DIPLOMARBEIT

Effects of binaural jitter on sensitivity to interaural time differences in hearing-impaired listeners

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Zusammenfassung

Interaurale Laufzeitdifferenzen (ITD) eines Signals sind wichtig für die Schallquellenlokalisation und für die Sprachwahrnehmung im Störgeräusch. Während sich bei niedrigen Pulsraten von hochfrequent gefilterten Pulsketten die ITD Sensitivität bei steigender Signaldauer verbessert, tritt eine solche Verbesserung bei hohen Pulsraten nicht auf. Dieser Effekt wird als binaurale Adaptation bezeichnet. Binaurale Adaptation führt bei hohen Pulsraten dazu, dass der Beginn eines Schallereignisses maximale perzeptive Gewichtung hat, während das fortlaufende Signal nur wenig zur Wahrnehmung von ITD beiträgt. Die Einführung von binaural synchronisierter Zufälligkeit (binauraler Jitter) in der zeitlichen Struktur der Stimulation verbessert die ITD Sensitivität bei Normalhörenden und Cochleaimplantat Trägern. Diese Studie prüft die Hypothese, dass auch bei Personen mit cochleärem Hörschaden binaurale Adaptation auftritt und somit durch die Einführung von binauralem Jitter die Wahrnehmung von ITD bei höheren Pulsraten verbessert werden kann. Zusätzlich wird getestet, ob die Einhüllende des Signals für tiefe Trägerfrequenzen (500 Hz) eine Rolle spielt. Die ITD Sensitivität von zwölf hörgeschädigten Personen mit mittelgradigem Innenohrschaden wurde bei 4000 Hz und 500 Hz, unter Verwendung einer links/rechts Unterscheidungsmethode, gemessen. Für 4000 Hz wurden Pulsketten mit Pulsraten von 400 und 600 Pulsen pro Sekunde und verschiedenen Graden an binauralem Jitter sowie Schmalbandrauschen verwendet. Die Hypothese wurde bestätigt, dass binauraler Jitter die ITD Sensitivität erhöht. ITD Sensitivität von Pulsketten mit mittlerem bis hohem Jitter entspricht in etwa der von Schmalbandrauschen. Für 500 Hz wur-

den Sinustöne mit verschiedenen Graden an zufälliger Frequenzmodulation ("gejitterte Töne"), Schmalbandrauschen, sinusförmig amplitudenmodulierte Töne und reine Sinustöne getestet. Gejitterte Töne zeigten keine Verbesserung der ITD Sensitivität gegenüber reinen Tönen. Sinusförmig amplitudenmodulierte Töne resultierten in einer geringfügig höheren ITD Sensitivität als alle anderen Signale. Schmalbandrauschen zeigte hingegen geringfügig niedrigere ITD Sensitivität als alle anderen Signale. Diese Ergebnisse zeigen, dass bei 500 Hz Feinstruktur die dominante Information für die Wahrnehmung von ITD darstellt, während die Einhüllende relativ geringen Einfluß hat. Insgesamt weisen die Hörgeschädigten eine gegenüber Normalhörenden um den Faktor 2-3 verschlechterte ITD Sensitivität auf, sowohl bei 500 Hz als auch bei 4000 Hz. In Übereinstimmung mit anderen Studien korreliert die ITD Sensitivität nicht mit dem Grad an Hörverlust. Die Ergebnisse zeigen die praktische Möglichkeit auf, die ITD Sensitivität von Hörgeschädigten bei hohen Frequenzen mittels der Einführung von binauralem Jitter in Hörgeräten zu verbessern.

Abstract

Interaural time differences (ITDs) provide important information for the localization of sound sources and understanding of speech in noise. For pulse trains at higher rates, the sensitivity to the ongoing envelope ITD is reduced, which is known as binaural adaptation. The effect of binaural adaptation is that for high pulse rates the begin of the signal receives maximum perceptual weight whereas the ongoing signal contributes little to ITD perception. Introducing binaurally-synchronized randomness of the timing of individual pulses (binaural jitter) improves ITD sensitivity of normal hearing and of cochlear implant listeners. This study tests the hypothesis that for higher pulse rates, binaural jitter improves ITD sensitivity also in hearing-impaired (HI) listeners with a moderate sensorineural hearing loss. Additionally, the effect of amplitude modulation in low-frequency signals is tested. ITD sensitivity was measured in twelve HI listeners at 4000 Hz and 500 Hz, using a left/right discrimination task. For 4000 Hz, stimuli were narrow-band noise (NBN) and bandpass-filtered click trains with and without jitter using pulse rates of 400 and 600 pulses per second. ITD sensitivity improved with increasing amount of jitter, supporting the hypothesis. ITD sensitivity for pulse trains with moderate and large amount of jitter was similar to that for NBN. For 500 Hz, stimuli were pure tones with random frequency modulation ("jittered tones"), NBN, sinusoidally amplitude modulated (SAM) tones and pure tones. Jittered tones showed no improvement in ITD sensitivity compared to pure tones. SAM tones showed slightly higher ITD sensitivity than all other stimuli. NBN showed slightly lower ITD sensitiviy than all other stimuli. The results indicate that at 500 Hz the fine structure is the dominant information for ITD perception, while the envelope has little effect. Overall, HI listeners show a 2-3 times lower ITD sensitivity at both 500 Hz and 4000 Hz compared to NH listeners. Consistent with the literature, ITD sensitivity does not correlate with the degree of hearing loss. The results show a practical possibility to improve ITD sensitivity of HI listeners at high frequencies by introducing binaural jitter in hearing aids.

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Contents

Chapter 1

Introduction

Hearing is one of the five human senses and a crucial ability. With the help of our ears information about our sound environment can be gathered. It is remarkably how well it is possible to separate and selectively pay attention to individual sound sources. The sound localization can be lifesaving, e.g. from a horn of an approaching automobile, a siren or a fire alarm. Furthermore, the sense of hearing plays a crucial part in our daily social life with relatives, friends, and colleagues. Hearing impaired (HI) listeners often loose the ability to localize the incoming sounds of the sound environment. Due to this fact HI listeners often reduce communication to the outside world and isolate themselves. They want to avoid the discomfort that lack of listening comprehension brings about in the day-to-day communication along with the obligation of constant clarification. Therefore, it is of great importance to be aware of possible hearing limitations. Early treatment offers the best chance to effectively deal with any hearing loss and also to prevent HI listeners from isolating themselves. The use of a hearing aid (HA) gives the opportunity to regain some hearing capability. However, it still may remain very difficult to localize the incoming sound and understand the spoken words. In order to improve space perception in noisy and reverberant environments and localization abilities, the binaural system plays a major role. This is the primary goal of research on bilateral hearing impairment. This study focuses on basic principles of sound source localization/lateralization of HI listeners based on the results of previous studies on normal-hearing (NH) listeners and cochlear-implant (CI) listeners.

1.1 Motivation

The motivation of this thesis was based on findings from recent studies on interaural time difference (ITD) sensitivity in cochlear-implant (CI) and normal-hearing (NH) listeners, and also previous studies on the binaural adaptation phenomenon.
In the early 80s, Hafter and collegues gave an important trigger for further research and the first background for this thesis. Hafter and Dye (1983) studied ITD sensitivity by investigating the effects of the stimulus duration and the modulation frequency on lateralization. They used 4-kHz modulated bandpass-filtered pulse trains. They showed evidence that with increasing modulation rate, the ongoing part of a pulse train receives progressively less perceptual weight with respect to ITD perception. These findings imply that with increasing pulse rate the onset becomes more and more important. This effect has been referred to as "binaural adaptation." Later studies have shown that binaural adaptation starts immediately after the first pulse (Saberi, 1996; Stecker, 2002). The effective consequence of the binaural adaptation effect may be a reduction of ITD sensitivity with increasing modulation rate. This is indeed supported by studies that tested ITD sensitivity as a function of modulation rate (e.g. Bernstein and Trahiotis, 2002). The discovery of the binaural adaptation phenomenon became another important trigger for auditory researchers. Hafter and Buell's (1990) interest was to find conditions which produce a recovery from binaural adaptation. To produce binaural adaptation they used a train of pulses with short inter-pulse intervals (IPIs), thus high modulation rates. A recovery from binaural adaptation was achieved by introducing a change or a "trigger" in the stimulus (Hafter and Buell, 1990; Stecker, 2002). The recovery effect occured when one or more intervals of the pulse train (with an IPI of 2.5 ms) were doubled or halved. Other "trigger" signals that were found to be effective were a diotic sinusoid or a noise burst.

These studies were the motivation to recent studies which investigated the binaural adaptation phenomenon with cochlear-implant (CI) listeners (Laback and Majdak, 2008). CIs encode acoustic information by means of high-rate electric pulses. It was hypothesized that the recovery effect can be used to improve ITD sensitivity in CI listeners at high rates. Previous studies showed that the ITD sensitivity of CI listeners decreases when pulse rates exceed a few hundred pulses per second (pps) (von Hoesel, 2008; Laback et al. 2007; Majdak et al. 2006). The question was raised if this pulse rate limitation for ITD perception of CI listeners is related to the binaural adaptation phenomenon. The recovery from binaural adaptation was also found in CI Listeners by introducing a new method which only contained temporal changes. The method used introduced binaurally-synchronized jitter (referred to as "binaural jitter") in the stimulation timing. Indeed, the binaural jitter was found to improve ITD sensitivity of CI listeners at high pulse rates (Laback and Majdak, 2008). Thus, "binaural jitter" reduced the pulse rate limitation, allowing ITD perception at much higher rates. Binaurally jittered stimulation may have an advantage in several aspects of binaural hearing for bilateral recipients of neural auditory prostheses such as cochlear implants.

It is known that HI listeners also have reduced sensitivity to ITD with a large intersubject variability. Thus, the goal of this thesis was to examine the ITD sensitivity for HI listeners for both the high and the low frequency region in acoustic hearing. For the high frequency region, it was investigated if improvements in ITD sensitivity can be achieved by introducing binaural-synchronized jitter in the stimulus timing. Bandpass-filtered pulse trains were used with pulse rates of 400 and 600 pulses per second (pps). For the latter rate, even NH listeners have difficulties in detecting ITD in the waveform (Majdak and Laback, 2009). It was also investigated if the performance for jittered pulse trains is similar to that for narrow-band noises (NBNs), as in normal-hearing subjects (Goupell et al. 2009). For the low frequency region, different types of stimuli were tested. It was investigated if binaural adaptation is also present and if a recovery may be induced by introducing binaurally-synchronized randomness. Furthermore, the contribution of periodic amplitude modulation at low frequencies was tested.

1.2 Structure of the Thesis

The aim of this thesis is to investigate the effects of ongoing envelope ITD in HI listeners. After a brief introduction, the thesis has the following structure:

Chapter 2 presents the fundamentals and is divided into four sections: the auditory system, ITD, psychophysical methods, and hearing loss. The fundamentals have the intention to outline the specific problems of the topic and the difficulties of the experiments performed to address the topic. Investigations on the function of hearing as a sensory organ of humans for the perception of sound waves are extremely complex. The purpose is to provide an understanding of the basic anatomy and physiology of the peripheral auditory system and of the central auditory system as far as it is relevant for ITD processing. Then, a section on the physical, physiological, and psychoacoustical nature of interaural time differences (ITD) is provided, supplemented by a brief summary of different theories and model conceptions. Lastly, general effects of hearing loss are described and a review of past research on ITD sensitivity in hearing-impaired (HI) listeners is given.

Chapter 3 provides detailed information about research on the effect of binaural adaptation which is known to limit ITD sensitivity at higher modulation rates in NH and CI listeners. It is shown that a recovery from binaural adaptation can be induced by introducing binaural jitter. This recovery effect is further explained and leads to the hypotheses outlined in chapter 4.

Chapter 4 reviews several reasons why sensorineural hearing loss (SNHL) could decrease or increase ITD sensitivity. This leads to the motivation and hypotheses for testing two frequency regions, the high-frequency and the low-frequency region, and to the design of the two experiments.

Chapter 5 provides a description of the two psychoacoustical experiments on ITD sensitivity in HI listeners. These experiments were performed to test primarily the hypothesis that binaural jitter improves ITD sensitivity in HI listeners. To test the hypotheses in a proper way, the psychoacoustical experiment has to be designed taking into account the proper allocation of methods, test-set up, calibration, pre-tests and the subsequent statistical analysis. The pre-tests were necessary to obtain the stimulus parameters required for the two main experiments. The pre-tests include the measurement of the absolute hearing threshold, a categorical loudness scaling, and a centralization procedure. Each of the two main experiments is subdivided into subsections, describing the stimuli, subjects, procedures, conditions, data analysis, individual and group results, their comparisons and a final discussion. The discussion includes mainly a comparison with previous studies and conclusions.

Chapter 6 discusses the general outcomes with respect to the fundamentals, previous studies and underlying effects.

Chapter 7 concludes and summarizes the findings from both experiments, 4000 Hz and 500 Hz.

In the **Appendix** additional information is provided. Examples for psychometric functions are plotted, the testing environment is described, and some additional information about the subject recruitment and a list of abbreviations are provided.

Chapter 2

Fundamentals

The fundamentals have the intention to outline specific problems of the topic and the difficulties of the experiments and to address the topic. Investigations on the function of hearing as a sensory organ of humans for the perception of sound waves are extremely complex. The purpose is to provide an understanding of the basic anatomy and physiology of the peripheral auditory system and of the central auditory system as far as it is relevant for ITD processing. Then, a section on the physical, physiological, and psychoacoustical nature of interaural time differences (ITD) is provided, supplemental by a brief summary of different theories and model conceptions. Lastly, dealing with the problem of hearing loss, general effects are described in detail and a review of past research on ITD sensitivity in hearing-impaired (HI) listeners is given. Terms and conditions are explained which are required for the experiments and the discussion.

2.1 The Auditory System

The peripheral auditory system (see figure 2.1), as part of the sensory system, consists of three main parts - the outer ear, the middle ear, and the inner ear. In the outer and middle ear (comprising the conductive system) the sound waves are conducted from

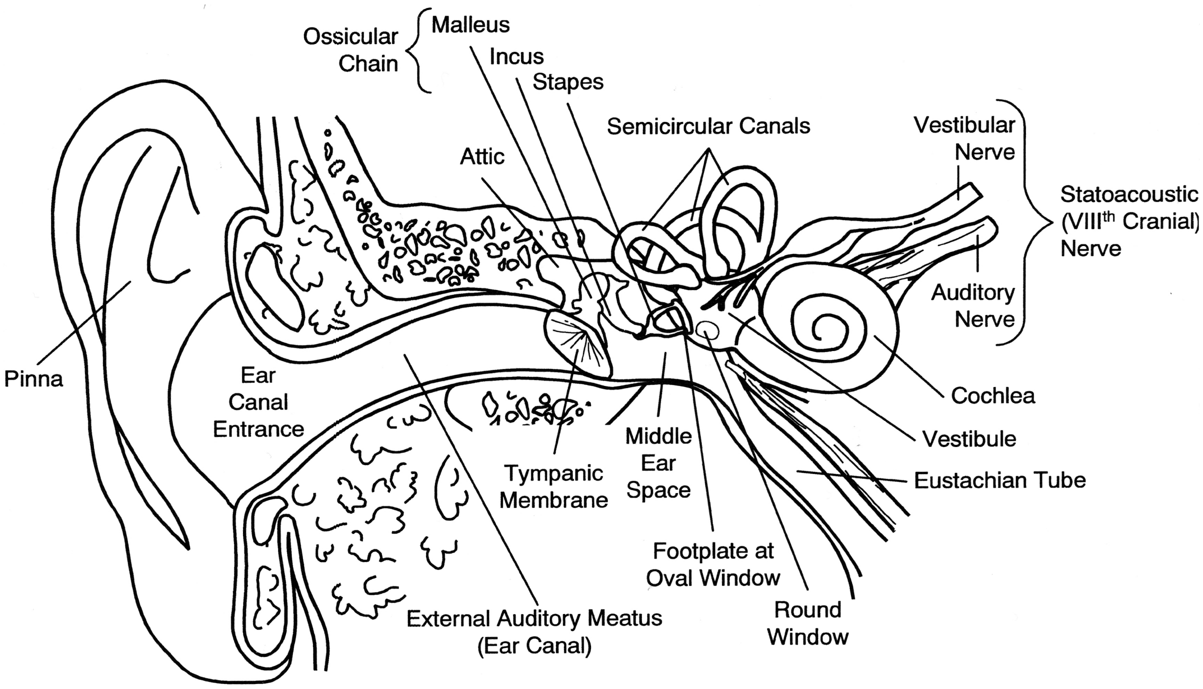


Figure 2.1: *The peripheral auditory system (Gelfand, 1997)*

the air to the inner ear while keeping their wave character. In the inner ear (cochlea) and the cochlea nerve (collectively called sensorineural system), the physiological response to the stimulus takes place. The hair cells are activated and their sensory response is encoded into a neural signal (electrical action potentials). Independent of the causes underlying the development of the auditory system, its characteristics have important implications for the analysis of hearing impairment as well as for the design of hearing aids. This section follows the book "essentials of audiology" from Stanley A. Gelfand.

2.1.1 Outer Ear

The outer ear involves the pinna and the ear channel. Particularly the pinna collects the entering sound waves which are transferred via the ear channel to the tympanic membrane. Due to the irregular and asymmetrical shape of the pinna which modifies the sound spectrum in a direction-dependent way, the pinna provides cues for sound localization (Blauert, 1983). The ear channel protects the tympanic membrane. In the frequency range in which the length of the ear channel is a quarter of the wavelength of the sound, the ear channel and thus tympanic membrane transfer sound waves particularly well. This is the reason why humans have the lowest absolute hearing threshold for frequencies around 4 kHz.

2.1.2 Middle Ear

The middle ear (or tympanic cavity) lies behind the tympanic membrane and is an air-filled cavity. It is connected to the mouth via the eustachian tube, which enables the equalization of pressure within the middle ear. The auditory ossicles consist of three small bones, malleus (hammer), incus (anvil), and stapes (stirrup) situated in this cavity. With the malleus, the ossicles are attached to the tympanic membrane. Its sound-induced vibratory motions are passed to the ossicles causing them to vibrate one after the other at the same frequency. The stirrup connected to the oval window transmits these vibrations to the inner ear.

The main function of the middle ear lies in the impedance matching between a low impedance of the pressure waves in air (small deflection forces and large deflection of the air particles) and a very high impedance in the fluid-filled inner ear creating a compression wave, see figure 2.2. This is reached by the three following mechanisms:

First, the area ratio advantage where the exerting force of the large area of the tympanic membrane is transmitted to the small area of the oval window (ratio 22:1), evoking from a lower pressure a high one by keeping an equal force (p = F/A).

Second, the vibrations of the curved tympanic membrane have larger displacement than the malleus attached to the tympanic membrane (approx. factor 2), which is caused due to a boost in force ($F_1 \times D_1 = F_2 \times D_2$). The flection of the membrane has the effect that a relatively great displacement of the membrane (caused by a slight force) induces only a relatively small deflection of the hammer handle with a corre-

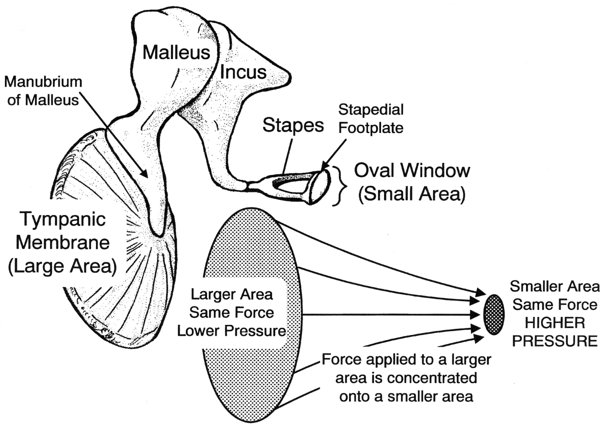


Figure 2.2: *"The area advantage involves concentrating the force applied over the tympanic membrane to the smaller area of the oval window." (Gelfand, 1997)*

spondingly greater force action on the hammer handle.

Third, the lever action of the ossicles enables an impedance matching (ratio 1.2:1) (greater force at a smaller displacement).

Altogether the force per unit of area is increased about fiftyfold. Without impedance matching sound would not be transferred into the fluid of the cochlea but reflected at the oval window (lower sensitivity). The most efficient range to transfer sound through the middle ear is that of 0.5 to 4 kHz. This feature contributes to our ability of hearing the faintest of sounds.

2.1.3 Inner Ear

The inner ear or cochlea forms an anatomical unit with the organ of equilibrium. The cochlea is embedded and packed into a very tiny space of the temporal bone of the skull, which is the strongest bone of the human body. The beginning of the cochlea, where the oval window is placed, is referred to as the base, while the end is at the apex, where the helicotrema (a small opening) is placed. The cochlea is a snail-shaped organ which is approximately 35-mm long and is divided by membranes into three fluid-filled compartments: scala vestibuli, scala media, and scala tympani. On the basilar membrane are hair cells placed, which are covered by the tectorial membrane. They form a spiral structure within the cochlea called the organ of corti.

The mode of vibration of the basilar membrane has crucial impact on the sound transformation. The periodic pressure stimulation from the oval window, where the stirrup is attached to the cochlea, causes a difference of pressure between scala vestibuli and scala tympani, which leads to the propagation of a traveling wave along this membrane. The pressure propagation is instantaneous, while the traveling wave develops as a consequence of the periodic oscillating difference of pressure between the two compartments (scala vestibuli and scala tympani).

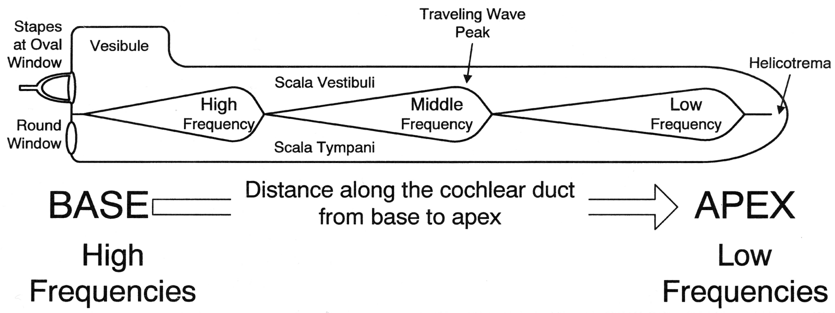


Figure 2.3: *"The traveling wave in the place coding mechanism of the cochlea." (Gelfand, 1997)*

The basilar membrane increases in width and decreases in stiffness from the oval window (also known as the base) towards the helicotrema (apex), which causes a different allocation of frequencies, usually called tonotopical organization, see figure 2.3. As a result, the traveling wave moves in the direction from high-to-low frequencies, and a particular frequency will maximally vibrate the membrane at a characteristic position along its length. High-frequency triggered waves have a maximum close to the base, whereas low-frequency triggered waves have a maximum close to the apex.

Along the basilar membrane which is covered by the tectorial membrane, the outer hair cells (OHCs) and inner hair cells (IHCs) (approx. 12.000 and 3.500, respectively) are arranged in rows (3-4 and 1, respectively) (Gelfand, 1997). At the upper end of each hair cell the stereocilia are located, which are connected to the tectorial membrane (see figure 2.8). At the lower pole of the IHCs a set of afferent nerve fibers begins, which connects to the brainstem and the cortex. The hair cells of the organ of corti do not activate action potentials unless the basilar membrane is moving upwards. This is called phase coupled discharge. It is evident that the sequence of action potentials reflects the time structure of a sound stimulus. The central auditory system can deduce a sound frequency from a corresponding time structure. The nerve fibers fire due to the depolarization of the hair cell, as soon as, the transmitter is set free. The firing is taken up by the synapses and is leading to a release of nerve impulses. The IHCs thereby represent, to a certain extent, a sensor for the movement of the basilar membrane. The OHCs are predominantly connected to efferent fibers. Furthermore, the OHCs are capable of an active contraction.

The function of the acoustic nerve and the auditory pathway consists in the encoding and processing of acoustic information in the form of a neural excitation pattern. The acoustic information is encoded in the acoustic nerve by means of the firing rate and the synchronization of the discharge rate of different nerve fibers. In the brain stem more complex functions are evaluated, e.g. the interaural comparison takes place in the superior olive (more details can be found in section 2.2.2).

Sound Coding in the Auditory System

The auditory nerve is the only neural connection between the cochlea and the brain stem. It should be contemplated how the fibers encode the acoustic information by using different firing rates and firing patterns of the IHCs. This encoding can be explained particularly by the impact the IHCs have on the depolarization while deflecting stereocilia in one direction, on the release of transmitter, and on the exhaustion of transmitter release with continuous stimulation. One property is the half-wave rectification. Since the hair-cells depolarize only during the deflection of the stereozilia in a given direction, only the rectified half-wave information is coded in the downstreamed auditory nerve.

Temporal and Place Coding

Auditory neurons represent frequency information by two types of coding. One of them is the phase-locking mechanism. If a certain threshold is exceeded the neural firing pattern is synchronized with the stimulus (half-) wave. The probability of a firing is largest with positive displacement of a signal and lowest with negative displacement of a signal. Thus, each individual nerve fiber has the characteristic to "phase lock" itself with a certain phase of a periodic signal. This simply means that there is a high probability that the firing takes place at a certain time during the period of a signal. Increasing the intensity of the stimulus does not only synchronize the spontaneous firing of the neuron but also rises the firing rate (spike per second). Note that the maximum discharge rate of one nerve fiber is about 1000/s (absolute refractory time of 1 ms), therefore the nerve fiber can follow the fine structure of the signal continuously only up to a frequency of 1 kHz. However, a certain degree of phase-locking to the stimulus remains (Rose et al., 1967), since after some recovery time, the neurons can again fire in phase.

A place coding is given by frequency specifity: If the frequency of a (sinusoidal) stimulus is systematically varied and the level is always adjusted in such a way that the firing rate of the auditory nerve fiber achieves a certain constant firing rate (e.g. ten percent above the spontaneous fire rate) the so-called tuning-curve is obtained. The best frequency of a neuron is given by the tip of the tuning curve. Each tuning curve thus indicates the range of frequencies over which a given nerve fiber responds maximally which allows to identify the frequency of the input signal.

Coding of the Dynamic Range

For the coding of sound intensity different mechanisms are responsible. With increasing sound level the excitation area on the basilar membrane is expanding. One consequence is a growing number of activated receptor cells. Another consequence is the rising probability of a release of action potentials as the deflection amplitude grows. This means that with growing sound intensity more and more nerve fibers are activated and the action potential rate of the single nerve fiber is increasing.

Fine structure vs. Envelope Coding

The temporal fine structure is usually referred to the carrier of a modulated signal or referred to the instantaneous phase of broadband signals. It is generally agreed on that the temporal fine structure is represented by the phase locking mechanism. Nerve spikes tend to synchronize to a specific phase of the carrier. The temporal envelope is usually referred to the amplitude modulation applied to the carrier signal in modulated signals. Envelope cues are represented as slowly-varying fluctuations of the short-term firing rate in auditory neurons are represented as envelope cues. For low-frequency signals up to 1500 Hz, mainly fine-structure, but also envelope cues are processed by the auditory system. For high-frequency signals over 1500 Hz, mainly envelope cues are processed by the auditory system (Lorenzi et al., 2006; Rose et al., 1967; Joris and Yin, 1992).

2.2 Interaural Time Differences (ITD)

2.2.1 General Overview

Interaural time difference (ITD) results from the spatial separation of the two ears. A sound source which is produced outside the median plane (off the midline) always reaches first the closer ear and then the farer ear. The wavefront sets up a time difference. This relative time shift between the two ears is called ITD and can range from 0 μs (for a sound source in the median plane) to 700 μs (for a sound source located at a side, depending on the head-diameter). ITD provides a cue concerning the direction of the sound source. This is an important information for the localization of sound sources and understanding speech in noise. The auditory system has a high capability regarding the localization of sounds. Lateral sound sources which differ only a few degrees in the horizontal direction can be resolved by our ear. The ITD sensitivity of listeners can be described by just noticeable difference (JND) for ITD. The

NH listener's JND for ITD in a signal under optimum conditions can be as little as ten microseconds (e.g. Klumpp and Eady, 1956; Zwislocki and Feldman, 1956).

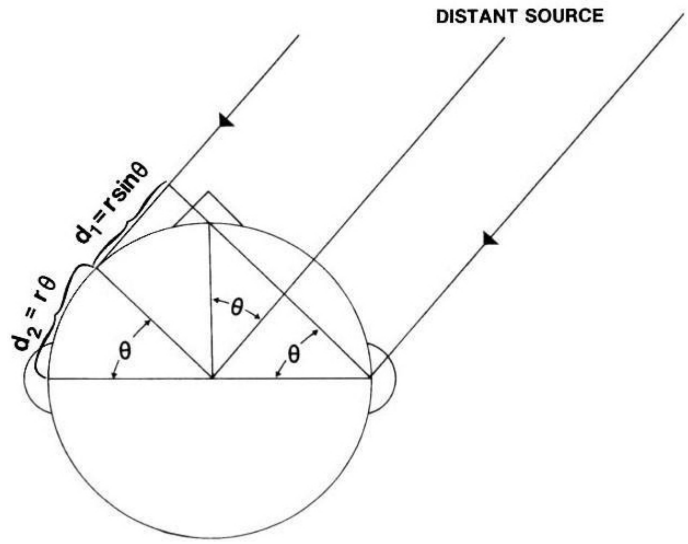


Figure 2.4: *Interaural Time Difference (Begault, 2001)*

ITD is a major cue for determining the azimuthal position of sounds. It can be assumed that a distant sound source is noticed by a spherical head with a radius r and its direction is specified by the azimuth angle θ (see figure 2.4). Then this sound reaches the right ear before the left one because of the supplementary distance d = $d_1 + d_2$ = r θ + r sin θ. By dividing the supplementary distance d by the speed of sound c, the formula for ITD is obtained:

$$\text{ITD} = \frac{r\theta + r sin\theta}{c}, -90^\circ \leq \theta \leq +90^\circ \text{ (Strutt, 1907).}$$

The speed of sound c equals about $343m/s$. It is of interest that the exact ITD value for a particular direction is primarily dependent on the head-width of the listener as well as on the reflections of the torso and pinna. To a certain extend it is also frequency-dependent because of the changes in the phase due to the reflections. Differences of the sound pressure level arriving at the two ears as a result of the shadowing effect of the head, pinna, and torso are called interaural level differences (ILD). In fact, the main functionality of the binaural auditory system can be understood in terms of its

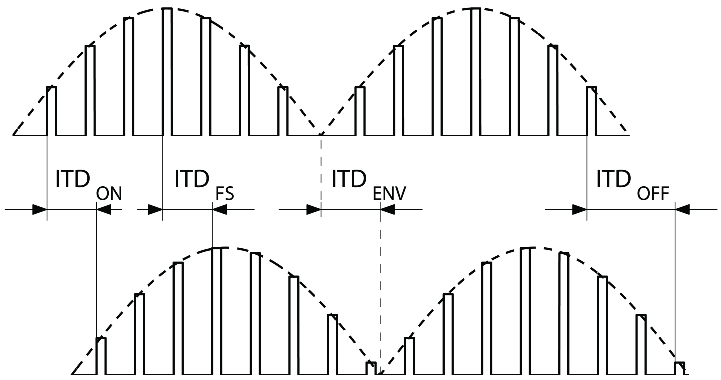


Figure 2.5: *Onset ITD (ITD_{ON}), fine-structure ITD (ITD_{FS}), envelope ITD (ITD_{ENV}), and offset ITD (ITD_{OFF}) in a modulated pulsatile stimulus. Adapted from Majdak (2008)*

sensitivity to ITDs or ILDs. There are two main types of ITDs which are processed differently by the auditory system in the timing of neural discharges: The first type is the ITD in the fast-varying fine structure of a signal, called fine-structure ITD (FS ITD), which depends on the phase locking mechanism (Young and Sachs, 1979). It is important for lateralizing sound sources (Wightman and Kistler, 1992; Smith et al., 2002) and understanding speech in noise (Nie et. al., 2005; Zeng et al., 2005). The second type is the ITD in the envelope of a signal which is transmitted by the slowly-varying fluctuations of a signal (see figure 2.5).

The ITD information in the envelope of a stimulus can be extracted by the auditory system in three different components: The ITDs in the onset and offset of a signal, referred to as "onset ITD" and "offset ITD", respectively. The ITD in the ongoing envelope part of a signal, referred to as "ongoing envelope ITD." Ongoing envelope ITD also relates to the signal's slowly-varying envelope and is a reliable information for signals containing high-frequency energy (Mcpherson and Middlebrooks, 2002).

Looking back into history, the human binaural system called for attention to a lot of auditory researchers since 1907, when John Strutt, who is also known as Lord Rayleigh, developed the "duplex theory" (Strutt, 1907). He proposed that ILD and ITD are complementary, implying localization information is provided all-over the audible frequency range. He found that localization of high-frequency sounds (above about

1500 Hz) is based on ILD because it resolves directional ambiguity which occurs for fine-structure ITD when the ITD approaches half of the carrier period. In contrast, localization of low-frequency sounds (below about 1500 Hz) is supposed to be based on ITD. According to Rayleigh's theory, ILDs are negligible in the low-frequency range. This theory contributed a lot to the scientific progress in understanding "normal" hearing.

Over 40 years later, another period of binaural modeling has started with Jeffress' prescient paper (1948). Jeffress suggested a neural coincidence mechanism to detect ITD. Coincidentally, Hirsch (1948) and Licklider (1948), described independently the origin of the binaural masking level difference. From then on, an explosion in experimental studies in subjective lateralization, binaural detection, and interaural level and time discrimination has begun. In the 1970s, many auditory researchers could prove the duplex theory by using pure tones and showed evidence that subjects are able to detect fine-structure ITD in the envelopes of high-frequency amplitude-modulated tones if the modulation frequency did not exceed a certain modulation frequency (e.g. Henning, 1974; McFadden and Pasanen, 1976; Nuetzel and Hafter, 1976). These investigations modified the duplex theory by saying that the upper limit of ITD detection is ascertained not only by the stimulus frequency, but more by its rate which refers to the occurrence of the characteristic of the signal carrying the interaural information either the fine structure or the envelope. In addition to the modified duplex theory Wightman and Kistler (1992) have shown that the ITD dominates the localized direction for broadband signals. In 2002, Macpherson and Middlebrooks could prove the duplex theory: They showed that ILD contrary to ITD has an obviously dominant impact for high-pass filtered noise, while for low-pass filtered noise it has not. Lateralization experiments showed that ILD evokes lateral-displacement for all frequencies, which is a hint that with the transition from lateralization (in-the-head-localization) to the externalization of the directional image not only the perceived position of the source is changing but also the localization process.

A general conclusion concerning ITD is that ITDs are important for horizontal plane sound localization. ITDs are most useful at low frequencies, however, if transient or periodic sounds have relatively low repetition rates, then the ITD can be localized even when they contain only high frequencies.

2.2.2 Coding of ITD in the Auditory System

An important physiological finding has been observed in the brainstem. A number of cells are probably useful to detect specific ITDs. The auditory nerve is the first switching station of the auditory information, where information is passed on partially directly to higher stations of the auditory system and passed on partially to the superior olive (SO) for the binaural comparison. The ITD detection is done by a binaural comparison. The SO is the first station of the auditory pathway, in which a binaural interaction takes place. The SO is subdivided into three different tracts: lateral superior olive (LSO), medial superior olive (MSO), and medial nucleus trapezoid body (MNTB). In the MSO every single neuron is innervated on both sides excitatory from the antero-ventral cochlear nucleus (AVCN), i.e. there are so-called excitatory-excitatory-cells (EE-cells) from ipsilateral and contralateral side. In the LSO, the neurons are directly, ipsilaterally, and excitatory stimulated while they are contralaterally, and inhibitory reached by the MNTB, i.e. there are the so-called excitatory-inhibitory-cells (EI-cells). After the binaural comparison in the SO, the evaluated ITD and ILD are passed on to the inferior colliculus (IC), which is a higher station of the auditory system.

A theoretical model for the binaural interaction of EE-cells was proposed by Jeffress in 1948, see figure 2.6. It is based on the convertion of ITD into a neural representation of the lateral position (Jeffress, 1948). In this model, the MSO neurons work as coincidence detectors: Jeffress (1948) postulated that there had to be specific neurons, "coincidence detectors", which show maximum response activity, if the sound comes from a certain direction. The coincidence detector fires, if it receives simultaneous neural input from both "sides", whereby the external ITDs are

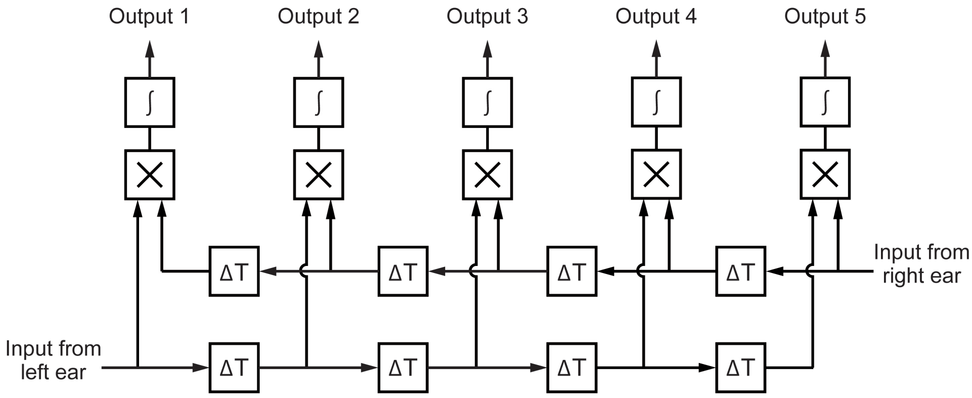


Figure 2.6: *Jeffress model is presented schematically. Boxes containing crosses are correlators (multipliers) that record coincidences of neural activity from the two ears after the internal delays (ΔT). (Stern et al., 2005)*

compensated by internal neural time differences. The core of this model is built of neuronal delay lines (e.g. given by run-time differences on the axons of the neurons) and downstream coincidence neurons, which fire during simultaneous excitation on the two input channels. The average firing distribution of these coincidence-neurons reflects the occurrence of an ITD arising between the two ears. Thus, the Jeffress model represents an interaural cross-correlation network. The conversion of temporal information to such a rate code was postulated, although at that time they could not refer directly to an appropriate physiological counterpart, and they did not have the technical possibilities to use physiological measurement in the brain stem on a single-cell level. Therefore, the Jeffress model can be seen as a black box model without specifications, which postulates a functional mechanism for the localization of acoustic sources (Dau, 2002).

A variation of the Jeffress model is represented by the model of inhibitory coincidence detectors after Lindemann (1986), see figure 2.7, which is adapted to 2.6. Lindemann's model could be composed of the EI-cells discovered in the LSO: The coincidence detectors receive inhibitory input from the contra-lateral side, so that the time-delayed inputs which move opposite to one another extinguish themselves.

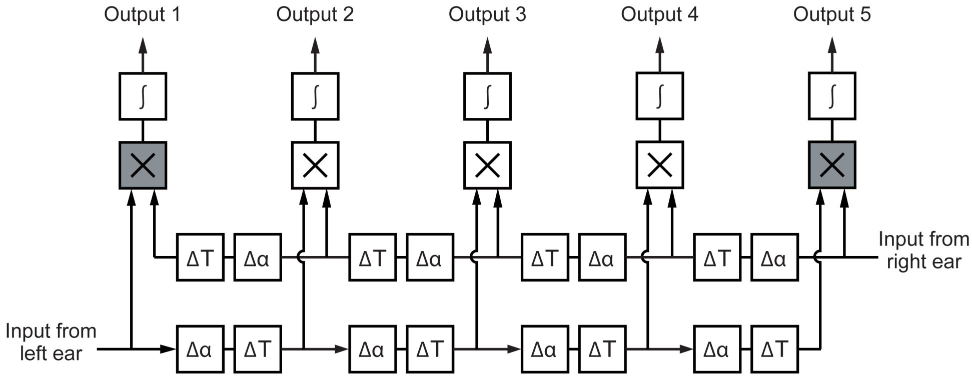


Figure 2.7: *Lindemann's model is presented schematically. $\Delta\alpha$ denotes an attenuator. All other conventions as in Fig. 2.6. At the two ends of the delay lines, the shaded boxes indicate correlators that are modified to function as monaural detectors. (Stern et al., 2005)*

A further advantage of this model is the conversion of ILD into a separate neural pattern, so that ILD can be compared to ITD. This allows to model the psychophysically measurable time-intensity-trading, i.e. the compensation of a given ITD by an ILD. Latest models are based on the idea that the two broad hemispheric spatial channels are the key to ITD encoding and not the maximum responses of ITD functions (McAlpine, 2002). The general properties of coding of ITD in the auditory system have been investigated nowadays. The investigations still continue with the goals to obtain a full understanding of the ITD encoding. Generally, most publications deal with the concept that the brain is sensitive to ITD and compares input signals from both ears. This general functionality is commonly incorporated into computational auditory models using interaural crosscorrelation. Some of these models play a significant role, expanding our understanding of different binaural phenomena (Colburn, 1996).

2.3 Psychophysical Measurement

Psychophysical measurements often seek to measure the sensitivity to a physical parameter, e.g. the ITD. The sensitivity is described by means of the so-called psychometric function. The psychometric function describes the sensation of the subject in response to the parameter as a function of the size of the parameter. In case of ITD, this could be the probability of correct left/right discrimination based upon ITD. In many cases, one attempts to determine a certain just noticeable difference (JND), which indicates the size of the test parameter for which the subject shows a predefined probability of performance, e.g. left/right discrimination. There are different classes of psychophysical methods to measure sensitivity. Two of them will be applied in the present study: the method of constant stimuli and the adaptive methods. Both methods are explained by an example of measuring ITD. Psychophysical methods are also used to measure the subjective effect evoked by a physical parameter. An example of such a method is given in the description of the "Method of Adjustment".

2.3.1 Method of Constant Stimuli

A set of stimuli with different ITD values is presented in random order. The ITD values, which are determined by means of pilot experiments, surround the expected threshold, i.e. a part is under and a part is above threshold. The number of repetitions (e.g. 100) should be equal for each ITD value. The measurement of one (presentation + answer) trial of the different ITD values is done as follows: First, the test person listens to a reference stimulus which contains zero ITD, perceived at a centralized position. Second, a target stimulus is played which contains an ITD and is perceived either more to the left or more to the right ear. After the measurement, a data set is obtained, which contains the different ITD values, the number of responses and the percentages of correct responses. The ITD JND is obtained by calculating the ITD that corresponds to e.g. 75 % from these tallies.

2.3.2 Adaptive Methods

In adaptive procedures the size of the test parameter, e.g. ITD, depends on the responses of the subject to the previous stimuli. The most common implementation of adaptive procedures is the 1-up and 3-down procedure: the ITD is decreased after 3 positive response and thus the condition is made more difficult. The ITD is increased after 1 negative response and thus the condition is made easier again. A sequence of decreasing or increasing ITDs is called a staircase, and a transition from decreasing to increasing is called a turnaround or a reversal. The adaptive procedure is continued over several reversals (between 8 and 16) in order to make the ITD converging at the JND. In case of the 3 down - 1 up rule, the procedure converges at the 79 % correct point on the psychometric function. In general, adaptive methods converge on a certain JND value of the test variable (e.g. ITD), which corresponds to a defined %-point at the psychometric function. Thus, in an adaptive method, the JND is obtained by the procedure - in contrast to the method of constant stimuli, where the JND is calculated.

Method of Limits The method of limits is a sub-group of the adaptive methods. The stimulus is under control of the experimenter, and the test person responds after each presented stimulus. Beginning with a ITD value clearly above the JND, the ITD value is successively reduced after each trial, for positive (+) responses of the test person (e.g. the subject could lateralize based upon a ITD). Such a downward movement is stopped, as soon as the response is negative (-). Then an upward movement begins. This upward movement begins with a ITD value clearly below the JND. This is continued until the answer becomes positive (+) again. The hypothetical JND lies between the lowest noticeable and the highest not noticeable ITD. The average value of the transition points over several movements is defined as the final ITD JND. An important feature of the method of limits is that the starting level of each movement is random within a specified range.

Method of Adjustment This method is explained by means of the example of a centralization procedure. The stimulus containing the adjusted parameter, in this case the interaural level difference, is continuously controlled by the test person (contrary to the discrete experimenter controlled change with the method of limits). The test persons' task is to center the stimulus as accurately as possible. The starting level of each item is usually roved. To find the individual centralized image, the test person moves the spatial position of the stimulus continuously to the left or to the right side by adjusting the ILD in predefined steps (e.g. 1 dB), using two labeled buttons. When the centralized image is found, the test person confirms the centralized image.

2.4 Hearing Loss

The general term "hearing loss" or "hearing impairment" stands for a permanent impairment of the auditory system, which results in difficulties in the audibility of sounds, and the subjective quality of super-threshold sounds. Increase of bilateral hearing-impaired (HI) listeners have difficulties in understanding speech in noisy environments and localizing sound sources. There is an important distinction between two kinds of hearing losses, conductive hearing loss and sensorineural hearing loss, and there also exists the combination of these two types of losses.

First, the conductive hearing loss is present when the middle ear is damaged. Thus, the sound transmission to the inner ear is reduced. To solve the problem a hearing aid (HA) is often very effective, which simply amplifies the incoming sound in the frequency region of the conduction loss.

Second, the sensorineural hearing loss (SNHL) or cochlea hearing loss is present when the cochlea is damaged (e.g. the hair cells, see figure 2.8). This damage can not be medically corrected, meaning it is a permanent and irreversible hearing loss. Usually the transformation of the incoming sound of the cochlea into neural excitation patterns is disturbed. This disturbance can be located either in the inner ear or at the auditory nerve. Usually it is difficult to distinguish between these two origins, therefore the general term SNHL has been established. It is of interest that the motivation for this study are hearing effects occurring in listeners with this kind of hearing loss - SNHL. There are different reasons which can cause a SNHL. The most common SNHL can be traced back to noise-induced hearing loss and aging. Other causes are due to toxic drugs, head injury, diseases (e.g. viruses, tumors), and birth injury or hereditary.

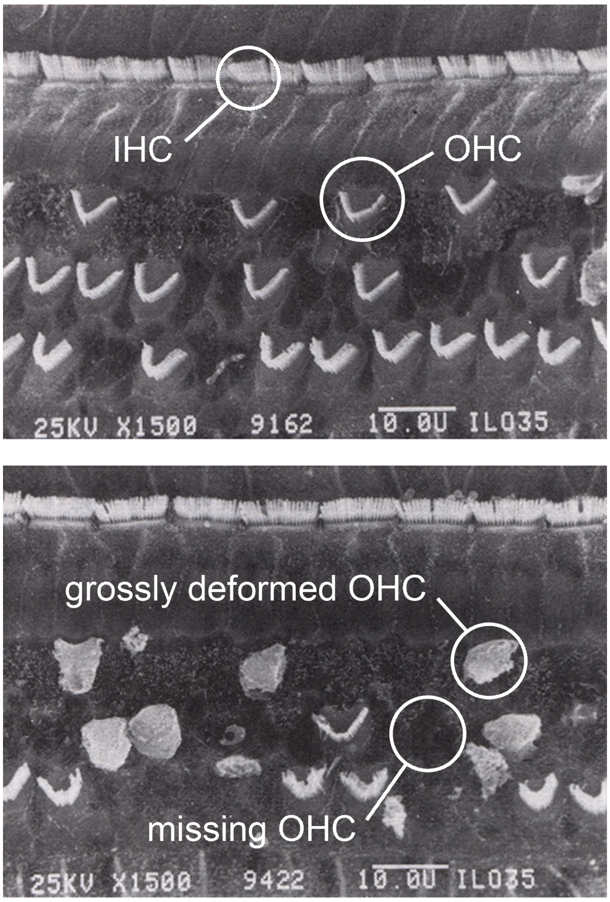


Figure 2.8: *Examples of damaged hair-cells (Moore, 1995).*

For SNHL, HAs provide limited benefit as their goal is to amplify sound, but this approach is limited because the cochlea is not capable anymore to process the sound property (see section 2.4). Listeners with a severe to profound SNHL have a medical option to regain hearing capacity by being supplied with a cochlear implant (CI). To bypass the damaged part of the cochlea, a CI passes sound signals directly to the auditory nerve. The CI electrically stimulates the neurons in the cochlea. It is advantageous that the degeneration of the auditory system is as short as possible, while the duration of the deafness is as small as possible so that CI listeners can use the cochlear-implant.

The severity of a hearing loss is expressed by its degree and described in table 2.1 according to Goodman (1965). The boundary between the normal limits of hearing and the mild hearing loss has been lowered to 16 dB hearing level (HL). An important parameter characterizing a hearing loss is its shape as a function of frequency.

Degree of hearing loss	**Hearing loss range [dB HL]**
Normal limits	- 10 to 26
Mild hearing loss	27 to 40
Moderate hearing loss	41 to 55
Moderately severe hearing loss	56 to 70
Severe hearing loss	71 to 90
Profound hearing loss	over 90

Table 2.1: *Classification of the degree of hearing loss (Goodman, 1965).*

The most important criterion for determining the severity of a hearing loss is an audiogram. The **audiogram** is also an important basis for the diagnosis of a hearing disorder (location/position along the auditory pathway). The absolute hearing threshold of a signal is the lowest perceivable sound level of the signal in absolute silence. An audiogram measures an individual's threshold at different frequencies relative to 0 dB hearing level (HL) and its result shows the deviation from what is usually referred to as "normal" hearing. The reference level of a HL differs with frequency corresponding to a minimum audibility field (MAF) also called the audibility curve. The MAF as a function of frequency represents the averaged "normal" hearing threshold. The sensation level (SL) gives the number of dB that a sound is presented at a certain level above its absolute threshold for this particular sound. For example, if the sound is presented at 48 dB SPL and the absolute threshold is 18 dB SPL, then the SL is 30 dB. In other words, the SL is the dB-difference between the hearing level of a signal and the absolute threshold for a particular sound.

Middle ear and inner ear components of a hearing loss can be distinguished by measurement of the air-conduction threshold and the bone-conduction threshold. The air conduction is measured by playback of a headset, whereas the bone conduction is determined by a bone conduction receiver attached to the cranial bone. Sound induces the same traveling (wave) oscillations of the basilar membrane no matter whether it reached the inner ear via cranial bone or via middle ear.

2.4.1 Sensorineural Hearing Loss Effects

One common defect is the degeneration of OHCs and IHCs (see figure 2.9). In figure 2.8, a comparison is shown of normal and damaged hair cells. In case of cochlear hearing impairment, various reasons lead to a failure or destruction of the stereocilia or of the whole cellular body. Due to present conceptions of the functionality of hair-cells and their meaning for cochlear processes, it is assumed that a damage to the OHCs reduces the active processes of the cochlea. This causes a reduction in sensitivity and sharpness of the tuning of the basilar membrane, particularly at low levels, or destroys these active processes completely. Due to the OHC damage, for HI listeners, the tuning curve of a nerve fiber in the auditory nerve is flattened at the resonance point. This means that the excitation threshold as a function of the frequency of the sinusoidal stimulus results in a bad frequency selectivity. In other words, HI listeners have flatter and broader auditory filters, the excitation pattern has a fuzzy peak in comparison to NH listeners (see figure 2.10). This is a result of the damaged OHCs and with their damage the frequency selectivity and basilar tuning are lowered (Moore, 1998). In addition, the absence of frequency selectivity causes the absence of non-linear effects observed in normal hearing, e.g. combination tones, two-tone suppression, and level dependency of the masking. Generally, these functions are important for the capability of the auditory system to separate different frequency components of sounds.

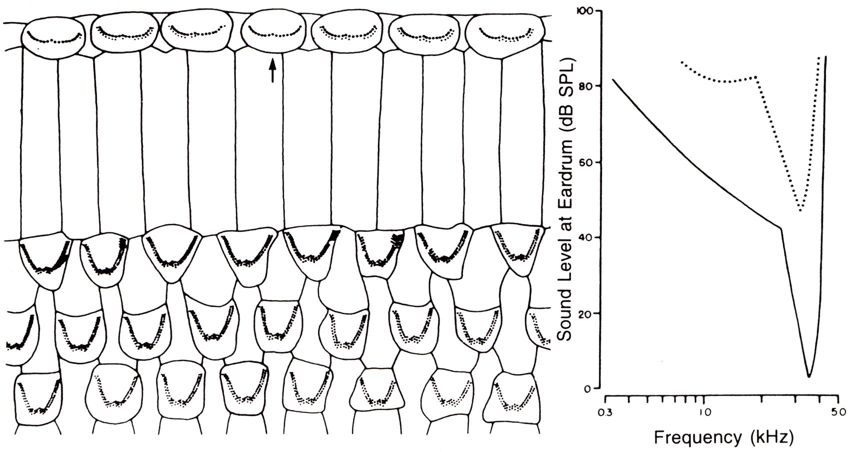


Figure 2.9: *The left part shows a schematic diagram of an organ of Corti with moderate damage to IHC stereocilia (arrow) and minimal damage to OHC stereocilia. The right part shows a normal neural tuning curve (solid) and an abnormal tuning curve (dotted) appropriate to the presented hearing loss (Moore, 1995).*

The dynamic range with its naturally occurring acoustic signal level is compressed into a relatively small range of deflections on the basilar membrane. If these processes fail, the deflections for small input signal levels lie below the perception limit, whereas the deflections for middle to high input levels are approximately normal. This leads to a larger slope of the loudness function.

In contrast, a damage to the IHCs (or transducer cells) leads to a decrease of overall sensitivity. This means that the incoming sound has to be amplified in order to achieve the same neural excitation level. IHC damage can also destroy the precision of the synchronization of the neural impulses to the cochlear-filtered signal waveform, thus evoke a reduction in phase locking. For ITD sensitivity, the reduction of IHCs could mean that the quality of the information of the IHC-channels is lower, which in turn could lower the performance.

Having a combined damage of IHCs and OHCs both the frequency selectivity and the sensitivity are strongly concerned.

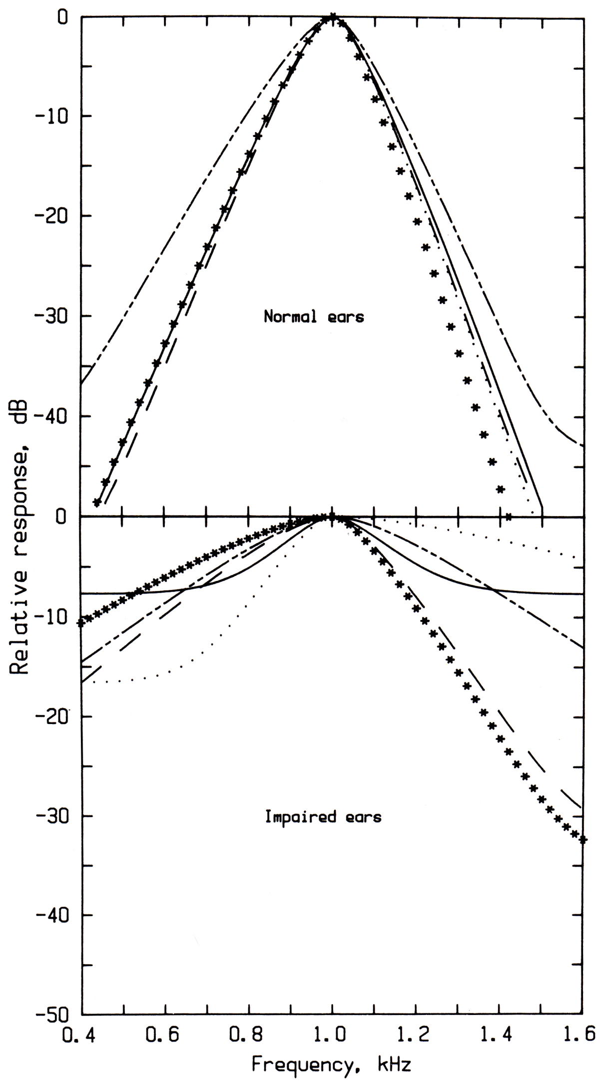


Figure 2.10: *The filter shapes at a CF of 1 kHz for normal (top panel) and impared (low panel) ears of subjects with unilateral SNHL. The filter shapes of the impaired ears vary in shape across subjects and are all broader than for the normal ears (Moore, 1995).*

2.4.2 ITD Sensitivity in SNHL

In this section, a review is given about previous studies on binaural performance, particularly ITD sensitivity, of HI listeners. In general, perceptual orientation within the auditory environment relies on the physiological functioning of both ears and their neural interaction. This is called binaural interaction. It has an substantial impact on the localization of sound sources and understanding of speech in noise. These impacts are both influenced by a hearing impairment (Durlach et al., 1981). ITD sensitivity is known to be of great importance for localizing sound sources and understanding speech in noise for NH listeners (Smith-Olinde et al., 1998; Bronkhorst and Plomp, 1988; Wightman and Kistler, 1992; Mcpherson and Middlebrooks, 2002). Thus, it is expected that reduced ITD sensitivity as a consequence of hearing impairment is detrimental for those abilities. It is interesting that relatively little research has been conducted on ITD sensitivity or in general on binaural performance of HI listeners.

Hawkins and Wightman (1980) and Durlach et al. (1981) provided an initial start-up for studies on ITD sensitivity in HI listeners. Durlach et al. (1981) summarized and reviewed the aspects of studies investigated before 1980. Until 1980, it was not clear if damage to the auditory periphery affects the sensitivity to ITD. Especially, it was not clear how the extent of hearing loss affects the ITD sensitivity due to sensory-related losses or abnormal response-related factors. These latter factors can interact with peripheral-sensory and/or central limitations. It is difficult to assess the HI listener's condition, when the HI listener is only confronted with one task instead of a battery of tests reallowing to relate the performance to each other. Another aspect was a lack of information according to the treatment of asymmetric hearing losses, especially if HI listeners' ITD sensitivity changes when listening to stimuli with constant SPL at both ears compared to listening to stimuli with constant SL. In the following, literature on ITD sensitivity in HI listeners is summarized. All presented studies presented their stimuli via headphones.

Hawkins and Wightman (1980) tested eight HI listeners with mild to moderate SNHL, two of whom had unilateral losses, and three NH listeners. They used 250-ms narrow-band noise (NBN) bursts at two frequencies, centered at 500 and 4000 Hz. All stimuli were presented at a SPL of 85 dB and a SL of 30 dB. HI listeners were generally less sensitive than NH listeners for both levels and frequencies. For both groups of listeners, the sensitivity was higher for a CF of 500 Hz than of 4000 Hz.

Buus et al. (1984) measured ITD sensitivity in four NH and ten HI listeners with SNHL, using 30-ms sinusoids presented at 100-dB SPL with the three different frequencies 500, 1000, and 4000 Hz. Seven HI listeners had normal ITD sensitivity at 4000 Hz, despite hearing losses between 50 and 70 dB. At 500 and 1000 Hz, mildly impaired listeners had nearly normal ITD sensitivity, whereas more severely impaired listeners had very low ITD sensitivity.

Smoski and Trahiotis (1986) tested two NH and four HI listeners with mainly high-frequency SNHL. They used different stimuli: sinusoids and NBN centered at 500 Hz, and SAM and NBN centered at 4000 Hz. All stimuli were presented at two different levels, 80 dB SPL and 25 dB SL. For the HI listeners, ITD sensitivity of 4000 Hz was reduced compared to the NH listeners when the stimulus had a constant SPL, but there was no difference between the groups for a constant SL. At 500 Hz, where there was no hearing loss, the ITD sensitivity was slightly reduced compared to the NH subjects.

Kinkel et al. (1991) measured ITD JNDs for NBN stimuli centered at 500 Hz and 4000 Hz in fifteen NH and 49 HI listeners with, on average, a high-frequency SNHL. A SPL of 75 dB was used. For eleven HI listeners the levels were increased by 20 dB to reach their "most comfortable level". HI listeners showed a lower ITD sensitivity (for 500 Hz: mean $\pm$ std.dev: 213.5 μs $\pm$ 293.5 μs; for 4000 Hz: 531.3 μs $\pm$ 355.8 μs) than NH listeners (for 500 Hz: 37.5 μs $\pm$ 32.7 μs; for 4000 Hz:81.3 μs $\pm$ 37.6 μs). However, some of the HI listeners were as sensitive as NH listeners. Due to the large number of HI listeners, Kinkel et al. (1991) are a good reference for a large inter-individual variability among HI listeners. For both frequencies, there was a significant difference between both listener groups ($p \leq 0.01$). The frequency-dependency of ITD sensitivity, which is described in the literature is verified by the fact that the ITD sensitivity for low frequencies (under 1500 Hz) is higher (the JNDs are thus smaller) than for high frequencies (higher JNDs) (Kinkel et al., 1991).

Gabriel et al. (1992) measured ITD JNDs for two NH and four HI listeners with different configuration and degree of hearing loss. They used 1/3-octave band noises centered at frequencies in octave steps from 250 Hz to 4000 Hz and different levels for each listener and frequency. The levels were 30 dB SL at each frequency unless the level exceeded the discomfort threshold. The HI listeners showed large inter-individual differences, even if they had a similar hearing loss. The group performance showed that HI listeners were less sensitive to ITD than the NH listeners, although in some individual cases, their ITD sensitivity was comparable to that of NH listeners. One HI listener did not show any ITD sensitivity and another one was sensitive only for 500 Hz. Two HI listeners showed quite good ITD sensitivity at lower frequencies and a lower ITD sensitivity at high frequencies. There was no apparent relation between ITD sensitivity and the audiometric patterns.

Koehnke et al. (1995) measured ITD sensitivity in nine NH and eleven HI listeners for NBNs centered at 500 Hz and 4000 Hz. The stimuli were presented at an SPL of 75 dB for both NH and HI listeners. For the HI listeners with a hearing level greater than 55 dB, the SPL was 95 dB. ITD sensitivity of the HI listeners was generally poorer than of NH listeners. The results cannot be explained in terms of available audiometric and psychophysical measurements.

Smith-Olinde et al. (1998) measured the ITD JNDs for three NH and six HI listeners with SNHL. They used NBNs centered at 500 Hz and 4000 Hz. The higher level for each subject was used, either the SPL of 77 dB or the SL of 28 dB. The HI listeners showed lower sensitivity than the NH listeners.

Lacher-Fougère and Demany (2005) measured thresholds to detect interaural phase differences in SAM tones in seven NH listeners and nine HI listeners with a mild to moderate, symmetrical hearing loss. A SPL of 75 dB was used. The interaural phase differences were added either to the carrier signal (fine structure) with frequencies of 250, 500, or 1000 Hz or to the envelope with modulation frequencies of 20 or 50 Hz. In general, the interaural phase sensitivity was lower for the HI listeners than for the NH listeners. The degradation in sensitivity was larger for carrier interaural phase differences than envelope interaural phase differences. The outcomes indicate that one consequence of SNHL is a degradation in the ITD sensitivity to the fine structure.

In summary it is clear that ITD sensitivity can markedly vary across HI listeners.

Thus, another question which arises is if there is a correlation between the degree of hearing loss and the sensitivity to ITD. Hawkins and Wightman (1980) found that correlation in the expected direction for NBN at 85-dB SPL both at 500 and 4000 Hz, thus a large degree of hearing loss is associated with low ITD sensitivity. Hall et al. (1984) found the same type of correlation for 70-dB, 500-Hz tone bursts. Lacher-Fougère and Demany (2005) found a correlation between carrier interaural phase sensitivity and the degree of hearing loss at 1000 Hz, but not at 500 Hz. They also found correlations between the envelope interaural phase sensitivity and the degree of hearing loss. In contrary to these studies, other studies did not find a correlation between the ITD sensitivity and the degree of hearing loss (e.g. Gabriel et al., 1992; Koehnke et al., 1995). Note that some studies confirm a large reduction of ITD sensitivity at low frequencies even if the absolute thresholds are normal at low frequencies and elevated at high frequencies (Hawkins and Wightman, 1980; Smoski and Trahiotis, 1986; Lacher-Fougère and Demany, 2005). Searching for a correlation between the age of the HI listeners and the fine-structure or envelope ITD sensitivity, so far no study has proven such a correlation. Such studies with HI listeners are difficult to evaluate, because of the inter-individual variability of the binaural performance of HI listeners even with similar audiograms and the same hearing loss types or with the same etiology (e.g. Durlach et al., 1981; Gabriel et al., 1992; Koehnke et al., 1995).

There is generally large variability of ITD JNDs between individual HI listeners (e.g., Hawkins and Wightman, 1980; Häusler et al, 1983; Smith-Olinde et al., 1998). At least a portion of the HI population has a lower ITD sensitivity compared to NH listeners (e.g. Gabriel et al., 1992; Koehnke et al., 1995; Koehnke and Besing, 1996; Smith-Olinde et al., 1998; Kinkel et al, 1991; Lacher-Fougère and Demany, 2005).

Chapter 3

Binaural Adaptation

In this chapter the phenomenon of binaural adaptation and the recovery from binaural adaptation is explained based on the background presented in the previous section.

3.1 Binaural Adaptation in Normal-Hearing Listeners

Hafter and Dye (1983) were the first to demonstrate the so-called binaural adaptation phenomenon. They studied the ITD sensitivity in high spectral regions by using 4000-Hz bandpass-filtered click trains composed of 1 to 32 clicks. They systematically varied the click rate. They found that at lower pulse rates the ITD sensitivity increases with increasing signal duration. This can be explained by a model of temporal integration of the ITD information in the ongoing part of the signal. Increasing signal duration at high rates resulted in less improvement of ITD sensitivity than predicted by the temporal integration model. This indicates that ITD information after the onset contributes less at higher pulse rates than at lower pulse rates (Hafter and Dye, 1983; Buell and Hafter, 1988). Using similar stimuli, Saberi (1996) applied the "observer weighting" technique to study the contribution of different components of the stimulus to ITD perception. In that study, the ITD of individual pulses was controlled independently to ascertain their effects on the listener's perception. The results showed that at higher pulse rates the first pulse receives most perceptual weight, while the weight of the ongoing pulses is much lower. Temporal weighting functions were also obtained by Stecker and Hafter (2002), however presenting the pulse train in the free field and using a localization task. The main findings confirmed those of Saberi (1996). According to Yost and Hafter (1987) the effect of binaural adaptation also affects other types of stimuli, e.g. noise, low-frequency pure tones, and high-frequency AM stimuli.[1]

Hafter and Dye (1983) also showed that binaural adaptation cannot simply be explained by adaptation behavior of the auditory nerve. A typical behavior of auditory nerve fibers is adaptation. Even though this leads also to an emphasis of "onset" response, Hafter and Dye (1983) concluded that binaural adaptation occurs at higher auditory centers beyond the auditory nerve.

Bernstein and Trahiotis (2002) studied three different types of stimuli (SAM tones, so-called "transposed" tones, and pure tones) to study the effect of modulation rate on ITD sensitivity, keeping the stimulus duration constant across rates. ITD sensitivity was found to degrade with increasing modulation rate of SAM and transposed tones. This is consistent with the results of other studies (Henning, 1974; Bernstein and Trahiotis, 2002; Majdak and Laback, 2008). All those studies show the reduction of envelope ITD sensitivity for stimuli with increasing modulation rates.

3.2 Recovery from Binaural Adaptation with Binaural Jitter in Cochlear-Implant and NH Listeners

Based on the finding that the main ITD-based lateralization cue for stimuli with a high envelope rate results from the onset of a signal, Hafter and Buell (1990) wanted to know which condition could evoke a restart of the central processing leading to a recovery from binaural adaptation. They investigated the phenomenon of the recovery from binaural adaptation based on the idea that introducing a change into

[1] This is not confirmed for NBN and low-frequencies, e.g. Bernstein and Trahiotis (2002).

the ongoing signal would evoke a restart of the binaural processing. They used similar stimuli to Hafter and Dye (1983) which were click trains. They inserted different types of triggers, including temporal gaps, squeezes, bursts of noise and tones. These inserted triggers caused an improvement in ITD sensitivity. The observed recovery from binaural adaptation was interpreted as a restarting of the binaural system by the trigger, enhancing the importance of the signal portions following the trigger. This in turn results in an improvement of ITD sensitivity. This effect of recovery from binaural adaptation was confirmed by Stecker and Hafter (2002), even though they used pulse trains in a free-field centralization task, which involves both ITD and ILD cues. These studies were performed in NH listeners.

Studies with CI listeners show that the ITD sensitivity decreases with increasing pulse rates (Majdak et al., 2006; Laback et al., 2007; van Hoesel, 2007), which is reminiscent of the phenomenon of binaural adaptation. Laback and Majdak (2008) hypothesized that introducing a temporal trigger, change in the interpulse-interval (IPI), might improve ITD sensitivity in electric hearing, similar to the effect observed by Hafter and Buell (1990) for acoustical stimulation. Additionally, to multiply the effect of recovery based on one trigger, all IPIs were randomly varied (jittered). In order to preserve the ITD this jitter was synchronized between the two ears and it was called "binaural jitter" (Laback and Majdak, 2008). By applying binaural jitter, the ITD sensitivity of CI listeners increased strongly for higher pulse rates, even as high as 1515 pps. That study showed that binaural jitter resolves the pulse rate limitation in CI listeners and allows ITD perception at high rates.

Thus, the effect of binaural jitter was also of interest for NH listeners to clarify whether they show a similar improvement of ITD sensitivity due to binaural jitter as CI listeners. Goupell et al. (2008) studied the effect of binaural jitter for pulse trains bandpass-filtered at high center frequencies. Their findings are consistent with the results for CI listeners, showing that introducing binaurally-synchronized jitter in the stimulus timing strongly improves ITD sensitivity in acoustic hearing. They also showed that the relative IPI is more important than the absolute IPI in the context of the surrounding pulses (Goupel et al., 2008).

Chapter 4

Hypotheses

For NH and CI listeners the limited ITD sensitivity at higher modulation rates is related to the phenomenon of binaural adaptation as described in chapter 3. It has been shown that recovery from binaural adaptation can be induced by introducing binaural jitter. Thus, the question arises if there is also a benefit from binaural jitter in the perception of ITD for HI listeners? Before returning to this question, some aspects of SNHL are taken into account which could influence ITD sensitivity.

There are several reasons why SNHL could *decrease* ITD sensitivity:

- A reduction of the number of functioning IHCs could lead to a poorer phase-locking of the neural response to the stimulus and thus to reduced ITD sensitivity (Johnson and Kiang, 1976; Lacher-Fougère et al., 2005)
- A loss of the active mechanism on the basilar membrane due to degeneration of outer hair cells (OHCs) could disrupt the binaural cross-correlation process (Robles and Ruggero, 2001). Some animal experiments have shown that the precision of the phase-locking mechanism is significantly influenced by the loss of OHCs (Woolf et al., 1981), whereas other studies did not find a quality loss of phase-locking (Evans, 1979; Miller et al. 1997)
- Interaurally asymmetric loudness distortion could compromise ITD sensitivity

due to the lack of a centralized auditory image.

- In SNHL, the auditory filters are broadened, which could reduce spacial hearing abilities in complex auditory environments due to excessive interaction of spectral content from different sources in a single (broadened) auditory filter. The larger bandwidth of the auditory filters changes the waveform of the internal signal, which may influence the internal interaural correlation, which in turn might limit ITD sensitivity.

However, there are also reasons why SNHL could *increase* ITD sensitivity:

- The broadened auditory filters could result in better temporal resolution and thus better convey modulation information (Moore, 1995; Oxenham and Bacon, 2003).

- The loudness recruitment effect could enhance the effective modulation depth of the internal signal.

To study how binaural jitter affects ITD sensitivity in listeners with SNHL, two experiments were designed considering two frequency regions. In the first experiment, a center-frequency of 4000 Hz was used, which represents a high-frequency region where only the envelope ITD is processed by the auditory system. For the second experiment, 500 Hz was used, which represents a low-frequency region where fine-structure and envelope ITD is processed by the auditory system. This is because the neurons are able to phase-lock to the fine structure of sounds at low frequencies. For both experiments, the following hypotheses were tested:

For high frequencies, one approach to improve ITD sensitivity at high rates is to introduce binaural jitter (Laback and Majdak, 2008; Goupell et al., 2008). It is hypothesized that HI listeners also benefit from the effect of introducing binaural jitter in perceiving ITDs. The extent of this improvement may depend on different parameters such as ITD, pulse rate, and the amount of jitter. Gaussian narrow-band noises (NBN) were also tested in order to compare the performance for this signal with that for the binaurally-jittered pulse trains. The idea behind this comparison is that the NBN also contains temporal randomness in the envelope. It is hypothesized that the ITD sensitivity of HI listeners to binaural-jittered pulse trains will approach the ITD sensitivity for NBN.

For low frequencies, in natural signals, both the envelope and the fine structure are delayed. However, it is unclear whether amplitude modulation (AM) is important in this frequency region. On the one hand, Sterbling et al. (2003) showed that the discharge rate in some IC neurons in awake rabbits increases when periodic envelope ITD cues were added. On the other hand, for humans, Henning (1980), Bernstein and Trahiotis (1985) and Schiano et al. (1986) showed small or negligible effects of adding envelope ITD cues on ITD sensitivity, even though neurons are capable of simultaneously encoding the temporal characteristics of the modulation. Thus, the effect of AM at low frequencies is unclear and will be tested. It is hypothesized that some types of binaural adaptation also occurs at low frequencies as it is present at high-frequencies, where the ITD cues are extracted from the AM, and that a recovery effect can be induced by introducing binaurally-synchronized jitter. If these hypotheses will be confirmed, these findings may indicate that the ITD sensitivity of HI listeners can be improved by introducing randomness into the AM at low frequencies.

Different stimuli that contain temporal randomness were tested at low frequencies. One is referred to as jittered tones, and corresponds to a jittered pulse train that is bandpass-filtered in the frequency region of the pulse rate. The second is NBN. These stimuli contain ITD both in the fine structure and in the envelope, and contain random amplitude fluctuations, which may cause a recovery from binaural adaptation. The amount of fluctuation depends on the bandwidth of the NBN, and on the amount of jitter for the jittered tones. A stimulus with periodic AM, more precisely, a sinusoidally amplitude modulated (SAM) tone, was also included. The SAM tone contains ITD in the fine structure as well as in the envelope. Lastly, a pure tone was tested because it contains only fine-structure cues. Thus, it is hypothesized that the lowest performance on ITD occurs for pure tones.

It is also of interest to compare the sensitivity of HI listeners in the high-frequency and low-frequency region, given that they have approximately the same hearing loss in those two frequency regions. Therefore, the results are compared to investigate the difference between those frequency region and to draw conclusion on the relative degradation in ITD sensitivity at low and high frequencies.

Chapter 5

Experiments

This chapter provides a description of the two experiments on ITD sensitivity in HI listeners. As mentioned in the introduction, the role of ITD for sound localization and for the binaural processing can be studied with headphone-experiments, where spatial parameters (e.g., ITD and ILD) can be independently controlled. These psychoacoustical experiments were performed to test different hypotheses, the most important of which stating that binaural jitter improves ITD sensitivity in HI listeners (chapter 4). To test the hypotheses in a proper way, the psychoacoustical experiment has to be designed taking into account the proper allocation of test persons to experimental conditions and the subsequent statistical analysis. Therefore, the experimental design covers the following steps:

1. A definition of the method used including the test persons, the test set-up, and the calibration of the stimuli.

2. A specification of the pre-tests including the measurement of the absolute hearing threshold, a categorical loudness scaling to obtain the most comfortable level, and a centralization procedure. The latter was used to be sure that the reference stimuli are perceived as a centralized image. These pre-tests were intended to provide testing conditions that are best comparable to each other and to NH listeners in term of the perceived lateral position. Thus, those pre-test had to be

preformed before the main tests.

3. A determination of the experimental design for the first and second experiment, which contains high-frequency stimuli and low-frequency, respectively.

5.1 General Methods

This section describes the methods used in the pre-tests and the main experiments.

5.1.1 Subjects

The HI listeners were chosen according to the following requirements:

- The degree of hearing loss had to be moderate, which means that the listener's pure tone audiograms fell between 40 and 70 dB HL (see section 2.4) at the tested frequencies of 4000 Hz and 500 Hz. The SNHL should be at least 40 dB HL, because a conduction hearing loss was not expected to affect ITD sensitivity. However, due to the limited availability of subjects also HI listeners who had a lower absolute threshold were tested. For 4000 Hz, there are two exceptions with higher absolute thresholds. For 500 Hz, there are two exceptions with lower absolute thresholds.
- The test persons should have no central hearing loss, because this would make the interpretation of the results much more complicated.
- Their speech intelligibility should be good enough to communicate with the experimenter with or without a hearing aid (HA), so that they are able to understand the given instructions.

To select the subjects, these required conditions were given to several otorhinolaryngologists. For further information about the subject recruitment see appendix D. In total, thirteen subjects were tested. Their specifications are listed in table 5.1. After the pre-tests, the HI listeners were trained on a baseline condition (see Experiment I in subsection 5.3.3) before beginning the main experiments and the data collection. This performance for the baseline condition was not sufficient for one subject (HI13). HI13 was not sensitive to ITDs as large as 1000 μs using broadband noise, even after several hours of training. Nevertheless, she is included in the table to provide information for later analysis. None of the subjects had ever participated in psychoacoustical experiments before. Table 5.1 shows that the subjects suffer from different types of hearing loss. The HI listeners ranged in age from 26 to 81 years. Their audiograms show that only one HI listener (HI11) has a mixed hearing loss with a bone-conduction threshold between 15 and 30 dB HL. All other HI listeners have a SNHL of 54.1 dB HL for 4000 Hz and 39.4 dB HL for 500 Hz, on average, and a bone-conduction threshold of maximally 10 dB HL. The absolute hearing thresholds of the subjects, measured during the pre-test, are listed in table 5.2. The duration of the SNHL of the left and right ears is shown in table 5.1 as well. All subjects who were able to estimate the duration of their losses stated the same duration in years for both ears. All subjects suffer from binaural deprivation (hearing loss relating to both ears) but most of them could not state the duration. Five subjects were male (HI03, HI04, HI08, HI09, and HI10) and eight subjects were female.

5.1.2 Test Set-Up

All subjects were tested in a double-walled anechoic booth. Different stimuli were presented via headphones (Sennheiser HDA200). Almost all signals were presented binaurally (on both ears) via the left and right channel of the headphones. An exception was the measurement of the absolute hearing threshold (see section 5.2.1). A personal computer was used for controlling the psychoacoustic experiments. The software applications which were used for the experiments of this thesis were written for the software framework ExpSuite. ExpSuite is a software framework which is developed at the Acoustic Research Institute (ARI) of the Austrian Academy of Science.

Subject	Participating in the experiments	Etiology	Age (yr)	Duration of SNHL (yr)		Binaural Deprivation Duration (yr)	Type of HA
				L	R		
HI01	I + II	presbyacusis	76	5	5	*	ITE
HI02	I + II	noise-induced	80	7	7	*	BTE
HI03	I + II	unknown/gradually	57	8	8	*	ITE
HI04	I + II	presbyacusis	81	*	*	*	BTE
HI05	I + II	hereditary	40	40	40	6	ITE
HI06	I + II	hereditary/progressive	54	14	14	13	BTE
HI07	I + II	hereditary	26	26	26	*	BTE
HI08	I + II	mumps/infection	39	39	39	*	ITE
HI09	I	presbyacusis	81	*	*	*	BTE
HI10	I	sudden HL	72	3	3	2	BTE
HI11	I	presbyacusis, tympanosklerose	52	*	*	*	BTE
HI12	I + II	hereditary	40	40	40	6	ITE
HI13	no	hereditary	55	47	47	29	BTE

Table 5.1: *Personal data of the subjects. The symbol * indicates that the information is unknown.*

Further information can be found in the appendix C. The signal path was as follows: The signal was generated in Matlab and stored as a WAV-file, sent via pure data to a 24-bit stereo AD/DA converter (AD/DA 2402 from Digital Audio Denmark). Then, the analog signal was amplified by a headphone amplifier (HB6, TDT) and then passed through a programmable attenuator (TDT PA4, TDT). For all experiments the gain of the amplifier and the attenuator was set to 0 dB.

5.1.3 Calibration

For the calibration of the system, it is crucial to know the correct sound pressure level (SPL) re 20 μPa at the listener's ear. The calibration system is shown in figure 5.1. The dB SPL value at the headphone was obtained by placing the headphone on an artificial ear (4153 from Brüel & Kjær) that was connected to a sound level meter (Investigator 2260 from Brüel & Kjær). The sound level meter settings were adjusted to a fast time constant and a linear frequency weighting. Each stimulus at each frequency (500 and

4000 Hz) was calibrated separately (see 5.3.1 and 5.4.1).

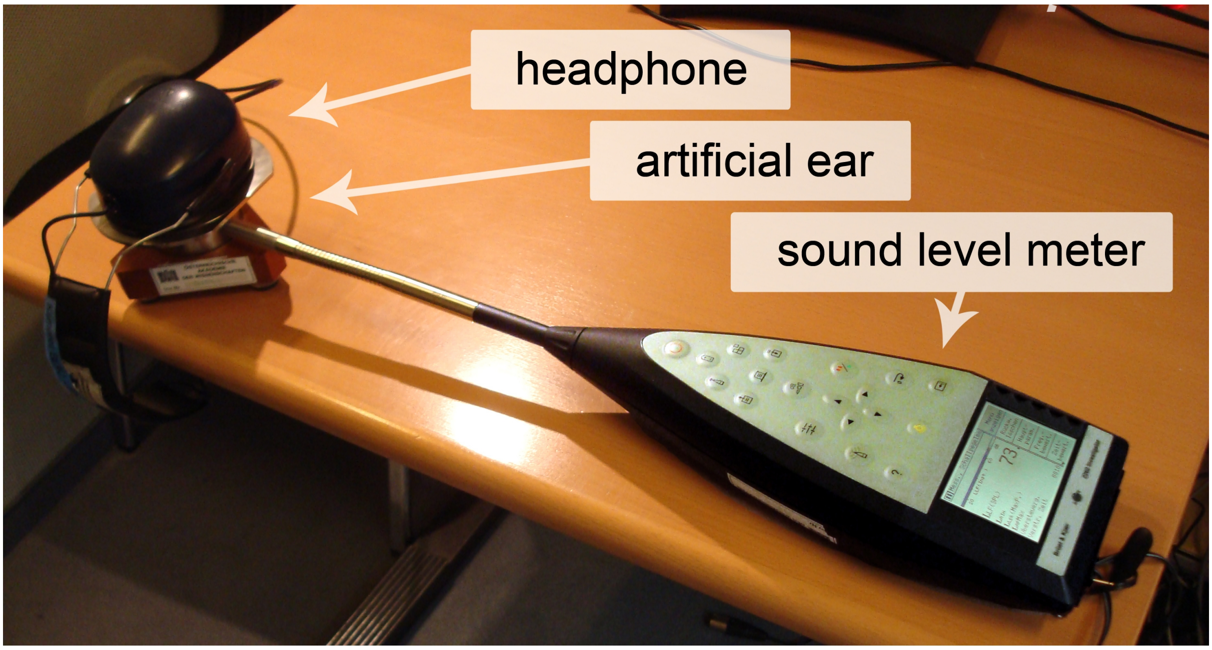


Figure 5.1: *The Calibration System*

5.2 Pre-Tests

Pre-tests were needed to obtain comparable testing conditions for each subject. Previous studies on HI listeners usually used constant SL or constant SPL to test ITD sensitivity. This is not the case for this study. For measuring ITD, it is important that the subject perceives the test reference stimulus at a centered position (in the median plane). Therefore a procedure to ensure the perception of a centralized auditory image was developed. Further, the absolute level of the stimulus is important for ITD sensitivity. It seemed to be helpful to use the most comfortable level (MCL) for each subject, because subjects show different degrees of hearing losses and even the same hearing loss may indicate a different loudness sensation. Thus, the pre-tests determine the stimulus levels at both ears that lead to a centered auditory image with a comfortable loudness. In order to know the hearing level (HL) of each subject, his/her absolute

subject	Experiment I: 4000 Hz				Experiment II: 500 Hz			
	THR L	Std. L	THR R	Std. R	THR L	Std. L	THR R	Std. R
HI01	44.6	0.47	58.2	0.16	16.8	0.36	41.0	0.52
HI02	62.9	0.49	54.5	0.37	40.5	1.41	38.0	0.78
HI03	59.8	0.78	55.6	0.93	40.8	0.47	50.2	1.10
HI04	71.1	0.47	48.3	0.37	19.4	1.56	14.5	0.94
HI05	60.0	0.63	57.2	0.35	45.0	0.94	60.0	0.75
HI06	48.9	0.15	57.3	0.40	50.0	0.62	51.0	0.60
HI07	25.9	0.63	31.7	0.16	15.6	0.30	30.0	0.30
HI08	46.4	0.71	48.9	0.53	44.8	0.78	54.2	0.16
HI09	60.8	0.47	64.8	0.63	45.9	0.63	25.8	1.09
HI10	42.5	0.46	61.2	0.37	52.2	0.86	37.2	1.56
HI11	59.7	0.31	53.0	0.63	63.7	0.63	61.0	0.15
HI12	65.3	0.14	56.1	0.09	49.1	0.12	44.1	0.06
HI13	60.1	1.09	82.5	0.16	62.9	0.16	46.2	0.93
AVE & Std.	54.0	12.4	54.6	8.6	40.3	14.5	42.2	13.5

Table 5.2: *The table shows the mean absolute threshold in dB HL and its standard deviation for the left and right ear. In the last row the averaged absolute hearing threshold and its standard devriation over twelve HI listeners is calculated. HI13 is not included, because of no ITD sensitivity.*

hearing thresholds were measured at both frequencies in advance. After the pre-tests, "comparable" testing conditions should be given for all HI listeners.

5.2.1 Measurement of Absolute Hearing Threshold

The absolute hearing threshold was measured at both 500 and 4000 Hz. A three-alternative forced choice procedure was used. The stimulus which had to be detected, the target, was presented in one interval out of three. The target interval was randomized. The subject was asked to indicate in which of the three intervals the target was presented. The adaptive procedure used in this experiment was a transformed up-down procedure (Levitt, 1971) with a three-down one-up rule, which estimates the 79,4% point on the psychometric function. Three-down one-up means that three correct responses are required to decrease the stimulus and one wrong response is sufficient to increase the level. The initial step size was set to 5 dB and it was halved after two turnarounds. A run was based on 12 turnarounds and the threshold was the mean of the last eight turnarounds. At least two runs were tested for each subject and the absolute threshold was definded as the mean over the runs. As signal, a sinusoidal was used with a frequency of 500 Hz and 4000 Hz, respectively. The rise-time and fall-time of the stimulus was taken according to standard audiometric measurements. To specify the absolute thresholds in hearing level (HL), the offset reference equivalent threshold SPL for circumaural earphones (Sennheiser HDA200, IEC316 with Type 1 Adaptor) was taken using the ANSI S3.6-1996. Table 5.2 shows the mean absolute thresholds in dB HL with its standard deviation across the two to four repetitions.

5.2.2 Categorical Loudness Scaling

HI listeners usually have different absolute thresholds on their two ears. Thus, the question arised at which levels the stimulus should be presented at the two ears of each subject. Laback and Majdak (2008) tested CI listeners at the most comfortable level which was determined using a "monaural" procedure. In the present study, a procedure was used to determine the MCL which measures the loudness functions of the individual listener by a computer controlled procedure. The procedure was developed by Wippel (2007), based on the Oldenburg adaptive and constant stimuli procedures for normal hearing listeners (Brand, 2002). This procedure measures the subjective loudness growth as a function of the current level of the acoustic stimulus. The dynamic range is divided into several, verbal categories, including the categories "not audible", "very soft", "soft", "middle soft", "middle", "middle loud", "loud", and "very loud". The original scale with German verbal attributes is shown in figure 5.2. The listeners were encouraged to use also the categories in between the verbal categories.

The MCL was defined as the 50% point of the loudness function. The categorical loudness scaling includes two procedures, a monaural and a binaural procedure. In the monaural procedure, the stimulus is presented to each ear separately. In the binaural procedure, the stimulus is presented binaurally, using the results of the monaural procedure for the selection of stimulus level at the two ears. The binaural MCLs obtained by the binaural procedure were used in the next step to centralize the auditory image. Pulse trains were used as stimuli. For 4000 Hz, 400 pps or 600 pps pulse trains were used, see 5.3.1. For 500 Hz, filtered 500 pps pulse trains were used that effectively represented pure tones, see subsection 5.4.1. The stimulus length was 500 ms. For the other stimuli tested in the main experiment, the same SPLs were used.

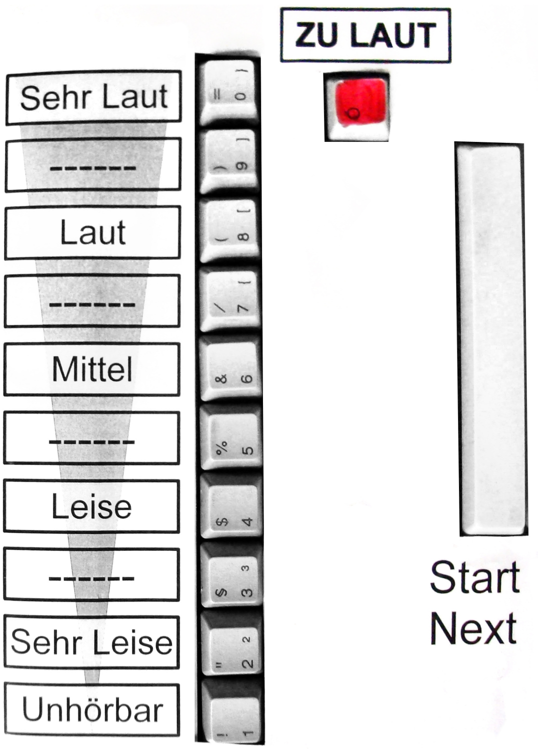


Figure 5.2: *Verbal categorical loudness scale covering the dynamic range used for the measurement of the monaural and binaural MCLs.*

5.2.3 Centralization Procedure

To centralize the auditory image, the method of adjustment was used. The listeners' task was to center the stimulus as accurately as possible. The reference levels at the two ears were the binaural MCLs, taken from the the categorical loudness scaling. The starting levels were roved in the range of $\pm$ 8 dB. The HI listener adjusted the level ratio at the two ears in steps of 0.5 dB by using two buttons, while the sum of the two levels was kept constant. The goal was to perceive the sound neither to the left nor to the right side. When a centralized image was achieved, the listener confirmed this by pressing a third button. The listeners had an unlimited amount of time to do the task. For each frequency, the task was performed at least six times, and the final balanced levels were determined by averaging across the six repetitions. The same stimuli as for the categorical loudness scaling were used.

5.3 Experiment I: High-Frequency Stimuli

In Experiment I, high-frequency stimuli were used to investigate the effect of binaurally-synchronized jitter in pulse trains on ITD sensitivity in HI listeners. Furthermore, NBN was used to compare the ITD sensitivity for this signal with that for pulse trains. The results were compared to the results obtained with CI listeners reported in Laback and Majdak (2008), and to the results obtained with NH listeners reported in Goupell et al. (2009). As mentioned in section 2.4.2, the ITD perception of HI listeners was already investigated in other studies. These studies showed a high inter-individual variability of ITD sensitivity in HI listeners. These studies presented the stimuli either at a constant SPL and/or a constant SL at the two ears. This could cause an auditory image not being centralized, which in turn could reduce ITD sensitivity and increase the inter-individual variability. In the present study, the stimuli were adjusted in level to evoke a centralized auditory image.

5.3.1 Stimuli

In the HI literature, experiments often used stimuli with a center frequency (CF) of 4000 Hz. To have comparable conditions, the decision was made to also use stimuli with a CF of 4000 Hz. For such a high CF, there is no phase-locking to the fine structure, thus the ITD information can be extracted only from the envelope. Two different types of stimuli were used: pulse train and narrow-band noise (NBN). The sampling rate was 96 kHz. The pulse trains consisted of 10.4 μs long monophasic pulses corresponding to one sampling interval. The pulse trains were passed through a digital sixth-order butterworth bandpass filter with slopes of 18 dB/oct. The filter was centered at 4000 Hz. The bandwidth (BW) was 1304 Hz, which was proportional to the bandwidth of 1500 Hz at a CF of 4600 Hz which was used for previous studies at the Acoustics Research Institute. The second type of stimuli was NBN centered at 4000 Hz with two different bandwidths (BWs). The first BW was 942 Hz, which corresponds to 1/3 octave. The second BW was the same as for the pulse trains (1304 Hz). The stimuli had a 500-ms duration. In order to reduce ITD cue during the onset and offset of the stimulus, linear ramps of 150 ms were applied to the pulse trains. Thus, the full-on duration of the stimulus was 200 ms. Continuous background noise was presented to mask any low-frequency components that could be used as binaural cues. It was binaurally-uncorrelated, white noise, filtered with a fourth-order lowpass filterwith a cut-off frequency of 1500 Hz.

The stimuli were presented at intensity levels corresponding to the individually measured levels at the two ears that evoked a centralized comfortable auditory image. Those levels are presented in table 5.3. The SPL of the background noise was 18 dB below the SPL of the target signal for the ear with the higher hearing threshold.

5.3.2 Test Conditions

There were three independent variables in the experiment: ITD, pulse rate, and the amount of jitter k. The ITD was used for both types of stimuli, whereas the pulse rate

subject	level	
	ear L	ear R
HI01	103	103
HI02	88	91
HI03	92	91
HI04	92	94
HI05	93	92
HI06	82	85
HI07	76	75
HI08	75	76
HI09	94	97
HI10	91	96
HI11	80	79
HI12	87	86
AVE	87.8	88.8
95% CI	7.9	8.4

Table 5.3: *The stimulus SPLs in dB are presented for each listener*

and the *k* values were just used in the pulse trains. The ITD was implemented by delaying the stimulus at one ear relative to the other ear. The ITD values tested for all listeners were 100, 200, 400, and 600 μs and the smaller two ITD values 20 and 40 μs were tested additionally if a test person had enough time. For the pulse trains, two different pulse rates were tested, 400 pulses per second (pps) and 600 pps. These pulse rates correspond to inter-pulse-intervals (IPIs) of 2500 and 1667 μs, which will be referred to as the *nominal* IPIs. These two pulse rates were chosen based on the following two requirements. First, the rate should be high enough to show reduced ITD sensitivity (possibly due to binaural adaptation) and thus leave room for improvements from jitter. Second, the rate should not be too high in order to represent real-life conditions. The third independent variable was the amount of jitter, specified by the parameter *k*. A jittered pulse train was created as a sequence of pulses, which were generated one after another. On the nominal IPI of each single pulse, a uniformly distributed jitter ranging between $\pm k \cdot IPI$ was applied. For the experiments, the parameter k was varied between 0 (no jitter, periodic condition) and 1 (maximum jitter). Thus, the largest possible IPI was twice the nominal IPI (for $k = 1$), whereas the smallest possible IPI was 0 (for $k = 1$). A k of zero resulted in a periodic condition, which means that there was no jitter included in the timing of the pulses. The jitter was synchronized between the left and right ear in order to preserve the ITD information which was referred to as binaurally-synchronized or binaurally-synchronized jitter, see figure 5.3 and figure

5.4. For each repeated stimulus a new random jitter manifestation was generated. For all listeners, the amounts of jitter being tested were $k = 0$, $1/4$, $1/2$, and $3/4$.

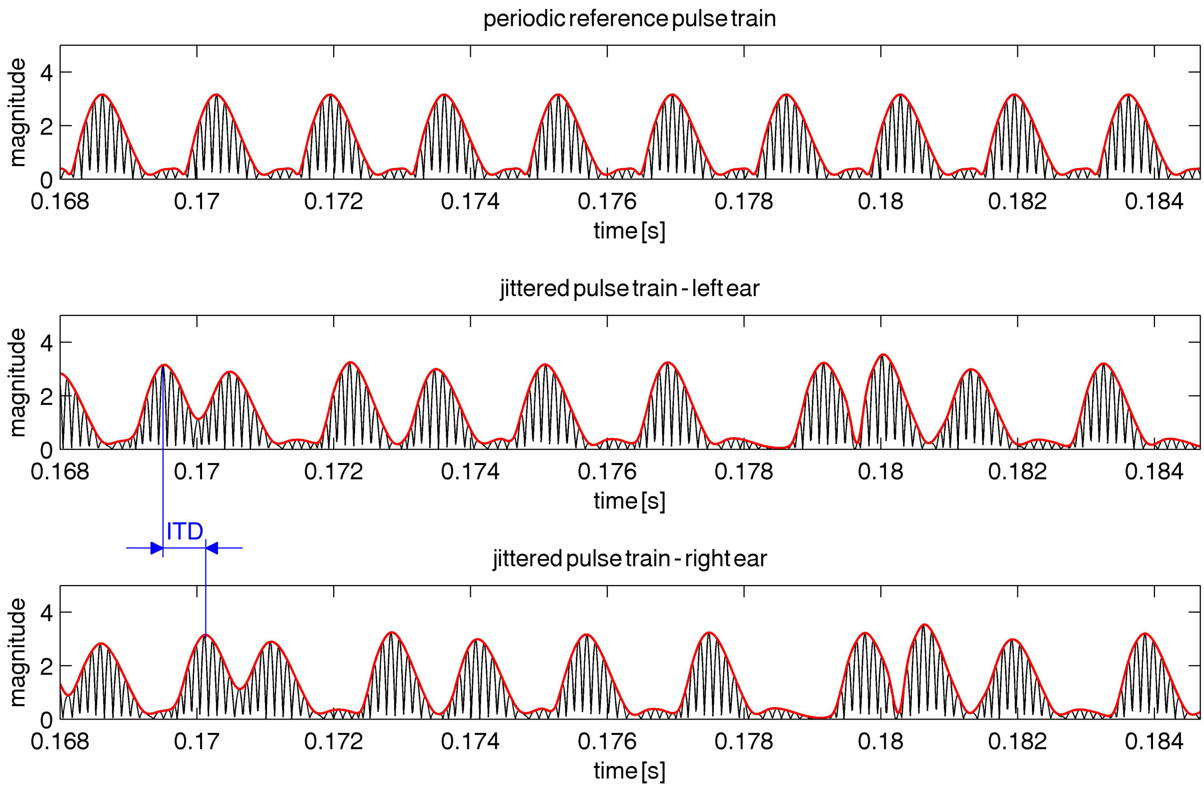


Figure 5.3: *An excerpt from a 600-pps pulse train. The upper panel shows the periodic reference signal. The middle panel shows the left ear signal containing a k value of 1/2, and the lower panel shows the corresponding right ear signal with an ITD of 600 μs. The envelopes of all signals are shown in red.*

5.3.3 Procedure

To measure the ITD sensitivity, a lateralization discrimination task was used in combination with the method of constant stimuli. The test person listened to a reference stimulus, followed by a target stimulus which was perceived either more towards the left or towards the right ear due to the ITD. The task was a two-interval, two-alternative forced-choice paradigm. The first interval, referred to as the reference stimulus, con-

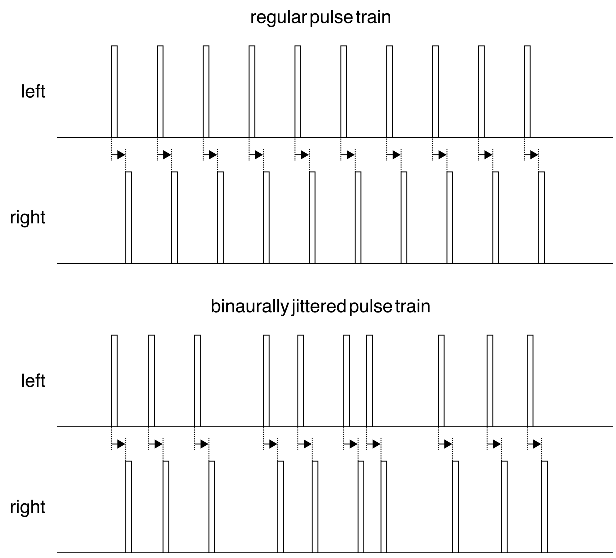


Figure 5.4: *Schematics of a periodic pulse train (upper panel) and of a binaurally jittered pulse train (lower panel). Note that the binaural jitter preserves the interaural time difference. Adapted from Laback and Majdak (2008)*

tained zero ITD and zero k. The amplitudes at the two ears depended on the results of the loudness centralization task completed before and caused a centralized image. The second interval, referred to as the target stimulus, contained non-zero ITD and different k values. There was a 400-ms silent interval between the reference and target stimulus. The listeners task was to indicate if the second stimulus was perceived either to the left or to the right side compared to the reference stimulus by pressing the corresponding button on a joy pad. Visual feedback about the correctness of the response was given after each trial. The start of a new trial was initiated by pressing a button. Before starting the main experiments, the subjects were trained in this task, using a baseline condition. The baseline condition used ITDs between 600 μs and 1000 μs. All types of stimuli and pulse rates were used. If the listener was not sensitive to any of the three stimuli types, a final check of the presence of ITD sensitivity was performed by testing broadband noise. In case of no ITD sensitivity even for this stimulus, the test person was excluded from the tests. This was the case for one HI listener (HI13). All other listeners were trained until they showed a stable performance and reached a minimum score of about 70% for a 400 or 600 pps pulse train with an ITD of 600 μs. The training lasted between fifteen minutes and four hours.

ITD sensitivity was determined by measuring psychometric functions, (see appendix A) for ITD using the method of constant stimuli. 100 repetitions per condition were presented in a balanced, random format, with 50 targets leading on the left and 50 targets leading on the right side. Thus, the chance rate was 50% and any percentage of left/right discrimination (P_c), which exceeds the rate of 59%, indicates a significant lateralization ability. The main experiment consisted of four blocks, pulse trains with two rates and NBNs with two BWs. Each block consisted all the combinations of ITDs and *k* values in randomized order. The order of the main four blocks was randomized and balanced over the listeners. For the pulse trains, 400 pps or 600 pps, the main experimental blocks contained each 1600 trials consisting of 100 presentations of four ITD values and four *k* values. For the two NBNs, the main experimental blocks contained each 400 to 600 trials consisting of 100 presentations of four to six different ITD values. The listeners usually made a break every 250 to 300 trials, which was approximately every 10 to 15 minutes. The minimal testing time was five hours. The tested conditions depended on the availability and performance of the subjects. Twelve HI listeners were tested for the 400-pps pulse trains. HI04 showed a generally low ITD sensitivity in the training, therefore the ITD value of 100 μs was not tested. For HI09 and HI10, the order of stimulus presentation was modified, because they seemed to be confused by changing conditions on a trial-by-trial basis. For every condition, two blocks of 50 items were created. These blocks were tested in a completely randomized order. Each block consisted of one ITD value and one *k* value. HI 09 and HI10 were tested for ITDs of 400 μs and 600 μs for all *k* values. Additionally, HI09 was tested for an ITD of 200 μs for *k* = 1/2 and *k* = 3/4. For the 600 pps, only six HI listeners (HI01, HI03, HI06, HI07, HI08, and HI11) performed the test. This was because of their restricted availability or because of their generally low ITD sensitivity. For the NBN with a BW of 1304 Hz, all HI listeners were tested. Eight subjects (HI01, HI03, HI06, HI07, HI08, HI09, HI11, and HI12) were also tested with additional smaller ITD values. For the NBN with a BW of 924 Hz, only eight HI listeners were tested. In addition, six of them were also tested at the smaller ITD values.

5.3.4 Data Analysis

The results of the experiment were evaluated and analyzed in two ways:

1. A multiway repeated-measures analysis of variance (RM ANOVA) was used. The RM ANOVA analyzes effects of different independent variables, irrespective of overall differences in performance between subjects. The basic concept of the ANOVA is the comparison of the levels of a factor. If more than one factor is used, then the interaction between the factors (e.g. ITD and stimulus type) can be analyzed, too. Before performing the ANOVA the P_c values were transformed using the rationalized arcsine transform, which is recommended by Studebaker (1985), in order not to violate the homogeneity of variance assumption needed for an ANOVA. If a factor in an ANOVA is shown to have a significant effect, it is necessary to know which factor levels are different from each other. Subsequent Tukey post hoc "honestly significantly different" (HSD) tests were performed which show the significance of the differences between individual factor levels. Differences with p-values ≤ 0.05 are considered as significant.

2. Just noticeable differences (JNDs) were calculated "from a maximum-likelihood cumulative Gaussian fit" to psychometric functions. The 75%-JND was used, allowing for a good comparison to relevant literature (see appendix A). The JNDs were calculated using the software package "psignifit" version 2.5.41 for MATLAB described in Wichmann and Hill (2001a, 2001b). In conditions where all P_c values were either above 80% or below 75% JNDs were not determined. In the result section, these conditions are denoted as ND.

5.3.5 Results: Individual Stimulus Types

In the following, the results for the 4000 Hz stimuli, pulse-trains at 400 and 600 pps with and without jitter, and NBN are presented.

To show statistical significance two different kinds of data-analysis were used. First, for analysing the effects for the whole subject group, RM ANOVA was used. With the RM ANOVA the effects of the parameters *k*, ITD, and pulse rate on the measured left/right discrimination scores are studied. Second, the JNDs were calculated (see section 5.3.4).

5.3.5.1 400 pps

For the rate of 400 pps, the individual results for the 12 HI listeners are presented in figure 5.5. The figure is subdivided into 12 panels, one panel for each listener. The ordinate shows the correct percentage of left/right discrimination (P_c) as a function of ITD in μs. The parameter is the amount of jitter *k*.

The results for individual listeners were divided into three groups. The first group shows high ITD sensitivity even for the periodic condition, which are HI06, HI03, HI01, and HI07. Second, the HI listeners, HI08, HI11, HI02, HI09, and HI10 show low sensitivity for the periodic condition. However, their performance shows general sensitivity in the other conditions with binaural jitter. The third group, including HI12, HI04, and HI05, are the HI listeners whose performance is mostly in the range of chance rating. Although these subjects showed some ITD sensitivity in the pilot tests, their sensitivity obviously degraded in the main experiment, possibly due to fatigue as a result of the long testing duration.

In general, the data of the sensitive HI listeners show that sensitivity improves with increasing ITD. For the periodic condition (*k* = 0), the high-sensitive listeners are already sensitive to ITDs as low as 100 μs. Their P_c score increases with increasing ITD by 30% from an ITD of 100 μs to an ITD of 600 μs. By adding binaural jitter, their sensitivity improves. However, the fact that their P_c approaches 100% for larger ITD values,

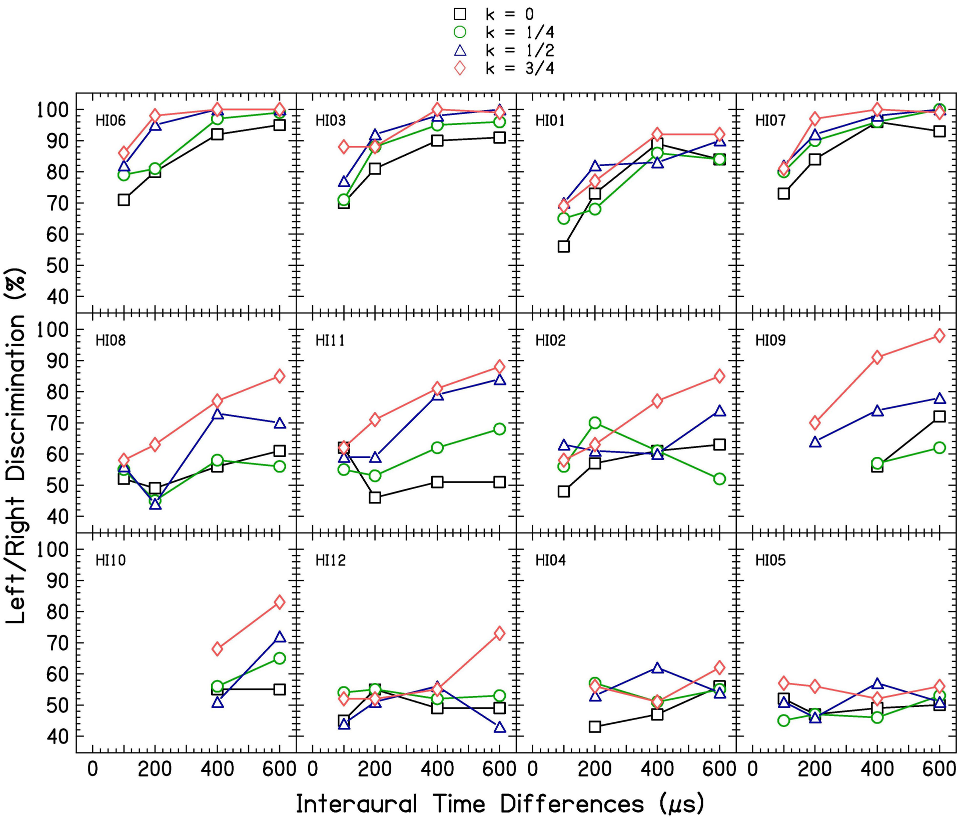


Figure 5.5: *Individual results for center frequency of 4000 Hz with a pulse rate of 400 pps*

indicates that the performance is limited by the ceiling, thus possibly under-estimating the improvements from jitter. For the low-sensitivity listeners, no sensitivity is found for the periodic condition. By adding jitter to the pulse-trains, their left/right discrimination scores increase up to 30%, particularly at larger ITD values. For this group, the performance for the jittered condition is not limited by the ceiling. For the third group, the performance does not exceed the range of chance rating with and without jitter.

The effect of the factors k and ITD were analyzed using a two-way RM ANOVA over all twelve HI listeners. The main effects are significant for both k [$F(3,174) = 25{,}623$; $p < 0.0001$] and ITD [$F(3,174) = 41{,}466$; $p < 0.0001$] but the interaction between ITD and k is non-significant [$F(9,174) = 0{,}798$; $p = 0.623$]. Then, the Tukey HSD post-hoc tests were performed on the factor k. The most interesting comparisons are those between the periodic condition ($k = 0$) and the jittered conditions: They are non-significant for $k = 1/4$ (p=0.226), but significant for $k = 1/2$ ($p < 0.0001$) and $k = 3/4$ ($p < 0.0001$), respectively. The differences between the conditions $k = 1/4$ and $k = 1/2$, between $k = 1/4$ and $k = 3/4$, and between $k = 1/2$ and $k = 3/4$ are all significant (p=0.033, p<0.0001, p=0.001, respectively).

In order to find out if having included the third group, which shows no sensitivity, has an effect on the significance of the outcomes, a second two-way RM ANOVA with the factors k and ITD was performed on the results of the nine HI listeners (first two groups) only, who show ITD sensitivity. The effects do not change (k: [$F(3,130) = 39{,}496$; $p < 0.0001$], ITD: [$F(3,130) = 64{,}045$; $p < 0.0001$], and $k \times$ ITD: [$F(9,130) = 1{,}219$; $p = 0.291$]). Also, the Tukey HSD post-hoc tests for the factor k support the outcomes of the first RM ANOVA, however, with slightly stronger effects. There was still a non-significant difference between the periodic condition and the smallest k value (p=0.133), but all other p-values are lower than before. On the basis of the second RM ANOVA, it is shown that the non-sensitive listeners do not have an important influence on the outcomes.

The results were used to estimate JNDs, which are shown in table 5.4.

	High-sensitivity				Low-sensitivity				No-sensitivity				
k	HI01	HI03	HI06	HI07	HI02	HI08	HI09	HI11	HI04	HI05	HI12	AVE	95% CI
0	219.0	111.8	127.4	104.4	ND	ND	624.7	ND	ND	ND	ND	237.5	291.1
1/4	213.8	107.6	<100	76.5	ND	ND	>1000	846.4	ND	ND	ND	311.1	359.4
1/2	130.4	86.6	76.2	67.8	>1000	581.7	448.2	334.4	ND	ND	ND	246.5	143.0
3/4	135.5	94.6	89.8	119.3	362.3	>1000	235.1	261.4	ND	ND	613.3	243.5	140.2

Table 5.4: *JNDs in μs estimated for pulse trains of 400 pps for each individual subject and condition. "ND" indicates that the JND could not be determined because the performance was substantially within the chance rate. "<100" indicates that the JND could not be obtained, the performance is higher than 75% for all tested ITDs. ">1000" indicates that the performance was generally above the chance rate, however the JND obtained by extrapolation of the performance was larger than 1 ms.*

5.3.5.2 600 pps

The individual results of the six HI listeners tested at 600 pps are presented in figure 5.6. In general, two of the six listeners, HI06 and HI07, show ITD sensitivity for the periodic condition. By adding jitter to the pulse trains, the ITD sensitivity increases by 30% for ITDs of 100 μs and by 50% for ITDs of 600 μs, where the ceiling of performance is reached.

A two-way RM ANOVA was performed with the factors k and ITD for the six HI listeners (N=6). The main effects are significant for both k [F(3,96)=66,446; p<0.0001] and ITD [F(3,96) = 33,597; p < 0.0001] and also the interaction between ITD and k is significant [F(9,96) = 6,345; p < 0.0001]. Then, Tukey HSD post-hoc tests were performed for the factor k. For the periodic condition, the ITD sensitivity is significantly lower in comparison to all other values of k (p$\leq$ 0.001). The differences between the factor levels k = 1/4 and k = 1/2, and between k = 1/4 and k = 3/4, between k = 1/2 and k = 3/4 are significant (p$\leq$ 0.001, p$\leq$ 0.001, and p=0.01, respectively). The estimated JNDs are reported in table 5.5.

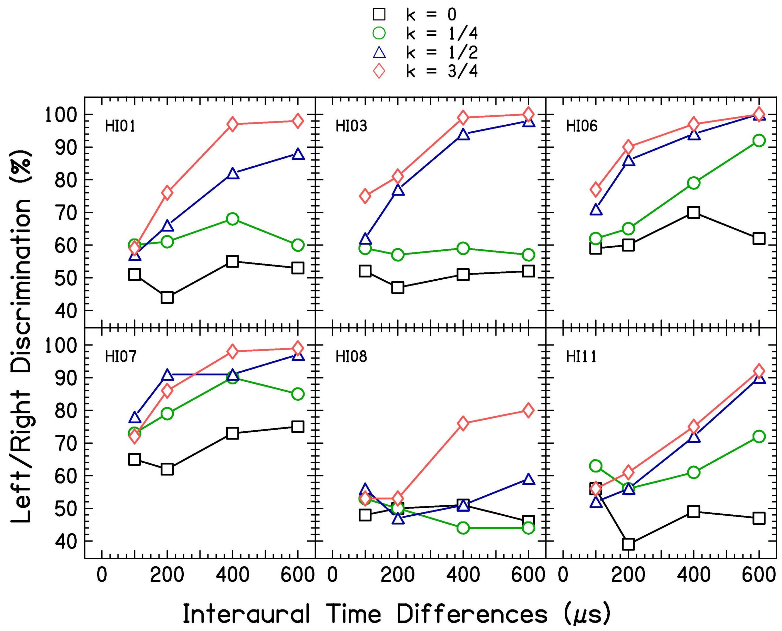


Figure 5.6: *Individual results for center frequency of 4000 Hz with a pulse rate of 600 pps*

k	HI01	HI03	HI06	HI07	HI08	HI11	AVE	95% CI
0	ND	ND	ND	593	ND	ND	593	0
1/4	>1000	ND	303.9	84.1	ND	>1000	194	415.6
1/2	269.2	180.2	124.8	61.2	ND	427.9	212.7	199.3
3/4	186.5	128.9	90	117.8	424.2	369.8	219.6	103.8

Table 5.5: *JNDs in μs estimated for pulse trains of 600 pps for each individual listener and condition. All other conventions as in table 5.4*

5.3.5.3 Narrow-Band Noise (NBN)

The individual results of the eleven HI listeners tested on NBNs for both BWs are presented in figure 5.7. No systematic differences can be observed between the two bandwidths.

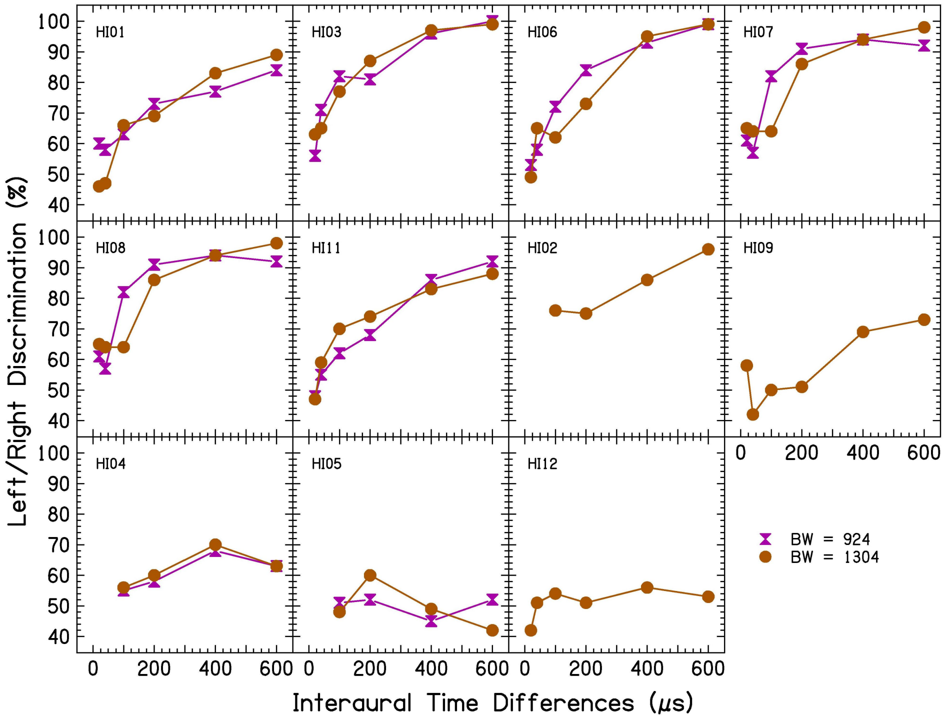


Figure 5.7: *Individual results for center frequency of 4000 Hz for narrow-band noise*

The results of the individual listeners were divided into three groups. The first group has high ITD-sensitivity, consisting of the seven HI listeners HI01, HI03, HI06, HI07, HI08, HI11, and HI02. The two HI listeners (HI04 and HI09) who show a low ITD sensitivity form the second group. The third group consists of the two HI listeners (HI05 and HI12) who performed at chance. For the group with high ITD sensitivity, the results are homogeneous across individual listeners. The P_c score increases with increasing ITD by 30% from an ITD of 20 μs to an ITD of 600 μs.

The effects of ITD and BW were analyzed by using a two-way RM ANOVA for those eight HI listeners, who were tested at both bandwidths. The effect of

BW	High-sensitivity							Low-sensitivity		No-sensitivity	
(in Hz)	HI01	HI03	HI06	HI07	HI02	HI08	HI11	HI09	HI04	HI05	HI12
924	287.2	84.1	131.2	70.5	-	262.1	234.4	-	ND	ND	-
1304	94.6	83.2	184.4	115.9	144.9	349.3	ND	549.7	ND	ND	ND

Table 5.6: *JNDs in μs estimated for NBN for each individual listener and bandwidth (BW) in Hz. "ND" indicates that JNDs were not determined because the performance was substantially within the chance rate."-" indicates that the BW was not tested.*

ITD is significant [F(5,92)=53,161; p<0.0001], but the effect of BW is not significant [F(1,92)=0.027; p=0.869]. The interaction between ITD and BW is not significant [F(5,92)=0,298; p=0.913].

A second two-way RM ANOVA was performed for the six listener (HI01, HI03, HI06, HI07, HI08, and HI11) who were only tested at both BWs and who show homogeneous ITD sensitivity. This analysis was performed to find out if including the less-sensitive listeners affected the general outcomes of the first ANOVA. The second ANOVA shows effects similar to the effects found in the first ANOVA (ITD: [F(5,76) = 71,199; p < 0.0001], BW: [F(1,76) = 0,033; p = 0,857], and ITD $\times$ BW: [F(5,76) = 0,192; p = 0.964]. On the basis of the second RM ANOVA, it is shown that the non-sensitive HI listeners do not have an important influence on the outcomes of the ANOVA. Due to the non-significance of the factor bandwidth, the data for the two bandwidths were pooled for further analysis.

The JNDs are reported in table 5.6. For the high-sensitive listeners, the BW of 924 Hz shows average JNDs of 178.3 $\pm$ 86.4 μs and the BW of 1304 Hz 162.0 $\pm$ 90.2 μs. This confirms that there is no difference in ITD sensitivity. For the low-sensitive listeners, no comparison can be made between the BWs.

5.3.6 Results: Comparison between Stimulus Types

In this section, the results are compared between the different stimulus types for the six HI listeners who completed all of those conditions. In figure 5.8, the results for all three different stimulus types are presented for each individual HI listener.

These data have already been shown in the figures in section 5.3.5 and are replotted for direct comparison between the stimulus types. The means over the listeners for the three stimulus types with their 95% confidential intervals are plotted in figure 5.9. The left panel shows the results for the 400 pps data and NBN, and the right panel shows the results for the 600 pps data and NBN. In both panels, the NBN represents the same data.

5.3.6.1 400 pps vs. 600 pps

In this section, the two pulse rates 400 pps and 600 pps are compared with each other. A three-way RM ANOVA was performed for the six HI listeners tested on both pulse rates, to analyze the differences between the pulse rates 400 and 600 pps. The factors pulse rate, k, and ITD were used. The main effects are significant for pulse rate [$F(1,192) = 95{,}626$; $p < 0.0001$], for k [$F(3,192) = 77{,}771$; $p < 0.0001$], and for ITD [$F(3,192) = 74{,}865$; $p < 0.0001$]. Furthermore, also the interactions of main interest, $k \times$ ITD and pulse rate $\times\ k$ are significant [$F(9,192) = 4{,}550$; $p < 0.0001$, and $F(3,192) = 5{,}398$; $p = 0.001$, respectively]. When increasing the pulse rate from 400 pps to 600 pps, the decrease of performance was stronger for the periodic condition than for the jittered condition. Then, the Tukey HSD post-hoc tests were performed on the factor k. The differences between the periodic condition and all jittered conditions are significant ($p<0.0001$). The differences between the conditions $k = 1/4$ and $k = 1/2$, between $k = 1/4$ and $k = 3/4$, and between $k = 1/2$ and $k = 3/4$ are significant ($p < 0.0001$, $p < 0.0001$, $p = 0.001$, respectively). Due to the significance of the factor pulse rate, 600 pps pulse trains yield a generally lower sensitivity than 400 pps pulse trains. The two pulse rates are individually analyzed and compared to NBN.

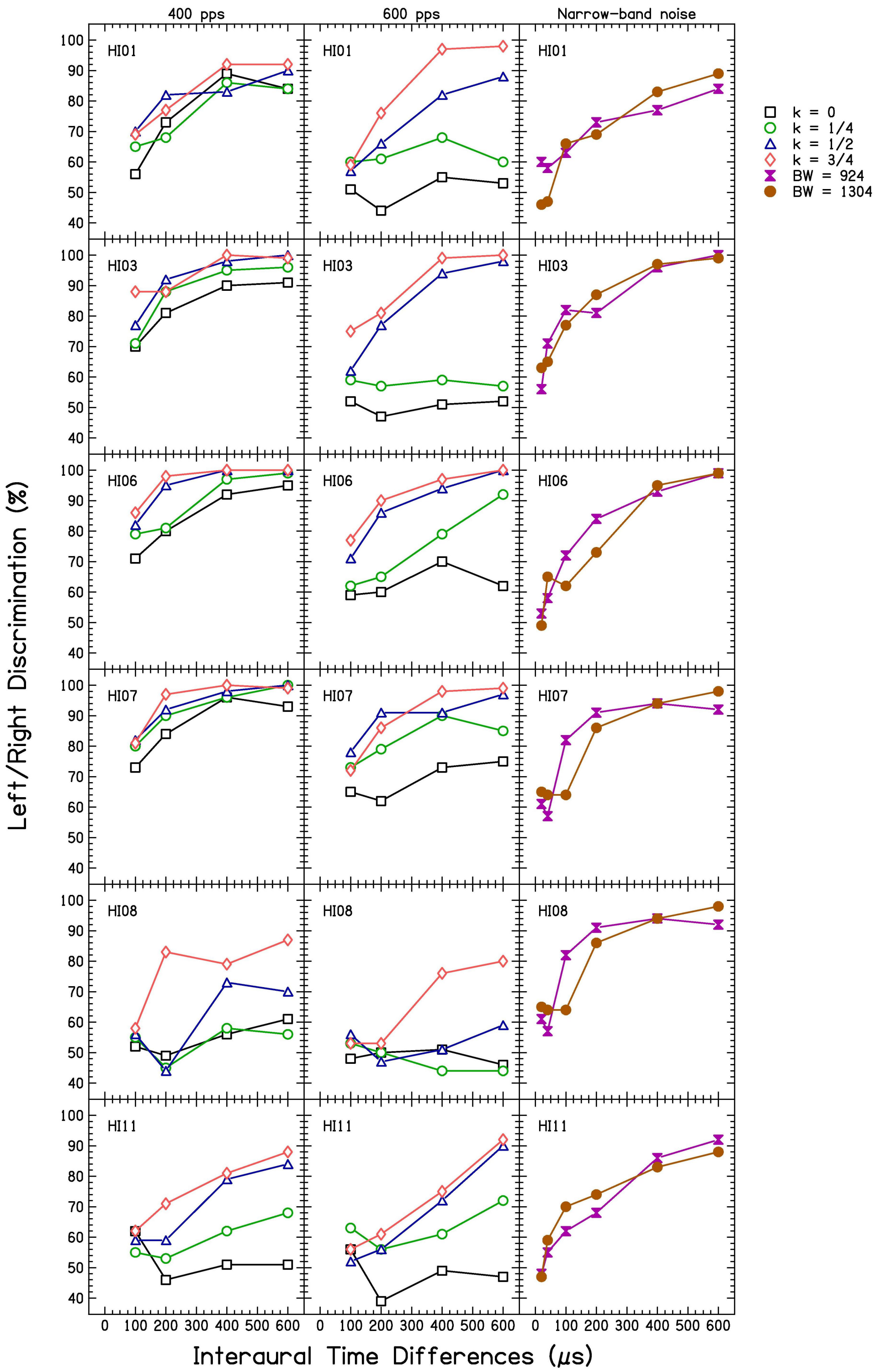


Figure 5.8: *Results for the three different stimulus types at 4000 Hz for those subjects who were tested with all three stimulus types.*

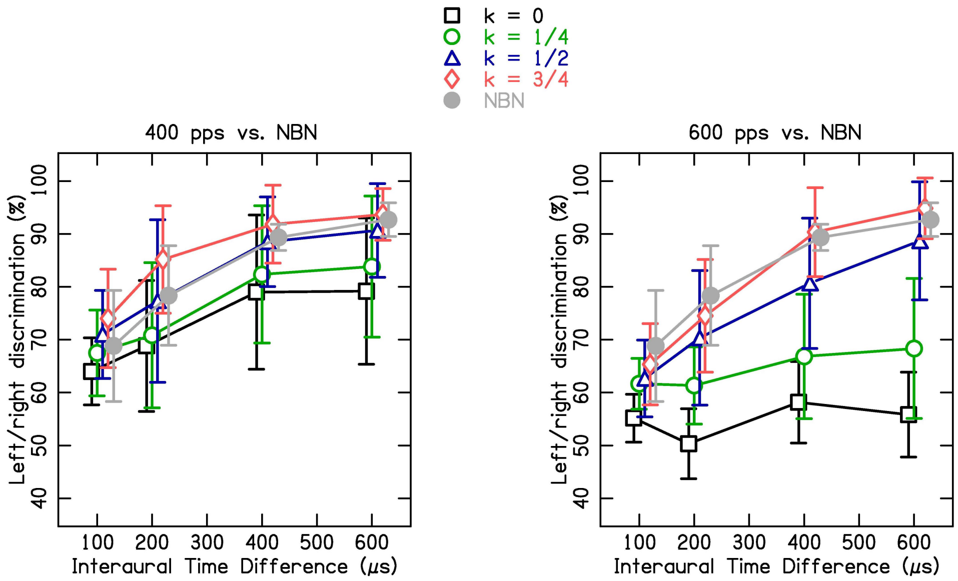


Figure 5.9: *Average performance for the 400 pps pulse train compared to NBN (left) and for the 600 pps pulse train compared to the NBN (right). The data for NBN are averaged over the two bandwidths.*

5.3.6.2 400 pps vs. NBN

To analyze the differences between the two different stimulus types 400 pps and NBN, two-way RM ANOVAs were performed on two groups of HI listeners.

For the six HI listeners tested for both pulse rates and for NBN, a two-way RM ANOVA was performed, using the factors ITD and stimulus type. The levels of the factor stimulus type are represented by the different k values and NBN. This allows to directly compare the performance of the NBN for the different k values. The main effects are significant for both stimulus type [$F(4,144) = 17{,}119$; $p < 0.0001$] and ITD [$F(3,144) = 69{,}764$; $p < 0.0001$], but the interaction between the stimulus type and ITD is not significant [$F(12,144) = 52.321$; $p = 0.701$]. Then, the Tukey HSD post-hoc tests were performed on the stimulus type. The most interesting comparison was between the periodic condition and the other conditions which is non-significant for $k = 1/4$ (p

= 0,266), but significant for k = 1/2, k = 3/4, and for NBN ($p < 0.0001$, $p < 0.0001$, $p < 0.0001$, respectively). The differences are also significant between the conditions k = 1/4 and k = 1/2, between k = 1/4 and k = 3/4, between k = 1/4 and NBN, and between k = 3/4 and NBN ($p = 0.015$, $p < 0.0001$, $p = 0.028$, and $p = 0.01$, respectively), but non-significant between k = 1/2 and k = 3/4, and between k = 1/2 and NBN ($p = 0.158$ and $p = 0.955$, respectively). This non-significance between k = 1/2 and NBN indicates that the sensitivity for the NBN approximately equals that for pulse-train jittered with k = 1/2.

The RM ANOVA was repeated using the data of all twelve HI listeners tested with 400 pps pulse trains and NBN. The results for the main effects and interaction are the same as for the subset of six listeners, i.e. stimulus type [$F(4,254) = 17{,}315$; $p < 0.0001$], ITD [$F(3,254) = 50{,}262$; $p < 0.0001$], and stimulus type × ITD [$F(12,254) = 0{,}618$; $p = 0.826$]. Then, the Tukey HSD post-hoc test was performed on the factor stimulus type. The most interesting comparisons between the periodic condition and the other conditions are non-significant for k = 1/4 ($p = 0{,}443$), but significant for k = 1/2, k = 3/4, and NBN ($p < 0.0001$, $p < 0.0001$, $p < 0.0001$, respectively). The differences between the conditions k = 1/4 and k = 3/4, between k = 1/2 and k = 3/4, and between k = 1/4 and NBN are significant ($p < 0.0001$, $p = 0.008$, and $p < 0.0001$, respectively), but they are not significant between k = 1/4 and k = 1/2, between k = 1/2 and NBN, and between k = 3/4 and NBN ($p = 0.111$, $p = 0.483$, and $p = 0.193$, respectively).

5.3.6.3 600 pps vs. NBN

For the six HI listeners tested with both 600 pps pulse trains and NBN, a two-way RM ANOVA was performed, using the factors stimulus type and ITD. The main effects are significant for k [$F(4,144) = 68{,}749$; $p < 0.0001$], for ITD [$F(3,144) = 50{,}791$; $p < 0.0001$], and for the interaction between k and ITD [$F(12,144) = 5{,}021$; $p < 0.0001$]. Then, the Tukey HSD post-hoc test was performed on the factor stimulus type. The periodic condition is significantly different from all other conditions ($p \leq 0.001$). All the differences between the conditions $k = 1/4$ and $k = 1/2$, between $k = 1/4$ and $k = 3/4$, and between $k = 1/2$ and $k = 3/4$ are significant ($p < 0.0001$, $p < 0.0001$, $p = 0.02$, respectively). Furthermore, the differences between the conditions k=1/4 and NBN and between $k = 1/2$ and NBN are significant ($p < 0.0001$, $p = 0.011$, respectively). However, $k = 3/4$ is not different from NBN ($p = 0.998$), which indicates approximately the same ITD sensitivity for pulse trains with $k = 3/4$ and NBN.

5.3.7 Discussion

This discussion section of Experiment I compares the results of Experiment I to previous studies testing ITD sensitivity in HI listeners (Smith-Olinde et al., 1998; Koehnke et al., 1995; Gabriel et al., 1992; Kinkel et al., 1991; Smoski and Trahiotis, 1986; and Hawkins and Wightman, 1980) as well as NH listeners (Goupel et al., 2009) and CI listeners (Laback and Majdak, 2008).

For NBN centered at 4000 Hz, the results for the eight HI listeners, who were sensitive to ITD, were compared with the results of Smith-Olinde et al. (1998), Koehnke et al. (1995), Gabriel et al. (1992), Smoski and Trahiotis (1986) and Hawkins and Wightman (1980). All of them measured ITD-JNDs using similar stimuli. The averaged ITD JNDs and 95% confidential intervalls are shown in figure 5.10. It seems that the HI listeners of our study were, on average, more sensitive to ITD than the subjects of Koehnke et al. (1995), Kinkel et al. (1991), Smoski and Trahiotis (1986), and Hawkins and Wightman (1980). However, in general, the results indicate that at least some HI listeners showed ITD sensitivity comparable to some HI listeners of Smith-Olinde et al. (1998), Koehnke et al. (1995), Gabriel et al. (1992), Smoski and Trahiotis (1986), and Hawkins and Wightman (1980). In contrast, there is a clear evidence that the HI listeners in our study are much more sensitive than the HI listeners from Kinkel et al.'s (1991) study. One reason for the better ITD JNDs may be that our stimuli were

	High-sensitivity				Low-sensitivity					
listener	HI01	HI03	HI06	HI07	HI02	HI08	HI09	HI11	Ave	Std.
HI	94.6	83.2	184.4	115.9	144.9	349.3	549.7	ND	217.4	159.3
NH	22.3	60.3	81.6	-	112.6	132.9	201.8	-	101.9	57.1

Table 5.7: *Individual JNDs in μs estimated for NBN for HI listeners from our study and NH listeners from Goupell et al. (2008).*

adjusted to evoke a centralized auditory image. In contrast, other studies presented stimuli either at a constant SPL and/or at a constant SL which might have resulted in a non-centralized auditory image. This in turn may lead to reduced ITD sensitivity and increase the inter-individual variability. Comparing the performance directly to NH listeners, Koehnke et al. (1995) and Gabriel et al. (1992) reported elevated ITD JNDs of HI listeners. For Koehnke et al. (1995), this may be due to the the fact that they presented their stimuli at the same SPL of 75 dB for both groups. In contrast, Smoski and Trahiotis (1986) reported that the performance of HI listeners is in general not poorer than for NH listeners, when presenting the stimuli at a constant SL of 25 dB. However, in our study, the stimuli were presented at a centralized SPL. By comparing our HI listeners to NH listeners of Goupell et al. (2008), some individual ITD JNDs were found to be similar (see table 5.7), while the averaged ITD JNDs for HI listeners are about 100 μs lower, amounting to a factor of 2.1.

In all these studies listeners who were not sensitive to ITD, in terms of a JND higher than 1 ms, were excluded. In Experiment I of our study, only three HI listeners out of eleven performed poorer than 1 ms which is a small percentage compared to the other studies. The results show that introducing binaural jitter in the stimulus timing for the pulse rate of 400 pps improves ITD sensitivity for most of the HI listeners. Four HI listeners showed high ITD-sensitivity even for the periodic condition. Thus, the improvements due to the binaural jitter might have been under-estimated because of ceiling effects. The five low-sensitive HI listeners showed low sensitivity for the periodic condition and large improvements due to binaural jitter. Three HI listeners did not show any ITD sensitivity at 4000 Hz. The results for the NBN were found to be comparable to the results for the jitter with $k = 1/2$. Increasing the pulse rate from 400 pps to 600 pps, the performance for the periodic condition decreased and the binaural jitter had a significantly stronger effect on ITD sensitivity compared to 400 pps. At the rate of 600 pps, all six HI listeners showed a high ITD sensitivity when using binaural jitter. The amount of jitter for $k = 3/4$ resulted in a performance comparable to that for NBN. The results are consistent with the hypothesis that HI listeners can also benefit from the effect of introducing binaural jitter in perceiving ITDs.

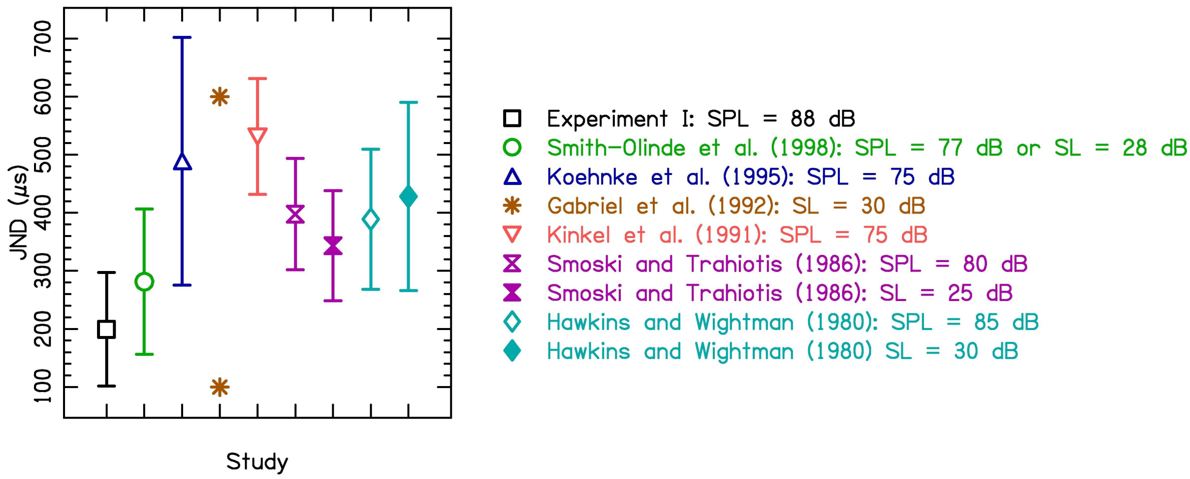


Figure 5.10: *Results from different studies on ITD sensitivity in terms of JNDs, using NBN. The HI listeners from each study were considered as a group and presented with its means ITD JNDs and the 95% confidence interval. In contrast, for the study of Gabriel et al. (1992), the individual JND ITDs of two HI listeners are shown.*

Only one study (Goupell et al., 2009) is available which used the same type of pulse trains with a pulse rate of 600 pps, to compare the jitter effect to NH listeners. The main difference to our study is that our HI listeners were tested at a CF of 4000 Hz and Goupell et al. used a CF of 4600 Hz. In figure 5.11, the individual JNDs for the 600-pps pulse trains (including three k values) are shown for HI and NH listeners. For the periodic condition, JNDs for most subjects were not determinable, but the difference in JNDs between one HI listener of the present study and the more sensitive NH listener from Goupell et al. (2009) is approximately 500 μs. For k values of 1/2 or 3/4, some HI listeners show largely improved JNDs that are comparable to those of the NH listeners. However, it is difficult to generalize, because large k values were not tested for the high-sensitive NH listeners. Another aspect is that the JNDs were determined at the 70% point of the psychometric function in Goupell et al. (2009) and at 75% in our study.

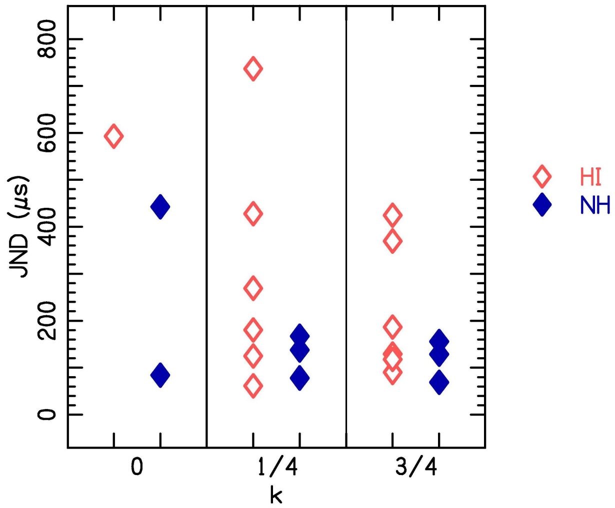


Figure 5.11: *JNDs in μs for 600-pps pulse trains for individual HI (empty symbol) and NH (filled symbol) listeners.* Note that several JNDs could not be determined (see text).

For 400 pps, a qualitative comparison can be made to Goupell et al. (2009), who tested six NH listeners, and to the study of Laback and Majdak (2008), who tested five CI listeners. In these studies, stimuli were trapezoidally modulated pulse trains. The levels were adjusted to evoke a centralized auditory image for each pulse rate. In figure 5.12, the ITD JNDs for the three studies are summarized. For the periodic condition, the HI listeners performed worse than both the NH and CI listeners, who performed similar. While the CI listeners showed no improvement in the performance when adding jitter at 400 pps, both the HI listeners and the NH listeners showed significant improvements. Generally, in both of those studies, the ITD sensitivity decreased with increasing pulse rate for the periodic condition ($k = 0$), which is in agreement with our results and the concept of a rate limitation. The finding that the CI listeners did not show improved ITD sensitivity due to binaural jitter at 400 pps, whereas the NH and HI listeners did may be due to the added slowly-varying envelope modulation in the electric pulse train as a result of overlap of impulse responses for larger amounts of jitter. Thus, the larger the amount of irregularity in the pulse timing, the larger the improvement that occurred compared to the regular periodic pulse trains. In general, there were the same trends for HI, NH and CI listeners.

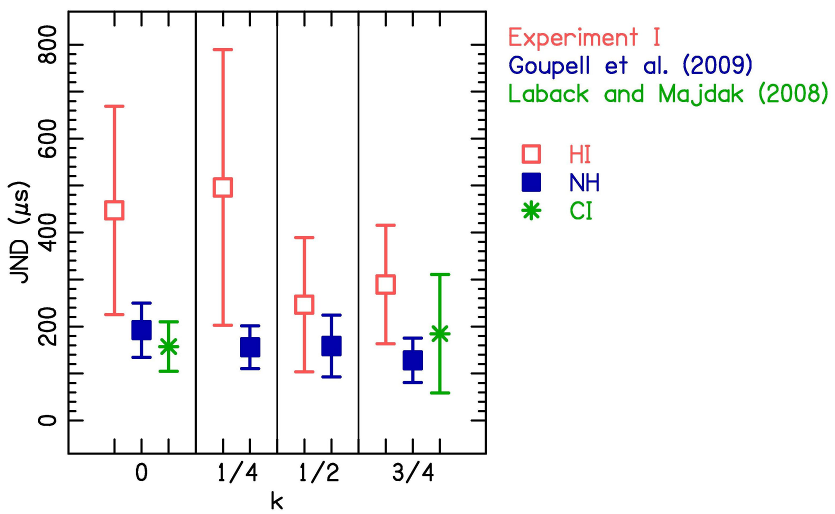


Figure 5.12: *Comparison of the effect of binaural jitter for pulse trains of 400 pps on ITD sensitivity between HI, NH, and CI listeners.*

Lastly, it is of interest if there is a correlation between the JNDs and the degree of hearing loss of the HI listeners. There is no significant correlation between the degree of hearing loss and the ITD JNDs for NBNs at a center frequency of 4000 Hz ($R^2 = 0.506, p = 0.246, N = 9$). In figure 5.13, the JNDs of each listener are shown as a function of the hearing loss in dB HL.

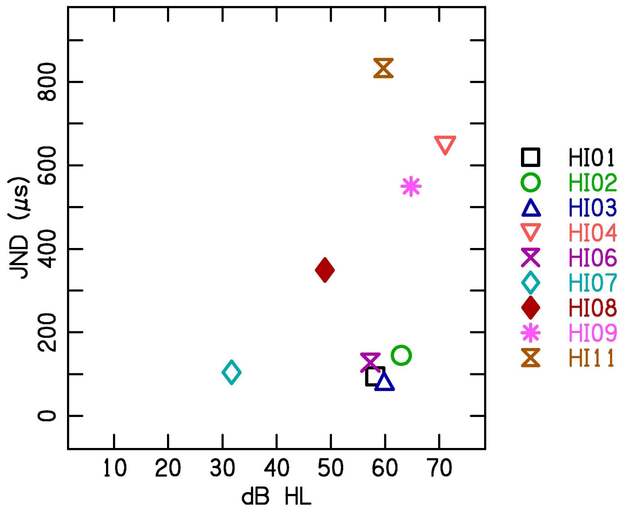


Figure 5.13: *JNDs for NBN at 4000 Hz as a function of the HL*

5.4 Experiment II: Low-Frequency Stimuli

In Experiment II, the performance of HI listeners on different types of low-frequency stimuli was tested and compared to that of HI listeners from other studies.

5.4.1 Stimuli

In order to measure ITD sensitivity at low frequencies, four different stimulus types, pure tones, jittered tones, sinusoidally-amplitude modulated (SAM) tones, and NBN were used. All stimuli were centered at 500 Hz and had a duration of 500 ms. The sampling rate was 96 kHz. As for the 4000-Hz stimuli, they had ramps of 150 ms to avoid onset and offset ITD cues.

The pure tone was defined by

$$s_{\sin}(t) = \frac{1}{2}\sin(2 \cdot \pi \cdot f_c \cdot t),$$

where f_c represents the carrier frequency which was set to 500 Hz, and t represents the time vector.

Jittered tones were generated by filtering jittered pulse trains. A series of five sixth-order bandpass filters was used. The bandwidth was 367 Hz.[1] Using a *k*-value of zero, the resulting signal approximates a pure tone. For *k*-values larger than zero, this stimulus corresponds to a pure tone with a random frequency modulation. The following *k*-values were used: 0.052, 0.104, 0.208, and 0.416.

The sinusoidally-amplitude modulated tone was defined by

$$s_{SAM}(t) = \frac{1}{2} \cdot \sin(2 \cdot \pi \cdot f_c \cdot t) \cdot [1 - \sin(2 \cdot \pi \cdot f_m \cdot t + \pi)],$$

where f_c represents the carrier frequency (set to 500 Hz), f_m represents the modulation frequency (set to 50 Hz), and t represents the time vector.

As fourth type of stimulus, a one-third-octave NBN centered at 500 Hz with a BW of 115.3 Hz was used. Figure 5.14 shows the four signal types, the pure tone, the SAM tone, the jittered tone with k = 0.416, and the NBN. In the appendix B, the stimuli waveform and the spectra are plotted for the pure tone (Fig. B.1), for the SAM tone (Fig. B.4), the jittered tones (Fig. B.2), and the NBN (Fig. B.3). The stimuli were presented at intensity levels corresponding to the individually measured levels at the two ears that evoked a centralized and comfortable auditory image. Those levels are presented in table 5.8.

The parameter ITD was used in the same way as in Experiment I (5.3.1) with ITD values of 20, 40, 100, 200, 400, and 600 μs, but not all values were used for all listeners, depending on their sensitivity revealed in the training.

For each listener, an individual SPL for the right and left ear was used (according to the pre-tests) which was the same for all stimuli.

[1]Unfortunately, during the finalization of this thesis an error was found. The error occurred in the setting of Experiment II for two HI listeners, HI02 and HI03, while measuring the ITD sensitivity of the jittered tones. Instead of using a bandwidth of 367 Hz, the bandwidth of 85 Hz was used. The lower bandwidth is expected to result in a smaller improvement for the jittered stimuli relative to the pure tone. In fact, for HI02, the results are not different from the other listeners. For HI03, the performance for jittered tones was even better. This suggests that the wrongly set bandwidth has no effect on the interpretation of the results.

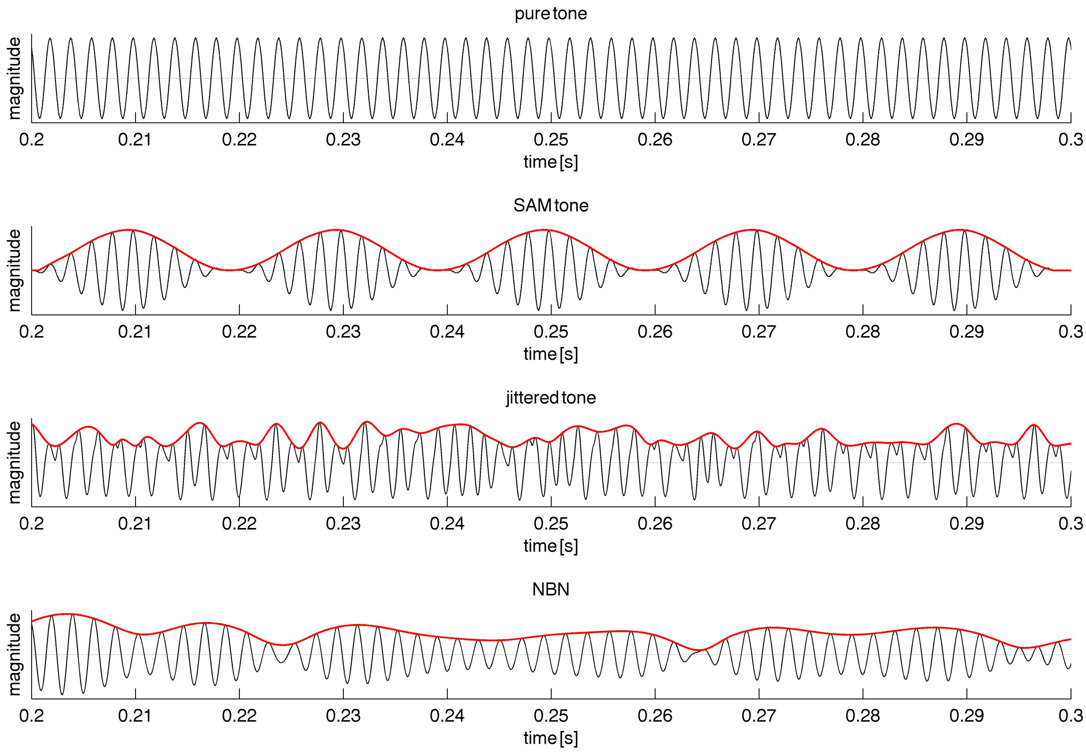


Figure 5.14: *Waveform excerpts from the four signals, pure tone, SAM tone, jittered tone with k = 3/4, and NBN, with a CF of 500 Hz are shown. For the latter three signals, also the envelopes (in red) are shown.*

		HI01	HI02	HI03	HI04	HI05	HI06	HI07	HI08	HI12	AVE	95% CI
ear	R	86	78	78	70	67	80	67	82	75	75.6	5.4
	L	90	79	78	67	68	78	68	82	76	76.2	4.7

Table 5.8: *The stimulus SPLs in dB are presented for each listener*

5.4.2 Procedure and Conditions

The procedure to measure ITD sensitivity in Experiment II was also a lateralization discrimination task in combination with the method of constant stimuli as described in section 5.3.3.

There were four experimental blocks. The order of the main four blocks was randomized and balanced over the listeners. For the pure tones, the sinusoidally-amplitude modulated (SAM) tones, and the NBN, a block contained 600 trials, consisting of 100 presentations of six ITD values. For the jittered tones, the experimental block contained 2400 trials consisting of 100 presentations of six different ITD values and four *k*-values. For three HI listeners, HI03, HI08, and HI12, the *k*-value of zero was included in the block of jittered tones. Thus the block length was increased to 3000 trials. The trials in the jittered-tone block were presented in completely randomized order. The listeners usually made a break every 250 to 300 trials, which was approximately every 10 to 15 minutes. The minimal testing time was four hours. Depending on the availability and performance of the subjects, different ITD values were tested with each subject. For the pure tones and for the jittered tones, HI02 was only tested on three ITDs (40, 100, and 200 μs), HI03 was also tested on three ITDs (20, 40, and 100 μs) and HI07 was tested on five ITDs (20, 40, 100, 200, and 400 μs). For the SAM tones, HI03 was tested on three ITDs (20, 40, and 100 μs) and HI04 and HI07 was tested on five ITDs (20, 40, 100, 200, and 400 μs). For the NBN, HI03 was just tested on three ITDs (20, 40, and 100), HI04 was tested at four ITDs (20, 40, 100, and 200 μs), and HI07 was tested on five ITDs (20, 40, 100, 200, and 400 μs).

For the second experiment, time limitations of three listeners (HI09, HI10, and

HI11) caused that only the other nine HI listeners (HI01, HI02, HI03, HI04, HI05, HI06, HI07, HI08, and HI12) were tested.

5.4.3 Data Analysis

The results of the experiment were evaluated and analyzed using:

1. a RM ANOVA (see section 5.3.4),
2. JNDs (see section 5.3.4),
3. the so-called critical difference (Thornton and Raffin, 1978) to explore the statistical significance of differences between conditions within individual listeners. It is based on the binomial distribution, which indicates whether the difference between two percent-scores is statistically significant or if it is due to random fluctuation.

5.4.4 Results: Individual Stimuli

In the following the results for the four tested stimulus types pure tone, jittered tones, SAM tones, and NBN, studied on the nine HI listeners that completed this experiment are described. Each figure is subdivided into nine panels which show the P_c scores as a function of ITD for each HI listener.

5.4.4.1 Pure Tone

Figure 5.15 shows the results for the pure tone condition for the nine individual HI listeners. In general, these results show an increasing P_c with increasing ITD. Five listeners, HI03, HI04, HI07, HI08, and HI12, are already sensitive to an ITD of 20 μs. For ITDs of 40 μs, eight HI listeners (except for HI01) were able to detect ITDs. HI01 is the only HI listener who almost did not show any ITD sensitivity. For three of those listeners (HI03, HI07, and HI12), the sensitivity of an ITD of 100 μs approaches the

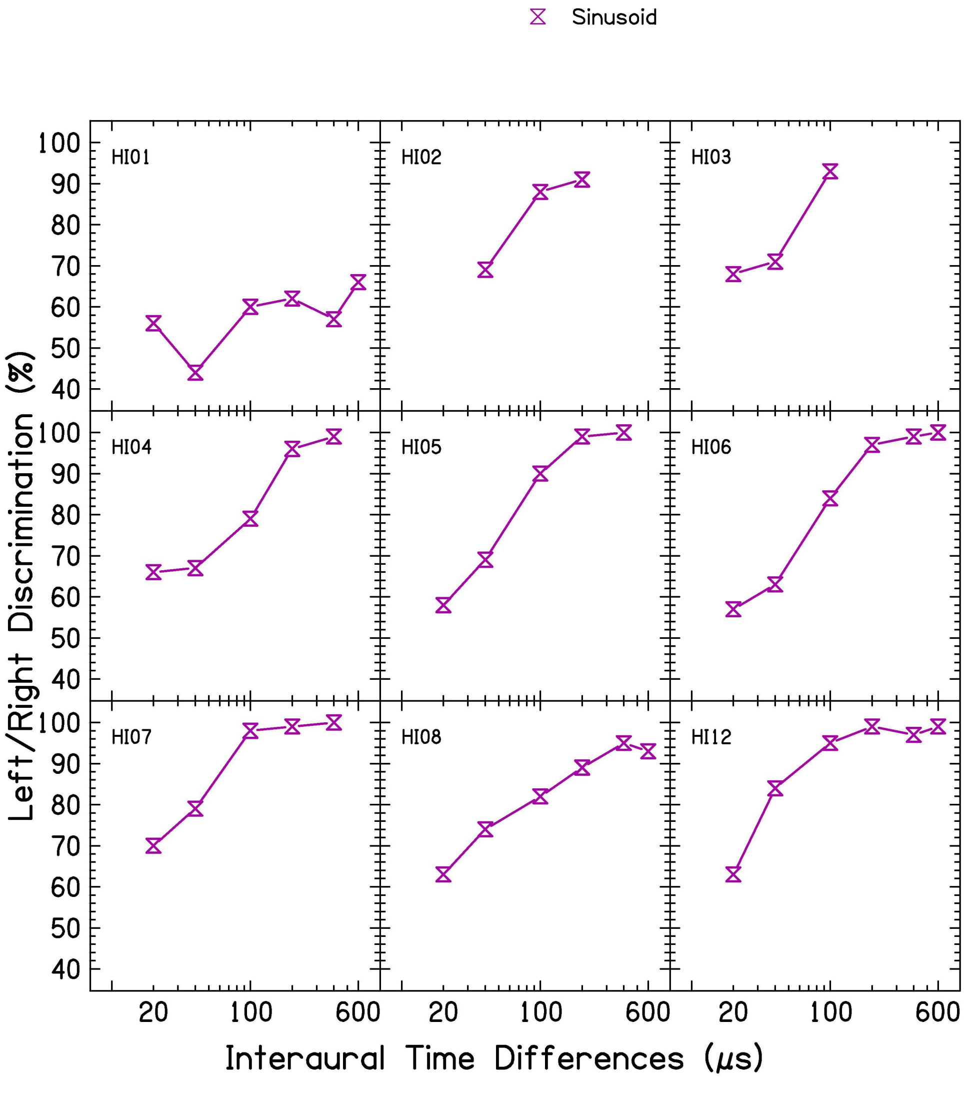


Figure 5.15: *Individual results for the pure tone with CF of 500 Hz*

ceiling, the maximal possible performance of 100%. The estimated JNDs for the pure tone are shown in table 5.10.

5.4.4.2 Jittered Tones

In figure 5.16 the individual results for the jittered tones on the same nine HI listeners are shown. The parameter *k* indicates the amount of binaural jitter. In general, the listeners' performance improves with increasing the ITD. It is difficult to derive any systematic effect of the parameter *k*. The data do not indicate a better performance of HI listeners with an increasing amount of binaural jitter.

This is supported by a two-way RM ANOVA, which analyzed the effect of the factors k and ITD over all nine HI listeners. The effect of the factor ITD is significant [$F(3, 184) = 242, 911; p < 0.0001$]. However, the effect of k is non-significant [$F(3, 184) = 2.216; p = 0.089$] and the interaction between ITD and *k* [F(3,184) = 0.614; p = 0.860], too. Table 5.9 shows the estimated JNDs for the jittered tones. On average the HI listeners have similar JNDs for all *k* values.

Additionally, a binomial test was performed for three listeners, HI03, HI08, and HI12, for which the pure tone condition (*k* = 0) was included in the randomized block of jittered tones. Thus, the order of conditions is balanced, allowing to perform a statistical analysis within an individual subject. Note that because of this, figure 5.16 includes also the results for the pure tone in case of the three listeners. The objective was to study the significance of the difference between the factor levels *k* = 0 and *k* > 0. For HI03, there are four significant differences for two different ITDs, 20 μs and 40 μs. For the ITD of 40 μs, the significant differences are found between *k* = 0 and the factor levels *k* = 0.052, *k* = 0.104, *k* = 0.208, and *k* = 0.416, which are supported by p < 0.001, p < 0.001, p < 0.001, and p = 0.01, respectively. For the ITD of 20 μs, *k* = 0 and all other *k* values are also significant, which is supported by p-values of 0.001. This means that in case of HI03 for the jittered condition (*k* > 0) higher ITD sensitivity than for the periodic condition was found. For HI08, there are three significant differences found

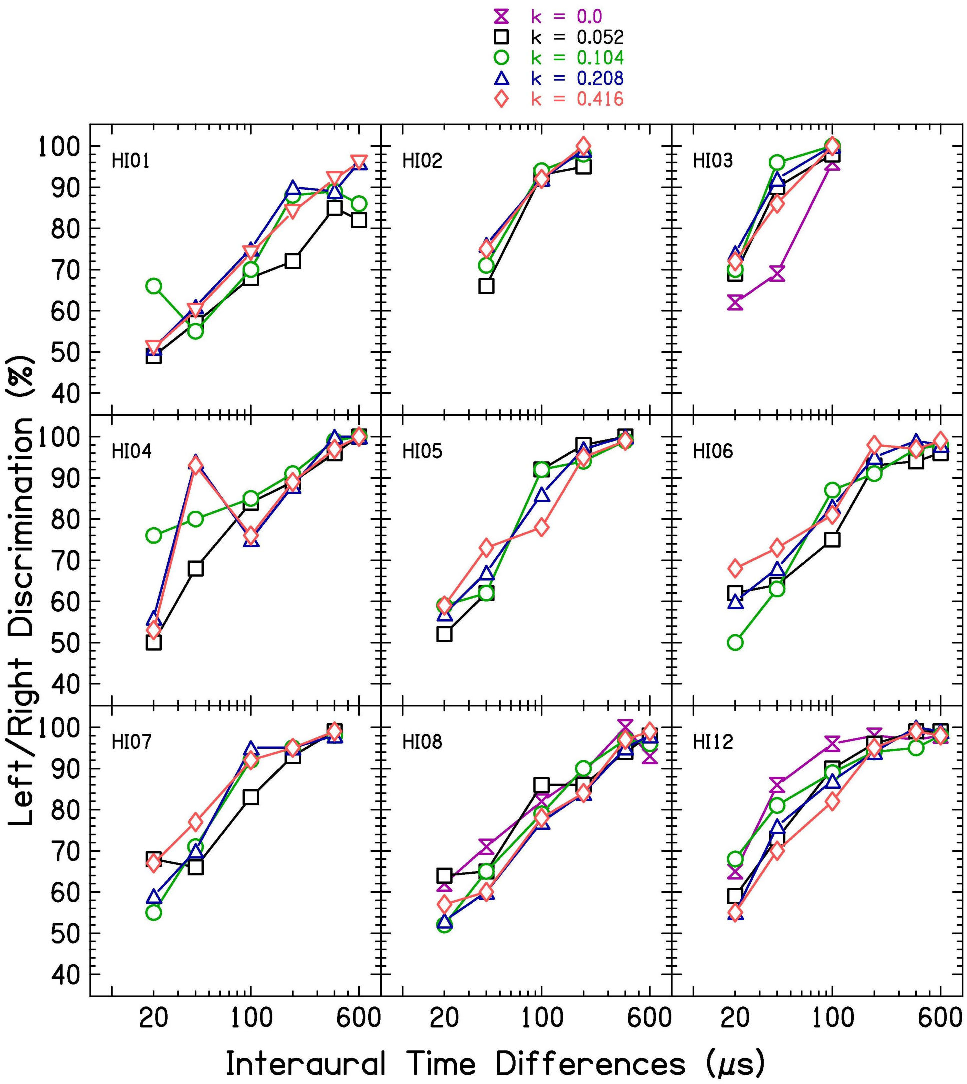


Figure 5.16: *Individual results for the jittered tones centered at 500 Hz. For listeners HI03, HI08, and HI12, also the result for the periodic condition (k = 0) are included, since this condition was included in the randomized experimental block.*

k [μs]	HI01	HI02	HI03	HI04	HI05	HI06	HI07	HI08	HI12	AVE	95% CI
0.052	203.5	49.5	23.8	78.6	61.8	70.3	57.5	66.5	46.7	73.1	10.6
0.104	96.8	45.0	22.9	27.7	47.5	69.1	46.7	78.0	25.9	51.1	5.2
0.208	89.1	38.5	21.0	47.7	62.3	60.0	43.1	108.1	52.2	58.0	5.5
0.416	108.2	42.8	24.7	49.4	63.7	44.5	33.0	103.5	63.8	59.3	6.0

Table 5.9: *JNDs in μs are estimated for pulse trains of 500 pps for each individual subject and condition. "95% CI" is referred to the 95% confidence interval.*

at two different ITDs. For the ITD of 400 μs, two significant differences are between k = 0 and k = 0.052, and between k = 0 and k = 0.208 (p = 0.003 and p = 0.009, respectively). HI08 shows higher ITD sensitivity for the periodic condition than for these two jittered conditions (k = 0.052 and k = 0.208). The third significant difference is at an ITD of 600 μs between k = 0 and k = 0.416 (p = 0.028). Thus, for the highest ITD value, HI08 shows a better ITD sensitivity for k = 0.416 than for the periodic condition. For HI12, there are four significant findings at two different ITDs, which are for an ITD of 40 μs between k = 0 and k = 0.052, and between k = 0 and k = 0.416, which is supported by p = 0.023 and p = 0.006, respectively. For the ITD of 100 μs the significant differences are between k = 0 and k = 0.208, and between k = 0 and k = 0.416, which is supported by p = 0.022 and p = 0.001, respectively. HI12 shows higher ITD sensitivity for the periodic condition than for the jittered conditions. In summary, the analysis of the individual data for the three listeners HI03, HI08, and HI12 reveals only one subject for which there seems to be an improvement by introducing binaural jitter.

5.4.4.3 Sinusoidally Amplitude Modulated (SAM) Tones

The different line graphs in figure 5.17 show the results for the SAM tones for the nine HI listeners. The HI listeners are subdivided into different groups according to their ITD sensitivity. The results of HI07, HI08, and HI12 show similar sensitivity. Their P_c increased with increasing ITD. However, they do not detect an ITD of 20 μs, but their results almost reach the ceiling for an ITD of 200 μs. In comparison to these three

HI listeners, HI02 and HI06 already show a very high ITD sensitivity for ITDs of 100 μs. HI03 and HI04 are the only ones from the nine HI listeners who are even sensitive for ITDs of 20 μs (P_c = 70%). Among the nine HI listeners, HI01 shows the lowest sensitivity. For ITDs below 100 μs, HI01's P_c is at random. For an ITD of 100 μs, HI01 performs above chance, and the maximum performance of 86% is obtained for an ITD of 400 μs. The estimated JNDs for SAM tones are shown in table 5.10.

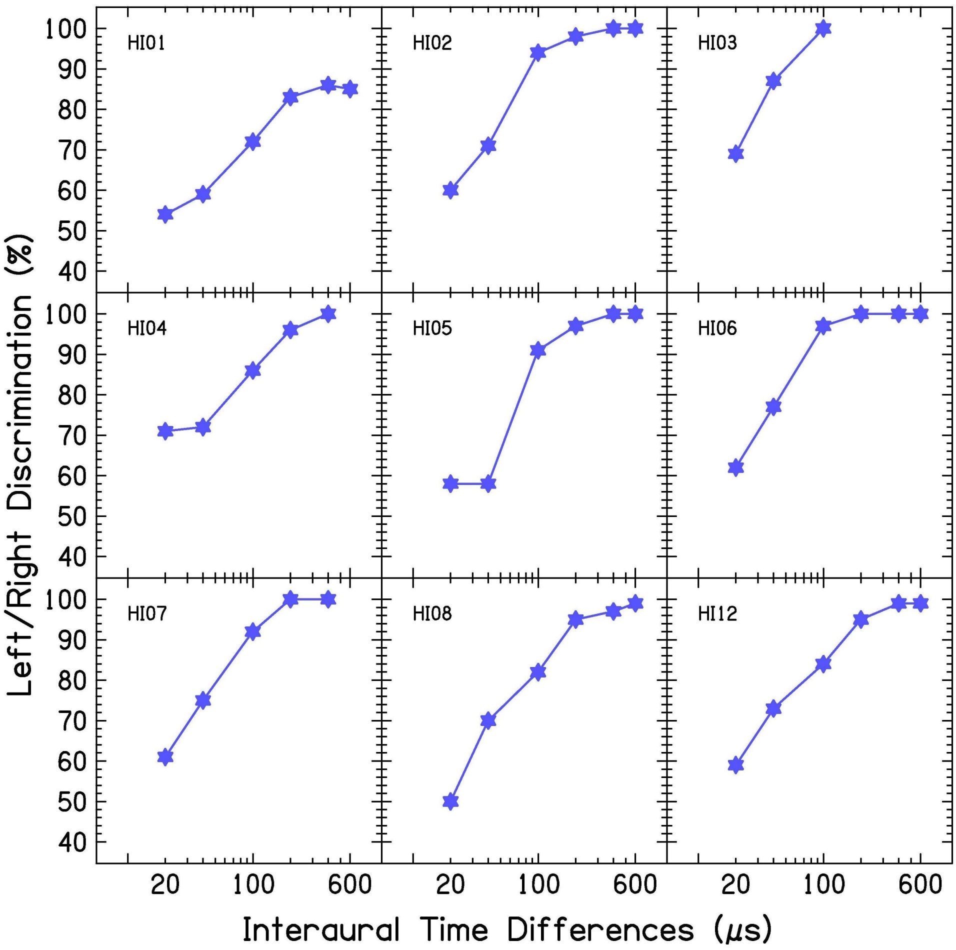


Figure 5.17: *Individual results for the sinusoidally amplitude modulated tones.*

stimulus	HI01	HI02	HI03	HI04	HI05	HI06	HI07	HI08	HI12	AVE	95% CI
SAM tone	123.2	45.5	25.8	42.0	62.4	35.4	41.1	66.9	54.2	55.2	17.6
Pure Tone	ND	54.0	39.9	61.9	53.5	69.0	29.4	52.5	27.3	48.5	9.7
NBN	65.7	51.6	17.7	58.2	182.3	211.8	29.4	147.6	196.7	106.8	47.5

Table 5.10: *JNDs in μs estimated for the three stimuli SAM tone, pure tone, and the NBN for each individual subject. "ND" indicates that the JND could not be determined. "AVE" indicates the across-subject average JNDs, and "95% CI" the 95% confidence interval.*

5.4.4.4 Narrow-Band Noise

The different line graphs in figure 5.7 show the results for the NBN on the nine HI listeners. Of the nine HI listeners, HI03 is the only one who shows high ITD sensitivity with P_c = 83% at an ITD of 20 μs. The second HI listener, who is able to detect such a small ITD, is HI07 with P_c = 70%. Her performance shows ceiling effects for ITDs above 40 μs. The performance of HI02 is quite similar to that of HI07. The difference is that HI02 is able to detect ITD from 40 μs on and saturates at an ITD of 200 μs. HI01 detects a ITD from 100 μs on with high performance of P_c = 81%, has the highest performance at 200 μs with P_c = 94%. HI05, HI06, HI08, and HI12, do not show any sensitivity to ITDs lower than 200 μs, but an increasing P_c with increasing ITD.

The estimated JNDs for NBN are shown in table 5.10.

5.4.5 Results: Comparison between Stimulus Types

5.4.5.1 Pure Tone vs. Jittered Tones

In figure 5.19 the group results of the jittered tones with the different factor levels of k including the pure tone condition (k=0) are shown for all nine listeners. In general, the ITD sensitivity increases with increasing ITD, from scoring at random to almost at the ceiling.

For the nine listeners, a two-way RM ANOVA was performed, using the factors ITD and stimulus type s. The factor levels of the factor stimulus type s are repre-

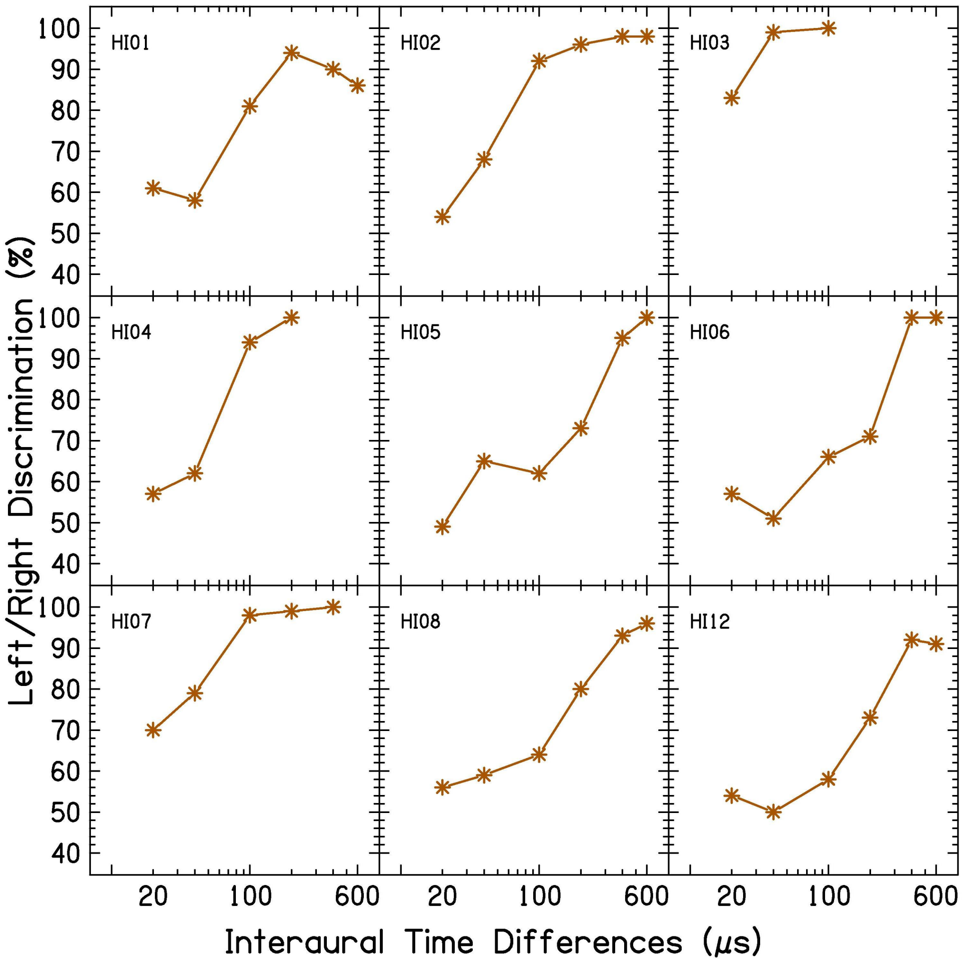


Figure 5.18: *Individual results for NBN centered at 500 Hz, for each individual HI listener.*

sented by the different *k* values. The effect is significant for ITD [F(5,228) = 211,311; p < 0.0001], but non-significant for *k* [F(4,228) = 1,432; p = 0.225]. The interaction between *s* and ITD (stimulus type × ITD) is also non-significant [F(20,228) = 45.932; p = 0.859]. As there is no significant difference between the results for the jittered tones and the pure tone, the stimuli were pooled for further comparisons and are referred to as jittered tones.

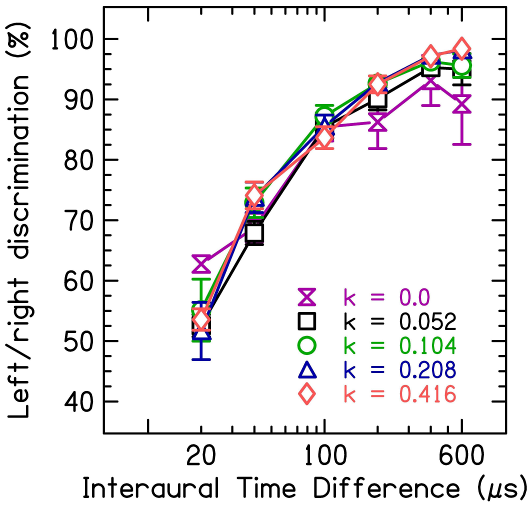


Figure 5.19: *The results for the pure tone and the jittered tones at a CF of 500 Hz are shown with their mean values and their 95% confidence intervals.*

5.4.5.2 Jittered Tones vs. SAM vs. NBN

In figure 5.20 the group results for the pooled jittered tones, the SAM tone, and the NBN are shown for all nine listeners. In general, the data show that the HI listeners are sensitive even to the lowest ITD value for all three stimuli.

A two-way RM ANOVA was performed on the data of all nine HI listeners. The factors stimulus type and ITD were used. The main effects are significant for both stimulus type [F(2,325) = 9.378; p < 0.0001] and ITD [F(5,325) = 172.353; p < 0.0001], but the interaction between stimulus type × ITD is non-significant [F(10,325)=0.746;

p=0.819]. The Tukey HSD post-hoc test was performed to analyze the differences between the individual stimulus types. The results for the SAM tone show significantly higher performance compared to the results for the jittered tones and NBN (p = 0.019 and p < 0.0001, respectively). The results for jittered tones show a significantly higher performance difference from the results for the NBN (p = 0.008). Thus, the HI listener show the lowest ITD sensitivity for NBN.

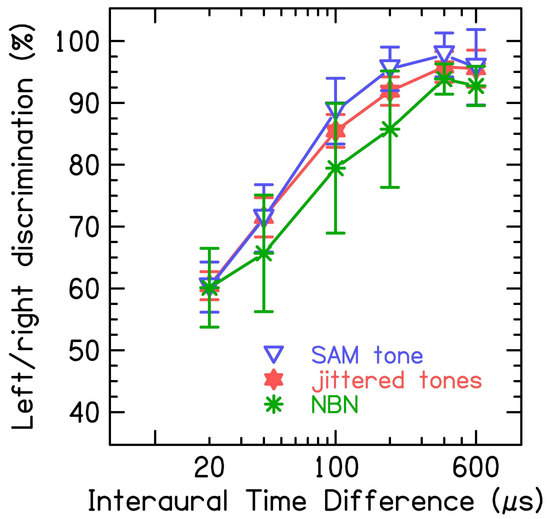


Figure 5.20: *The results for the jittered tones, the SAM tone, and the NBN at a CF of 500 Hz are shown with their mean values and their 95% confidence intervals.*

5.4.6 Discussion

For the four different stimulus types, pure tone, jittered tones, SAM tone, and NBN, the HI listeners were sensitive to ITD. The overall ITD sensitivity increased with increasing ITD. It often reached the ceiling at an ITD of 400 μs. The general performance was quite similar across HI listeners. For the SAM tone—a signal which contains periodic amplitude fluctuation—the sensitivity was found to be slightly but significantly higher than for all other stimulus types. Note that the JNDs calculated from the pure tone and SAM ones results did not reveal a higher performance for the SAM tones. This raises the potential problem of reducing the information contained in a psychometric function to a single parameter, the JND, as discussed in Majdak and Laback (2008). The direct comparison of the psychometric function is the more powerful method. For jittered tones and for the pure tone, similar ITD sensitivity was observed. This indicates that binaural jitter does not have an effect on ITD sensitivity in the low-frequency region. For NBN, the ITD sensitivity was slightly but significantly lower than for all other stimulus types. In general, even though all the effects reported are small, the results indicate that periodic amplitude modulation improves ITD sensitivity, while random amplitude modulation, as present in the NBN, appears to lower ITD sensitivity.

For the pure tone, NBN, and SAM tone, the ITD JNDs of HI listeners can be compared to those obtained by other studies (Hawkins and Wightman, 1980; Buus et al., 1984; Smoski and Trahiotis, 1986; Kinkel et al., 1991; Gabriel et al., 1991; Koehnke et al., 1995; Smith-Olinde et al., 1992; Lacher-Fougère and Demany, 2005). For pure

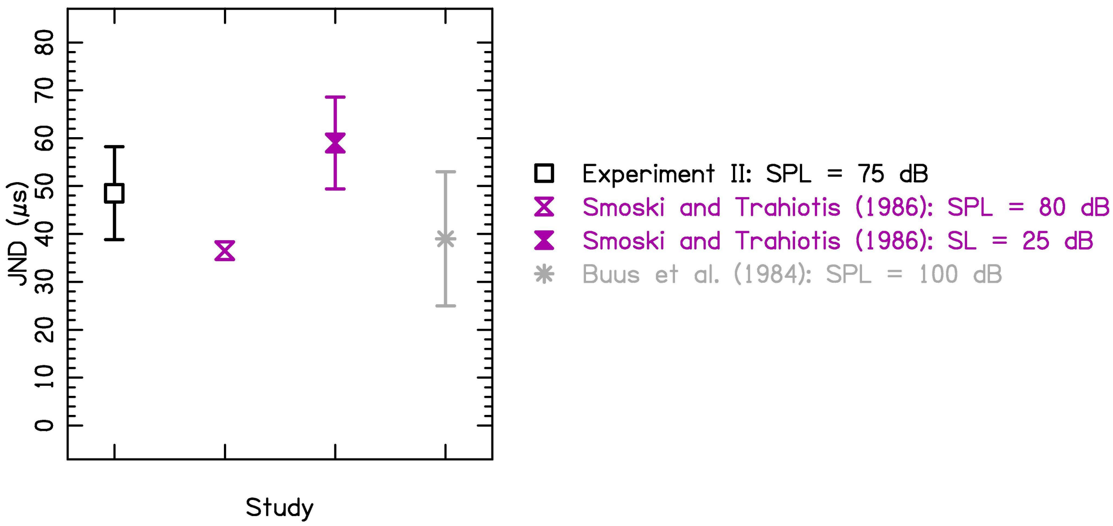


Figure 5.21: *Comparison between different studies with respect to their averaged ITD JNDs for pure tones centered at 500 Hz.*

tones, Buus et al. (1984) and Smoski and Trahiotis (1986) measured ITD JNDs which are shown in comparison to our results in figure 5.21. Interestingly, the ITD JNDs of our study were in the range of those obtained by Buus et al. (1984) and Smoski and

Trahiotis (1986), even though the latter study tested HI listeners with SNHL at high frequencies, but normal absolute thresholds at low frequencies, which may be expected to result in relatively better ITD JNDs for low frequencies.

For NBNs, our results on ITD JNDs are compared to those of Smith-Olinde et al. (1998), Gabriel et al. (1992), Kinkel et al. (1991), Smoski and Trahiotis (1986), and Hawkins and Wightman (1980) and are shown in figure 5.22. The ITD JNDs obtained by Smoski and Trahiotis (1986) show a higher performance than our data. This may be due to the fact that their HI listeners had mild SNHLs for low frequencies whereas ours had moderate SNHLs. The data from Hawkins and Wightman (1980) indicate the same, while some of the HI listeners tested, had only a mild hearing loss at low frequencies. The ITD JNDs of our study were in the range of the studies of Smith-Olinde et al. (1998), Koehnke et al. (1995), Gabriel et al. (1992), and Kinkel et al. (1991). While Smith-Olinde et al. (1998) and Gabriel et al. (1992) show, on average, higher ITD JNDs, Koehnke et al. (1995) and Kinkel et al. (1991) show, on average, poorer ITD JNDs in comparison to our study.

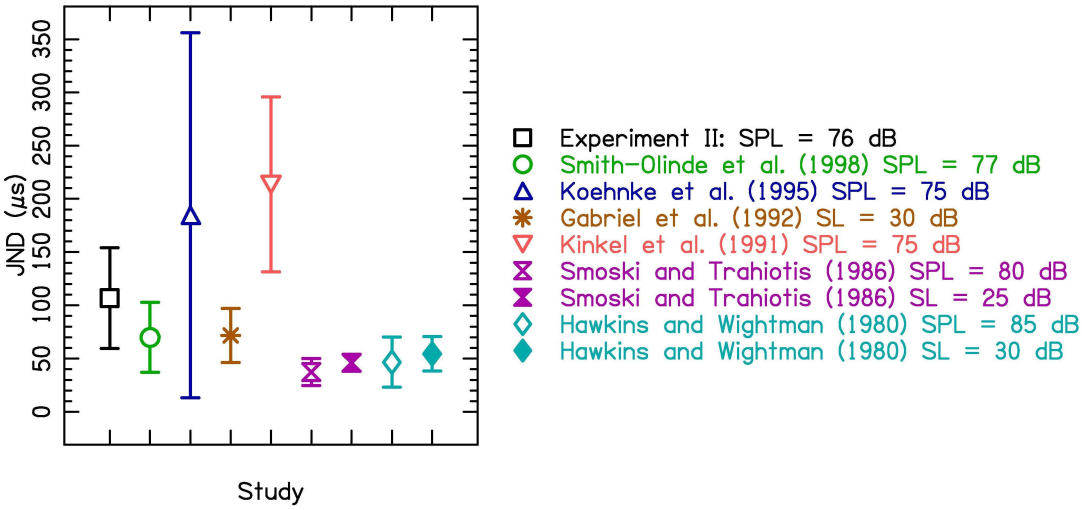


Figure 5.22: *Comparison between different studies with respect to their averaged ITD JNDs for NBN centered at 500 Hz.*

In the present study, the best performance was obtained for SAM tones. Only the study of Lacher-Fougère and Demany (2005) tested a similar type of stimulus as in the present study (f_c = 500 Hz and f_m = 50 Hz). Thus, a quantitative comparison appears to be possible between those two studies. Lacher-Fougère and Demany (2005) measured 191.7 μs and the present study measured 46.7 μs. This large difference (ratio of 4.1) between those two studies is probably due to the different types of ITD tested. Lacher-Fougère and Demany (2005) presented ITD only in the fine structure, while the present study used waveform ITDs. Setting the envelope ITD to zero, as done in Lacher-Fougère and Demany (2005), produces conflicting ITD cues in the fine structure and envelope that could result in lower ITD sensitivity.

The relatively similar performance for pure tones and other stimulus types with AM indicates little contribution of envelope ITD in the low frequency region. This is consistent with the study of Bernstein and Trahiotis (1985) for NH listeners. They found relatively little contribution of envelope ITD to the extent of lateralization in the 500 Hz region. This in turn indicates the dominance of fine-structure ITD in the low-frequency region for both HI and NH listeners.

Even though fine structure ITD appears to be the dominant cue at low frequencies for both HI and NH listeners, the absolute sensitivity for fine-structure ITD is reduced in HI listeners. This can be most easily seen by comparing JNDs for pure tones. Zwislocki and Feldman (1956) and Klump and Eady (1956) showed an average performance of 17 μs compared to 48.5 μs for the HI listeners in the present study, which implies a 2.9 times worse performance. The JNDs of the HI listeners of the present study are consistent with the JNDs for HI listeners reported in Buus et al. (1984). In the study of Buus et al. (1984), NH and HI listeners were directly compared. They tested five HI listeners with an, on average, 50 dB HL at 500 Hz (thus comparable to the present study) and obtained an average JND of 48.2 μs. The four NH listeners had an average JND of 23.3 μs. This implies a 2.1 times worse performance for the HI listeners in comparison to the NH listener in Buus et al.'s (1984) study.

Note that this ratio is 4.3 times lower than the ratio found by Lacher-Fougère and Demany (2005), who found a ratio of 9, comparing NH and HI listeners' performance

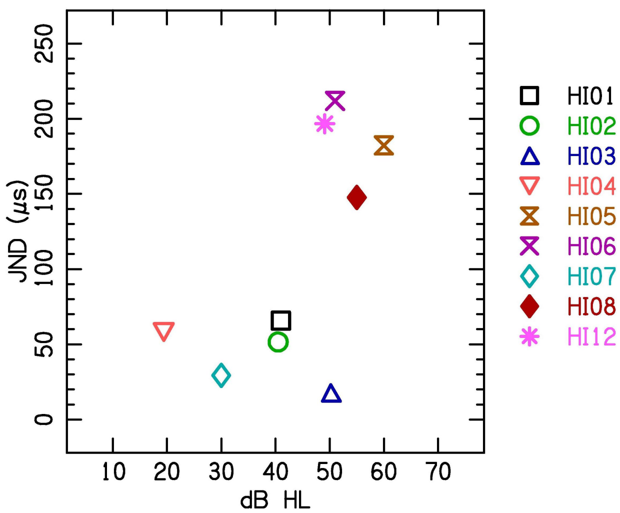


Figure 5.23: *For NBN, the JNDs of the HI listeners are shown as a function of the absolute hearing threshold at 500 Hz (for the ear with the greater loss in case of inequality).*

for fine-structure ITD in SAMs. Given the similar methods applied in the present study and in Lacher-Fougère and Demany (2005), it appears that the different outcomes are due to the interaction between fine structure and envelope ITD cues in Lacher-Fougère and Demany (2005). It is possible that this interaction has different consequences on ITD sensitivity in the two groups of listeners. It seems reasonable that using pure tones for comparing fine-structure ITD sensitivity is less affected by uncontrolled factors and thus are the better signals to describe the deficit in the fine-structure ITD perception in hearing impairment.

In figure 5.23 the JNDs are presented as a function of the absolute hearing threshold at 500 Hz of the ear with the greater loss (in case of inequality). The JNDs were not significantly correlated with the absolute hearing thresholds ($R^2 = 0.619, p = 0.076, N = 9$). This result is consistent with some previous studies (Lacher-Fougére and Demany, 2005; Smoski and Trahiotis, 1986) but not with other studies (e.g. Hawkins and Wightman, 1980). The present results suggest that other consequences of hearing loss besides the absolute threshold are determinant for ITD sensitivity.

Independent of the absolute hearing thresholds, it seems to be reasonable to assume that a deficit in the monaural encoding of the fine structure may be present. Similar suggestions have been made on the basis of different results (Hall et al., 1984; Buus et al., 1984; Lacher-Fougère and Demany, 1998; Moore and Skrodzka, 2002; Buus et al., 2004). Lacher-Fougère and Demany (2005) did not find an effect of the modulation frequency f_m for SAM stimuli at 500 Hz. This was consistent with the results reported for SAMs by Durlach et al. (1981), who also found no effect of f_m. This may indicate that for HI listeners the phase locking mechanism is impaired.

Chapter 6

General Discussion

The aim of this thesis was to obtain further insight into the ITD perception of HI listeners. This topic is of interest due to the fact that ITDs provide important information for localizing sound sources (e.g. Macpherson and Middlebrooks, 2002) and for understanding speech in noise.

Generally, there are several options to present binaural stimuli. NH listeners show symmetrical absolute hearing thresholds. Therefore, for NH listeners, there should be no marked difference in the perceived lateral position of stimuli presented either at equal SPL, SL, or loudness at the two ears or when adjusting the interaural level difference to centralize the auditory image. In contrast, for HI listeners, different methods of presenting the stimuli can lead to significantly different auditory image positions and thus different ITD sensitivity. In this study, the most comfortable levels at the two ears were determined and, based on those, the interaural level difference was adjusted to center the auditory image. This should have resulted in optimum conditions for ITD sensitivity measurements that are best comparable to NH listeners. For NBN at 4000 Hz, ITD sensitivity of the HI listeners tested in the present study, expressed in terms of JNDs, was higher than for the listeners in most previously reported studies (Koehnke et al., 1995; Kinkel et al., 1991; Smoski and Trahiotis, 1986; Hawkins and Wightman, 1980). This might be due to the fact that the present study used stimuli that were carefully adjusted to obtain a centralized auditory image, while the other studies presented the stimuli mostly at a fixed SPL or a fixed SL which can lead to an uncentered image. An exception is Kinkel et al. (1991), who also adjusted the stimuli for a centralized auditory image. Therefore, even though no strong conclusion can be drawn, using centered test stimuli is advantageous for measurements of ITD sensitivity.

In general, studies which compared ITD JNDs between HI and NH listeners found that some individual HI listeners show similar sensitivity to some individual NH listeners. However, when the group performance is evaluated, HI listeners are less sensitive to ITD than NH listeners. Comparison between the results of the present study and NH studies from the literature supports this conclusion.

There is large inter-individual variability in ITD sensitivity between HI listeners. A correlation to the hearing loss was not observed in the current study, neither at 500 nor at 4000 Hz, which is consistent with the studies of Smoski and Trahiotis (1986), Gabriel et al. (1992), Koehnke et al. (1995), and Lacher-Fougère and Demany (2005). However, the studies of Hawkins and Wightman (1980) and Hall et al. (1984) found a correlation. Currently, it does not seem to be possible to draw general conclusions about the degree of hearing loss on ITD sensitivity of HI listeners. This might be due to the usually relatively small number of HI listeners tested in psychoacoustic studies. However, other, more likely explanations may be the consequences of SNHL (as mentioned in chapter 4), which are not necessarily correlated with the degree of hearing loss. If the SNHL would simply function as an attenuator, presenting the stimuli at the same SL for HI and NH listener should resolve the discrepancy in ITD sensitivity. There are indications that this is not the case (Hawkins and Wightman, 1980; Smoski and Trahiotis, 1986; Gabriel et al., 1992; Smith-Olinde et al., 1998). The results of the present study lend further support to the view that other aspects of SNHL besides absolute hearing thresholds influence ITD sensitivity.

If the important sound information were "simply" the arrival time of neural impulses at the binaural cross-correlation processor, then it is difficult to understand why bilaterally symmetrical HI listeners show poor ITD sensitivity, assuming that the cross-correlation process is not impaired in SNHL. This seems to imply that the neural-spike patterns arriving at the binaural processor are disrupted.

The motivations for the experiments described in this thesis, were previous studies on the binaural adaptation phenomenon and especially on the recovery from binaural adaptation. For acoustic hearing, Hafter and Buell (1990) reported that a recovery from binaural adaptation can be induced by inserting a temporal gap or squeeze in the ongoing signal which leads to temporary changes in the spectrum. For electric hearing, Laback and Majdak (2008) found that using binaural-synchronized jitter, which causes only temporal changes in the ongoing signal, improves ITD sensitivity. Similar results were also found for NH listeners (Goupell et al., 2009) using jittered acoustic pulse trains. The recovery effect has not been tested before in HI listeners. Hence, the question arised if HI listeners also benefit from binaural jitter in ITD perception for high-frequency filtered pulse trains. Thus, in Experiment I binaurally-synchronized jittered pulse trains and periodic pulse trains, filtered at a high center frequency were tested. The onset cues were reduced by using long temporal ramps. The results for periodic pulse trains showed decreasing ITD sensitivity with increasing pulse rate. In many cases, for the periodic condition, JNDs could not be determined, which is consistent with previous results for acoustic hearing at the same pulse rates (Majdak and Laback, 2009; Goupel et al., 2009). In general, these results are consistent with the concept of binaural adaptation occuring at high modulation rates, as also occuring in NH and CI listeners. When introducing binaurally-synchronized jitter to the pulse trains, the ITD sensitivity largely increased for the HI listeners, which is consistent with the hypothesis that introducing a change in the ongoing signal causes a recovery from binaural adaptation. For 400-pps pulse trains, the high-sensitive HI listeners' performance for larger ITD values was limited by ceiling effects. Thus, the effect of binaural jitter was possibly under-estimated. Low-sensitive HI listeners showed an improvement for $k = 1/2$ compared to the periodic condition and a further improvement for $k = 3/4$. For 600 pps, the improvement from binaural jitter was generally large. There was already a significant improvement for $k = 1/4$. In agreement with previous studies on binaural jitter (Laback and Majdak, 2008; Goupell et al. 2009), the ITD sensitivity increased with increasing amounts of jitter.

NBNs were tested to compare the results to those for the pulse trains. The NBN contained temporal randomness in the envelope, which is comparable to the temporal randomness in pulse trains with larger amounts of jitter. For 400-pps trains, the HI listeners showed similar performance for pulse trains with $k = 1/2$ and NBN. For a larger amount of jitter ($k = 3/4$) the performance was even higher than for NBN. For 600 pps, the HI listeners showed similar performance for pulse trains with $k = 3/4$ and NBN. The latter result is supported by the study of Goupell et al. (2008) testing NH listeners. In summary, the results showed similar performance for pulse trains with larger amounts of jitter and NBN.

A recent study (Goupell et al., 2008) investigated the origin of the improvement in ITD sensitivity caused by binaural jitter using a model based on neural response properties in the auditory periphery and midbrain. Their intention was to compare changes in the neural response from binaural jitter to the corresponding behavioral changes. They showed that for the ongoing signal the synchrony in the neural spikes increases with increasing amounts of jitter. Also, the firing rate of the modeled MSO neurons increases with increasing jitter. The qualitative similarity in the psychoacoustically observed jitter effect between NH and HI subjects indicates that the underlying processes are similar. To model the ITD sensitivity and the effect of binaural jitter in the impaired ear, it would be useful to have physiological data on the timing characteristics of neural firing in SNHL. Studying the neural effects in impaired acoustic hearing may also lead to conclusions about mechanisms underlying normal acoustic hearing.

Experiment II tested the ITD sensitivity of the same HI listeners tested in Experiment I to different types of low-frequency stimuli. The effect of introducing binaurally-synchronized random frequency modulation to a pure tone (jittered tone) was shown to have no effect on ITD sensitivity. As illustrated by Blauert (1981), frequency modulation of a pure tone is converted into amplitude modulation at the output of the auditory filters. Thus, the result implies that adding random amplitude modulation to a pure tone in the low-frequency region does not enhance ITD sensitivity. The results for NBN showed even a slight decrement in ITD sensitivity compared to the pure tone. It was further found that adding periodic amplitude modulation to a pure tone slightly-but-significantly improves ITD sensitivity. Taken together, these results indicate that while the added periodic amplitude modulation obviously supports the extraction of the ITD information, replacing the periodic amplitude modulation by a random amplitude modulation does not cause an additional advantage, as might have been expected based on the results for binaural jitter at high frequencies. Even though the presence of binaural adaptation at low frequencies was not directly tested, the lack of improvements from binaurally-synchronized randomness in the envelope does not suggest the presence of binaural adaptation. The generally small effect of amplitude modulation indicates the dominance of fine-structure ITD in the low-frequency region in HI listeners. This is consistent with NH listeners, for which fine-structure ITD is known to be a stronger lateralization cue than envelope ITD at low frequencies (Bernstein and Trahiotis, 1985).

The present study indicates that our HI listeners, while showing comparable cochlear hearing loss at low frequencies, yield less reduction in fine-structure ITD sensitivity (relative to NH listeners) than the HI listeners tested in Lacher-Fougère and Demany (2005). Those authors suggested that in HI listeners fine-structure ITD sensitivity is more impaired than envelope ITD sensitivity. It is thus interesting to compare the relative impairment between low frequencies and high frequencies in the HI listeners of the present study. For pure tones at 500 Hz, the HI listeners of the present study and the NH listeners of Zwislowski and Feldman's (1956) study were compared. The ratio of ITD JNDs is 2.9. This can be compared to Buus et al. (1984), who measured JNDs for pure tones at 500 Hz in both HI and NH listeners and found a ratio of 2.1. For NBN at 4000 Hz, the ratio of JNDs between the HI listeners of the present study and the NH listeners of Goupell et al. (2008) were compared. The ratio is 2.1, see table

5.7. These ratios lead to the comparison between 500 Hz and 4000 Hz. It should be noted beforehand that the relative degradation of the HI listeners of the present study at low frequencies is possibly underestimated, because the absolute hearing thresholds at 500 Hz are 11 dB lower than at 4000 Hz. The degradation in ITD sensitivity seems to be slightly stronger for low-frequency fine-structure ITD than for high-frequency envelope ITD. However, the difference seems to be much smaller than indicated by Lacher-Fougère and Demany (2005), who tested fine-structure and envelope ITD sensitivity by attempting to separate these two cues at a given frequency region.

There are also practical application of the results. For high frequencies, introducing binaural jitter via hearing aids may improve ITD sensitivity for HI listeners. Especially in reverberant environments where fine-structure ITD cues may be disrupted, the relative contribution of envelope ITD cues could be high, and thus improving envelope ITD sensitivity might be particularly helpful. For the low-frequency region, periodic amplitude modulation improves ITD sensitivity a little bit compared to an unmodulated pure tone, but irregular amplitude modulation has been shown to have no or even a detrimental effect. Thus, there appears to be little room for improvement in the low-frequency regions.

Chapter 7

Summary and Conclusion

In summary, ITD sensitivity was measured in thirteen listeners with a moderate sensorineural hearing loss in two lateralization discrimination experiments.

The first experiment tested pulse trains with and without binaural jitter and narrow-band noise centered at a center frequency of 4000 Hz. The conclusions are:

- Introducing jitter in the stimulus timing improves ITD sensitivity, in particular for the pulse rate of 600 pulses per second.
- For narrow-band noise, ITD sensitivity of HI listeners was similar to that for 400 pulses per second trains with moderate jitter and to that for 600 pulses per second trains with large jitter. This similarity is consistent with previous studies with normal hearing subjects.
- Overall, the effect of temporal randomness can be generalized to normal and impaired acoustic hearing and electric hearing.
- It is suggested that introducing binaurally-synchronized jitter in hearing aids may lead to improved ITD sensitivity.
- Stimuli which are adjusted to evoke a centralized auditory image appear to cause optimal ITD sensitivity.

- No correlation between ITD sensitivity and the absolute hearing thresholds was found.

The second experiment tested pure tones, jittered tones, sinusoidally-amplitude modulated tones, and narrow-band noise centered at a center frequency of 500 Hz. The conclusions are:

- Introducing randomness into the envelope modulation does not improve ITD sensitivity.
- Periodic amplitude modulation improves ITD sensitivity slightly but significantly.
- ITD in the fine structure appears to be the dominant cue and ITD in the envelope appears to contribute relatively little.
- No correlation between ITD sensitivity and the absolute hearing thresholds was found.

Appendix A

Psychometric Functions

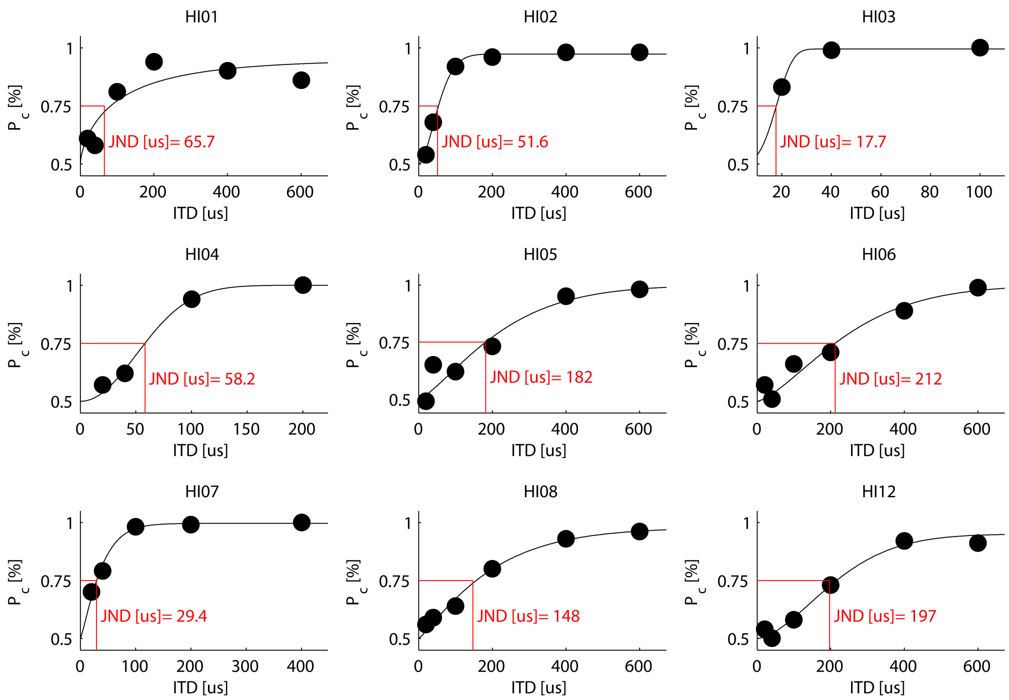


Figure A.1: *The psychometric functions for the NBN at a center frequency of 500 Hz*

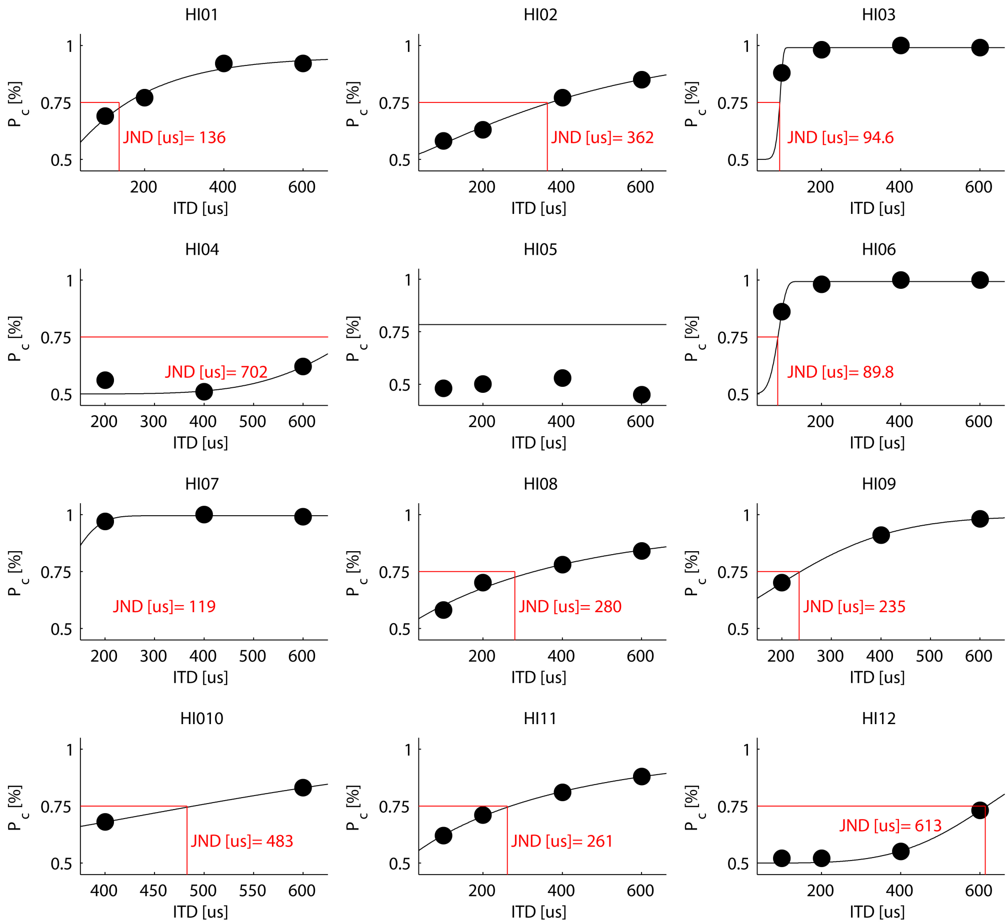


Figure A.2: *The psychometric functions for the 400 pps pulse train with a* k = *3/4 at a center frequency of 4000 Hz. For HI03, HI06, and HI07, the measured JND is most probably lower than estimated from the psychometric function. For HI04 and HI05, the psychometric function was not determined.*

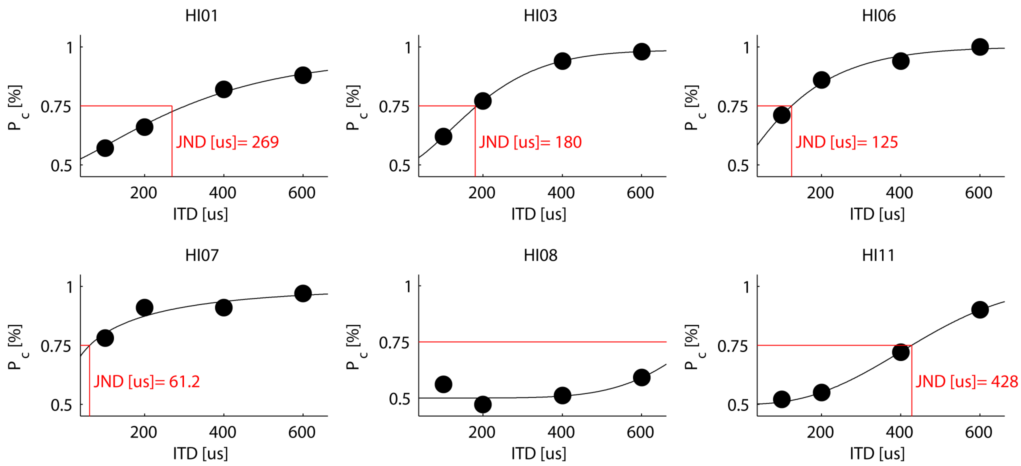


Figure A.3: *The psychometric functions for the 600 pps pulse train with a* k = *1/2 at a center frequency of 4000 Hz. For HI08, the psychometric function was not measureable.*

Appendix B

Experiment II: Stimuli Waveform and Spectra

For the experiment II, the stimuli waveforms and spectra are plotted. Note that the jittered tone with k = 0.0 was only additionally used, while testing jittered tones in a randomized order. Otherwise a pure tone was used.

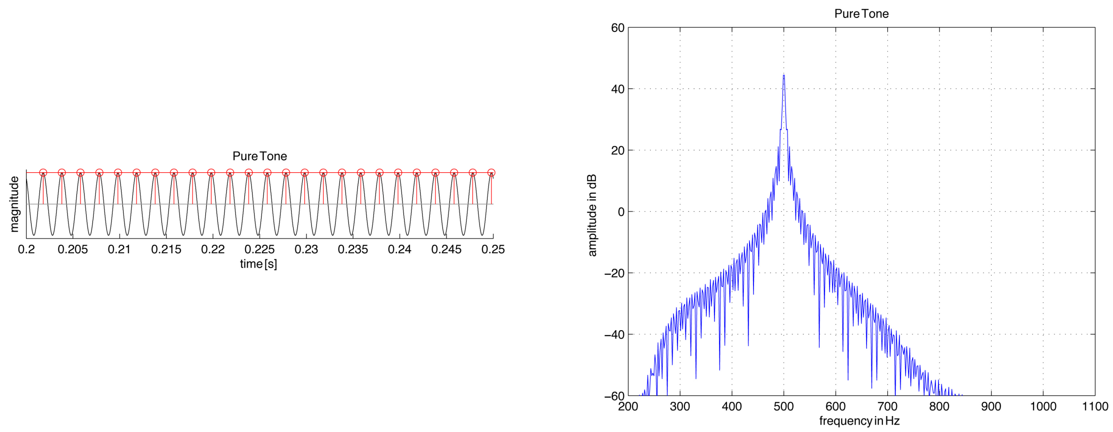


Figure B.1: *Stimuli waveform (left) and the spectra (right) for the pure tone are shown.*

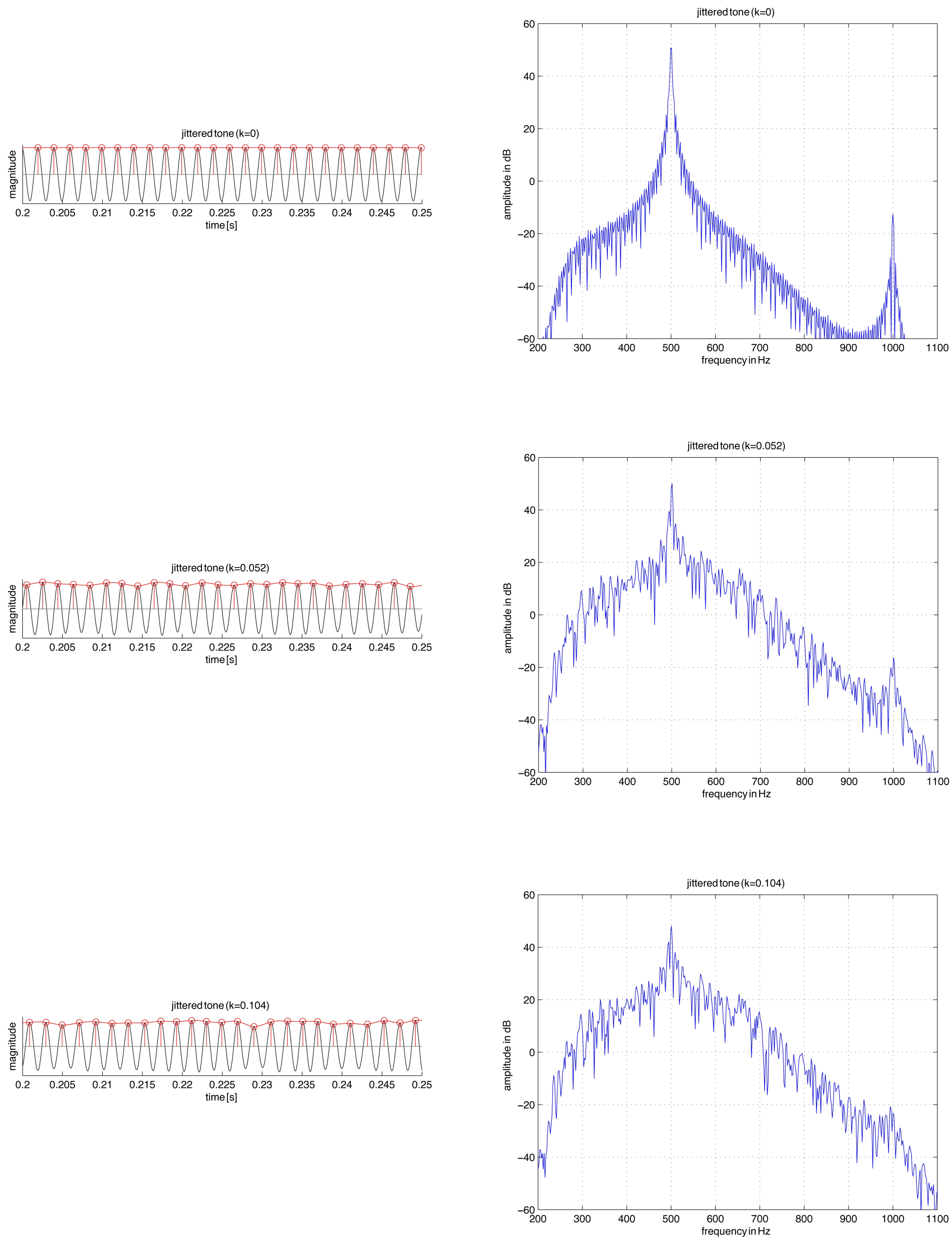


Figure B.2: *Stimuli waveform (left) and the spectra (right) for the jittered tones with* k = *0.0,* k = *0.052, and* k = *0.108 are shown.*

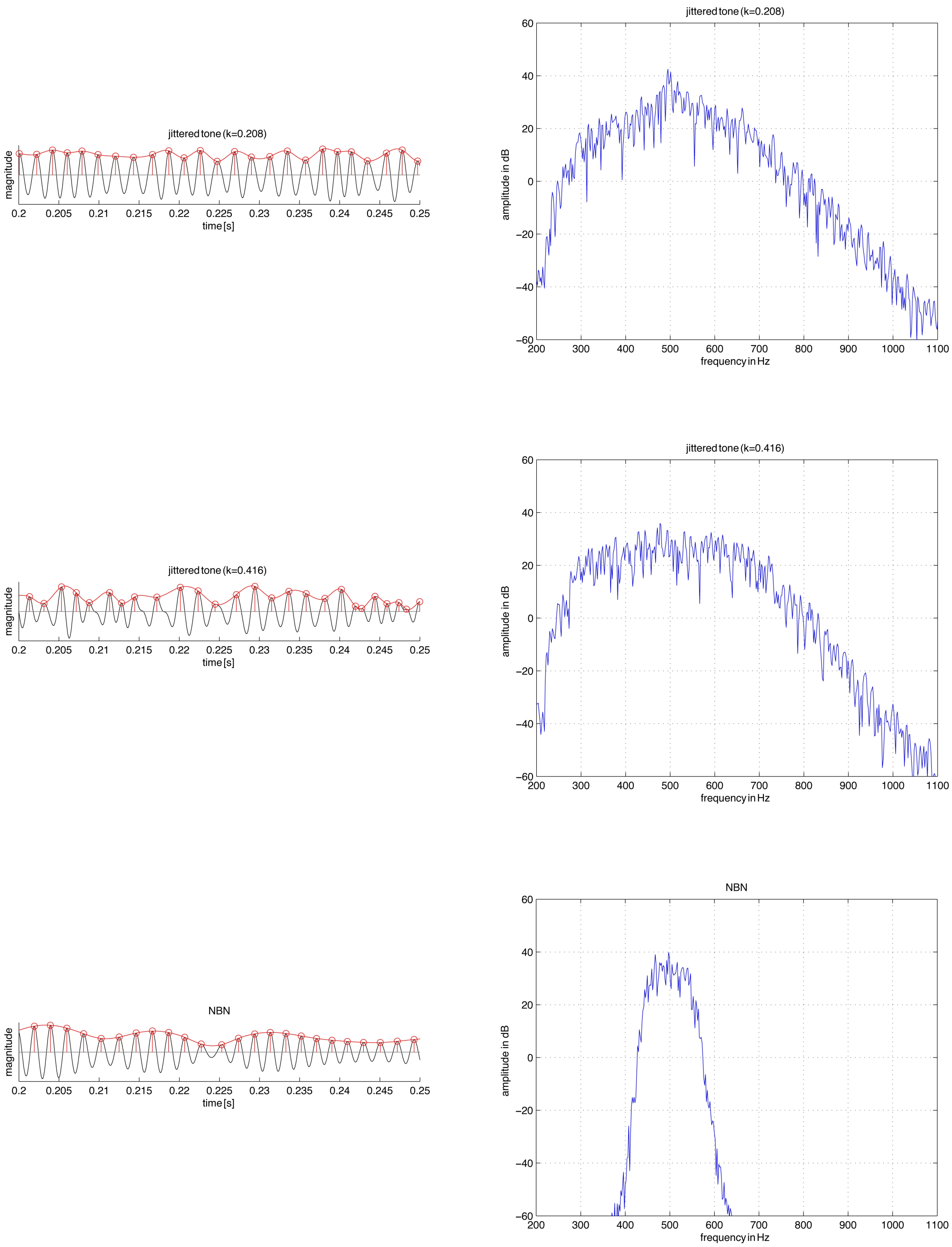
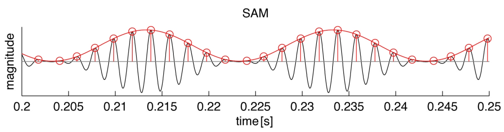


Figure B.3: *Stimuli waveform (left) and the spectra (right) for the jittered tones with* k = *0.208* k = *0.416, and NBN are shown.*



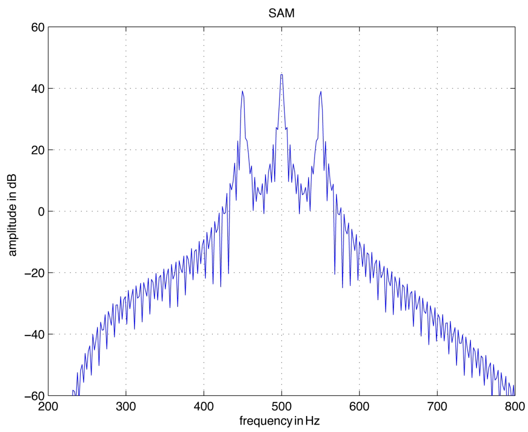


Figure B.4: *Stimuli waveform (left) and the spectra (right) for the SAM tone are shown.*

Appendix C

ExpSuite

"ExpSuite" is a software framework suite used for implementing psychoacoustical experiments. With its various modules, stand-alone applications can be developed and extended. The framework supports acoustic stimulation as well as electric stimulation with CIs. For the present thesis, the acoustic stimulation was used. ExpSuite comprises libraries implemented for software modules in Visual Basic, Matlab, and Pure Data (PD). These three components work together as follows: Visual Basic provides the graphical user interface, gives control over the experiments, and serves as a link between the two other modules. Matlab creates and inspects the stimuli and visualizes the results. PD is used to playback the stimuli.

Visual Basic forms the core of the framework. It has the purpose that for a new psychoacoustical experiment, an already existing application can be adapted by implementing new and specific functions. Visual Basic is directly linked to Matlab to generate signals in a vector-oriented way. Thus, the signals are processed by Matlab and sent back to the Visual Basic core. The acoustic stimulation is done by the real-time signal processing environment PD. The interaction between Visual Basic, Matlab, and PD can be controlled using a Graphical User's Interface. Additionally, to allow mixing signals and outputting them to a multi-channel sound interface, PD includes units enabling the user to generate signals in real-time, do complex filtering, and record sounds simultaneously with playback. Furthermore, its graphic environment module provides real-time visualization tools. PD uses the ASIO drivers, which feature data acquisition with low latencies and multi-channel signal presentation. PD and Visual Basic are linked to a network connection, so that for the processing of computationally intensive PD tasks additional computers within the network can be used.

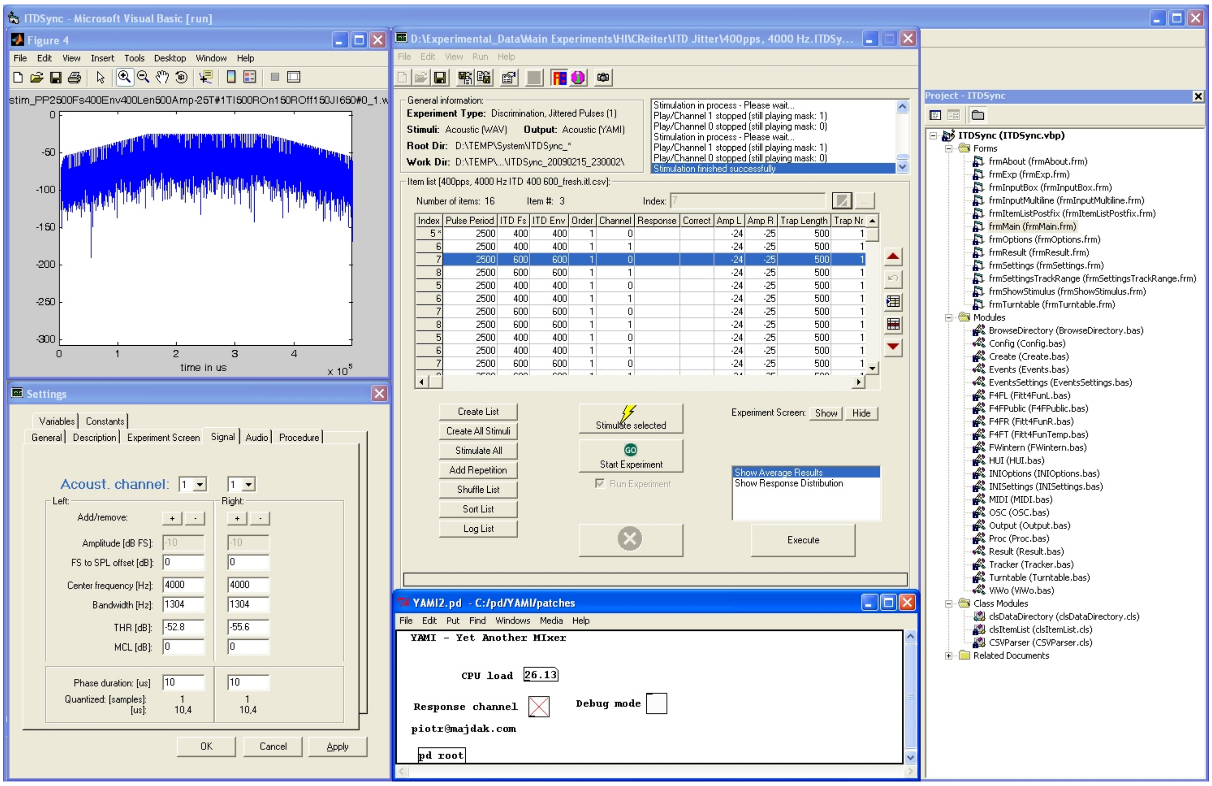


Figure C.1: *Different interfaces of ExpSuite*

Appendix D

Subject Recruitment

The subject recruitment process was long and difficult. It was appropriate and non-coercive. The subjects were chosen due to specific requirements as mentioned in subsection 5.1.1. These requirements were given to different appropriate institutions, otorhinolaryngologists and hearing aid technicians (listed below). All of them were contacted by myself and with the help of Bernhard Laback. They were asked to motivate potential subjects but not to unduly influence or force them to participate in the experimental study. An invitation letter with information about the study was given to the respective institution in case that a subject was willing to participate.

I want to thank all institutions for their interest in my thesis and especially the persons who helped me in the recruitment process.

- Mr. Lehner from Neuroth Corp., who organized four subjects to participate in the study.

- VOX - Schwerhörigenverband Österreichs (www.vox.at), especially Mag. Tamegger and Mr. Senkyr. Thanks to them three subject were able to participate.

- Dr. Stefan-Marcel Pok (Landesklinikum St. Pölten), who organized one subject to participate.

- One person has responded to a leaflet which was distributed at an otorhinolaryngologist's ordination.
- The other four subjects were friends.

I also gratefully thank the HNO Gesellschaft Österreich (ear, nose, and throat association of Austria) for publishing the call for recruiting subjects via their public page (www.hno.at).

Appendix E

Abbreviations

ANOVA	analysis of variance
AM	amplitude modulation
AVCN	antero-ventral cochlear nucleus
AVE	average
BTE	behind-the-ear hearing aid
BW	bandwidth
CF	characteristic frequency or center frequency
CI	cochlear implant
CN	cochlear nucleus
DCN	dorsal cochlear nucleus
EE	excitatory-excitatory
EI	excitatory-inhibitory
HA	hearing aid
HI	hearing impaired
HL	hearing level
IC	inferior colliculus
ILD	interaural level difference
IPD	interaural phase difference

IPI	inter-pulse-interval
ITD	interaural time difference
ITE	in the ear hearing aid
LSO	lateral superior olive
MSO	medial superior olive
NBN	narrow-band noise
NH	normal-hearing
PVCN	postero-ventral cochlear nucleus
RM	repeated-measures
SAM	sinusoidally amplitude modulated or modulation
SL	sensation level
SNHL	sensorineural hearing loss
SOC	superior olivary complex
SPL	sound pressure level

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