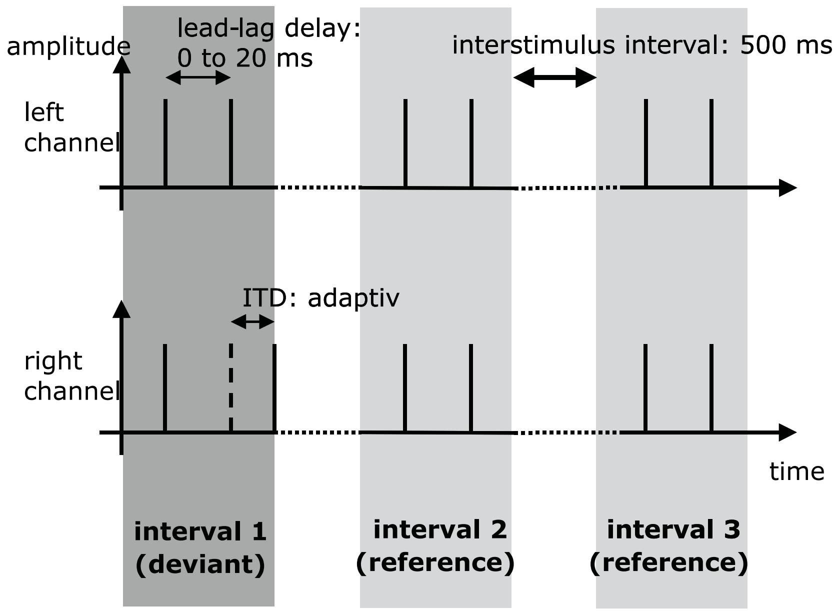


Fig. 3.2: Sketch of the time signal as used in Experiment I ('3-I 6-AFC single'). Three intervals were presented whereof one was a deviant (in this example interval 1) and two were reference stimuli, each consisting of one lead-lag double click-pair. The deviant differs from the reference as a lag-ITD was embedded in either the left or right channel. There was no lag-ITD in the lag of the reference stimuli. Lead-ITDs of both the deviant and the reference were zero. The interstimulus interval was 500 ms yielding a stimulus repetition rate of 2 Hz. The lead-lag delay was kept constant within a single measurement and randomly chosen out of eight different values (0, 1, 2, 3, 5, 7, 10 and 20 ms), the lag-ITD was varied adaptively. In Experiment II ('3-I 6-AFC train') each interval consisted of twelve double click-pairs (not shown). In this case the deviant interval consisted of eleven reference stimuli and one deviant at a random position of the interval and had an embedded lag-ITD.

subject. The respective buttons were enlightened when the corresponding interval was presented (e.g., button one and two were enlightened during the presentation of the first interval). Each button represents two decisions. For example, the first button stands for the decision that the deviant appeared in the first interval and was perceived on the left side. The second button stands for the decision that the deviant appeared in the first interval and was perceived on the right side and so on. As the subjects had to press one of the six buttons after the third interval this procedure is called a 3-I 6-AFC procedure.

A sketch of the time signal as used in the '3-I 6-AFC single' experiment (Experiment I) is shown in Fig. 3.2. In this experiment each interval consisted of one double click-pair, in the '3-I 6-AFC train' experiment (Experiment II) each interval consisted of twelve double click-pairs. Both the time interval between two double click-pairs and the time interval between two intervals of the trial were 500 ms yielding a stimulus repetition rate of 2 Hz.

In the '3-I 6-AFC single' experiment the lead-lag delay was varied as a parameter with values of 0, 1, 2, 3, 5, 7, 10 to 20 ms (presented in randomized order). As the measuring time was twelve times longer in the '3-I 6-AFC train' experiment the lateralization threshold was only determined for lead-lag delays of 1, 5 and 20 ms (presented in randomized order).

The procedure of Experiments I and II is called *adaptive* because the lag-ITD was increased after each incorrect response and decreased after two successive correct responses (1-up 2-down). Additionally, the step-size was varied during one measurement. The initial lag-ITD was $\pm$ 430 μs (this corresponds to a lateralization of approximately half the way between the center of the head and the respective ear). The initial step-size was 42 μs (8 samples) which was reduced to 21 μs (4 samples) after the first upper reversal and reduced to the final step-size of 10 μs (1 sample) after the second one. All lead-ITDs were zero.

3.2.5 Experiment III, the 'pick-out' procedure

In the 'pick-out' experiment stimulus sequences as shown in Fig. 3.3 were presented to the subjects. Each sequence consisted of about 210 stimuli (lead-lag click-pairs) and had durations close to two minutes. The stimuli were presented at a repetition rate of 2 Hz (the same repetition rate as in Experiments I and II).

At randomly chosen positions of the sequence the lag click had positive or negative interaural time differences of 150, 300, 450, 600, 750 or 900 μs, respectively. These time shifts were inserted in the lag click in such a way that the lead-lag delay in the right channel was either enlarged (positive ITD) or shortened (negative ITD) which leads to a lateralization to the left or right hand side, respectively.
Each of the 12 deviants was embedded 3 times in each sequence on condition that

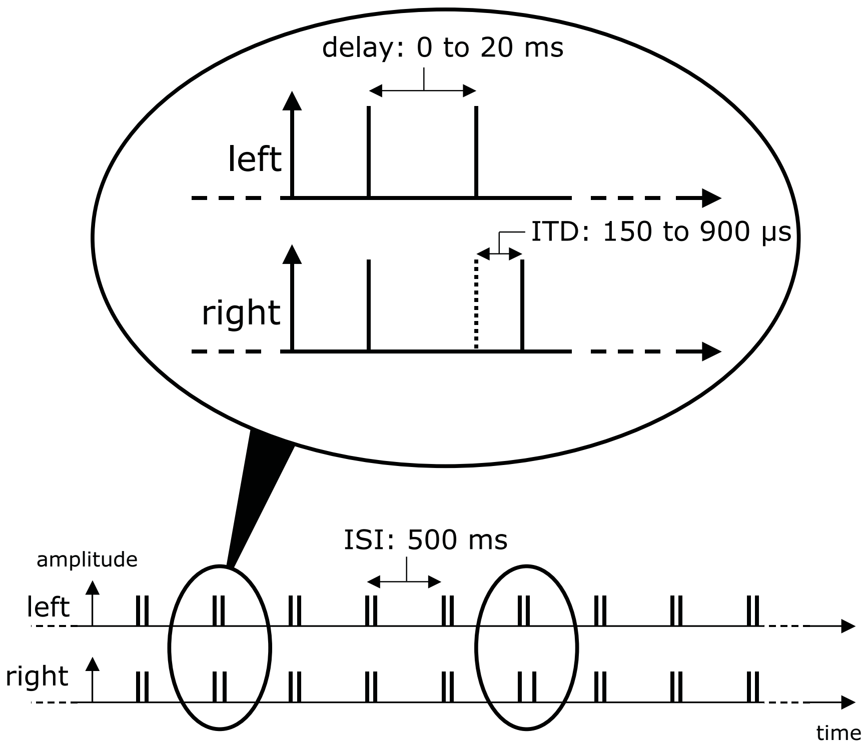


Fig. 3.3: Sketch of the stimulus sequence as used in the 'pick-out' experiment (Experiment III). Overall, the sequence consisted of about 210 lead-lag click-pairs. The interaural time difference of the lag click of the deviant, see enlarged cut-out, was varied from 0 μs up to $\pm$ 900 μs in steps of $\pm$ 150 μs. The lead-lag delay was varied from 0 ms up to 20 ms. Within one sequence the lead-lag delay was kept constant.

at least three and at most ten reference stimuli followed a deviant. Overall, there were 36 deviants and about 200 reference stimuli in each sequence.
The lead-lag delay was also varied as a parameter over the sequences but was constant within one sequence. As eight different lead-lag delays were applied, a total of 40 different sequences (5 sequences per lead-lag delay) were presented.

Subjects were asked to hit either the left or right predetermined button on the keyboard as soon as possible after they detected a deviant stimulus. Thus, the attention was turned strongly to the stimulus sequence. The subjects received no feedback during the measurement.
Before data were collected, all subjects were introduced to their task and went through a training session consisting of three sequences. No subject reported any problems with the task although some mentioned that high concentration was needed.
In Experiment III ('pick-out') six sampling points of the psychometric function were determined for each side. A subjects' response was treated as a 'hit' if the correct button on the keyboard was pressed within one second after the presentation of the deviant. No response or a delayed response was treated as a miss or false alarm, respectively. This yields percent correct performances for the fixed lag-ITDs for each subject. A psychometric function according to equation

$$f(x) = \frac{1}{1 + e^{(a+bx)}} \tag{3.1}$$

was fitted to the six sampling points where a determines the horizontal shift and b the slope of the function. From this function the 70.7 percent correct performance value was interpolated.

During all experiments particular attention was paid to the subjects' vigilance. Most subjects performed about five measurements in a row until they reported getting tired, i.e., they listened and responded to five sequences which lasted about 15 to 20 minutes.

All statistical tests that were performed were Wilcoxon tests using an α-value of 0.05.

3.3 Results

Figure 3.4 shows lateralization thresholds as obtained by all three experiments. Shown are lag-ITDs that led to 70.7 percent correct performances. Thresholds determined by the '3-I 6-AFC single' experiment (Experiment I) were plotted as circles, thresholds determined by the '3-I 6-AFC train' experiment (Experiment II) were plotted as triangles and thresholds of the 'pick-out' experiment (Experiment III) were plotted as diamonds. Open symbols represent data averaged across those five subjects that participated in all experiments, closed symbols represent data averaged across eight subjects (only five subjects participated in the '3-I 6-AFC train' experiment). Upward-pointing errorbars show the interindividual standard deviation calculated across eight subjects, downward-pointing errorbars those calculated

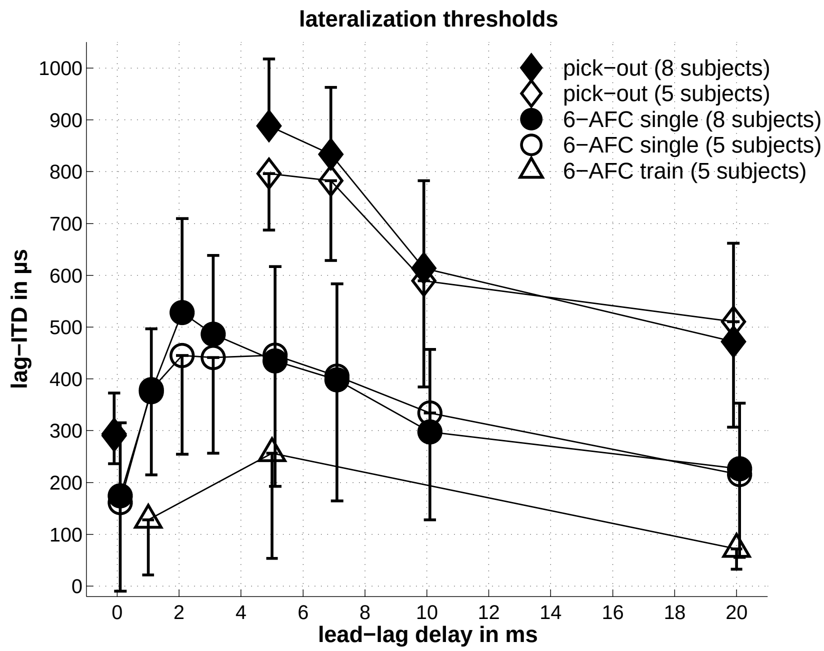


Fig. 3.4: Lateralization thresholds obtained by Experiment I ('3-I 6-AFC single', circles), Experiment II ('3-I 6-AFC train', triangles) and Experiment III ('pick-out', diamonds). Lag-ITDs that yield 70.7 percent correct performances were plotted as a function of the lead-lag delay. Open symbols show data averaged across those five subjects that participated in all experiments, closed symbols show data averaged across eight subjects. Errorbars indicate interindividual standard deviations.

across five subjects. For a better representation of the errorbars of different experiments, values of the same lead-lag delays were slightly shifted.

Lateralization thresholds for lead-lag delays of 1,2 and 3 ms could not be determined in the 'pick-out' experiment as none of the pre-selected lag-ITDs between 150 μs and 900 μs yielded a higher performance than 70.7 percent correct (see also Fig. 3.7). All lag-ITD values averaged across all eight subjects do not differ significantly from those averaged across the subset of five subjects (Wilcoxon tests, $p < 0.05$). Overall, the 'pick-out' experiment yielded the highest lag-ITD values with the highest value of about 900 μs at a lead-lag delay of 5 ms. Thresholds obtained by the '3-I 6-AFC train' experiment are much lower with a lag-ITD value below 300 μs for a lead-lag delay of 5 ms. The '3-I 6-AFC single' experiment yielded lag-ITD values that assume intermediate values with a maximum of about 520 μs at a lead-lag delay of 2 ms. The lag-ITD threshold value at a lead-lag delay of 5 ms is about 440 μs. Threshold characteristics for all experiments are similar, i.e., for lead-lag delays from 2 ms to 7 ms lag-ITD values are higher than those obtained by lead-lag delays of 0, 10 or 20 ms.

Except for a lead-lag delay of 0 ms, lag-ITD values obtained by the 'pick-out' experiment (Experiment III) differ significantly from those obtained by the '3-I 6-AFC single' experiment (Experiment I).

Figure 3.5 and 3.6 show the distribution of the depressed keys of the '3-I 6-AFC single' experiment (Experiment I). Each of the eight panels in Fig. 3.5 represents one of the lead-lag delays of 0, 1, 2, 3, 5, 7, 10 and 20 ms, respectively. Each panel contains four bars that show the number of <u>c</u>orrect/<u>f</u>alse <u>i</u>nterval and <u>c</u>orrect/<u>f</u>alse <u>d</u>irection identifications which were accumulated across all eight subjects. For this analysis only those key presses were evaluated with respective lag-ITD values between 300 μs and 500 μs, respectively, i.e., lag-ITDs near the threshold. The upper left panel shows the response key distribution for a lead-lag delay of 0 ms. For this lead-lag delay almost all responses were correct and only a few direction confusions and false interval identifications occurred.

Figure 3.6 shows the number of correct responses (first bars in panels of Fig. 3.5) as black down-pointing triangles, direction confusions (second bars in panels of Fig. 3.5) as gray up-pointing triangles and the number of false interval identifications (sum of third and forth bars in panels of Fig. 3.5) as gray diamonds as a function of the lead-lag delay. Additionally, the relation between the number of correct responses and direction confusions is shown as open squares as a function of the lead-lag delay. Noticeably, all curves are highly dependent on the lead-lag delay. The largest number of correct responses was obtained for a lead-lag delay of 1 ms. It decreases with increasing lead-lag delay and reaches its minimum at a lead-lag delay of 3 ms. It increases again close to the maximum value for a lead-lag delay of 20 ms. The number of direction confusions shows the opposite characteristic: for lead-lag delays

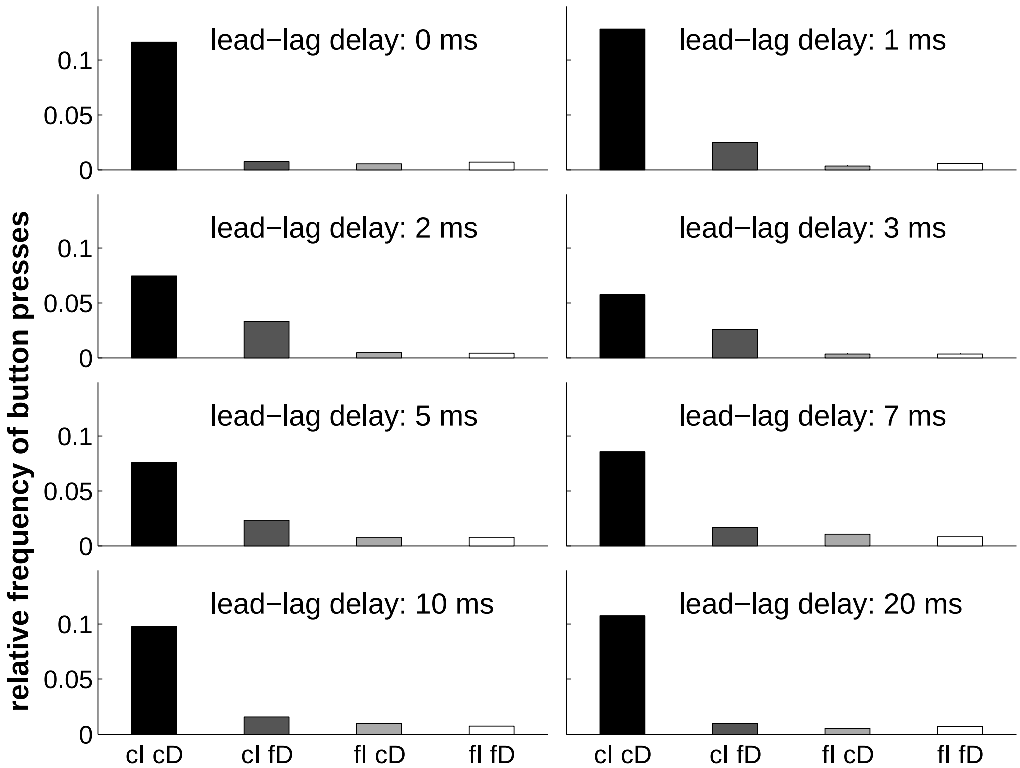


Fig. 3.5: Plot of the distributions of the number of key presses for lead-lag delays of 0, 1, 2, 3, 5, 7, 10 and 20 ms of Experiment I. The number of key presses were accumulated across eight subjects and normalized by the total number of key presses (33.600). Different bars show the distribution among the correct and false identifications of the interval ('cI', 'fI') and direction ('cD','fD'), respectively.

of 0 ms and 20 ms the number of direction confusions is small and the maximum is reached for a lead-lag delay of 2 ms. Hence, the relation between the number of direction confusions (open squares) and the number of correct responses show the same general characteristic as the direction confusions, i.e., the maximum is reached at lead-lag delays of 2 ms and 3 ms whereas smaller and larger lead-lag delays yielded considerably lower values.

The number of false interval identifications also seems to depend on the lead-lag delay. It reaches the smallest value for a lead-lag delay of 3 ms. For smaller and larger lead-lag delays greater numbers of false interval identifications occur at a lead-lag delay of 7 ms.

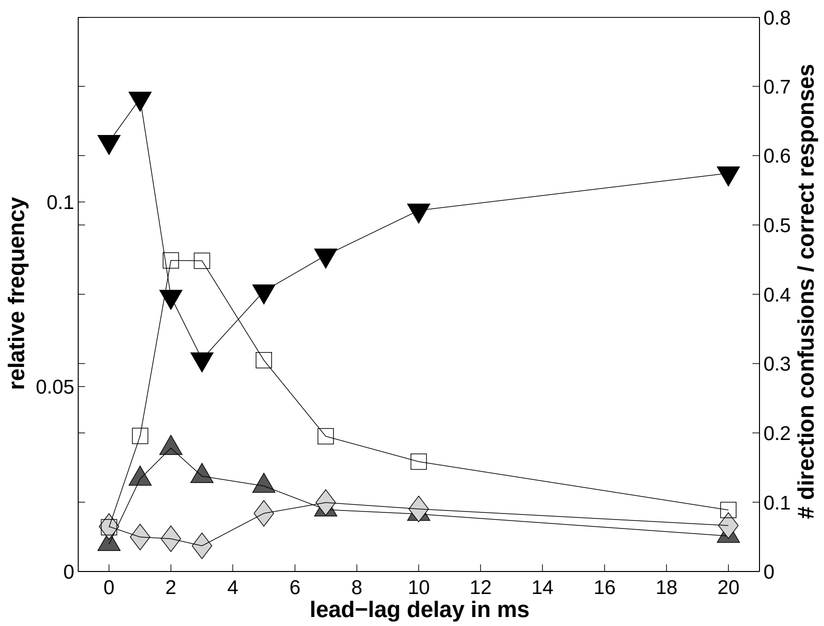


Fig. 3.6: The relative frequency of correct responses (black down-pointing triangles), direction confusions (gray up-pointing triangles) and false interval identifications (gray diamonds) as obtained by the '3-I 6-AFC single' experiment (Experiment I) as a function of the lead-lag delay (left scale, i.e., the number of key presses normalized by the total number of key presses in Experiment I that is 33.600). Additionally, open squares show the relation between the number of direction confusions and correct responses (right scale).

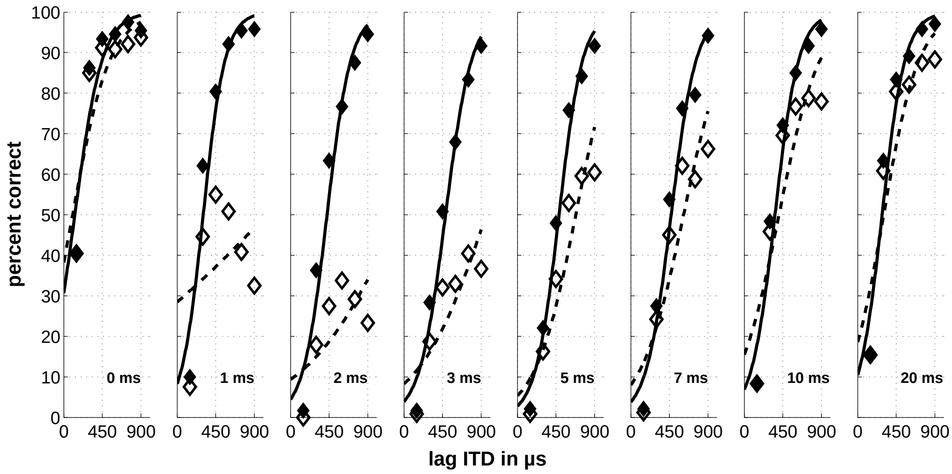


Fig. 3.7: Percent correct performances averaged across eight subjects as obtained in Experiment III ('pick-out') were plotted in dependence on the lag-ITD. Each of the eight insets represents one of the eight different lead-lag delays in ascending order (from left to right). Psychometric functions were fitted to both the percent correct performances of the discrimination threshold (filled symbols) and the lateralization thresholds (open symbols). Percent correct performances of the discrimination threshold were obtained by only considering the choice of the correct interval. Similar performances for the lateralization thresholds were obtained by considering the choice of the correct side within the correct interval, additionally.

Figure 3.7 shows mean results of the 'pick-out' experiment (Experiment III). As the task of the subjects was both to identify the deviants and, additionally, to assign them to either the left or right side, responses were analyzed as correct interval identifiers (filled symbols) as well as correct interval *and* correct direction identifiers (open symbols). Note that responses represented by the open diamonds are a subset of those shown by the filled diamonds. Additionally, psychometric functions were fitted to either data sets. For lead-lag delays of 0, 10 and 20 ms, respectively, both psychometric functions are similar. In contrast to that, for lead-lag delays from 1 ms to 7 ms both psychometric functions show considerable differences, especially for lead-lag delays from 1 ms to 3 ms. In the latter cases even for lag-ITDs of 900 μs percent correct performances do not exceed values of 60 percent.

A striking result is that for lead-lag delays of 1 ms and 2 ms the lateralization thresholds even decrease with increasing lag-ITDs (see Fig. 3.7). This effect is analyzed in more detail in Fig. 3.8 where hits and direction confusions of the 'pick-out' experiments are plotted. As described in section 3.2 in this experiment deviants with positive and negative lag-ITDs were presented. Mean values of the results of both sides are plotted. Each panel of Fig. 3.8 shows the number of hits and direction confusions accumulated across eight subjects as a function of the six fixed lag-ITDs. As the total number of deviant identifications is expected to increase with increasing lag-ITD both the number of direction confusions and the number of hits are expected to increase, too. In fact, the number of direction confusions increases with increasing lag-ITDs (see open bars in Fig. 3.8). However, at least for lead-lag delays of 1 ms and 2 ms the number of hits only increases for lag-ITDs up to 450 μs and 600 μs, respectively. Unexpectedly, for these lead-lag delays, *decreasing* number of hits were obtained for increasing lag-ITDs. For some lead-lag delays and lag-ITDs the number

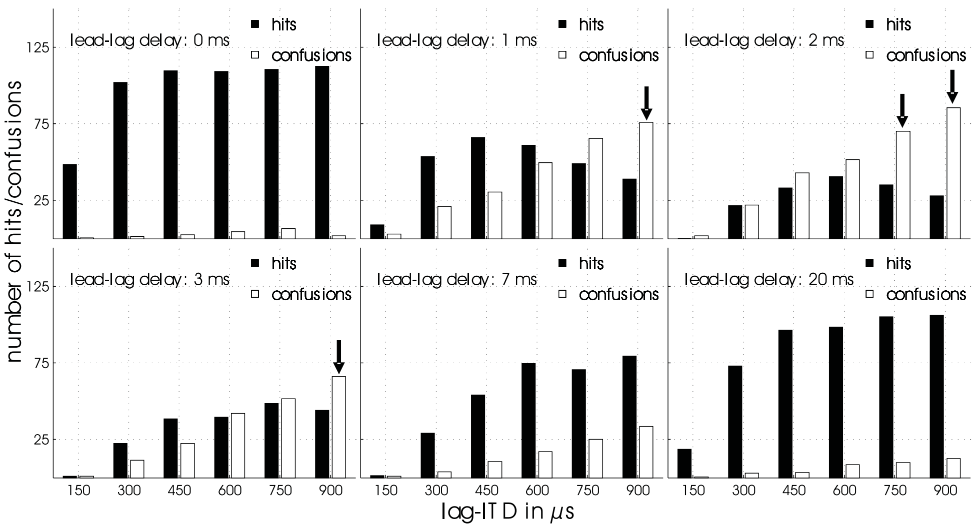


Fig. 3.8: Illustration of hits (filled bars) and direction confusions (open bars) that occurred in the 'pick-out' experiment in dependence on the lag-ITDs and lead-lag delays. Data were accumulated across eight subjects. Mean hits and mean direction confusions of lateralizations to the left and right hand side are shown. Arrows indicate those number of direction confusion values that are significantly larger than the corresponding number of hit values.

of direction confusions is significantly larger than the corresponding number of hits (Wilcoxon tests, $p < 0.05$, marked by an arrow in Fig. 3.8).

Figure 3.9 shows the percent correct performances of the 'pick-out' experiment as a function of the number of reference stimuli that preceded the deviant. As mentioned in section 3.2 the sequences of the 'pick-out' procedure were designed with the constraint that between three and ten reference stimuli preceded (followed) a deviant. Not all combinations of numbers of reference stimuli presented before the deviant and lag-ITD values are covered.

The solid lines represent percent correct performances for the deviants from the left, the dashed lines percent correct performances for the deviants from the right,

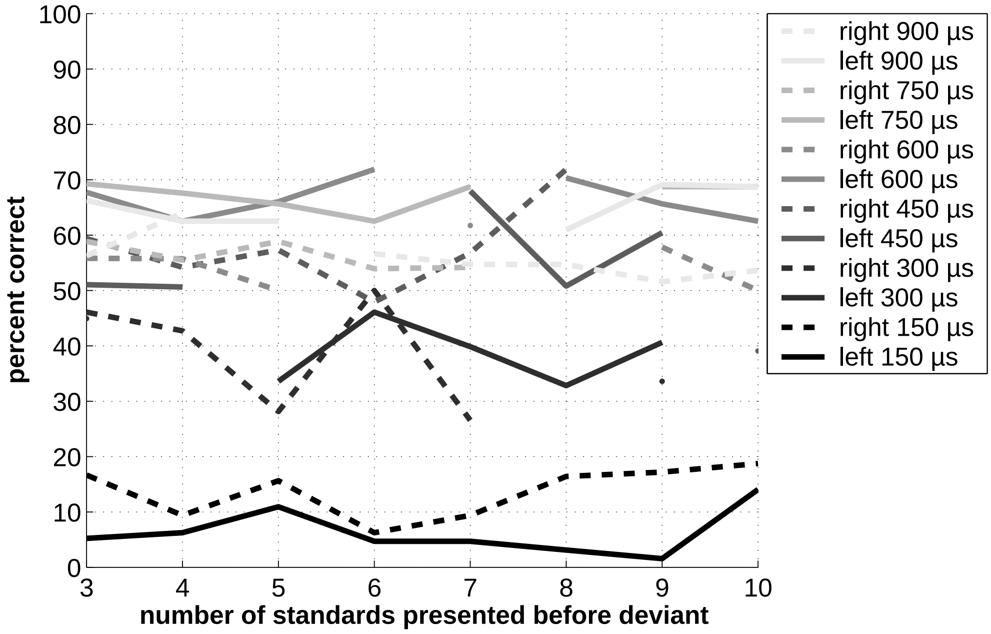


Fig. 3.9: Percent correct performances for all deviants of the 'pick-out' procedure as a function of the number of reference stimuli presented before the deviant averaged across all subjects and lead-lag delays. Dashed lines indicate percent correct values for the deviants that were lateralized to the right hand side and the solid lines indicate the percent correct values for the deviants that were lateralized to the left hand side. Not each number of reference stimuli was presented before each deviant so that some values are missing.

respectively. Performance values were averaged across all subjects and all lead-lag delays.

As Fig. 3.9 shows, no consistent asymmetry between performances for deviants from either side can be observed. Additionally, for all deviants of each side the percent correct performance is nearly independent of the number of reference stimuli preceding the deviant.

Figure 3.10 compares lateralization thresholds (filled symbols) as obtained in the present chapter with the discrimination thresholds (open symbols) obtained in chap-

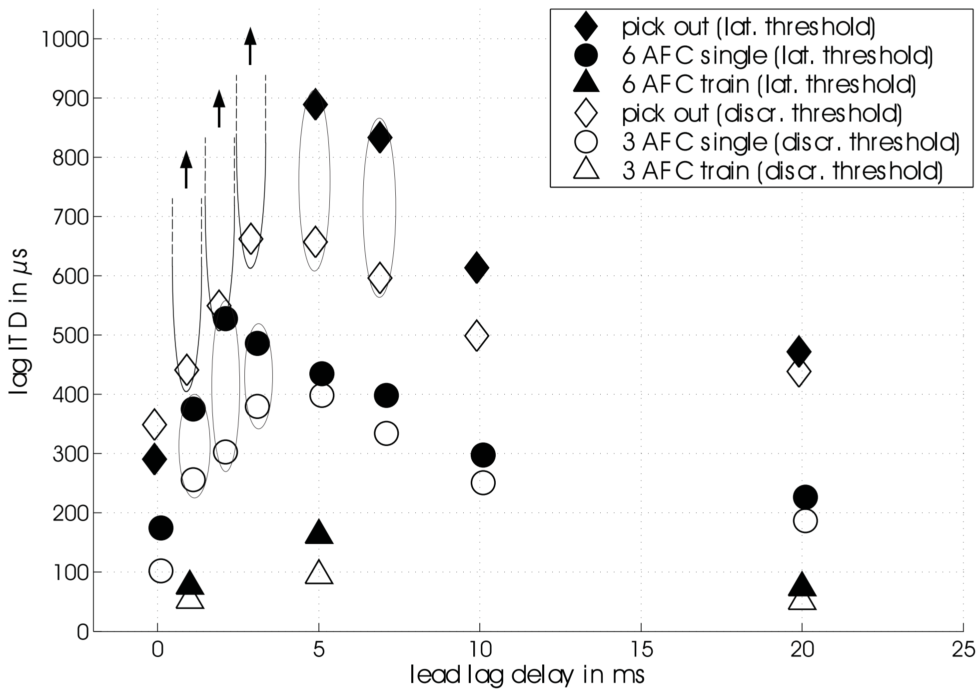


Fig. 3.10: Comparison of discrimination thresholds (open symbols) as obtained in chapter 2 (see also Fig. 2.6) and lateralization thresholds (filled symbols) as obtained in this chapter (see also Fig. 3.4). For a better view errorbars were omitted. Encircled pairs of discrimination and lateralization threshold values indicate significant differences according to Wilcoxon tests ($p < 0.05$). As the lateralization thresholds for lead-lag delays of 1, 2 and 3 ms are infinite because subjects in these cases did not reach percent correct rates exceeding 70.7 percent, the difference between the discrimination and the lateralization thresholds was interpreted as being significant which is displayed as open ellipses with an arrow pointing to infinite lag-ITD values.

ter 2. The same symbols as in Fig. 3.4 represent thresholds obtained by Experiment I to III. Significant differences between both types of tasks are encircled. They occur for the 'AFC single' experiments for lead-lag delays of 1, 2 and 3 ms and for the 'pick-out' procedure for lead-lag delays from 1 ms to 7 ms. For lead-lag delays at 0 ms and from 10 ms to 20 ms the difference between the discrimination threshold values and the lateralization threshold values is not significant. However, all lateralization threshold values lie about 50 μs above the discrimination threshold values.

3.4 Discussion

In this chapter the amount of directional information suppression in several precedence-effect-type conditions was determined as a function of the lead-lag delay in order to separate the detectability of directional cues from other detected changes in a lead-lag click-pair. Additionally, the influence of adapting the stimulation towards real-life conditions is studied, i.e., increasing the stimulus timing uncertainty, varying the number of reference stimuli that precede the deviant and applying continuous stimulation.
Experiments performed in this chapter differ from those from chapter 2 because those experiments did not determine which cue actually led to the discrimination judgement and therefore did not determine to what extent discrimination judgements are based on directional cues. Rather, performance might as well be based on spectral cues or the number of perceived images.
Additionally, by combining both the results of chapter 2 and chapter 3 it is possible to analyze whether lateralization performance exhibits a different dependency on the lead-lag delay and adaptation behavior than the discrimination performance.

Relating the lateralization thresholds as obtained in this chapter to those determined in previous studies shows that similar results were received although different paradigms were applied. For example, lateralization thresholds obtained with the 6-AFC paradigm of the present study are in agreement with lateralization thresholds determined by Saberi and Perrott (1990) and Tollin and Henning (1998). However, thresholds determined by Saberi and Perrott are somewhat lower and their standard deviations are smaller, but, in line with results of the present study, highest lateralization thresholds were obtained for a lead-lag delay of 2 ms. Lateralization thresholds obtained by Tollin and Henning also agree with those obtained in this study: in both studies lateralization thresholds are rather individual and vary considerably across subjects. In addition, the range of lead-lag delays where thresholds are increased is similar in both studies (1 ms to 10 ms). Furthermore, lateralization thresholds obtained with lead-lag delays around 20 ms are increased compared to those obtained with lead-lag delays close to 0 ms.

3.4.1 The relation between discrimination and lateralization thresholds

Comparing both the lateralization thresholds as obtained in this chapter and the discrimination thresholds as obtained in chapter 2 reveals that both thresholds differ significantly in their dependency on the lead-lag delay: the strongest suppression of directional information (lateralization thresholds) was found for a lead-lag delay of 2 ms, while the strongest overall information suppression (discrimination thresholds) was found for a lead-lag delay of 5 ms, i.e., increase and decrease of the suppression of directional information is obtained for smaller lead-lag delays than for the suppression of other information.

The increase of the lateralization threshold of the present study is due to two effects that both contribute to the precedence effect: first, the increase of the discrimination threshold for all lead-lag delays as already shown in chapter 2. Second, the additional increase of the lateralization threshold in excess of the discrimination threshold (Fig. 3.10). This difference between both thresholds is dependent on both the lead-lag delay and the paradigm: for the 'AFC single' experiments lateralization thresholds are significantly increased compared with the discrimination thresholds for lead-lag delays from 1 ms to 3 ms. For the 'pick-out' procedure differences between both thresholds are significant for lead-lag delays from 1 ms to 7 ms. The differences between discrimination and lateralization thresholds may be due to a stronger suppression of directional information than other information (e.g., spectral information) that help to discriminate deviants from reference stimuli. For lead-lag delays where both thresholds are rather similar additional cues do not help in the discrimination task significantly, but were suppressed similarly to directional cues. However, for all lead-lag delays discrimination thresholds tend to be lower than corresponding lateralization thresholds, albeit these differences are not significant.

Another reason for the difference between both thresholds may be an incorrect interpretation of the available cues by the auditory system for certain stimulus configurations: as described in chapter 3.3 in the 'pick-out' experiment subjects perceived deviants consistently on the opposite side at least for lead-lag delays from 1 ms to 3 ms. This hypothesis is based on the increasing number of directional confusions arising in the 'pick-out' experiment even if the discrimination performance increases, too. This is a striking result as intuitively the number of direction confusions is not expected to exceed the number of correct direction identifications. However, the latter even *decreases* with increasing lag-ITD. Hence, for lag-ITDs of 750 μs and 900 μs the number of direction confusions is partly significantly larger than the number of hits. This is observable for deviants of both sides which shows that subjects did not always press the same button when they were insecure about their lateralization of the deviant. If this would be the case, hits and direction confusions would occur with equal frequency. As the number of confusions is partly significantly larger than the number of hits, it is more likely that subjects lateralized consistently the deviants on the opposite side. This suggests that directional information was not suppressed but was misinterpreted by the auditory system.

According to this explanation, the reason that lateralization thresholds could not be determined in the 'pick-out' measurement for lead-lag delays from 1 ms to 3 ms was not that lag-ITD values were too small, but the cues caused by the lag-ITDs were misinterpreted consistently by the subjects. This 'anomalous lateralization' was previously described by Tollin and Henning (1999) who also used ITDs (anomalous lateralization using interaural intensity differences were, e.g., described by Gaskell, 1976, 1983). In their study Tollin and Henning determined lateralization thresholds using a three click arrangement and varying the inter click interval (ICI) from 0.2 ms up to 5 ms. Their results show nearly 100 percent correct lateralization performances for ICIs of 0.1 ms and ICIs larger than 1 ms. For ICIs in-between lateralization performances decreased considerably. Values of about ten percent which is far below the chance level of 50 percent were obtained for ICIs around 0.5 ms indicating a consistent lateralization on the opposite side as expected. In several subsequent experiments Tollin and Henning investigated the spectral influence of the lag click on the compound stimulus. They found a 'dominant region around 750 Hz' and they concluded that the information provided by the lag click is not suppressed at all but contributes to the overall acoustical information provided by the compound stimulus. The anomalous lateralizations found in the 'pick-out' experiment of the present study may be explained similarly, although they were obtained at larger lead-lag delays.

Another important fact arises from the comparison of discrimination and lateralization thresholds: namely, for all paradigms that were applied in both studies, for lead-lag delays from 1 ms to 20 ms, not only the directional information of the lag is suppressed but, in addition, even non-directional cues provided by the stimuli (such as, e.g., spectral changes) are suppressed. Previous studies that determined lateralization thresholds could not assess the suppression of other than the directional information as they did not determine the corresponding discrimination thresholds. In combination with results of chapter 2 the present study reveals the difference between the suppression of directional and other information that is affected by the change of the lag-ITD.

3.4.2 The usage of monaural and binaural cues in the discrimination task of chapter 2

As shown in chapter 2, the gradual decrease of the discrimination performance for lead-lag delays up to 5 ms can be predicted satisfyingly by both an analytical and a perception model that evaluate monaural stimulus parameters. In contrast, for larger lead-lag delays both models predict a further decrease of the discrimination performance whereas an increasing performance was obtained in the behavioral tasks. This failure of the monaural models at predicting discrimination performances for lead-lag delays larger than 5 ms suggests that binaural cues, which were suppressed due to the precedence effect for smaller lead-lag delays, help to improve the discrimination performance.

Lateralization thresholds as obtained in this chapter support this assumption of chapter 2: namely, discrimination performance is improved by the usage of binaural cues for lead-lag delays larger than 5 ms. As can be seen in Fig. 3.10, depending on the applied paradigm, discrimination and lateralization thresholds do not differ significantly for lead-lag delays larger than 3 ms (AFC paradigm) and 7 ms ('pick-out' paradigm). This indicates that for these lead-lag delays the discrimination performance is dominated by the usage of binaural cues, i.e., lateralization performance. As monaural cues were not suppressed as strong by the precedence effect as binaural cues for lead-lag delays up to 5 ms and 10 ms, respectively, the discrimination performances for these lead-lag delays is dominated by the monaural cues.

3.4.3 Adaptation effects

Multiple presentation of the reference stimulus within one trial as well as continuous stimulation exert similar influences on the lateralization threshold as on the discrimination thresholds (see chapter 2), i.e., lateralization thresholds as obtained in the '3-I 6-AFC train' experiment (Experiment II) are substantially *decreased* compared with the lateralization thresholds as obtained in the '3-I 6-AFC single' (Experiment I) experiment. The difference between both thresholds is assumed to result from a more distinct internal representation of the reference stimulus as it is presented repeatedly which facilitates the discrimination task. In contrast, lateralization thresholds as determined by the 'pick-out' procedure (Experiment III), where also multiple reference stimuli were presented, are *increased* compared with the lateralization thresholds as determined in the '3-I 6-AFC single' experiment. This considerable difference is assumed to result from at least two effects: first, a speed-accuracy trade-off mechanism produced by the continuous presentation mode in which subjects are forced to respond very quickly and second, the larger stimulus timing uncertainty arising due to the design of the 'pick-out' procedure. In the '3-I 6-AFC train' experiment subjects are aware that only one deviant will be presented among 35 reference stimuli, i.e., the stimulus timing uncertainty is very low as only one deviant is expected to occur. Therefore, the internal representation of the reference stimulus can be established very well and becomes more distinct - considerably better than in the '3-I 6-AFC single' experiment. Thus, the inserted lag-ITD is perceived more easily which leads to decreased thresholds. In contrast to that, in the 'pick-out' experiment, subjects do not know what type of stimulus (deviant or reference stimulus) will be next. For this reason, the internal representation cannot be established as well as in the '3-I 6-AFC train' experiment. Instead, each new stimulus is evaluated separately, i.e., subjects changed their strategy to perform the task. Influences of the different types of procedures that were applied are discussed in more detail in chapter 2.

Generally, it can be concluded that the adaptation processes observed in this study are not similar to the buildup effect described in the literature: previous studies as performed by Freyman et al. (1991) or more recently by Krumbholz and Nobbe (2002) that address the buildup effect, have shown that the *echo threshold* is increased as multiple repetitions of the lead-lag click-pair (reference) were preceding the test click-pair (deviant). Freyman et al. (1991) asked their subjects whether they perceived an echo, Krumbholz and Nobbe (2002) asked their subjects whether they perceived one or two auditory events. Thus, in both studies subjects were asked to indicate the number of perceived events. On the other hand, subjects that performed *lateralization threshold* measurements as described in this study had to assign the deviant to either the left or right hand side, i.e., to assign the stimulus to a direction. Hence, the determination of the lateralization and the echo thresholds are basically two different tasks. Results of the analysis concerning within-sequence adaptation effects in the 'pick-out' experiments were shown in Fig. 3.9. Obviously, lateralization performance is not dependent on the number of reference stimuli preceding the deviant in this procedure. This might not surprise as studies performed by Djelani (2001) showed that the buildup effect does not break down after a single stimulus being presented from a deviating direction. Therefore, a single deviant within a sequence of reference stimuli is not expected to break down the buildup effect and thus the buildup effect, if operating at all in lateralization tasks, would be expected to operate at a saturated level throughout the whole sequence.

3.5 Conclusions

Results of this chapter can be summarized as follows:

- A significant difference exists in the dependency on the lead-lag delay between the discrimination and lateralization thresholds: the maximum suppression of directional information was found for a lead-lag delay of 2 ms, while the maximum overall information suppression was found for a lead-lag delay of 5 ms, i.e., increase and decrease of the suppression of directional information is obtained for smaller lead-lag delays than for the suppression of other information. In addition, lateralization performance in the '3-I 6-AFC single' experiments for lead-lag delays from 1 ms to 3 ms and in the 'pick-out' experiment for lead-lag delays from 1 ms to 7 ms is significantly worse than the discrimination performance. These differences can be explained by an additional suppression of directional information as well as by a misinterpretation of the lateralization cues by the auditory system, i.e., consistent 'anomalous' lateralizations were observed in the 'pick-out' paradigm for certain stimulus configurations.

- The difference between lateralization and discrimination thresholds observed here also indicates that monaural cues dominate performance for lead-lag delays smaller than 5 ms, whereas binaural cues can be utilized for larger lead-lag delays.

- Adaptation effects produced by a repetitive stimulation exert similar influences on the lateralization thresholds as on the discrimination thresholds obtained in chapter 2: probably, due to a more distinct internal representation of the reference stimulus both the discrimination thresholds and the lateralization thresholds are decreased if twelve double clicks ('3-I 6-AFC train' experiment) are presented within one interval instead of a single double click ('3-I 6-AFC single' experiment). If a continuous stimulus presentation mode is employed ('pick-out' procedure), however, discrimination thresholds as well as lateralization thresholds are increased in comparison to those thresholds obtained by 3-I 6-AFC procedures which can be explained by a speed-accuracy trade-off mechanism and a larger stimulus timing uncertainty (see also chapter 2).

- The adaptation processes observed here are unlike the 'buildup effect' of the echo threshold which occurs if multiple references are presented and the number of perceived auditory events is reported.

- Overall, the results observed here show that the precedence effect produces a larger suppression of directional information if the stimulus presentation is adapted to real-life conditions, i.e., employing a continuous stimulation as well as a higher stimulus timing uncertainty, than under more artificial conditions using solitary stimulus presentation, i.e., the precedence effect may operate in everyday life even more effectively as so far found in artificial environments.

Chapter 4

Neural correlates of the precedence effect in auditory evoked potentials

ABSTRACT

The precedence effect in subjective localization tasks reflects the dominance of directional information of a direct sound (lead) over the information provided by one or several reflections (lags) for short delays. The current study aims at neurophysiological correlates for the precedence effect in humans by recording auditory evoked potentials. In order to investigate whether the stimulus features or the perception of the stimulus is reflected on the ascending stages of the human auditory pathway, auditory brainstem responses (ABRs) as well as cortical auditory evoked potentials (CAEP) using double click-pairs were recorded. Potentials were related to results of previously obtained psychoacoustical data.

In ABR measurements double click-pairs with lead-lag delays from 0 ms to 20 ms and interaural time differences (ITDs) in the lag click of 0 μs and 300 μs were applied. Corresponding potentials show an emerging second wave V for lead-lag delays larger than 2 ms which increases gradually in amplitude and latency. In potentials obtained from non-zero ITD stimuli, the embedded ITD could be found. However, the amplitudes of the second wave V were not decreased for a lead-lag delay around

5 ms as could be expected from previous psychoacoustical measurements. Hence, ABRs are assumed to reflect stimulus features rather than the perception of the stimulus.
The mismatch negativity component of the CAEP for double click-pairs was determined using a deviant with an ITD of 800 μs in the lag click. The comparison between the obtained MMN components and the psychoacoustical data shows that the MMN is related to the perception of the stimulus, i.e., the precedence effect.
Generally, findings of the present study suggest that the precedence effect is not a result of an insufficient sensitivity of the peripheral processing (bottom-up). Rather, the precedence effect seems to reflect cognitive processes on higher stages of the auditory pathway which may lead to top-down processes.

4.1 Introduction

If a sound is emitted in a reverberant environment, a complex mixture of acoustic signals comprising the direct sound (lead) and several reflections (lags) reaches the two ears. Although lead and lag sounds may carry contradictory directional information, the human auditory system manages well to resolve the location of the sound source. It is commonly believed that this ability is assisted by the *precedence effect*, a term that pools several phenomena which describe the dominance of directional information of a leading sound over directional information provided by lagging sounds for short delays.
The precedence effect was first described by Wallach et al. (1949). Since then, many researchers have shed light on the relationship between the information which is provided by the lead and the lag, respectively. For a comprehensive review see, e.g., Zurek (1980), Blauert (1997) and Litovsky et al. (1999).
Single cell neurophysiological findings in several animals indicate that correlates of the precedence effect exist already at the level of the colliculus inferior, i.e., response rates of single neurons depend similarly on the direction of lead and lag sources and the lead-lag delay like the perceived location of the compound stimu-

lus (lead and lag) in corresponding behavioral tasks performed by humans or cats (see, e.g., Tollin and Yin, 2003). Examinations were made in different species, e.g., in the external colliculus of the colliculus inferior (IC) of the barn owl (Keller and Takahashi, 1996), the IC of the rabbit (Fitzpatrick et al., 1995) and the IC of the cat (Litovsky, 1998; Litovsky and Yin, 1998; Litovsky and Delgutte, 2002; Yin, 1994). Thereby, researchers found evidences that suggest a progressive increase of the suppressive effect of the leading stimulus along the ascending auditory pathway (Fitzpatrick et al., 1995). Furthermore, results indicate that the precedence effect is not only based on binaural cues but is also observable in the elevational plane (Litovsky et al., 1997).

Commonly, researchers used double click-pairs providing directional information and recorded responses from single neurons. Yin (1994) recorded response patterns of single neurons in the IC of the cat for click stimuli that were presented to the cats either via headphones or loudspeakers. Using short lead-lag delays response patterns of the lagging click were suppressed. Recovery curves (response to the lag as a function of the lead-lag delay) show a huge variability for different cells. The median lead-lag delay for a 50 percent recovery was 20 ms, including values from 1 ms to 100 ms.

Similar results were obtained by Litovsky et al. (2001) and Litovsky and Delgutte (2002) who recorded response patterns from single neurons of the IC of anesthetized cats as a function of the azimuth and the lead-lag delay using virtual acoustics. For similar directions of lead and lag source the response to the lag was suppressed whereas for different directions only the lag elicited a response. This relationship between responses to lead and lag was found in many neurons for delays up to 35 ms. Hence, for these lead-lag delays the response to the lag is predictable from the response to the lead. For larger lead-lag delays the response to the lag recovered, i.e., a response to either lead and lag is elicited. Recovery curves obtained by Litovsky and Delgutte (2002) are similar to those of Yin (1994). A 50 percent recovery was found for a lead-lag delay of 32 ms.

Fitzpatrick et al. (1999) found increasing recovery times in neurons along the ascending auditory pathway. They determined recovery curves, i.e., the increasing

response to the lag which is suppressed due to the presence of the lead as a function of the lead-lag delay, for different structures of the auditory pathway of cats and rabbits from the auditory nerve up to the cortex. They obtained short recovery times (50 percent recovery) around 2 ms for the early stages like the auditory nerve (cat), the anteroventral cochlear nucleus (cat) and the superior olivary complex (rabbit). In neurons of the IC (rabbit) recovery times average around 7 ms and for neurons of the auditory cortex (rabbit) recovery times around 20 ms were determined.
Noticeably, results of all the before mentioned studies do not reveal whether the suppressive influence of the lead on the response to the lag is specific to location information as non of these researchers found systematic differences between the recovery times obtained from monaural and binaural stimulation. However, in these studies researchers also found many neurons whose responses to the lag were not suppressed due to the presence of the lead and whose characteristic is uncorrelated and therefore unpredictable from the response to the lead. This argues against a complete monaural suppression effect like forward masking because not all responses from all neurons were suppressed. This may be interpreted as a specific information suppression, i.e., some information is suppressed and other information is passed to higher levels of the auditory pathway.

Although many researchers investigated the precedence effect in humans it is still unknown whether it is a result of peripheral or central processes. Blauert (1997, p. 420) describes the precedence effect as 'the result of evaluation and decision processes in higher stages of the nervous system during which, in addition to auditory cues, cues from other sensory modalities and prior knowledge are taken into consideration.'. The precedence effect is in his point of view a top-down process, where peripheral processes play an important role. He points out that the central nervous system decides whether a cue is enhanced or suppressed and therefore controls in this sense the peripheral processing.
In contrast, Hartung and Trahiotis (2001) emphasize the importance of peripheral processes. They show that the precedence effect can to a great amount be explained by peripheral processes without any top-down processes. In short, they propose peripheral auditory filters where within-filter interactions occur which argues for

bottom-up processes in the precedence effect.

As known to the author, so far no neurophysiological correlate of the precedence effect was found in humans. The current study therefore uses electroencephalography (EEG) in order to gain knowledge about how the precedence effect is reflected in the successive auditory processing stages in the human brain. Especially, the question is addressed whether the precedence effect results from an insufficient sensitivity of peripheral processing (bottom-up effect) or from specific cognitive processes (top-down effect).

In order to investigate several levels of the auditory pathway, both auditory brainstem responses (ABRs) and cortical auditory evoked potentials (CAEPs) are recorded.

The representation of stimulus features in the ABRs would argue for a sufficient sensitivity of the peripheral processing and support the hypothesis of a top-down process in generating the precedence effect. On the contrary side, the representation of the perceived auditory image in the ABR would argue for a bottom-up process. In addition to the ABRs MMN components of the CAEP were determined using stimuli that are known to evoke the precedence effect in behavioral tasks. The MMN component is believed to be produced by a process that compares the neuronal trace elicited by a frequent reference stimulus ('standard') with any new incoming auditory event ('deviant') that produces its own neuronal trace, i.e., an MMN component is produced if a significant difference between standard and deviant is perceived by the auditory system. Hence, MMN components can only be elicited if information related to the altered stimulus feature has at least partly been processed before.

The results of psychophysical measurements reported before (chapter 2 and chapter 3) are compared with the amplitudes and latencies of the MMN components obtained in this chapter. As the generation of the MMN components is assumed to be dependent on the perception of the stimulus, MMN components recorded here are expected to reflect the results of the psychoacoustical measurements, i.e., a small MMN amplitude is expected for lead-lag delays where a high discrimination threshold was obtained and vice versa. An agreement between psychoacoustical and physiological data would indicate that information related to the precedence effect is at least partially processed prior to the stage of the generation of the MMN. Additionally, this would show that the precedence effect is still effective on the level of the MMN.

4.2 Methods

4.2.1 Apparatus

A sketch of the setup for the EEG recordings is plotted in Fig. 4.1. Basically, both the setup for the acquisition of ABRs and that for the CAEPs are identical. Stimuli were generated digitally on a DSP32C card and were DA-converted at a sampling frequency of 50 kHz. Signals were presented to the subjects by insert-ear-phones (Etymotic Research ER-2).

The EEG was recorded from 3 (ABR) or 31 (CAEP) positions of the scalp, respectively. All electrodes were referenced to CZ. Additionally, in the CAEP experiments the HEOG and VEOG were recorded by bipolar electrodes.
Recorded signals were pre-amplified inside the electrically and acoustically shielded booth by a factor of 150. Outside the booth the signals passed a DC-coupled differential amplifier where they were further amplified by a factor of 33 1/3 yielding

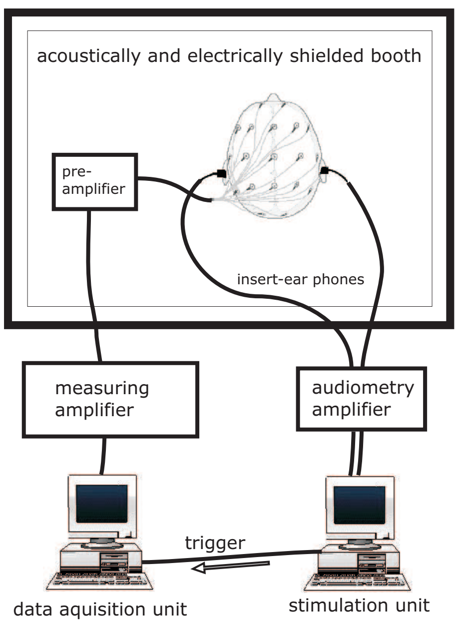


Fig. 4.1: Sketch of the EEG recording setup. Stimuli were presented via insert-ear phones. The EEG was recorded from 31 or 3 electrodes, respectively.

a total amplification of 74 dB. Raw data were stored continuously to disc with a sampling frequency of 10 kHz for the ABR recordings. For the CAEP recordings a sampling frequency of 1 kHz was used. The artifact level for all recordings was set to $\pm$ 500 μV. Epoching, filtering, artefact rejection, sorting and averaging of the data was done offline.

4.2.2 Subjects

All subjects that took part in either the ABR or CAEP recordings were normal hearing according to their audiogram (hearing loss $<$ 20 dB between 0.125 kHz and 8 kHz). They all participated in previous EEG experiments and were therefore familiar with the recording procedure.
Overall, six subjects took part in the ABR recording experiments. During the recordings they lay in a darkened booth and were asked to relax. Some of them even managed to sleep as the stimuli were presented at a level of 40 dB SL (sensation level). A total of eight subjects participated in the CAEP recordings. During these recordings subjects sat in a reclining chair and watched a self-selected subtitled movie. All except one subject that participated in the CAEP recordings also participated in at least one of the ABR recordings.

4.2.3 Paradigm and stimuli

ABR recordings

Auditory brainstem responses were recorded in two different experiments:

- **Experiment I:** Recording of ABRs using diotic double click-pairs with lead-lag delays from 0 ms to 5 ms in steps of 1 ms.

- **Experiment II:** Recording of ABRs using diotic (lag-ITD = 0 μs) as well as dichotic (lag-ITD = 300 μs) double click-pairs for lead-lag delays of 0, 5 and 20 ms.

Sketches of the stimuli are shown in Fig. 4.4 and Fig. 4.6, respectively. Each single click had a duration of 60 μs (3 samples). In Experiment I diotic stimuli were used and the lead-lag delay was varied. In Experiment II both the lead-lag delay and the interaural time difference of the lag were varied. In both experiments stimuli were presented within sequences in random order. Each sequence contained 10.000 stimuli. On average, the interstimulus interval was 70 ms (a jitter of 10 ms was employed) each sequence had a duration of about 12 minutes.

CAEP recordings

Cortical auditory evoked potentials were collected according to the paradigm of the mismatch negativity. Two types of stimuli, reference and deviant stimuli, were applied (see Fig. 4.2). Reference stimuli (left panel) consisted of a lead and a lag stimulus. Both stimuli had an ITD of zero. Deviants also contained a lead and a lag stimulus. In contrast to the reference stimuli, deviants had an interaural time delay of 800 μs in the right channel of the lag. This yields a lateralized perception to the left hand side. Like in the ABR recordings each single click had a duration of 60 μs

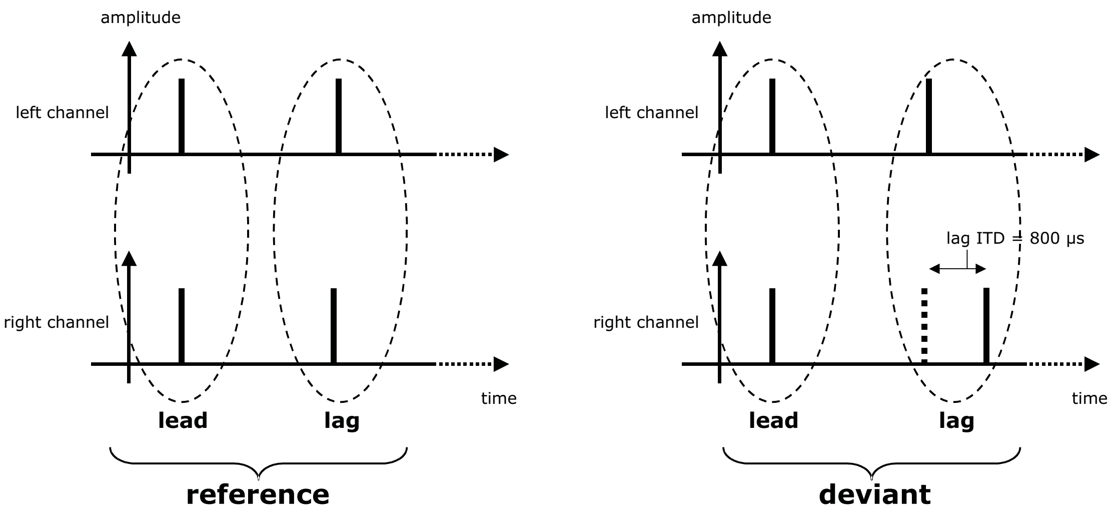


Fig. 4.2: Sketch of reference and deviant stimuli that were used for the CAEP recordings. Each stimulus consists of two double click-pairs, lead and lag. The reference stimulus on the left was a diotic stimulus. In contrast to that, the deviant stimulus on the right side was a dichotic stimulus which had a lag-ITD of 800 μs.

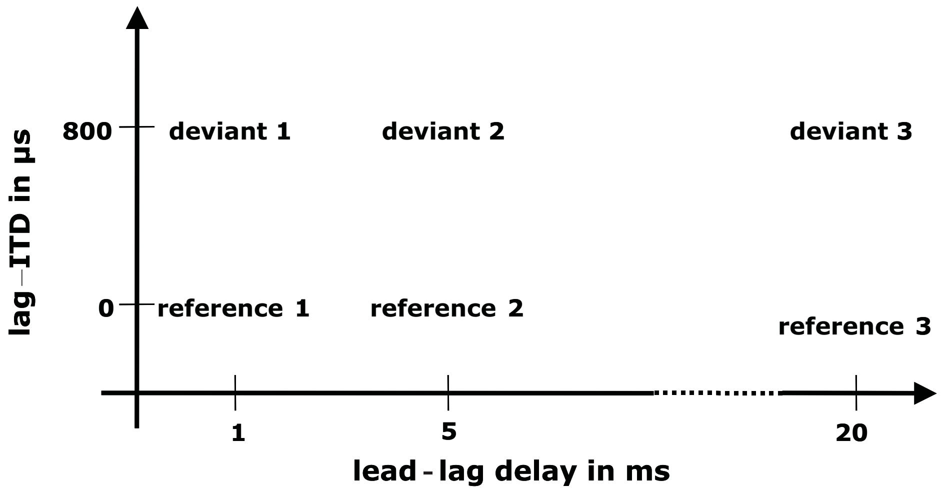


Fig. 4.3: Overview of the stimulus parameters that were applied for the CAEP recordings. Lead-lag delays of 1, 5 and 20 ms were used. Within a stimulus sequence the lead-lag delay was fixed. For each lead-lag delay the reference stimuli had a lag-ITD of 0 µs and the deviants had a lag-ITD of 800 µs.

(3 samples). Lead-lag delay values of 1, 5 and 20 ms were applied (see Fig. 4.3).

Throughout the CAEP recordings stimuli were presented within sequences with a stimulus repetition rate of 2 Hz. All stimuli within one sequence had the same lead-lag delay. Each sequence contained frequent (about 88 percent) reference and rare (about 12 percent) deviant stimuli which appeared at randomly chosen positions of the sequence. Each sequence contained 2.100 stimuli (1850 reference and 250 deviant stimuli) and had a duration of 17.5 minutes. Overall, responses to 1.000 deviants and 7.400 references were collected for each subject and each lead-lag delay yielding a net measuring time of 3.5 hours which was distributed over two sessions.

4.2.4 Data analysis

Data analysis for ABR and CAEP recordings were nearly identical. Recorded potentials of all experiments were cut into epochs with durations of 70 ms (ABRs) or 500 ms (CAEP), respectively. Epochs were filtered with a recursive bandpass filter of second order and corner frequencies of 100 Hz and 1.500 Hz (ABRs) or 1 Hz and 20 Hz (CAEP), respectively. As a 'forward-backward' filter design was applied no dispersion due to different group delays occured. After filtering, epochs obtained by identical stimuli were sorted and averaged. Artifacts were accounted for by an iterated weighted averaging technique, i.e., epochs were weighted with their inverse power (for details see Riedel, 2003).

For both ABR experiments amplitudes and latencies of the first prominent wave V (V_a) for each lead-lag delay were obtained by determining the maximum voltage values in the time interval from 6.5 to 7.5 ms after stimulus onset. This was a simple and adequate method as all peaks fell within this time interval.
For the second wave V (V_b) the lookup interval was shifted in latency according to the lead-lag delay. In order to gain accuracy, data of Experiment II were upsampled by a factor of 10, i.e., the sampling frequency was changed from 10 kHz to 100 kHz.

For CAEP experiments difference waveforms were obtained by subtracting the mean response to reference stimuli from the mean response to deviant stimuli. The standard error of the difference curves was determined according to equation

$$\sigma_{\mathrm{diff}} = \sqrt{\sigma_{std}^2 + \sigma_{dev}^2} \tag{4.1}$$

Additionally, data was rereferenced to NZ (nose) in order to facilitate comparisons with data of other studies. Latencies of the MMN components were detected by determining the largest peak of each difference waveform. Peak-to-peak values were determined by detecting the following minimum that matches the criterium that the peak-to-peak value exceeds the value of at least $2\sqrt{2} \cdot \sigma$ where σ is the standard error.

4.3 Results

4.3.1 Results of ABR recordings

Figure 4.4 shows ABRs of Experiment I for subject S1. In the leftmost column sketches of the stimulus signals are shown. They differ due to their lead-lag delay. In the right column corresponding ABRs of Experiment I of three channels (A_1, A_2

and IZ) are depicted. Errorbars at a latency of 1 ms mark intraindividual standard errors. For a lead-lag delay of 0 ms the typical characteristics of an ABR for a transient stimulus are observable. Its most prominent component is wave V (V_a) at a latency around 7 ms. For lead-lag delays larger than 1 ms a second wave V (V_b) emerges.

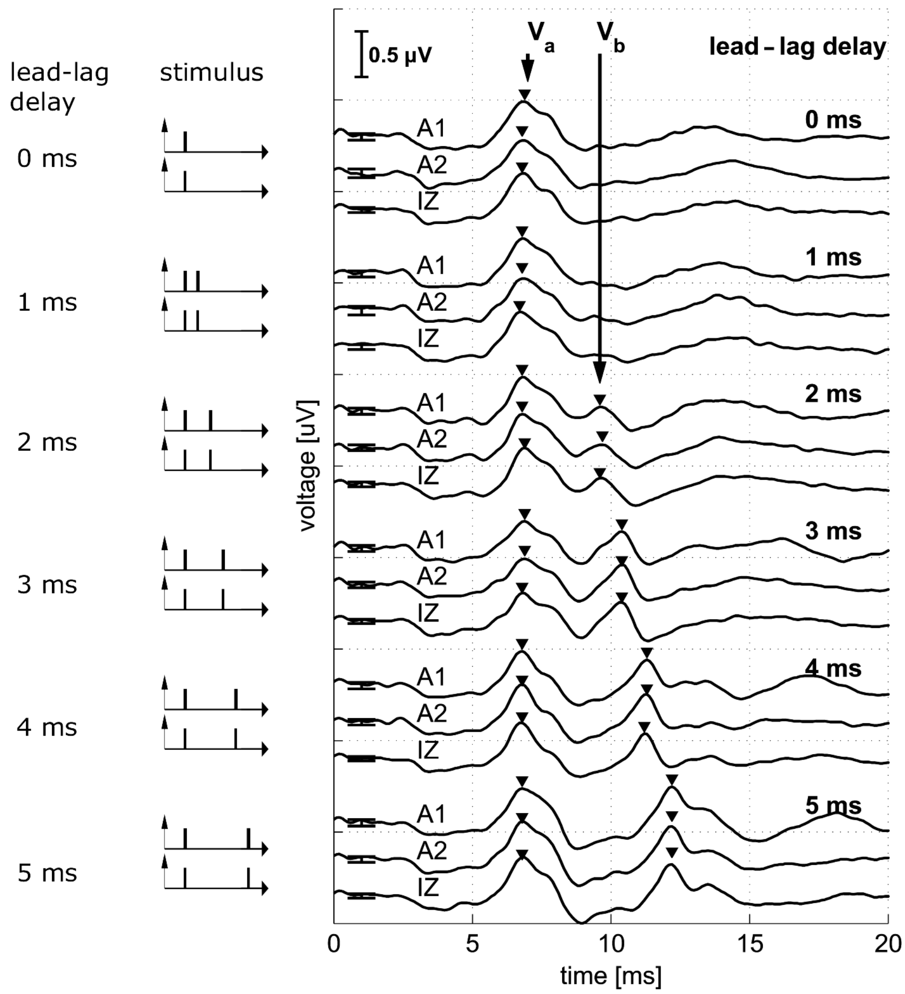


Fig. 4.4: **Left panel:** *Sketch of the time signals used for the ABR recordings in Experiment I (diotic stimulation) with increasing lead-lag delay (0 ms to 5 ms).* **Right panel:** *Corresponding ABRs of subject S1. Potentials of three channels (A1, A2 and IZ) are shown for each lead-lag delay. Errorbars at a latency of 1 ms indicate the intraindividual standard error.*

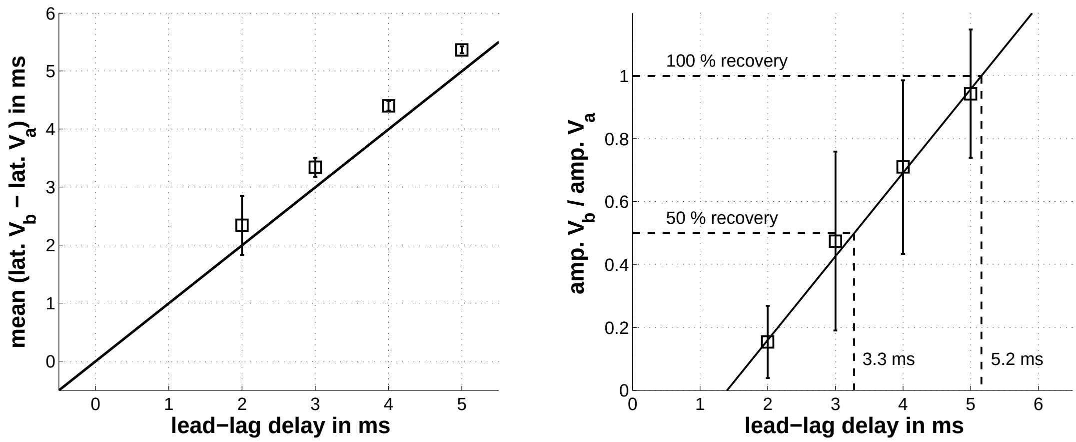


Fig. 4.5: **Left panel:** *Plot of the latency differences between the second and first wave V (lat. V_b − lat. V_a) of the ABRs obtained in Experiment I as a function of the lead-lag delay.* **Right panel:** *Plot of the amplitude ratio between the second and first wave V (amp. V_b/amp. V_a) as a function of the lead-lag delay. Both the amplitude and the latency of the second wave V_b can be determined for lead-lag delays larger than 1 ms. Both plots show mean values averaged over all subjects and channels and interindividual standard deviations. A line was fitted to the amplitude ratio values in order to obtain the 50 and 100 percent recovery values.*

In Fig. 4.5 differences in latency (left panel) and amplitude (right panel) between this emerging wave V_b and the first wave V_a averaged across all channels and all subjects are shown. The latency difference between the first and second wave V ($lat.\ V_b - lat.\ V_a$) increases as linearly as the lead-lag delay of the stimulus. However, all latency differences are about 0.4 ms larger than the lead-lag delay of the stimulus. Interindividual standard deviations of the latency differences decrease with increasing lead-lag delay.

The right panel of Fig. 4.5 shows the amplitude ratio of the second and first wave V, ($amp.\ V_b/amp.\ V_a$). The amplitudes of wave V_b increase fairly linear with increasing lead-lag delay. All values were normalized to the mean amplitude value of the first wave V (mean across all channels and subjects for each lead-lag delay). The amplitude of wave V_b at a lead-lag delay of 5 ms is similar to that of wave V_a. A line was fitted to the increasing amplitudes of wave V_b using a χ^2 criterium, i.e., weighting the four amplitudes by their corresponding interindividual standard deviation. This fit allows to determine the 50 and 100 percent recoveries of wave V_b which were found for lead-lag delays of 3.3 ms and 5.2 ms, respectively.

Results obtained from Experiment II are depicted in Fig. 4.6 and Tab. 4.1. The left column in Fig. 4.6 displays the stimulus signals that were applied in order to obtain the respective ABRs shown on the ride hand side. Row 1, 3 and 5 show results of the

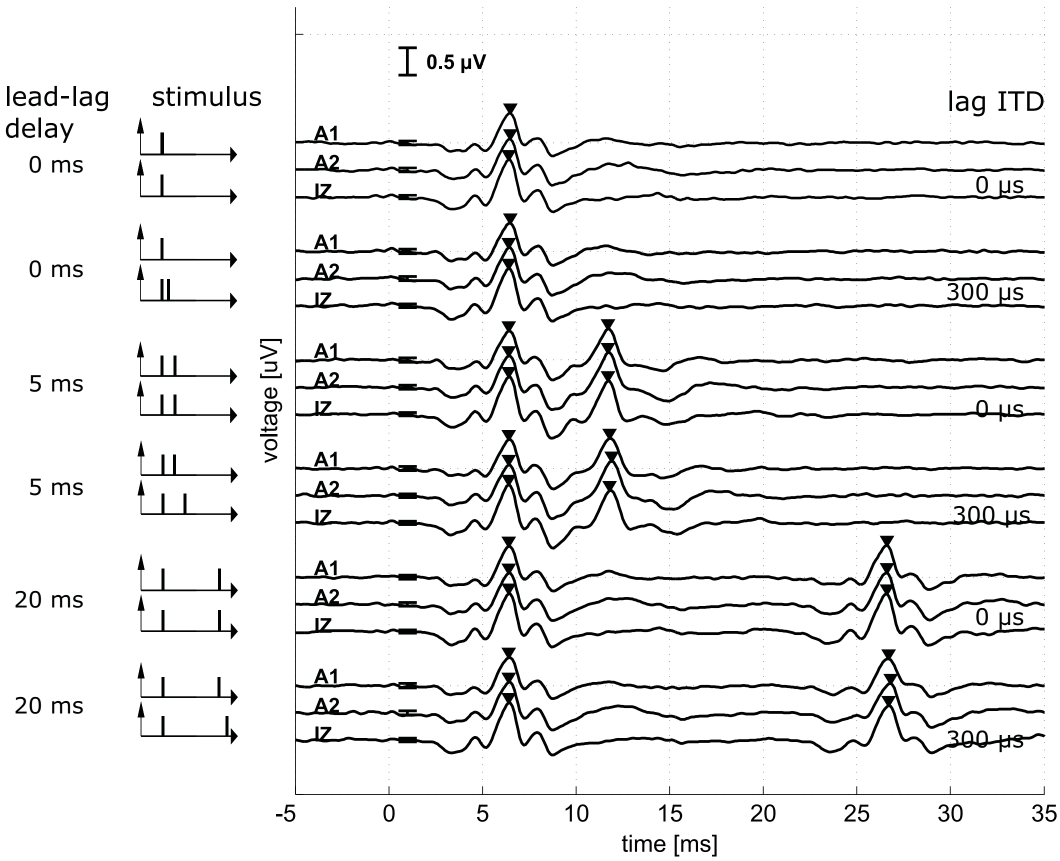


Fig. 4.6: **Left panel:** *Stimuli that were applied in Experiment II. Diotic as well as dichotic double click-pairs with lead-lag delays of 0, 5 and 20 ms were presented. Dichotic stimuli had a lag-ITD of 300 µs.* **Right panel:** *Auditory brainstem responses of subject S2 as obtained from Experiment II. Data were collected from three channels (A_1, A_2 and IZ). Errorbars at a latency of 1 ms show the intraindividual standard error.*

lat. V_b − *lat.* V_a for Experiment II	lead-lag delay 5 ms	20 ms
ITD = 0 μs	5.30 ± 0.08 ms	20.11 ± 0.03 ms
ITD = 300 μs	5.41 ± 0.12 ms	20.26 ± 0.03 ms

Tab. 4.1: Latency differences (lat. $V_b -$ *lat.* V_a*) between* 1^{st} *and* 2^{nd} *wave* V *obtained for diotic (ITD = 0* μ*s) and dichotic (ITD = 300* μ*s) stimulation as obtained in Experiment II. Values for lead-lag delays of 5 ms and 20 ms are presented in the left and right column, respectively.*

diotic stimuli, i.e., neither lead nor lag had an ITD. In contrast, in rows 2, 4 and 6, the right channel of the lag stimulus is delayed by an amount of 300 μs yielding a dichotic stimulation. Potentials recorded from three channels (A_1, A_2 and IZ) for subject S2 are shown. Errorbars at a delay of 1 ms indicate intraindividual standard errors. Data obtained from Experiment II were upsampled by a factor 10 (from 10 kHz to 100 kHz) in order to gain accuracy in the amplitude and latency determination. Amplitudes of all wave Vs are nearly identical. According to Wilcoxon tests no significant differences were found for the amplitudes across different lag-ITDs or the two lead-lag delays. Overall, for lead-lag delays of 5 ms and 20 ms, latency differences between the first and second wave V are slightly larger than the lead-lag delay of the stimulus (see Tab. 4.1). On average, latency differences as obtained from dichotic stimulation are slightly larger than those obtained from diotic stimulation. Wilcoxon tests yielded significant differences ($p < 0.05$) between the latency differences of the first and second wave V of dichotic and diotic stimulation. This holds for both lead-lag delays (5 ms and 20 ms) and indicates that the ITD of the stimulus is reflected in the ABRs (see discussion).

4.3.2 Results of CAEP recordings

MMN components

Figure 4.7 shows difference curves rereferenced to NZ of a single subject. The 2-D sketch on the left hand side shows the channel positions of the frontal part of the head. Corresponding difference curves for lead-lag delays of 1, 5 and 20 ms are shown on the right hand side. MMN components that are larger than the intraindividual standard error in each channel for each lead-lag delay peak at a latency around 180 ms.

Difference curves of another subject are shown in Fig. 4.8. The layout of the plot is the same as in Fig. 4.7. However, differences curves in channels where the MMN component does not exceed the intraindividual standard error are plotted in thin

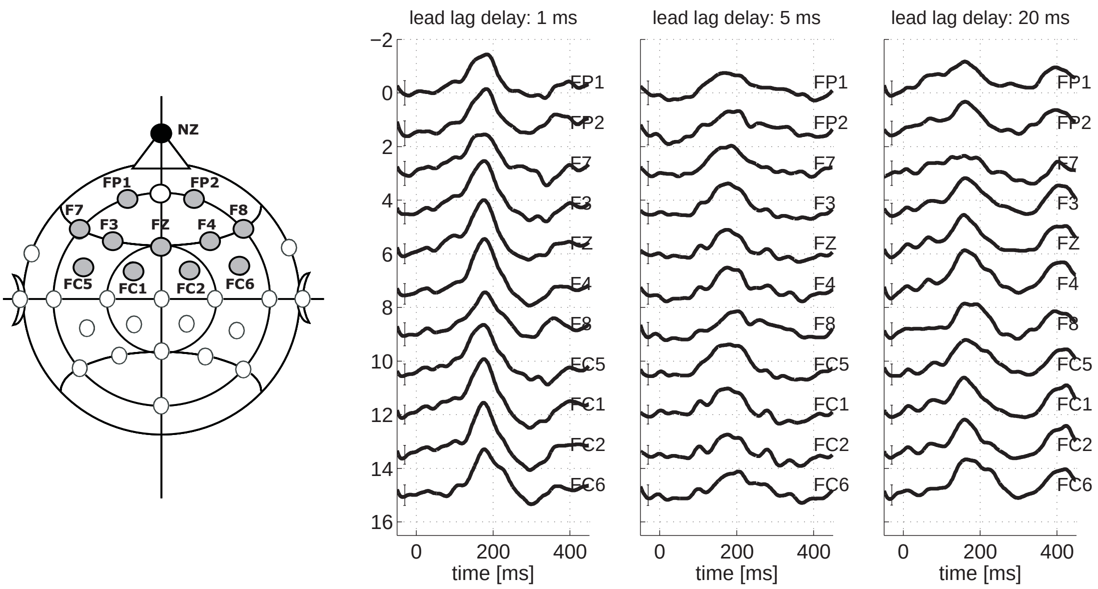


Fig. 4.7: Difference curves of the frontal channels for a single subject rereferenced to NZ. **Left panel:** *2-D plot of the electrode positions on the scalp.* **Right panel:** *Difference curves (response to deviant minus response to reference stimulus) for lead-lag delays of 1, 5 and 20 ms. Errorbars at a latency of -30 ms in each channel show the intraindividual standard error. MMN components in all channels are larger than the respective intraindividual standard error.*

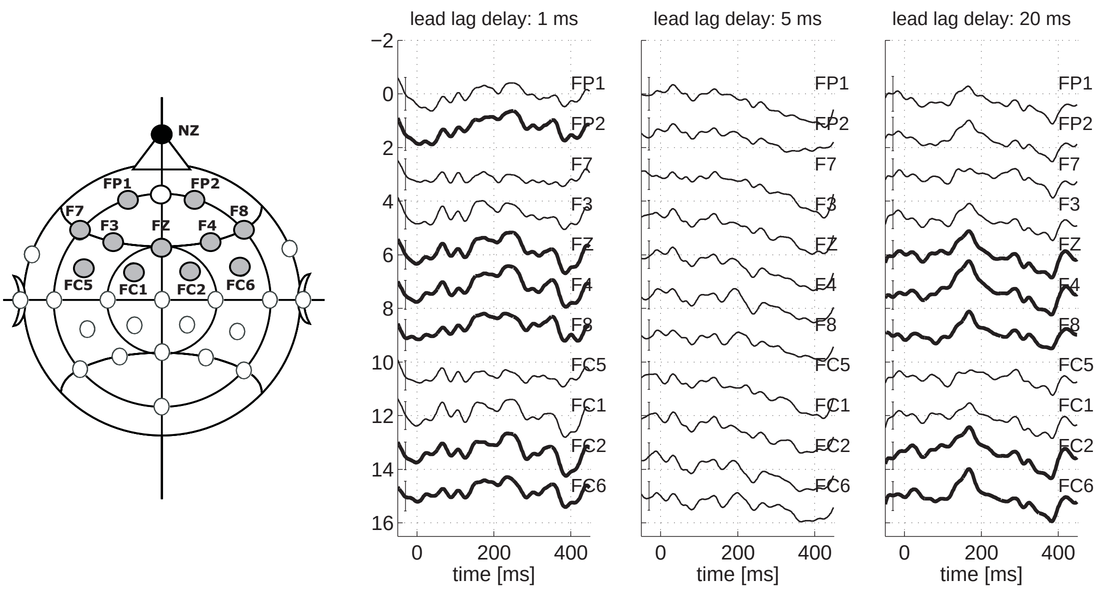


Fig. 4.8: Difference curves of the frontal channels for a single subject rereferenced to NZ. **Left panel:** *2-D plot of the electrode positions on the scalp.* **Right panel:** *Difference curves (response to deviant minus response to reference stimulus) for lead-lag delays of 1, 5 and 20 ms. Errorbars at a latency of -30 ms in each channel show the intraindividual standard error. Thin lines indicate channels in which the MMN component is smaller than the respective intraindividual standard error.*

lines.

Figures 4.7 and 4.8 show that subjects that participated in the CAEP recordings could be divided into two groups according to their potentials, i.e., if most MMN components of the frontal channels were larger than the corresponding intraindividual standard error (for lead-lag delays of 1 ms and 20 ms), subjects were assigned to group A (see Fig. 4.7). According to this criteria five subjects were assigned to group A and three subjects were assigned to group B.
Data of both groups will be shown in the following.

In Fig. 4.9 difference waveforms for channels of the frontal scalp referenced to NZ (see inset of Fig 4.9) averaged across all five subjects of group A are shown. The leftmost column shows difference curves as obtained with a lead-lag delay of 1 ms. Errorbars at a latency of -30 ms in each channel indicate mean intraindividual standard errors averaged across these five subjects. In each channel and for each lead-lag delay an MMN component is observable. As positive voltage values are plotted downwards, all MMN components are directed upwards. Their maximum as well as the following minimum are marked with triangles. Latencies of the maxima and peak-to-peak values between maxima and minima were determined. According to Wilcoxon tests MMN peak-to-peak values for a lead-lag delay of 5 ms are significantly smaller than those for lead-lag delays of 1 ms and 20 ms, respectively. Additionally, MMN latencies are significantly smaller for a lead-lag delay of 5 ms in comparison to MMN latencies for lead-lag delays of 1 ms and 20 ms.

Figure 4.10 shows mean difference waveforms averaged across the three subjects of group B. For a lead-lag delay of 20 ms, a small MMN component seems to appear

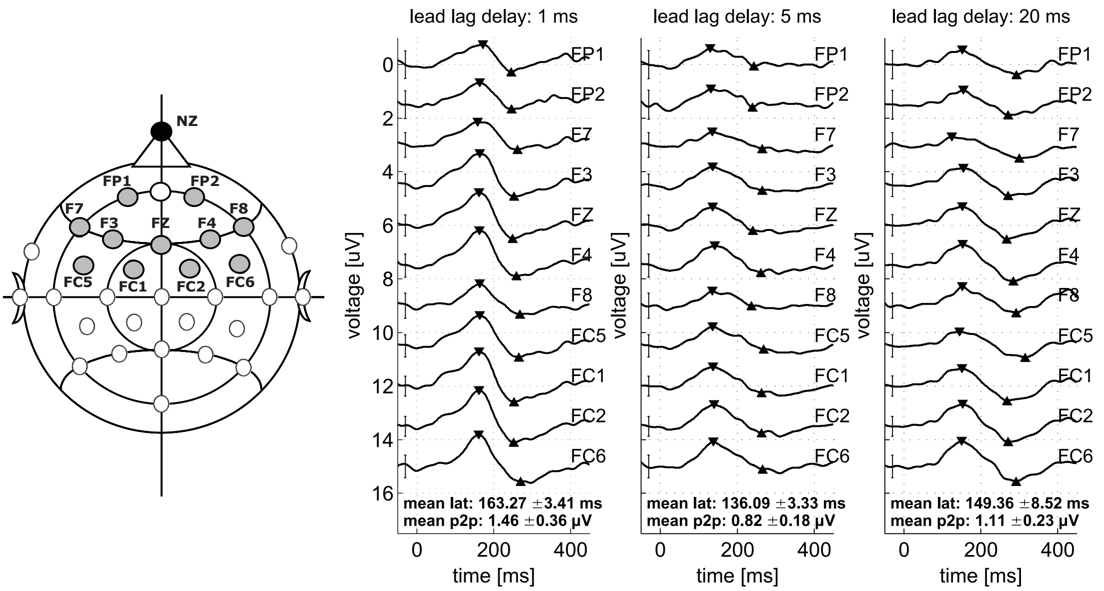


Fig. 4.9: Difference curves of the frontal channels averaged across the five subjects of group A. **Left panel:** *2-D plot of the electrode positions on the scalp.* **Right panel:** *Difference curves (response to deviant minus response to reference stimulus) for lead-lag delays of 1, 5 and 20 ms. Errorbars at a latency of -30 ms in each channel show the mean intraindividual standard error over subjects. Additionally, for each lead-lag delay mean peak-to-peak amplitude (p2p) and latency (lat) of the MMN components were determined and depicted on the bottom of each column.*

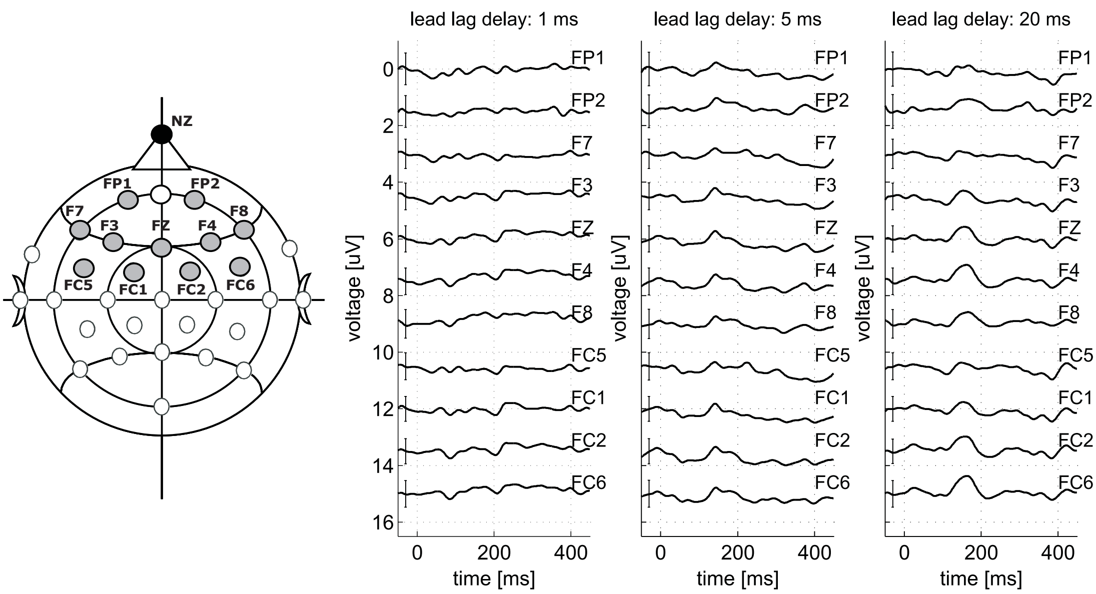
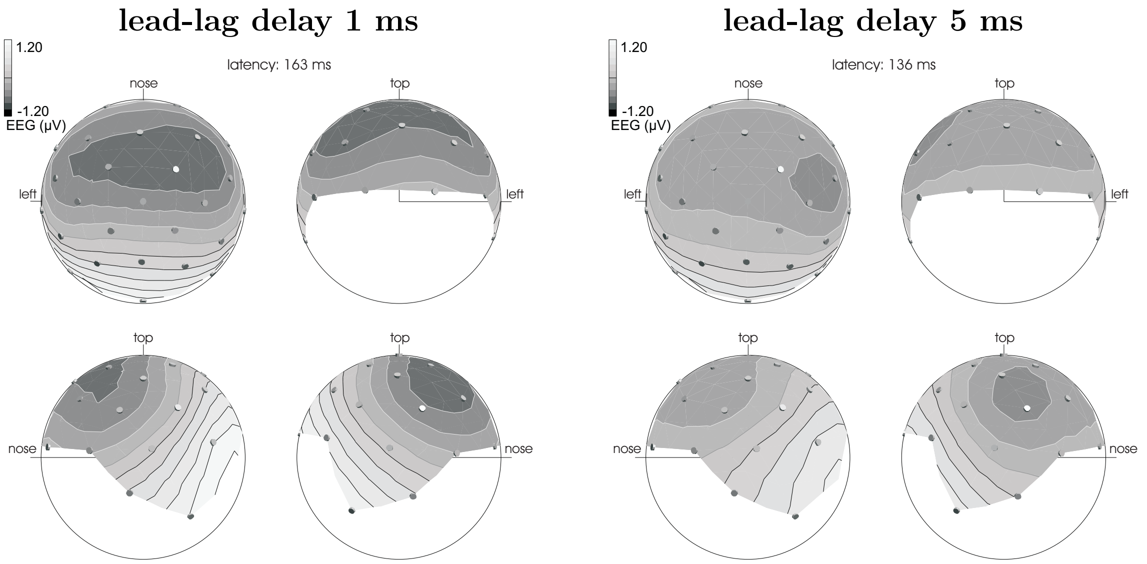


Fig. 4.10: Difference curves of the frontal channels averaged across the three subjects of group B. The layout of the figure is the same as in Fig. 4.9. In no channel any component matched the criterium that the peak-to-peak value between maximum and the following minimum exceeds $2\sqrt{2} \cdot \sigma_m$ where σ_m is the mean intraindividual standard error.

in some channels. However, none of the components in any channel matched the criterium that the peak-to-peak value of any maximum and any following minimum exceeds the value of $2\sqrt{2} \cdot \sigma_m$ where σ_m is the mean intraindividual standard error.

Figure 4.11 shows voltage maps of MMN components averaged across the five subjects of group A for lead-lag delays of 1, 5 and 20 ms, respectively. For this plot data were rereferenced to average reference. The latencies for the voltage maps were obtained by averaging the latencies of the maxima of the MMN components over the frontal channels (see electrode positions in Fig. 4.7 to Fig. 4.10). Figure 4.11 consists of three subplots. Each of them shows four different views on the voltage map. Absolute voltages are coded by a gray-scale. Additionally, electrode positions of a single subject that were fitted to a sphere (radius 9.1 $\pm$ 0.9 cm) are shown in each panel.

Voltage maps for all lead-lag delays look similar. A symmetric negative field in the frontal part of the scalp and a transition to positive voltages to the back of the head indicate a typical voltage distribution of an MMN component. However, voltages obtained for a lead-lag delay of 5 ms are decreased in amplitude compared to those obtained with a lead-lag delay of 1 ms and 20 ms, respectively (see voltage bar in



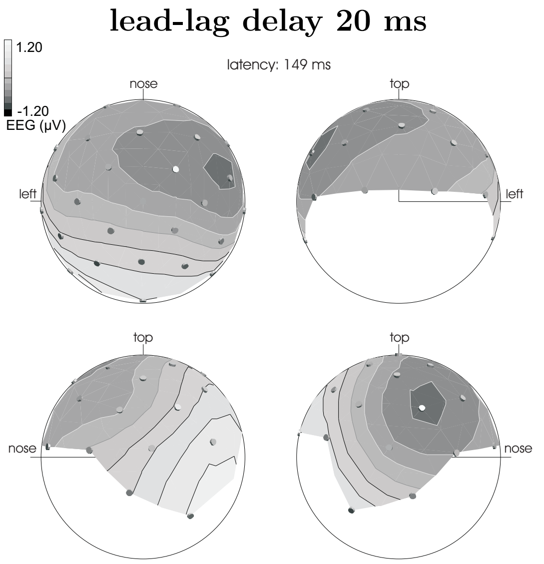


Fig. 4.11: Voltage maps for MMN components averaged across all subjects of group A obtained with lead-lag delays of 1 ms (upper left), 5 ms (upper right) and 20 ms (lower left). The MMN components were maximal at latencies of 163, 136 and 149 ms for lead-lag delays of 1, 5 and 20 ms, respectively. Each panel shows four perspectives: The top view (nose on top) is shown in the upper left panel, the front view in the upper right panel. Left and right views are shown in the lower left and right panels, respectively. Dark colors indicate negative voltages. Additionally, electrode positions were plotted.

upper left corner in each panel). Additionally, with increasing lead-lag delay the voltage distribution becomes more asymmetric preferring the right hand side, i.e., a stronger negativity on the right hand side than on the left hand side of the head is observable. This is not related to the lateralization of the stimuli presented where the lag stimuli provided a lateralization to the left hand side.

4.3.3 Relation between MMN components and performance in discrimination tasks

Cortical auditory evoked potentials were recorded according to the paradigm of the MMN presenting frequent reference (lag-ITD = 0 μs) and rare deviant stimuli (lag-ITD = 800 μs) for lead-lag delays of 1, 5 and 20 ms, respectively.

As described above subjects could be separated into two groups according to their recorded potentials. An MMN component is observable in frontal channels in subjects of group A whereas hardly any MMN component appears in subjects of group B. Results of the CAEP recordings of both groups can be related to the respective performance in the psychoacoustical tasks of chapter 2. There, a psychoacoustical procedure, the 'pick-out' paradigm, was applied. The stimulus sequence of that procedure was almost identical to the sequences employed in the MMN recordings from this study where also a continuous sequence was presented, encompassing frequent reference (lag-ITD = 0 μs) and rare deviant stimuli (lag-ITD $\neq$ 0 μs). The lag-ITD of the reference stimulus was zero. In chapter 2, while listening to the sequence, subjects had to perform a discrimination task, i.e., to pick out the deviants from the reference stimuli by pressing a button on a keyboard. Thus, a psychometric function was determined. Lag-ITDs that yielded 70.7 percent correct discrimination performances were interpolated to estimate the thresholds.
The following comparison can be performed between psychoacoustical and electrophysiological performance in both groups:

Group A: The MMN components of the five subjects of group A are dependent on the lead-lag delay. On average (see Fig. 4.9), amplitudes and latencies of the

	lead-lag delay		
	1 ms	5 ms	20 ms
MMN amplitude	1.46 ± 0.36 μV	0.82 ± 0.18 μV	1.11 ± 0.23 μV
amplitude ratio	100 %	56 %	76 %
discrimination threshold	334 ± 96 μs	549 ± 103 μs	327 ± 58 μs
threshold ratio	100 %	164 %	98 %

Tab. 4.2: Comparison between the psychoacoustical and the electrophysiological performance of the four subjects in group A that participated in both experiments. Results show, that the amplitudes of the MMN components decrease to a similar extent as the discrimination thresholds increase.

MMN components obtained with a lead-lag delay of 5 ms are significantly smaller compared to those MMN components obtained with lead-lag delays of 1 and 20 ms.

Table 4.2 shows both peak-to-peak amplitudes of the MMN components of the CAEP recordings and discrimination thresholds obtained from the 'pick-out' procedure averaged across those four subjects that participated in either experiment. Additionally, the ratios between the amplitudes and thresholds is specified, respectively. Results show that peak-to-peak amplitudes of the MMN components decrease comparatively to the same extent as the discrimination thresholds increase.

Figure 4.12 compares the absolute discrimination threshold values as obtained from the 'pick-out' paradigm in chapter 2 with predicted discrimination thresholds according to the ratio of the peak-to-peak amplitudes of the MMN components of the CAEP recordings. Both data sets were obtained by averaging the results of those four subjects in group A that participated in the CAEP recordings as well as in the psychoacoustical experiments (same values as in Tab. 4.2). The solid line in Fig. 4.12 indicates lag-ITDs that yield 70.7 percent correct discrimination performances for lead-lag delays from 0 ms to 20 ms in the psychophysical task. Errorbars indicate interindividual standard deviations across the four subjects. As individual discrimination performance differs considerably, comparatively large interindividual standard deviations appear (e.g., about 240 μs at a lead-lag delay of 3 ms). On

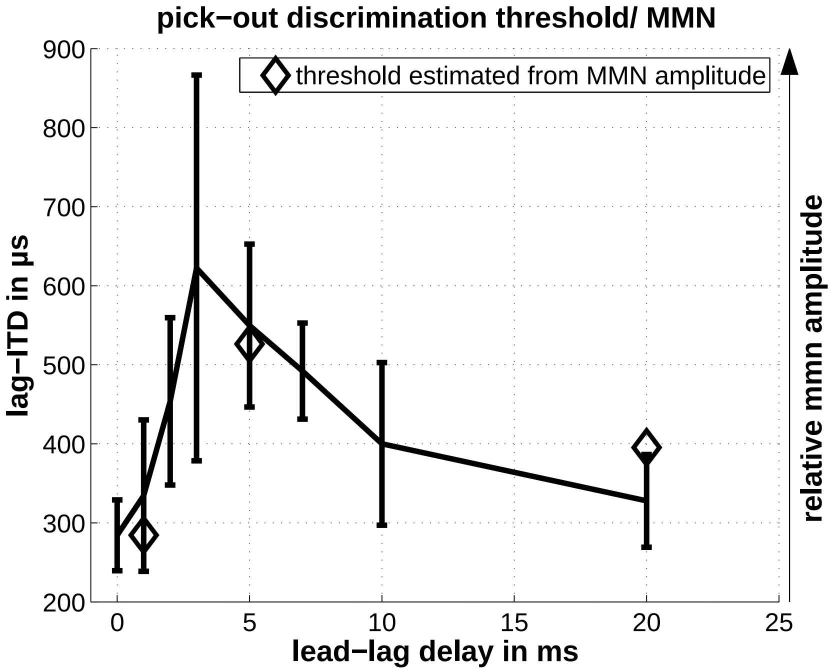


Fig. 4.12: Comparison between the psychoacoustical discrimination performance and the corresponding relative amplitude of the MMN component. Both data sets were averaged across the four subjects that participated both in the psychophysical discrimination study as well as in the EEG measurements. Lag-ITDs that yielded 70.7 percent correct performance in the discrimination task are plotted for lead-lag delays from 0 ms to 20 ms. Errorbars show interindividual standard deviations. Diamonds indicate the predicted discrimination threshold by analyzing the MMN amplitude. For details see text.

average, subjects achieved 70.7 percent correct performance in the psychoacoustical tasks for lag-ITDs far below 800 μs, the lag-ITD value of the deviant in the CAEP recordings for all lead-lag delays employed. This indicates that the conditions for the CAEP were all above detection threshold. Hence, a comparison between MMN data and psychophysiological data is achievable in this group of subjects.

The estimate of absolute discrimination thresholds from peak-to-peak amplitudes of the recorded MMN components was done by scaling the inverted peak-to-peak amplitude with a factor that provides the best fit to the empirical data as shown in Fig. 4.12 This scaling factor was determined by a least-squares-fit. Note, however,

that the current CAEP recordings were made at supra threshold level and therefore only provide indirect information about *absolute* discrimination thresholds[1].
As a result the estimated lag-ITD thresholds (diamonds in Fig. 4.12) for lead-lag delays of 1 ms and 5 ms lie slightly below the mean lag-ITD thresholds obtained in the 'pick-out' task. However, both of them lie clearly within the interindividual standard deviation while the value for 20 ms lead-lag delay exceeds the average behavioral thresholds by a little more than one standard deviation.

Group B: Hardly any MMN component was elicited in any of the three subjects of group B. Difference curves averaged over these subjects are displayed in Fig. 4.10. A comparison with psychoacoustic performance was achievable with this group of subjects because two out of the three subjects of group B showed a poor and very inconsistent performance in the training sessions of the 'pick-out' experiments and other psychoacoustic experiments of chapter 2. Additional measurements performed by one of these two subjects revealed that the respective discrimination thresholds lie far beyond 1.000 μs. Probably, at least in the case of the 'pick-out' paradigm, the pre-selected lag-ITD values were below or very close to the individual discrimination threshold. Hence, no consistent MMN recording has to be expected from these subjects. For this reason, they were excluded from these psychophysical measurements and asked to participate in supplementary tasks, i.e., their individual discrimination thresholds will be determined in future experiments with larger pre-selected lag-ITD values. The third subject of group B was not excluded from the psychophysical measurements but showed a very poor performance with a discrimination threshold of about 900 μs for a lead-lag delay of 5 ms.
Generally, in group A subjects, data sets of psychoacoustical and CAEP measurements show a high correlation, i.e., the relation between the discrimination thresholds obtained in psychophysical experiments of chapter 2 equals the relation of the

[1] An absolute discrimination threshold may be determined by varying the lag-ITD of the deviant. As mentioned in section 4.1 the occurrence of an MMN component is correlated with a discriminable change of the stimulus. Therefore, below the discrimination threshold no MMN is expected to be elicited whereas above the discrimination threshold an MMN component should be observable.

MMN amplitudes of the CAEP recordings. It seems that the amplitude of the MMN component reflects the detectability of the change between reference and target stimulus rather than any stimulus feature directly.

4.4 Discussion

The general finding of this study is that the ABR recordings performed with double click-pairs follow closely the properties of the stimuli, i.e., the second click-pair elicits a second wave V complex which can be predicted quite well from the response to single click-pairs. The CAEP recordings, on the other hand, seem to follow better the perceptual impression of double click-pairs that exhibit a reduced response to the lag stimulus for lead-lag delays in order of 5 ms. The different behavior of both types of electrophysiological recordings for the stimulus employed here will be discussed below.

4.4.1 Relation between ABRs and the precedence effect

Diotic stimulation

In the present study diotic double-click pairs were presented with interclick intervals from 0 ms to 5 ms. For lead-lag delays larger than 1 ms a second wave V emerges which gradually increases in amplitude with increasing lead-lag delay. For a delay of 5 ms the amplitudes of the first and the second wave V are almost identical.
To the best knowledge of the author, no ABR recordings were reported before using stimuli that are known to evoke the precedence effect. However, some researchers recorded ABRs using maximum length sequences with short interclick intervals (see, e.g., Eysholdt and Schreiner, 1982; Burkard et al., 1990; Burkard, 1991). These studies show that with increasing interclick intervals from 1 ms to 10 ms amplitudes of wave V increase from 0.2 μV to 0.35 μV and latencies decrease from about 7.7 ms to about 6.4 ms. A similar result was observed in the present study, i.e., an increasing amplitude of the second wave V with increasing lead-lag delay. For high repetition

rates (small interclick intervals) the auditory system does not seem to be able to elicit equal potentials to every stimulus but exhibits a refractory state that extends to an interval of about 5 ms. Additionally, Hey (2001) determined electrically evoked ABRs in cochlea implant patients using pulse-trains with inter-pulse intervals from 2 μs to 3.5 ms. In two patients he found a full recovery of the second wave V for an inter-pulse interval of about 3.5 ms which is 1.5 ms shorter than the lead-lag delay found for a full recovery in the experiments of the present study. However, for two other patients the amplitude of the second wave V did not reach a full recovery for an inter-pulse interval of 3.5 ms (the largest interval applied). Extrapolating the dependency of the amplitude of the second wave V on the inter-pulse interval as shown for both of these patients, a full recovery may be achieved for an interval of 4 ms to 5 ms, a value quite similar to that obtained in the acoustically evoked ABRs of the current study.

Other parallels can be found in results of physiological studies: Parham et al. (1996) determined spike rates of auditory-nerve-fibers of cats while presenting double-click pairs with lead-lag delays of 1, 2, 4, 8 and 16 ms. Results show a gradual recovery of the response to the second click which is comparable to the ABR findings of this study. A 50 percent recovery was found for a lead-lag delay around 2.5 ms which corresponds well to the value of 3.3 ms for wave V_b as obtained in Experiment I in the present study. For a lead-lag delay of 16 ms Parham et al. found nearly identical responses to lead and lag for a full recovery at a delay of 40 ms. However, ABR data as obtained from Experiment I in this study suggest a lead-lag delay of only 5.2 ms for a full recovery which is markedly smaller than predicted from these physiological results.

Different lead-lag delays for a 50 percent recovery were found by Fitzpatrick et al. (1999) who determined recovery curves for several structures of the ascending auditory pathway in animals. These structures were the auditory nerve (AN) and the anteroventral cochlear nucleus (AVCN) of the cat and the superior olivary complex (SOC), the IC and the auditory cortex (AC) of the rabbit. On early stages of the auditory pathway (AN, AVCN, SOC) Fitzpatrick et al. found a 50 percent recovery for a lead-lag delay around 2 ms. Later stages show increased lead-lag delays for a 50 percent recovery. In neurons of the IC a 50 percent recovery was found for lead-lag delays that average around 7 ms, for neurons of the AC they are about 20 ms. Overall, these values are smaller than those found by Parham et al. and are in better agreement with values predicted by the ABRs recorded in Experiment I of the present study. However, single neuron behavior can only roughly be transformed into a prediction of EEG recordings that include the average behavior of whole neuron populations. Hence, a coincidence with the 50 percent recovery rate is more likely to occur since it describes the behavior of all responding cells to a certain stimulus, while the complete recovery of the response can also be achieved by a different subset of neurons that respond to the second respective stimulus. Hence, the ABR data presented here and the neurophysiological data presented by Fitzpatrick et al. are not inconsistent.

It is known from psychophysical studies (see, e.g., the experiments in chapter 2 and chapter 3) that the precedence effect is strongest for lead-lag delays up to 5 ms. If the precedence effect would appear in ABRs of Experiment I and Experiment II, one might expect to see decreased amplitudes of the second wave V for a lead-lag delay of 5 ms compared to the amplitudes of the second wave V for a lead-lag delay of 20 ms. As described in chapter 4.3.1 this is not the case. All amplitudes of the second wave V are fairly identical. Therefore, no suppression effect can be observed in ABRs. Rather, a monotonous recovery of wave V is observed as the lead-lag delay increases which is consistent with physiological studies at the auditory nerve at brainstem level (Fitzpatrick et al., 1999). ABRs seem to reflect stimulus features (limited by recovery mechanisms) rather than the perception of the stimulus. As Fitzpatrick et al. found an increasing suppression characteristic on later stages of the ascending auditory pathway one might find suppression effects with longer durations on later stages. This is investigated by recording CAEP using the MMN paradigm (see paragraph 4.3.3).

As shown in Fig. 4.5 latency differences between both waves V are slightly larger than the lead-lag delay of the stimulus. This discrepancy of about 0.4 ms suggests that for the lead-lag delays employed in Experiment I both the first and the second wave V were not elicited complete independently, although their amplitudes were fairly identical. However, this discrepancy is expected to disappear for larger lead-lag delays than those employed in this study because for very large lead-lag delays responses to lead and lag are assumed to be elicited independently. This assumption is confirmed by the fact that in Experiment II, in the diotic stimulation condition, where a lead-lag delay of 20 ms was employed (see Fig. 4.1), the difference between both waves V is only 0.11 ms larger than the lead-lag delay of the stimulus, i.e., the discrepancy decreased from 0.4 ms to 0.1 ms.

Dichotic stimulation

Latency: In Experiment II of the ABR recordings dichotic stimuli were applied in order to determine the influence of a lag-ITD of 300 μs on the ABRs. As a result differences between the first and second wave V using dichotic stimuli (lag-ITD = 300 μs) were significantly increased by 0.11 ms and 0.15 ms (for lead-lag delays of 5 ms and 20 ms, respectively) compared with the corresponding differences using diotic stimuli (lag-ITD = 0 μs). This means that about half of the interaural delay of the stimulus is reflected in the ABR. This finding is in accordance with the double delay-line coincidence detection model proposed by Jeffress (1948).

Amplitudes: There are no significant differences of the amplitudes of the second wave V between lead-lag delays of 5 ms and 20 ms. Indeed, amplitudes of all waves V, elicited by lead or lag, are nearly identical for all lead-lag delays. No suppression effect of the second wave V for a lead-lag delay of 5 ms is observable. Amplitudes of the second wave V obtained by dichotic stimulation are identical to those obtained by diotic stimulation. A suppression effect could be presumed as results of the psychoacoustical tasks of chapter 2 and 3 showed increased discrimination and lateralization thresholds for a lead-lag delay of 5 ms. Hence, psychoacoustical data do not correlate with the amplitude characteristics of the second wave V.

As described in section 4.1 Litovsky et al. (2001) and Litovsky and Delgutte (2002) showed that responses of single neurons of the IC in cats to lead and lag are strongly modulated with lead azimuth for short lead-lag delays. Hence, one could argue that the amplitude of the second wave V as obtained in this study may also depend on the azimuth, i.e., the lag-ITD. However, ABRs as obtained in the present study do not contradict these physiological data, because, even if the number of neurons that respond to lead and lag may be identical for all speaker positions, most responses of single neurons are dependent on the positions of lead and lag speaker. Since ABRs as obtained in the present study reflect the summing potential, i.e., the compound activity of all neurons in the far-field, no amplitude effect may occur.

4.4.2 Relation between CAEP and the precedence effect

Results of the CAEP recordings show that the MMN was elicited by the lag-ITD of 800 μs in those subjects that are able to discriminate the deviant from reference stimuli in an appropriate psychophysical task ('pick-out' paradigm). As discussed in chapter 2 psychophysical discrimination performances were influenced by the precedence effect which is activated if two sounds are presented in close succession. As the amplitudes of the MMN components show a high correlation with the discrimination performances of the behavioral tasks it can be stated that a neurophysiological correlate for the precedence effect was found on the level of the CAEP.

Similar systematic differences between 'good performers' (both in MMN tasks and related psychoacoustical tasks) and 'poor performers' were reported by Lang et al. (1990) in a different experiment. MMN amplitudes obtained in the present study are in agreement with the amplitude characteristics of the results shown by Lang et al., i.e., subjects with a 'poor' performance showed significantly smaller MMN components than those subjects that showed a 'moderate' or 'good' discrimination performance. Additionally, poor and good performers in behavioral tasks are discriminable according to their MMN components. In the psychoacoustical tasks of both studies discrimination thresholds were determined. However, Lang et al. measured just noticeable pitch changes whereas in the present study just noticeable changes of any sound feature were evaluated.

As shown in Fig. 4.9 not only the mean MMN amplitudes but also the mean latencies of the MMN for different lead-lag delays differ significantly. Latencies obtained with lead-lag delays of 1 ms and 20 ms are significantly larger than latencies obtained with a lead-lag delay of 5 ms. This finding contrasts with the results obtained in the before mentioned study by Lang et al. (1990). In their study, latencies decreased with increasing MMN components. It is not clear if this discrepancy between both studies is due to the different stimuli and tasks employed or due to other factors. A systematic variation of the lag-ITD and lead-lag delay would show in more detail how amplitude and latency of the MMN component are connected to these two parameters.

MMN recordings with lateralized stimuli were, e.g., also performed by Schröger (1996) who applied a 900 Hz sinusoidal tone as well as a tone complex consisting of a 600 Hz and a 3.000 Hz component. Among others, deviants with an ITD of 300 μs were employed. The latencies of the MMN components obtained by Schröger are similar to those latencies of the MMN components obtained for a lead-lag delay of 1 ms in the present study (identical channels and references), although the stimulus parameters between both studies differ noticeably. This similarity of the latencies might be surprising as the ITD applied by Schröger is significantly smaller than the ITD applied in the present study (800 μs). This finding may suggest that the latencies of the MMN components are not critically dependent on the applied ITD. However, latencies of the MMN components of the present study vary with the perceived lateralization of the stimulus. Additionally, Schröger employed a deviant whose lateralization was produced by an interaural level difference of 11 dB. Corresponding MMN components differ between the sinusoid and the tone complex. However, those MMN components obtained from the sinusoid are comparable to those MMN components obtained with the ITD of 300 μs and therefore similar to those MMN components recorded in the present study.

The physiological correlate of the precedence effect seen in our MMN recordings agrees qualitatively with the recovery curves predicted by Fitzpatrick et al. (1999). In their physiological study they examined, among other neurons of different stages of the auditory pathway, single neurons of the IC and the auditory cortex of the cat.

Due to slow recoveries exhibited by neurons of the IC and especially the auditory cortex, they predict a dominance of information provided by the lead compared to the information provided by the lag for lead-lag delays up to 300 ms. Latencies of the MMN components as found in the results of the current study are clearly within this interval. This confirms the fact that the suppressive influence of the lead is still observable at these late stages of the auditory pathway like the auditory cortex.

Summarizing, ABRs reflect the stimulus features rather than its perception. Applying double click-pairs with a lead-lag delay of 5 ms, two waves V that are equal in amplitude were observed on the early stages of the auditory pathway. Additionally, an embedded ITD in the stimulus can also be observed in the potentials. This means, that directional information provided by a lag-ITD is not suppressed on the early stages of the auditory pathway but is reflected in the ABRs and therefore available to the auditory system on this level. In contrast, on the later stages, the characteristics of the recorded potentials, i.e., the MMN, reflects the perception of the stimulus rather than its features as these potentials relate to the performances obtained from psychoacoustical tasks. These findings suggest that the precedence effect is not the result of an insufficient accuracy of the peripheral processing.

4.5 Conclusions

From the results of the AEP recordings the following conclusions can be drawn:

- The characteristics of the ABRs as recorded in this study are similar to the characteristics of neural response patterns on early stages of the auditory pathway. In both cases the first click of a double-click pair evokes a recovery state of the neurons. Similar lead-lag delays, around 3.3 ms, were determined for a 50 percent recovery.

- ABRs of this study reflect stimulus features rather than the perception of the stimulus. Amplitudes and latencies of the ABRs were not influenced by the precedence effect as a change of the directional information (lag-ITD) was not suppressed, i.e., the second wave V was not reduced in amplitude applying a lead-lag delay of 5 ms and a lag-ITD of 300 μs.

- In the subgroup of four listeners that performed sufficiently well in the corresponding psychoacoustical task, a close correlation was found between the amplitude of the MMN components and the respective discrimination threshold obtained from the 'pick-out' procedure. This agreement can be interpreted as a neural correlate of the precedence effect in humans.

Chapter 5

Summary and outlook

The general goal of this thesis was to find a neurophysiological correlate of the precedence effect in humans and to shed light on the question on which stage of the auditory pathway information related to the precedence effect is processed. Investigations were made by means of psychoacoustics and auditory evoked potentials (AEPs). Preparative psychoacoustical measurements were performed in order to investigate the perception of stimuli that evoke the precedence effect under conditions of AEP recordings, i.e., investigating adaptation effects employing continuous stimulation. Using the same stimuli during psychophysical and neurophysiological measurements improves the significance of the comparison between both data sets.

The psychoacoustical measurements of chapter 2 mainly examined adaptation effects exerted by continuous stimulation and influences of the employed paradigm on the discrimination threshold of an interaural time difference (ITD). This ITD was inserted in the lag click of a lead-lag click-pair. Lead-lag delays from 0 ms to 20 ms were applied in continuous and non-continuous presentation modes. Discrimination thresholds that were obtained from different procedures and stimulation sequences cover a vast range. All discrimination thresholds that were obtained are highly dependent on the lead-lag delay and the results reflect several effects that influence discrimination threshold values: firstly, in non-continuous presentation modes adaptation effects are assumed to lead to a more distinct internal representation of the reference stimulus which facilitates the discrimination task and, therefore, yields

lower discrimination thresholds. Secondly, in contrast to this and probably due to a speed-accuracy trade-off mechanism, higher discrimination thresholds were obtained in continuous presentation modes. As subjects in this presentation mode are forced to respond very quickly, their responses lose accuracy. Additionally, discrimination thresholds obtained from the introduced 'pick-out' paradigm are even considerably further increased which is probably due to a higher stimulus timing uncertainty. Subjects during these measurements are assumed to evaluate each stimulus independently from previous repetitions as they could not predict when a deviant may occur because no intervals are marked like in the AFC paradigm. In the latter case, subjects could establish a distinct internal representation of the reference stimulus as they know that two intervals only consists of references.
A simple analytical model introduced in chapter 2 predicts the discrimination thresholds by determining the influence of the lag-ITD on the spectrum of the compound stimulus (lead and lag) for different lead-lag delays. Predictions of this simple approach were confirmed by an advanced perception model which evaluates the differences between both signals on the bases of their internal representations in the auditory system. Both models succeed in predicting the increase of the discrimination threshold for lead-lag delay from 1 ms to 5 ms, but they fail at predicting discrimination thresholds correctly for lead-lag delays larger than 5 ms because they only evaluate monaural stimulus features and therefore predict a further increase of the discrimination thresholds for larger lead-lag delays. However, since discrimination thresholds as obtained from the behavioral tasks decrease again for lead-lag delays larger than 5 ms, binaural cues are assumed to improve the discrimination performance as for these lead-lag delays they are not assumed to be suppressed by the precedence effect. In short, one important result of this thesis is that the perception of stimuli that evoke the precedence effect differs significantly between the conditions of common psychoacoustical tasks like AFC procedures and the conditions of AEP recordings that are characterized by continuous stimulation.

In contrast to the measurements of chapter 2 where *discrimination* thresholds were determined, measurements of chapter 3 determined *lateralization* thresholds. Therefore, the task of the subjects was not only to indicate any deviant but also to assign it

to either the left or right hand side. The general goal of chapter 3 was to investigate whether the dependency of lateralization thresholds on the lead-lag delay is similar to that of the discrimination thresholds as found in chapter 2. Furthermore, the comparison between both thresholds allows to separate the influence of directional cues (binaural cues) from other cues, e.g., spectral cues (monaural cues), in measurements of the discrimination and lateralization thresholds. Additionally, experiments of chapter 3 reveal whether adaptation processes and the change of stimulus timing uncertainty exert the same influence on the lateralization thresholds as on the discrimination thresholds. Therefore, similar to chapter 2, AFC procedures as well as the 'pick-out' procedure were employed.
Results of chapter 3 show that lateralization thresholds are also dependent on the lead-lag delay and the paradigm. However, their dependency on the lead-lag delay differs significantly from that of the discrimination thresholds. Maximum suppression of directional information (lateralization threshold) is obtained for a lead-lag delay of 2 ms whereas a maximum suppression of other information (discrimination threshold) is obtained for a lead-lag delay of 5 ms.
Results of chapter 3 support the assumption of chapter 2 that binaural cues help to improve the discrimination performance for lead-lag delays larger than about 5 ms because for these lead-lag delays lateralization thresholds were found to be similar to the discrimination thresholds suggesting that binaural cues dominate discrimination performance.
Additionally, the comparison between discrimination and lateralization thresholds of both chapters reveals that adaptation processes exert similar influences on both thresholds. This finding provides further evidence for the considerable effect of the stimulus timing uncertainty found in chapter 2. The difference between the low lateralization thresholds obtained in the non-continuous multiple reference presentation mode and the high lateralization thresholds obtained in the continuous 'pick-out' paradigm is very similar for both types of experiments.

Having investigated the perception of stimuli that evoke the precedence effect under conditions of AEP recordings in chapter 2 and chapter 3, the acquisition of auditory brainstem responses (ABRs) and cortical auditory evoked potentials (CAEPs) was done as described in chapter 4.

ABRs of diotic click-pairs were recorded with lead-lag delays from 0 ms to 5 ms. They show a second wave V for lead-lag delays larger than 2 ms. This second wave V increases gradually in amplitude and reaches an amplitude similar to the first wave V at a lead-lag delay of 5 ms. Latency differences between the first and second wave V are slightly but consistently larger than the lead-lag delay of the stimulus suggesting that both waves were not elicited completely independent yet for these lead-lag delays, although their amplitudes are similar. In an additional experiment ABRs of dichotic click-pairs (lag-ITD = 300 μs) were compared with corresponding diotic click-pairs applying lead-lag delays of 0, 5 and 20 ms. Amplitudes of the second wave V obtained by a lead-lag delay of 5 ms were not increased compared with the second wave V obtained with a lead-lag delay of 20 ms. A decreased amplitude of the second wave V could be expected for a lead-lag delay of 5 ms as the psychoacoustical measurements revealed increased discrimination thresholds for this lead-lag delay. However, all waves V that were elicited showed fairly identical amplitudes. Furthermore, latency differences between both waves V were significantly larger for the dichotic than for the diotic stimulation indicating that the lag-ITD of the stimulus is reflected by the ABRs.

An important result of the ABR recordings made in this thesis is that ABRs seem to reflect stimulus features rather than the perception of the stimulus. In addition, results show that the resolution of the first stages of the auditory pathway is high enough to follow the applied changes of the stimulus features. Moreover, ABRs as obtained in this thesis are in agreement with previous physiological studies that investigated response patterns of single neurons located in the auditory pathway of several animals.

CAEP were recorded according to the paradigm of the mismatch negativity (MMN) using double click-pairs with lead-lag delays of 1, 5 and 20 ms and lag-ITDs of 0 μs for the standards and 800 μs for the deviants. The MMN is assumed to appear in the difference curves, obtained by subtracting mean responses to standards from mean responses to deviants, if the auditory system detects a difference between both stimuli. Due to the appearance of the MMN components subjects could be

divided into two groups: difference curves obtained from subjects of group A show significant MMN components in the frontal channels of the scalp (referenced to the nose electrode) for all lead-lag delays whereas in subjects of group B no significant MMN was elicited for any lead-lag delay in any frontal channel. MMN components averaged across all subjects of group A show a significantly decreased amplitude for a lead-lag delay of 5 ms compared with those MMN components obtained with lead-lag delays of 1 ms and 20 ms. Hence, the MMN component of the CAEP reflects the perception of the stimulus rather than stimulus features.
The comparison between the discrimination thresholds obtained in the psychoacoustical measurements and the MMN amplitudes obtained in the CAEP recordings reveals a remarkable result. Namely, both data sets show a high correlation: those subjects that on the one hand were assigned to group A due to their MMN components and on the other hand also participated in the discrimination threshold measurements were all good performers in this psychoacoustical task. Furthermore, two subjects that were assigned to group B were excluded from the psychoacoustical task after the training session due to their poor performances. The third subject of group B was not excluded but showed a poor performance in the psychoacoustical task. This correlation between the performances in the MMN experiment and the psychoacoustical task can be interpreted as a neurophysiological correlate of the precedence effect.
Future experiments will determine the discrimination thresholds of those two subjects that were excluded after the training session employing a procedure that allows to determine even very high discrimination thresholds. First supplementary measurements for one of these two subjects revealed discrimination thresholds far beyond 1.000 μs.

Although many researchers investigated the precedence effect it is still unknown whether it is a result of peripheral or central processes. Blauert (1997, p. 420) describes the precedence effect as 'the result of evaluation and decision processes in higher stages of the nervous system during which, in addition to auditory cues, cues from other sensory modalities and prior knowledge are taken into consideration.'. The precedence effect is in his point of view a top-down process, where peripheral processes play an important role. He points out that the central nervous system decides whether a cue is enhanced or suppressed and therefore controls in this sense the peripheral processing.

Hartung and Trahiotis (2001) emphasize the importance of peripheral processes. They show that the precedence effect can to a great amount be explained by peripheral processes without top-down processes. In short, they propose peripheral auditory filters where within-filter interactions occur.

AEPs obtained in this thesis suggest that information related to the precedence effect is not processed on the early stages of the auditory pathway but is transferred to higher stages because in ABRs obtained in the present experiments no precedence-like effect could be observed whereas a neurophysiological correlate of the precedence effect was found in the CAEP.

Future work could further clarify several results presented in this thesis. As mentioned above, discrimination thresholds for those two subjects of group B that showed only a poor discrimination performance will be determined. Their thresholds are expected to be higher than those obtained from subjects of group A.

Moreover, the analytical approach introduced in chapter 2 which explains an increasing discrimination threshold for lead-lag delays from 1 ms to 5 ms should be tested in further psychophysical tasks. In these psychoacoustical experiments just noticeable differences of spectral notches will be determined.

In addition, dipole sources could be analyzed for the AEP in order to investigate the current data in even more detail. Furthermore, AEP recordings should be extended to middle latency auditory evoked potentials in order to investigate how the precedence effect is reflected on the level of the primary auditory cortex. Finally, CAEP could be recorded while subjects perform a discrimination task, i.e., performing a psychoacoustical and an electroencephalographical measurement simultaneously. Psychoacoustical and electrophysiological data obtained from this setup would provide the maximum possible comparability.

Obviously, the results determined in the current thesis could be extended in several directions. Nonetheless, by combining two means of audiological research the present work succeeds in finding a neurophysiological correlate of a cognitive effect - the precedence effect - in the human auditory system.

Bibliography

Blauert, J., 1997. Spatial Hearing: The Psychophysics of Human Sound Localization. The MIT Press, Cambridge, Massachusetts 02142. 9, 66, 68, 101

Burkard, R., 1991. Human brain-stem auditory evoked responses obtained by cross correlation to trains of clicks, noise bursts, and tone bursts. J. Acoust. Soc. Am. 90(3): 1398–1404. 88

Burkard, R., Shi, Y., Hecox, K. E., 1990. A comparison of maximum length and Legendre sequences for the derivation of brain-stem auditory-evoked responses at rapid rates of stimulation. J. Acoust. Soc. Am. 87(4): 1656–1664. 88

Clifton, R. K., 1987. Breakdown of echo suppression in the precedence effect. J. Acoust. Soc. Am. 82(5): 1834–1835. 2, 8

Csepe, V., Molnar, M., 1997. Towards the Possible Clinical Application of the Mismatch Negativity Component of Event-Related Potentials. Audiology & Neuro-Otology 2: 354–369. 4

Damaschke, J., Granzow, M., Riedel, H., 1998. Alternative definitions of the mismatch negativity. In: Dau, T., ed., Psychophysics, Physiology and Models of Hearing, pages 63–66. World Scientific, Singapore. 4

Damaschke, J., Granzow, M., Riedel, H., Kollmeier, B., 2000. Zusammenhang zwischen der Lateralisation aufgrund interauraler Zeit- und Pegeldifferenzen und kortikal evozierten Potentialen (MMN). In: Sill, A., ed., Fortschritte der Akustik - DAGA 2000, pages p. 326–327. DEGA e.V. 3

Djelani, T., 2001. Untersuchungen zum richtungsspezifischen Aufbau des Präzedenzeffektes. Fortschr. Akust. DAGA 2001, Deutsche Ges. Akust., D-Oldenburg. 10, 63

Egan, J. P., Greenberg, G. Z., Schulman, A. I., 1961. Interval of Time Uncertainty in Auditory Detection. J. Acoust. Soc. Am. 33(6): 771–778. 34

Eysholdt, U., Schreiner, C., 1982. Maximum length sequences – a fast method for measuring brain-stem-evoked responses. Audiology 21(3): 242–250. 88

Fitzpatrick, D. C., Kuwada, S., Batra, R., Trahiotis, C., 1995. Neural responses to simple simulated echoes in the auditory brain stem of the unanesthetized rabbit. J. Neurophysiol. 74(6): 2469–86. 3, 67

Fitzpatrick, D. C., Kuwada, S., Kim, D. O., Parham, K., Batra, R., 1999. Responses of neurons to click-pairs as simulated echoes: auditory nerve to auditory cortex. J. Acoust. Soc. Am. 106(6): 3460–72. 67, 89, 90, 93

Freyman, R. L., Clifton, R. K., Litovsky, R. Y., 1991. Dynamic processes in the precedence effect. J. Acoust. Soc. Am. 90(2): 874–884. 2, 8, 9, 10, 31, 41, 62

Gaskell, H., 1976. Anomalous lateralization in the precedence effect. J. Acoust. Soc. Am. 60(1): S103. 59

Gaskell, H., 1983. The precedence effect. Hearing Research 11: 277–303. 9, 40, 41, 60

Green, D. M., Swets, J. A., 1988. Signal Detection Theory and Psychophysics. Peninsula Publishing, P.O. Box 867, Los Altos, California 94023, USA. 34

Hartung, K., Trahiotis, C., 2001. Peripheral auditory processing and investigations of the 'precedence effect‘ which utilize successive transient stimuli. J. Acoust. Soc. Am. 110(3): 1505–1513. 68, 102

Hey, M., 2001. Kanaltrennung bei hochratiger sequentieller pulsatiler Elektrostimulation der Cochlea. Ph.D. thesis, C. v. O. University of Oldenburg. 89

Huber, R., 2003. Objective assessment of audio quality using an auditory processing model. Dissertation, University of Oldenburg, Oldenburg, Germany. 27

Jeffress, L. A., 1948. A place theory of sound localization. J. Comp. Physiol. 66(61): 468–486. 91

Keller, C. H., Takahashi, T. T., 1996. Responses to simulated echoes by neurons in the barn owl's auditory space map. J. Comp. Physiol. 178(4): 499–512. 3, 67

Krumbholz, K., Nobbe, A., 2002. Buildup and breakdown of echo suppression for stimuli presented over headphones - the effect of interaural time and level differences. J. Acoust. Soc. Am. 112(2): 654–663. 2, 9, 10, 31, 41, 62

Lang, A. H., Eerola, O., Korpilahti, P., Holopainen, I., Salo, S., Aaltonen, O., 1995. Practical Issues in the Clinical Application of Mismatch Negativity. Ear & Hearing 16: 118–130. 4

Lang, A. H., Nyrke, T., Ek, M., Aaltonen, O., Raimo, I., Näätänen, R., 1990. Pitch discrimination performance and auditiv-event-related potentials. In: Brunia, C. H. M., ed., Psychophysiological brain research, vol. 1, pages 294–298. 92, 93

Leek, M. R., Watson, C. S., 1984. Learning to detect auditory pattern components. J. Acoust. Soc. Am. 76(4): 1037–1042. 34

Litovsky, R. Y., 1998. Physiological studies of the precedence effect in the inferior colliculus of the kitten. J. Neurophysiol. 103(6): 3139–52. 3, 67

Litovsky, R. Y., Colburn, H. S., Yost, W. A., Guzman, S. J., 1999. The precedence effect. J. Acoust. Soc. Am. 106(4): 1633–1654. 2, 9, 10, 36, 41, 66

Litovsky, R. Y., Delgutte, B., 2002. Neural correlates of the precedence effect in the inferior colliculus: effect of localization cues. J. Neurophysiol. 87(2): 976–94. 3, 67, 91

Litovsky, R. Y., Lane, C. C., Atenicio, C., Delgutte, B., 2001. Physiological measures of the precedence effect and spatial release from masking in the cat inferior colliculus. In: Houtsma, A. J. M., Kohlrausch, A., Prijs, V. F., Schoonhoven, R., eds., Physiological and Psychophysical Bases of Auditory Function. Shaker Publishing, Maastricht, The Netherlands. 67, 91

Litovsky, R. Y., Macmillan, N. A., 1994. Sound localization precision under conditions of the precedence effect: Effects of azimuth and standard stimuli. J. Acoust. Soc. Am. 96(2): 752–758. 3, 8, 9

Litovsky, R. Y., Rakerd, B., Yin, T. C., Hartmann, W. M., 1997. Psychophysical and physiological evidence for a precedence effect in the median sagittal plane. J. Neurophysiol. 77(4): 2223–6. 67

Litovsky, R. Y., Shinn-Cunningham, B. G., 2001. Investigation of the relationship among three common measures of precedence: Fusion, localization dominance, and discrimination suppression. J. Acoust. Soc. Am. 109(1): 346–358. 3

Litovsky, R. Y., Yin, T. C., 1998. Physiological studies of the precedence effect in the inferior colliculus of the cat. I. Correlates of psychophysics. J. Neurophysiol. 80(3): 1285–301. 3, 67

Näätänen, R., 1995. The Mismatch Negativity: A Powerful Tool for Cognitive Neuroscience. Ear & Hearing 16: 6–18. 4

Näätänen, R., Alho, K., 1997. Mismatch Negativity-The Measure for Central Sound Representation Accuracy. Audiology & Neuro-Otology 2(5): 341–353. 4

Näätänen, R., Gaillard, A. W. K., Mäntysalo, S., 1978. Early selective-attention effect on evoked potential reinterpreted. Acta Psychologica 42: 313–329. 4

Otten, J., 2001. Factors influencing acoustical localization. Ph.D. thesis, Carl v. Ossietzky University Oldenburg. 5, 9

Paavilainen, P., Karlsson, M. L., Reinikainen, K., Näätänen, R., 1989. Mismatch negativity to change in spatial location of an auditory stimulus. Electroencephalogr Clin Neurophysiol 73(2): 129–141. 3

Parham, K., Zhao, H. B., Kim, D. O., 1996. Responses of auditory nerve fibers of the unanesthetized decerebrate cat to click pairs as simulated echoes. J. Neurophysiol. 76(1): 17–29. 89, 90

Perrott, D. R., Marlborough, K., Merrill, P., Strybel, T. Z., 1989. Minimum audible angle thresholds obtained under conditions in which the precedence effect is assumed to operate. J. Acoust. Soc. Am. 85(1): 282–288. 9

Riedel, H., 2003. Analysis of Early Auditory Evoked Potentials Elicited by Stimuli with Directional Information. BIS, Oldenburg. 74

Saberi, K., Perrott, D. R., 1990. Lateralization thresholds obtained under conditions in which the precedence effect is assumed to operate. J. Acoust. Soc. Am. 87(4): 1732–1737. 3, 8, 9, 40, 41, 58

Schröger, E., 1996. Interaural time and level differences: integrated or separated process. Hearing Research . 3, 93

Schröger, E., Eimer, M., 1996. Effects of lateralized cues on the processing of lateralized auditory stimuli. Biological Psychology 43: 203–226. 3

Schröger, E., Tervaniemi, M., Winkler, I., Wolff, C., Näätänen, R., 1997. Processing of interaural cues used for auditory lateralization as revealed by the mismatch negativity. In: Schick, A., Klatte, M., eds., Contributions to Psychological Acoustics: Results of the Seventh Oldenburg Symposium on Psychological Acoustics, pages 49–56. BIS, Oldenburg. 3

Schröger, E., Wolff, C., 1996. Mismatch response of the human brain to changes in sound location. Neuroreport 7(18): 3005–3008. 3

Shinn-Cunningham, B. G., Zurek, P. M., Durlach, N. I., 1993. Adjustment and discrimination measurements of the precedence effect. J. Acoust. Soc. Am. 93(5): 2923–2932. 2, 8, 9

Shinn-Cunningham, B. G., Zurek, P. M., Durlach, N. I., Clifton, R. K., 1995. Cross-frequency interactions in the precedence effect. J. Acoust. Soc. Am. 98(1): 164–171. 2

Stellmack, M. A., Dye, R. H. J., Guzman, S. J., 1999. Observer weighting of interaural delays in source and echo clicks. J. Acoust. Soc. Am. 105(1): 377–387. 9

Tollin, D. J., Henning, G. B., 1998. Some Aspects of the lateralization of echoed sound in man. I. The classical interaural-delay based precedence effect. J. Acoust. Soc. Am. 104(5): 3030–3038. 2, 8, 9, 29, 30, 40, 58

Tollin, D. J., Henning, G. B., 1999. Some Aspects of the lateralization of echoed sound in man. II. The role of the stimulus spectrum. J. Acoust. Soc. Am. 110(2): 838–849. 2, 8, 34, 41, 59, 60

Tollin, D. J., Yin, T. C., 2003. Psychophysical investigation of an auditory spatial illusion in cats: the precedence effect. J. Neurophysiol. 90(4): 2149–62. 67

Wallach, H., Newman, E. B., Rosenzweig, M. R., 1949. The precedence effect in sound localization. Am. J. Psychol. LXII(3): 315–336. 1, 2, 8, 40, 66

Watson, C. S., Kelly, W. J., Wroton, H. W., 1976. Factors in the discrimination of tonal patterns. II. Selective attention and learning under various levels of stimulus uncertainty. J. Acoust. Soc. Am. 60(5): 1176–1186. 34

Watson, C. S., Wroton, H. W., Kelly, W. J., Benbassat, C. A., 1975. Factors in the discrimination of tonal patterns. I. Component frequency, temporal position, and silent intervals. J. Acoust. Soc. Am. 57(5): 1175–1185. 34

Yang, X., Grantham, D. W., 1997. Cross-spectral and temporal factors in the precedence effect: Discrimination suppression of the lag sound in free-field. J. Acoust. Soc. Am 102(5): 2973–2983. 3, 9

Yin, T. C., 1994. Physiological correlates of the precedence effect and summing localization in the inferior colliculus of the cat. J. Neurosci. 14(9): 5170–86. 3, 67

Yost, W. A., Soderquist, D. R., 1984. The precedence effect: revisited. J. Acoust. Soc. Am. 76(5): 1377–1383. 9

Zurek, P. M., 1980. The precedence effect and its possible role in the avoidance of interaural ambiguities. J. Acoust. Soc. Am. 67(3): 953–64. 9, 66

Danksagung

Zum Schluss möchte ich mich bei einer Reihe derjenigen Personen bedanken, die sehr zum Gelingen dieser Arbeit beigetragen haben bzw. diese erst ermöglichten:

Mein erster Dank geht an Prof. Dr. Dr. Birger Kollmeier, der mit seinem vorbildlichen Einsatz die Infrastruktur der Arbeitsgruppe 'Medizinische Physik' in Oldenburg aufgebaut und stetig vergrößert und gesichert hat. Diese außergewöhnlich umfangreiche Infrastruktur war eine der wichtigsten Grundlagen meiner methodisch übergreifenden Arbeiten. Zudem war sein stetiges Interesse eine fortwährende Motivation und hat insbesondere in der Schlussphase einen sehr fruchtbaren Einfluss auf diese Arbeit gehabt.

Prof. Dr. Volker Mellert danke ich für sein Interesse an meiner Arbeit und für die Übernahme des Koreferats.

Ein besonderer Dank geht zu gleichen Teilen an Dr. Helmut Riedel und Dr. Jörn Otten, die stets ein offenes Ohr für meine Fragen hatten, mir in vielen fruchtbaren Gesprächen konstruktive Anregungen gaben und mit ihrer Kompetenz wesentlich zum Gelingen dieser Arbeit beigetragen haben.

Der sympathischen Arbeitsgruppe 'Medizinische Physik' danke ich für die stets harmonische und humorvolle Atmosphäre. Unter den vielen Mitgliedern der Arbeitsgruppe möchte ich insbesondere diejenigen hervorheben, die mir mit unermüdlicher Geduld für lange Zeit als zuverlässige und motivierte Versuchsperson zur Verfügung standen. Die sehr aufwendigen Messungen dieser Arbeit haben sie mit großer Konzentration vorbildlich absolviert.

Für ihren besonderen Einsatz, ihre stets gute Laune und ihre zuverlässige Unterstützung bei den arbeitsaufwendigen EEG Messungen bedanke ich mich besonders bei Anita Gorges. Darüber hinaus danke ich Ingrid Wusowski und Susanne Garre und für ihre Hilfe in bürokratischen Angelegenheiten.

Für das bereitwillige Korrekturlesen dieser Arbeit und den zahlreichen konstruktiven Anmerkungen danke ich besonders Dr. Michael Bellmann, Dr. Jörn Otten, Prof. Dr. Jesko Verhey und Dr. Helmut Riedel.

Ich danke meinen Freunden Dr. Michael Bellmann und Dr. Stephan Ewert, die mir fortwährend mit vielen fachlichen und persönlichen Gesprächen mit Rat und Tat zur Seite standen und dabei immer für gute Laune sorgten.

Ich danke insbesondere meinen Eltern und meinem Bruder, die mir durch Ihre fortwährende Unterstützung das Physikstudium ermöglichten, das mit dieser Arbeit ein schönen Abschluss erhält.

Maja danke ich für ihre liebevolle Unterstützung.

Lebenslauf

Am 29.11.1973 wurde ich als Sohn von Arno und Ingrid Damaschke, geb. Seidel, in Delmenhorst geboren. Dort besuchte ich von 1980 bis 1993, die Herrmann-Allmers Grundschule und Orientierungsstufe sowie das Max-Planck-Gymnasium, an dem ich im Sommer 1993 das Abitur ablegte.

Zum Wintersemester 1993/1994 begann ich aufgrund meines Interesses an Technik und Naturwissenschaften das Physikstudium an der Carl-von-Ossietzky Universität in Oldenburg. Dort erreichte ich 1995 mein Vordiplom. Mein Studium beendete ich erfolgreich im Juli 1999 mit meiner Diplomarbeit, die ich in der Arbeitsgruppe 'Medizinische Physik' bei Herrn Prof. Dr. Dr. Kollmeier über die Wahrnehmung räumlicher akustischer Stimuli sowie deren Verarbeitung vom auditorischen System schrieb.

Im Juli 1999 erhielt ich ein Doktorandenstipedium des Graduiertenkollegs Psychoakustik und begann mit der Arbeit an der vorliegenden Dissertation. Seit Januar 2002 bin ich als wissenschaftlicher Mitarbeiter in unterschiedlichen Projekten tätig.

Erklärung

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

Oldenburg, den 19. März 2004 Jörg Damaschke