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## Identification of the Smallest Perceivable Interaural Time Differences

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A thesis submitted in partial fulfillment of the requirements for the Master of Science degree in Neuroscience

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## Abstract

Several studies have reported human threshold interaural time differences (ITDs) near 10  $\mu$ s; however, none of these studies aimed to find the stimulus and experimental method that yields the lowest threshold. The goal of the current study is to systematically determine the stimulus and the experimental paradigm that yields the smallest threshold ITD and to provide an accurate reference value. We systematically varied seven parameters: stimulus waveform, stimulus level, stimulus duration, adaptive versus constant stimulus procedure, number of reference intervals, inter-stimulus pause duration, and inclusion versus exclusion of onset and offset ITD. The condition yielding the lowest threshold ITD was band-pass filtered noise (20-1400 Hz), presented at 70 dB SPL, with a short inter-stimulus pause of 50 ms, and an interval duration of 0.5 s. The average threshold ITD for this condition at the 75% correct level was 7.0  $\mu$ s for nine trained listeners and 17.7  $\mu$ s for 52 untrained listeners.

## Keywords

Auditory neuroscience, binaural hearing, psychoacoustics, interaural time difference, forced choice task, listening experiment, threshold ITD, diotic listening task

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## List of Abbreviations

2 AFC	Two-alternative forced choice
AFC	Alternative forced choice
$\mu$ s	Microsecond
avg.	Average
cm	Centimeter
DHLL	Dorsal nucleus of the lateral lemniscus
dB	Decibel
EE	Excitatory-excitatory type neuron
ENV	Temporal envelope
F	Female
$f$	Frequency
$f_0$	Fundamental Frequency
HL	Hearing Level
Hz	Hertz
IC	Inferior colliculus
ILD	Interaural level difference
ITD	Interaural time difference
kHz	Kilohertz
L/R	Left/Right
LSO	Lateral superior olive
M	Male
MHz	Megahertz
MNTB	Medial nucleus of the trapezoid body

ms	Millisecond
MSO	Medial superior olive
N	Number of participants
s	Second
S	Subject
SBCs	Spherical bushy cells
SPL	Sound Pressure Level
<i>t</i>	Time
TFS	Temporal fine-structure

## Chapter 1

### 1 Introduction

Humans and animals use their ears to localize sounds from their surroundings.

This localization process assists animals to detect food sources, sense potential danger of predators through directional cues and support humans during social interactions. To localize sound, the need for two ears is crucial. The information, from the differences in the sound's time of arrival and level, given to the two ears assists in determining the location of the sound's source (Strutt, 1907).

#### 1.1 Acoustical Basis for Spatial Hearing

The auditory system can estimate the sound source location by using the acoustical cues that result from a combination of sound waves from the target interacting with its own reflections from the room, the listener's head, and upper body. (Yost, 2013; Macpherson & Middlebrooks, 2002).

Accurate azimuthal sound localization is facilitated through so-called 'binaural hearing,' which is exploiting interaural level differences (ILD) and interaural time differences (ITD) (Strutt, 1907). Strutt primarily used pure tone stimuli to conduct localization experiments and proposed the 'Duplex Theory' that explains the left-right localization of tonal stimuli. According to this theory, high frequency sounds (over 2 kHz) are primarily localized by ILDs, which are caused by acoustical shadowing effect of the head (head blocking the sound waves that is traveling to the ear further from the sound source), and low frequency sounds (below about 1 kHz) are localized dominantly by ITDs (Fig. 1) (see also Macpherson & Middlebrooks, 2002; Keating, Nodal & King, 2014; Smith & Price, 2014; Grothe, Pecka & McAlpine, 2010).

For humans and many animals, ITD is the major acoustical cue for azimuthal sound localization (Benichoux, Rébillat & Brette, 2016). The magnitude of the ITD is influenced by several factors, such as the head size (distance between the two ears), and the azimuthal position of the sound (Smith & Price, 2014). A sound arriving from the midline ( $0^\circ$  azimuth angle) would reach each ear at the same time, regardless of the head size and sound frequency (Smith & Price, 2014). The ITD increases as the sound source is located at larger azimuth angles (Smith & Price, 2014). The maximum ITD will occur when the sound is either directly to the left or directly to the right of the head ( $90^\circ$  azimuth angle) (Fig. 2, point B). The bigger the size of the head, the longer the time for the sound waves to reach the opposing ear. For typical adult humans with a head diameter of approximately 16 cm, the maximum ITD is approximately 600 -700  $\mu$ s. Sign of the ITD (i.e. left ear leading or right ear leading) depends if the source is to the left or right of the head.

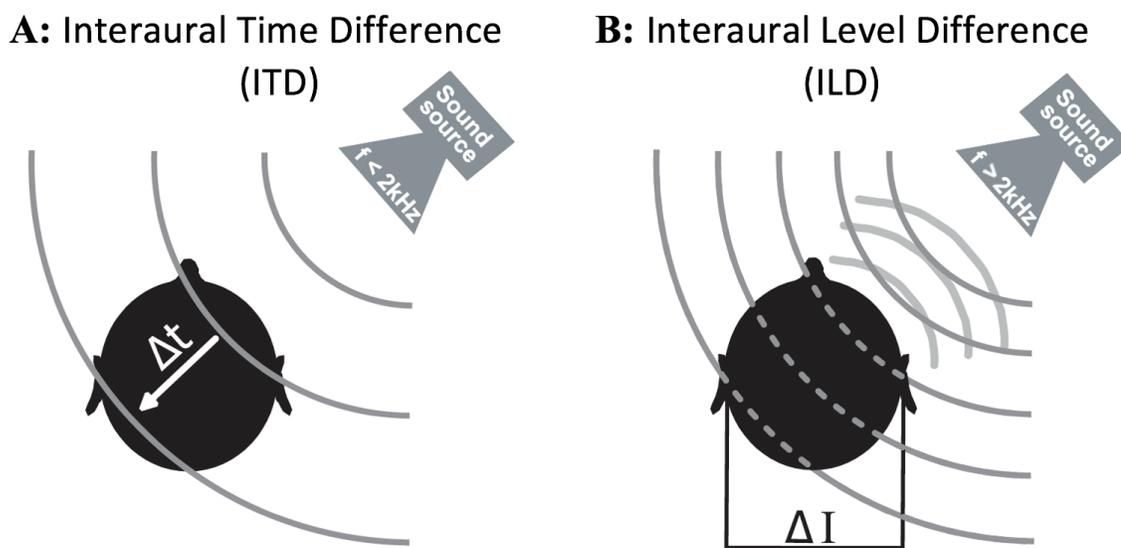


Figure 1. Acoustical cues for sound localization. A: The difference in arrival time of the sound waves between two ears ( $\Delta t$ ) is used to localize the sound source (ITD). B: At frequencies higher than 2 kHz, the acoustic head shadow effect produces an increasing difference in level of the sounds between the two ears ( $\Delta I$ ), which is used to localize a sound source (ILD). (© From “Mechanisms of sound localization in mammals,” by B. Grothe, M. Pecka, and D. McAlpine, 2010, *Physiological reviews*, 90, p. 985. Copyright 2010 by the American Physiological Society. The use of this image is by permission of the authors.)

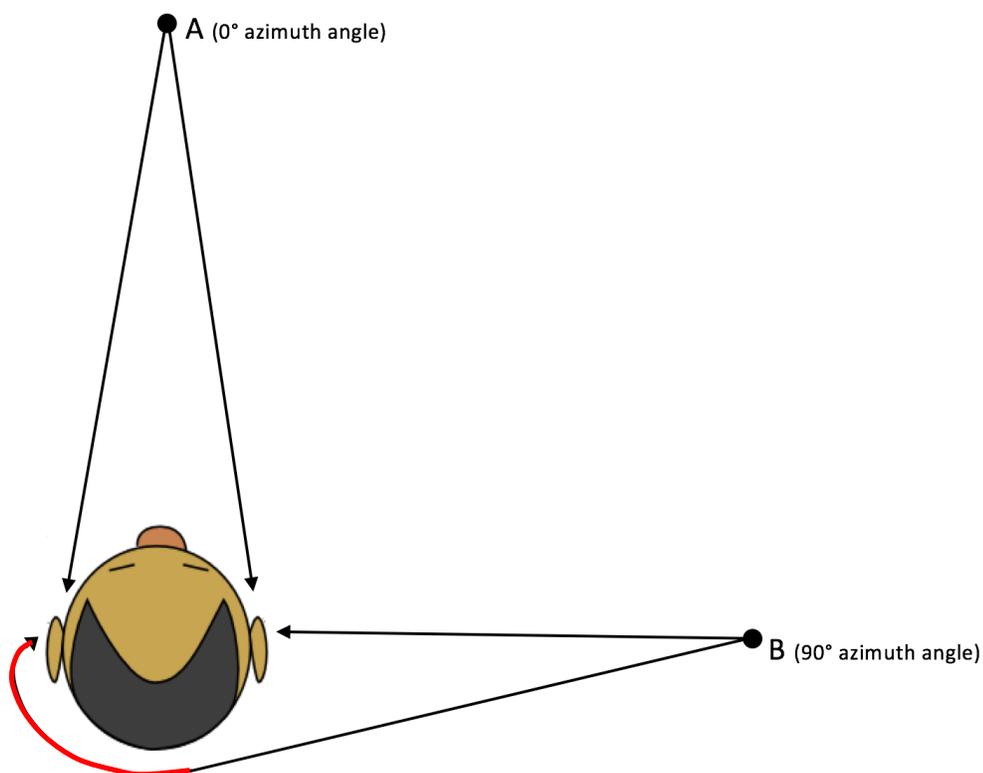


Figure 2. When the tone source is directly in front of the listener, the sound waves reach the left and the right ears at the same time (point A). When the tone is off to the side (point B), the sound waves reach the listener's right ear before they reach the left ear. To reach the left ear, the sound wave would have to diffract around the head (red curve). (Listener's head image: © Adapted from "Hrtf diagram" by Oarih~commons wiki, 2005, *Inkscape*. Creative Commons License: CC BY-SA 3.0.)

## 1.2 The Auditory System

After the sound waves arrive at the ears, they then travel through the external auditory ear canal and set the tympanic membranes into vibration (Fig. 3). The vibration of the tympanic membrane is transmitted through the middle ear to the inner ear by the middle ear ossicles. The middle ear ossicles perform two functions. One function is the impedance matching, which is to effectively transmit the vibrations from the air into the

fluid of the cochlea. If there were no middle ears, most of the sound would reflect off the cochlea because of the impedance mismatch (impedance in fluid is much bigger than in air). The middle ear ossicles overcome this impedance mismatch by increasing the sound pressure. The sound pressure increases as it travels from a large area of the tympanic membrane (ear drum) to the small area of the stapes (the third tiny bone – a part of the middle ear ossicles), along with the lever action of the ossicles (Kim & Koo, 2015). Another function is providing the cochlea with protection against loud low frequency sounds. The middle ear ossicles provide protection through the middle ear reflex, which tenses a muscle that stiffens the vibration of the ossicles to reduce the intensity of low frequencies being transmitted to the cochlea (Mukerji, Windsor & Lee, 2010).

The vibrations from the ossicles and the oval window displace the cochlear fluid at the round window, which initiates a wave of displacement (traveling wave) on the basilar membrane that travels from the base to the apex. Unusual for a snail-like structure the basilar membrane is narrower and stiffer at the base than at the apex causing different resonance frequencies along the basilar membrane. Therefore, different locations along the basilar membrane are effectively tuned to different frequencies, which establishes a spatial arrangement called tonotopic organisation. High frequencies are picked up at the base, whereas low frequencies resonate at more apical regions. Functionally this can be understood as an array of overlapping band-pass filters, often referred to as auditory filters (Rosen, Baker & Darling, 1998), and all these filters are operating simultaneously. A given location on the basilar membrane acts like a band-pass filter with its place-specific centre frequency and bandwidth (Yost, 2013). This means a specific location of

the basilar membrane will vibrate the best to only certain frequencies and attenuate other frequencies outside that location's bandwidth.

Along the length of the basilar membrane, there is the sensory epithelium called organ of Corti which contains two kinds of hair cells with stereocilia (hair-like projections at the top of the hair cells): Outer hair cells and inner hair cells. Outer hair cells amplify the mechanical movement of the basilar membrane in response to the tone near the characteristic frequency. Inner hair cells transduce mechanical vibration from the basilar membrane into bioelectric activity, and this bioelectric activity, in the form of neurotransmitter release, generates action potentials in the auditory nerve fibers.

The fundamental property of the action potentials of the auditory nerve fibers is its synchronization to temporal stimulus features (Verschooten & Joris, 2014). At low frequencies, the discharge probability is maximal at a preferred phase angle in the cycle of the sinusoidal stimulus (Rose et al., 1967). This type of neural synchronization to the stimulus waveform's fine structure is called phase locking (Verschooten & Joris, 2014). At very low frequencies (below about 400 Hz), neurons can fire action potentials at every cycle, which causes the frequency of action potential to be equal to the frequency of the stimulus waveform presented (Verschooten & Joris, 2014; Kim & Koo, 2015; Moon & Hong, 2014). At intermediate frequencies, neurons cannot fire every cycle because the neuron's firing rate is limited by the refractory period (unresponsive period after stimulation period), but if an action potential is produced it is still phase locked. In mammals, phase locking weakens around 1 kHz, because sound waves above this frequency cause a reduction in the size of the sinusoidal component of the inner hair-cell receptor potential (Moon & Hong, 2014; Palmer & Russel 1986). One form of temporal

information of the time signal at a specific position on the basilar membrane is called temporal fine structure (TFS, which can be obtained using Hilbert decomposition), and is represented by the phase locking at low and medium frequencies. Another form of temporal information called temporal envelope (ENV) is represented by the phase locking to amplitude variations (Palmer & Russel, 1986; Moon & Hong, 2014; Moore, 2008). TFS is the rapid oscillation rate that is similar to the center frequency of a stimulus, whereas ENV is characterized by the slower amplitude variations of the stimulus over time (Moon & Hong, 2014; Moore, 2008). As said above, phase locking is spike synchronization to temporal stimulus features. Therefore, phase locking of both left and right inputs to a binaural neuron is a strict prerequisite for ITD sensitivity. (Grothe & Park, 1998; Nelson, Mizumori & Weiner, 2013; Joris & Verschooten, 2013). In humans, phase-locking to the TFS can be exploited for ITD sensitivity up to 1400 Hz (Brughera et al., 2013).

After the cochlea translates the mechanical vibrations into neural responses, the neural information travels through the auditory nerve to the cochlear nucleus (Fig. 4). The main tracts and nuclei above the cochlear nucleus are stimulated binaurally, which means neural information from both ears will stimulate these structures. From the cochlear nucleus, the tracts lead to the superior olivary complex, where most of the initial binaural interaction occurs (Fig. 4) (Yost, 2013). The superior olivary complex is divided into three primary nuclei: Medial superior olive (MSO), lateral superior olive (LSO), and Medial nucleus of the trapezoid body (MNTB). Neurons in the MSO are primarily sensitive to ITD. The MSO primarily receives bilateral excitation from the spherical bushy cells (SBCs) in the cochlear nucleus (Grothe, 2003; Tollin, 2003). The MSO can

code ITD by coincidence-detection of the excitatory synaptic neurons (Grothe & Sanes, 1993). A single EE (excitatory-excitatory) type neuron in the MSO nucleus needs coincident inputs (spikes from the left and right that arrive simultaneously) to generate an action potential (i.e. increase the neuron's firing rate). The coincidences need to be precise, i.e. on a microsecond scale, in order for the neuron to convey the information reliably. If the relative timing of inputs is preserved through phase-locked inputs, the MSO output rate is effectively coding the stimulus ITD. Neurons in the LSO primarily code ILD. LSO receives excitatory inputs from the ipsilateral cochlear nucleus and inhibitory inputs from the contralateral cochlear nucleus (Tollin, 2003). The output from both MSO and LSO is then sent to the dorsal nucleus of the lateral lemniscus (DNLL), from there it is sent to the inferior colliculus (IC). The IC projects to the medial geniculate body, which, in turn, projects to the primary auditory cortex (Yost, 2013).

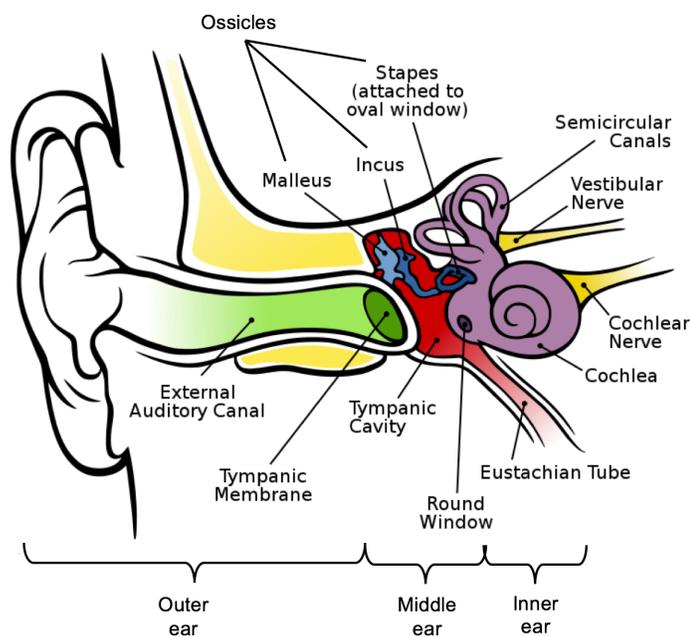


Figure 3. Anatomy of the ear. (© Adapted from “Perception Space—The Final Frontier,” by L. Chittka and A. Brockmann, 2005, *PLOS Biology*, 3, e.137. Creative Commons License: CC BY 2.5.)

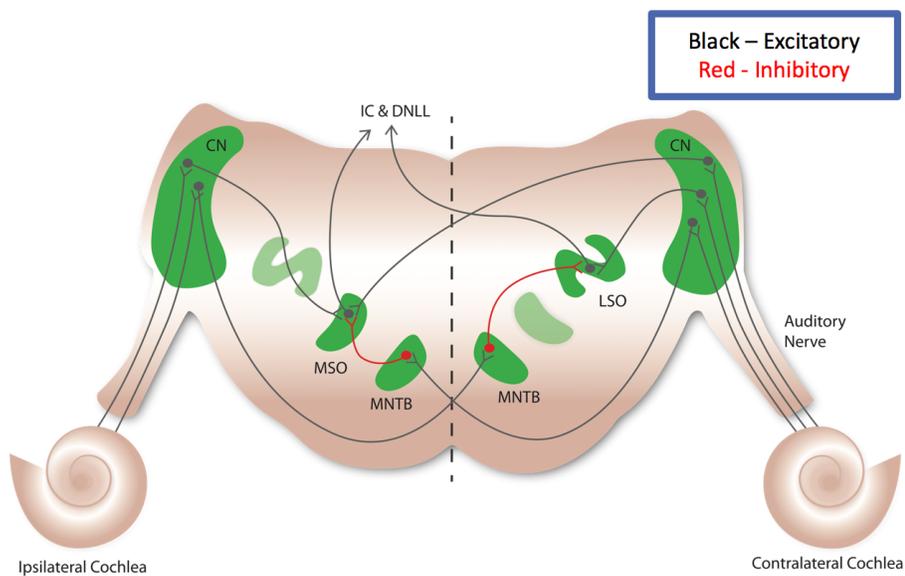


Figure 4. Cross sectional sketch of the main brainstem from the auditory pathway (© From “Models of the electrically stimulated binaural system: A review,” by M. Dietz, 2016, *Network: Computation in Neural Systems*, 27, p. 188. Copyright 2016 by Taylor & Francis. The use of this image is by permission of the author.)

### 1.3 Measurement Theory for ITD Sensitivity

The understanding of the overall function of the auditory system is investigated by various disciplines, especially by Neuroscience and Psychophysics (Plack, 2005). Auditory psychophysics, or psychoacoustics, is the psychological or behavioral study of hearing (Plack, 2005). In a psychoacoustic study, the participant is required to make a response to the presented sounds. The aim of psychoacoustic research is to determine the relation between the sounds (physical stimuli) and sensations produced in the participant (Plack, 2005).

The basis of classical psychophysics is the minimal signal energy that the participant can detect (Green & Swets, 1988). According to signal detection theory, the issue that the participant encounters when detecting weak signals is to decide (making a decision) whether a given sensory event was caused by a signal or by some type of random noise (Green & Swets, 1988). The decision-making process involves the participant observing the information acquired (the strength of the signal among the background noise), comparing that information to their criterion, and choosing one of the outcomes provided to them ('signal' and 'no signal') (Green & Swets, 1988).

The simplest psychophysical task that involves this issue of decision making is the yes-no task. In the yes-no task, the participant must respond whether the single stimulus on each trial contained the target or not (Green & Swets, 1988; Green, 1993). An example of the yes-no task is an audiogram. In an audiogram, the participant is asked to respond by clicking a button if they heard the stimulus (yes) or not clicking the button if they did not hear the stimulus (no).

In any one trial in the yes-no task there are two possible stimuli (signal or no signal) and two possible response (yes signal was presented or no signal was not

presented) (Green & Swets, 1988; Yost et al., 1974). The participant must choose either the stimulus (signal) or alternative stimulus (no signal) as a response for each trial (Green & Swets, 1988). The individual trials of this task are averaged and the estimates are made of the four probabilities that represents the stimulus-response matrix (Green & Swets, 1988). The probabilities of the stimulus-response matrix are: Hit, when the signal is present and the participant responds present; Miss, when the signal; is present and the participant responds absent; false alarm, when the signal is absent and the participant responds present; and correct rejection, when the signal is absent and the participant responds absent (Fig. 5) (Green & Swets, 1988). Of these four probabilities only two of them can provide independent information about the participant's performance. Once these two probabilities are determined, for an example the number of hits and false alarms, the other two probabilities can be determined by using the total number of each stimuli used by the experimenter (Green & Swets, 1988). The stimulus-response matrix can be utilized to determine the participant's performance accuracy (percent correct) and sensitivity ( $d'$ ). The proportion of correct responses (percent correct) can be calculated by adding the number hits and correct rejections and then dividing by the total number of responses. If two participants have the same accuracy, the sensitivity calculation would assist in determining which participant performed better. The  $d'$  for each participant would be computed by using z-scores for the hit rate and false alarm rate (Vermeiren & Cleeremans, 2012). The formula for  $d'$  is,  $d' = z(\text{FA}) - z(\text{H})$ , where the false alarm rate (FA) and hit rate (H) are the z-scores that corresponds to the right-tail probabilities (p-values) on a normal distribution (Stanislaw & Todorov, 1999). Therefore, even if two

participants have the same proportion of correct responses, the participant with a lower false alarm rate would have a better performance (better sensitivity).

	Respond " <u><i>Present</i></u> "	Respond " <u><i>Absent</i></u> "
Signal <u><i>Present</i></u>	<b>Hit</b>	<b>Miss</b>
Signal <u><i>Absent</i></u>	<b>False Alarm</b>	<b>Correct Rejection</b>

Figure 5. The Detection Matrix.

A disadvantage of using yes-no task is the tendency of the participant responding (response) ‘yes’ or ‘no’ affecting the performance. For an example, if the participant is biased towards saying the tone is ‘present’ to almost every trial presented, both the hit rate and false alarm rate would be high (the cost to increasing the number hits is paid in terms of false alarms) (Heeger, 1997). One way to eliminate this response bias is by using another well-known psychophysical task, the forced choice task (Green & Swets, 1988).

A typical form of forced choice task is two-alternative forced choice task (2 AFC) (Green & Swets, 1988). In this task, two observation intervals are provided (Green & Swets, 1988). A signal is always presented in either the first or second interval and the participant is forced to choose the one interval that mostly likely contained the signal. In every trial of a 2 AFC task, the participant receives both stimulus alternatives (‘signal’ and ‘no signal’), unlike in the yes-no task, in a random spatial or temporal order (Green & Swets, 1988). In the first interval, the participant’s decision is influenced by both their sensation and response bias. The same is true with the second interval. Since the response bias is constant and the participant is forced to choose the first or second interval, the

response bias cancels out. Similar to the yes-no task, participant's average responses from this task also estimate the four probabilities that represent the stimulus-response matrix. For example, if the participant incorrectly decided the signal was presented in the first interval it would be considered a false alarm, but if the participant correctly responds, the signal was presented in the second interval, it would be considered a hit. If the signal is too weak to be detected or the stimulus difference is too small to be noticed, the participant's performance would be at chance level (50% - equal hits and false alarm rates).

A left/right discrimination task can be conveniently measured as a 2 AFC task, because the left and right are two alternatives. This task is a special kind of 2 AFC task, because the participants are asked to determine the lateral position (instead of detecting the target interval) of the presented sound stimulus by comparing the two alternatives. The simplest case would therefore be a 1-interval 2 AFC task. An alternative is a 2-interval 2 AFC task, where one interval is left leading, the other one right leading. There are two possible ways of solving the left/right discrimination task. One way is the participants can map each interval of the stimulus presented on a lateralization axis and then determine the direction the stimulus was most towards (left or right). The second way is to view the transition between the two intervals as a lateral movement and then discriminate a movement from the left to the right from a movement from the right to the left.

As stated previously, the ability to discriminate between two stimuli can be expressed in terms of percentage correct responses as well as discrimination index,  $d'$  ("d-prime") (Plack, 2005).  $d'$  is a measure of a participant's ability to discriminate

between two stimuli.  $d'$  is defined as the difference between the means of the distribution divided by the standard deviation of the distributions (Plack, 2005; Levitt, 1971). The discriminability of a signal ( $d'$ ) increases with the signal (stimulus) strength.

For a task with a given number of alternatives,  $d'$  can be derived directly from the percent correct score. E.g., in the case of a two-alternative forced choice task, chance level is 50%, which corresponds to  $d'=0$ . For 3 AFC  $d'=0$  obviously corresponds to a 33% correct rate and 50% correct is already a  $d'=+0.6$  (Zwicker & Terhardt, 2013). As example, figure 6 shows the psychometric function from a 2 AFC task. Plotting percent correct on the ordinate and stimulus level (dB SPL) on the abscissa typically creates a cumulative Gaussian distribution (standard cumulative normal distribution), starting at chance level (Green & Swets, 1988).

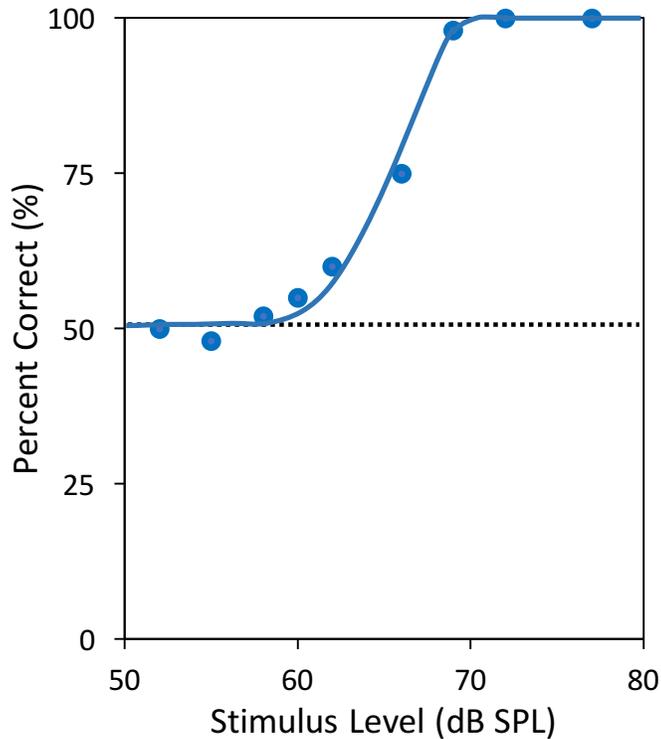


Figure 6. Psychometric function for a two-alternative forced choice discrimination task, portraying percent correct responses as a function of the stimulus level (dB SPL). Chance performance (50%) is shown by the horizontal dashed line.

Using the psychometric function, the signal level corresponding to a specific percent correct (given level of performance) can be determined. Such signal levels are commonly called the threshold (at the respective %-correct level) (Green, 1993; Wichmann & Hill, 2001). The two common thresholds used in differential sensitivity tasks are detection and discrimination thresholds. Detection threshold is the minimum signal strength needed to be detectable by the participant. Discrimination threshold is the smallest possible signal change needed to detect a difference in perception (just noticeable difference) by the participant. Just noticeable differences of ITD can be measured in an AFC (alternative forced choice) format by applying a target ITD to one

stimulus and another non-target ITD to the other intervals. The subject is asked e.g. to select the interval perceived further to the right.

Due to the gradual change of detectability with signal strength and the probabilistic response behaviour, determination of a threshold is not straightforward. Certainly many isolated AFC trials at several signal levels are necessary. Multiple procedures have been suggested for this important task. The most direct method is the so-called constant stimulus procedure: The participant is given a fixed set of AFC trials at several pre-defined signal strengths (Green & Swets, 1988). This conventional method was already indirectly introduced previously when the psychometric function was introduced -- the performance (proportion of correct responses) from this procedure can plot a psychometric function, which can be used to determine thresholds at corresponding percentages. Pilot experiments are usually performed to determine the fixed stimuli needed to be utilized in this procedure (Dai, 1995). The issue with this procedure is that it is very time consuming (Levitt, 1971).

An alternative are adaptive procedures, which are less time consuming, and typically have a higher efficiency (Levitt, 1971; Leek, 2001). A popular adaptive procedure is the transformed up-down procedure. It often starts with easily detectable stimuli and after every correct or wrong response that occurred in the previous trial or sequence of trials, the detectability of the stimuli would decrease or increase respectively in the subsequent trial (Levitt, 1971). Through the staircase-like structure (up and down), it will converge to a threshold at a certain percent correct performance level on the psychometric function (Levitt, 1971), which is then defined as the threshold. The transformed up-down strategy tends to converge on a stimulus level at which the

probability of an 'up' response equals the probability of a 'down' response sequence (the converging point would be the probability of positive response) (Levitt, 1971). For example, a two down one up adaptive procedure converges to 70.7% correct response level (probability of positive response converges at 0.7) on the psychometric function (Levitt, 1971; Saberi, 1995). The convergence is calculated by using the probability of a sequence from the 'down' group. The probability of getting a 'down' response sequence for a two down one up adaptive method is  $[P(X)]^2$  (after two positive responses the stimulus level decreases), where  $P(X)$  is the probability of a positive response at stimulus level 'X' (Levitt, 1971). Therefore, this transformed up-down method example converges on that 'X' value at which  $[P(X)]^2 = 0.5$  (transformed up-down strategy converges on the 50% point of the transformed response curve), thus  $P(X) = 0.707$  (Levitt, 1971).

The underlying psychometric function in an adaptive procedure should involve a monotonic relationship between the stimulus level and the performance level (proportion of positive responses) (Leek, 2001; Levitt, 1971). It is crucial that the adaptive procedure uses proper elements such as starting value, reversals and step-sizes to avoid problems like threshold biases, which is when the thresholds differ from what would be expected in fixed trials (Leek, 2001). It is important to have an idea about the psychometric function for the stimulus level being tested. If the experimenter does not know the steepness of the function and the step-size is too big then the presented stimulus level could jump from being easy to too hard. If the step-size is too small, the duration of the experiment would extend until it converges to a specific percentage level (which depends on the transformed up-down strategy being used) (Levitt, 1971).

In summary, a combination of various procedures need to be utilized together and various potential pitfalls need to be avoided to ultimately measure threshold ITD. As stated previously, a simple yes-no task has a bias (response bias); therefore, it would be ideal to measure threshold ITD using an AFC task such as 2 AFC (Green & Swets, 1988; Heeger, 1997). A 2 AFC task can be combined with either a constant stimulus or an adaptive (i.e. transformed up-down) procedure. However, an adaptive procedure has higher precision, time effectiveness in comparison to a constant stimulus procedure (Levitt, 1971; Leek, 2001). In addition, the transformed up-down adaptive procedure can converge onto different thresholds at different percent correct performance levels, which depends on transformed up-down strategy (Levitt, 1971). When using the transformed up-down adaptive procedure, it is very important to have proper values for its elements, such as starting value and step-sizes, because it may cause issues such as negatively influencing the performance of the participant (i.e. if the step-size is very large) (Levitt, 1971; Leek, 2001). Therefore, it is crucial that the experimenter designs the experiment accordingly to ultimately measure threshold ITD.

## 1.4 ITD Sensitivity in Humans and Animals

There are many studies on ITD sensitivity with humans as well as with animals. Among those studies, most animals have higher discrimination threshold ITDs than humans (Ebert Jr, Blanks, Patel, Coffey, Marshall & Fitzpatrick, 2008). Some common experimental animals used in auditory studies that use comparable methods are rabbits, cats, guinea pigs and barn owls. As reported by Ebert Jr. and colleagues (2008), rabbits have a minimum ITD of 40 to 60  $\mu$ s. The stimulus used to measure their minimum threshold ITD was band-limited noise (500–1500 Hz). In cats the threshold ITD is

approximately 30  $\mu$ s (Wakeford & Robinson, 1974). In guinea pigs the lowest threshold ITD was approximately 30  $\mu$ s (Shackleton, Skottun, Arnott, & Palmer, 2003). However, in barn owls the best threshold ITD is much lower than the other three species. They can resolve the threshold ITD of about 10  $\mu$ s at 3-11 kHz noise burst (Bala, Spitzer, Takahashi, 2003; Mazer, 1998).

The seminal threshold ITD studies in humans are from over 60 years ago: Zwislocki and Feldman (1956) reported threshold ITDs of about 14  $\mu$ s around the middle frequency range (500-1000 Hz) at 65 dB sound pressure level (SPL). Similarly, Klumpp and Eady (1956) reported a minimum pure tone threshold ITD of about 11  $\mu$ s at 1000 Hz. In the same article, participants obtained a threshold ITD of 9  $\mu$ s with a 150-1700 Hz noise stimulus. Lastly, Mill's (1958) study found at 750 Hz participants had a threshold of 10  $\mu$ s. These studies had a range of 3 to 10 participants.

Over the following decades many studies have investigated human threshold ITDs in various, typically more challenging complex conditions (e.g. Bernstein & Trahiotis, 2002; Henning, 1974; Bernstein & Trahiotis, 2008). However, neither the 1950s studies nor the follow-up studies aimed at determining the stimulus or the method that yields the smallest threshold ITD. Zwislocki & Feldman (1956) stated that “the effect of the [experimental presentation] method on the data remains an open question” and they only investigated noise and pure tone stimuli.

Recently, Brughera and colleagues (2013) revisited smallest pure tone threshold ITDs, and in line with the historic references, report the range of best sensitivity between 700-1000 Hz. In contrast to the historic literature, however, their average threshold ITD was closer to 20  $\mu$ s. Only their two most sensitive listeners had a minimum threshold ITD

of 11  $\mu$ s; while the other three participants scored between 16 and 36  $\mu$ s. This raises the question on the influence of the “subject factor”. Unfortunately, the details on subjects that participated in the 1950s studies are limited. In Zwislocki and Feldman’s (1956) report, there is no subject description and it is unclear if the participants were e.g. Zwislocki’s highly-trained laboratory members. Bernstein and Trahiotis (2016) demonstrated that even a slight sub-clinical hearing loss in participants can influence binaural perception. This implies that it is crucial to test and report if the subjects are normal-hearing. Ideally one goes beyond that by setting stricter inclusion criteria or by reporting individual audiometric thresholds.

## 1.5 Motivation for the Current Project

After reviewing the studies referenced in 1.4, two issues were identified: First, typically only one experimental parameter was varied systematically and results reported at which value this parameter results in the smallest threshold ITD. It remains unclear if the other fixed parameters and methods were all chosen optimally, to really yield the smallest overall threshold ITD. Second, the experimental methods of the most relevant studies differ substantially from today’s methods. Most prominent may be the difference between analogue and digital signal generation and the use of adaptive measurement paradigms (Levitt, 1971). An additional but smaller concern arises because the two most referenced studies (Klumpp & Eady, 1956; Zwislocki & Feldman, 1956) noted they were of preliminary nature. Despite this, these two studies are still frequently cited as best available references for the smallest human threshold ITD, including standard textbooks and articles from various disciplines such as perception (Plack, 2013), sound engineering (Carlile, 1996) or neuroscience (Campbell & King, 2004).

## 1.6 Current Project's Goal

The study had two directly connected goals. First, identification of the stimulus and experimental procedure resulting in the most sensitive ITD discrimination. The second goal that naturally followed was to accurately measure the threshold ITD for the respective stimulus and procedure. Two experiments were conducted – one for each of the two goals.

## Chapter 2

### 2 Experiment 1: Identification of Stimulus and Procedure Yielding Smallest Threshold ITD

#### 2.1 Objective and Approach

The purpose of this first experiment was to identify the stimulus and experimental procedure that results in the best ITD sensitivity, i.e. in the smallest threshold ITD. Seven stimulus parameters and procedure types were identified that either have been shown to influence ITD sensitivity or have differed across studies without being certain that they did not have an influence on the results. Parameters that have previously been shown to worsen sensitivity and stimuli that have been shown to be not ideal for ITD discrimination were not included. The tested parameters were: (1) stimulus waveform, (2) level, (3) stimulus duration, (4) inter-stimulus pause duration, (5) inclusion versus exclusion of stimulus onset and offset ITD, (6) constant stimulus presentation versus an adaptive staircase procedure, and (7) inclusion versus exclusion of diotic “cuing” intervals. Details on the stimuli are presented in Sec. 2.2.3 and details on all procedures in 2.2.4.

A complete examination of the seven-dimensional parameter space would result in 1056 conditions (11 stimuli x 3 levels x 2 stimulus durations x 2 inter-stimuli pause durations x 2 for onset and offset ITD included versus excluded x 2 for constant versus adaptive x 2 for cuing versus no cuing); which is not practicable to experimentally conduct on participants. To reduce the number of conditions, the arguably most important parameter “stimulus waveform” was tested first. Then, the best stimuli, from the stimulus waveform testing, were chosen to be tested with varying one of the other six parameters to identify the optimal presentation technique.

At this stage, it is unclear if there is a single most sensitive stimulus waveform. There may also be two or three similarly good stimuli that should be tested with the other parameters. Two or three stimulus waveforms multiplied with the other 96 parameter combinations, would still result in an unrealistically large 192 or 288 test conditions. As based on the rationales drawn from the literature and pilot experiments these parameters are not expected to heavily influence ITD sensitivity, especially not in an interactive manner. Therefore, only one parameter value at a time is varied from default, leading to only 8 conditions per stimulus (default + 2 additional levels + 5x1 other parameter).

## 2.2 Methods

### 2.2.1 Participants

Participants had to be young adults (18-39 years) with audiometric threshold equal or less than 10 dB HL at octave spaced frequencies from 125 to 8000 Hz. The reason for this strict criterion is that it has recently been shown that subjects with a slight or so-called hidden hearing loss have a reduced binaural release from masking (Bernstein & Trahiotis, 2016). To minimize a potential confound through hidden hearing loss this criterion was included.

A total of nine normal hearing trained participants aged between 18 and 38 years (avg. age = 23, F=6, M=3) participated in the experiment for between 15 to 19 hours. My supervisor and I were two of the nine participants. The other seven participants were compensated on an hourly basis. Five other individuals were not included for two different reasons: Two individuals' thresholds increased throughout the practice runs. They self-reported concentration problems. The other three individuals had one or more audiometric thresholds higher than 10 dB HL.

## 2.2.2 Apparatus

Stimuli were digitally generated in MATLAB (MathWorks, Natick, MA, United States) using the AFC software package (Ewert, 2013) for MATLAB and presented via a Focusrite Scarlett 2i2 2 In/2 Out USB sound card, a HB7 TDT headphone driver, and ER-2 tubephone insert earphones (Etymotic Research Inc., El Grove Village, IL, United States) to the subject seating in a double walled sound booth. The left and right ER-2 insert earphones were calibrated at 800 Hz, without any frequency-dependent correction.

## 2.2.3 Stimuli

Three different types of stimuli were tested in this experiment: Pure tones, tone complexes and noises.

### *Pure tones*

The first stimulus type were pure tones:

$$s(t) = \sin(2\pi ft).$$

Pure tones with three different frequencies were separately tested in this experiment: 600 Hz, 800 Hz, and 1000 Hz. Tones are the most basic, and fundamental class of stimuli that have been tested frequently. The frequency range was chosen based on consistent reports that the range for best sensitivity is between 600-1000 Hz (Brughera et al., 2013; Zwislocki & Feldman, 1956; Klumpp & Eady 1956).

### *Tone complexes*

The second stimulus type were tone complexes, i.e. multiple pure tones ( $f_1$ ,  $f_2$ ,  $f_n$ ) added in cosine phase:

$$s_{TC}(t) = [\cos(2\pi f_1 t)] + [\cos(2\pi f_2 t)] + \dots + [\cos(2\pi f_n t)]$$

Three different tone complexes were tested in this experiment: 100-1400 Hz with 100 Hz component intervals, 600-1000 Hz with 100 Hz component intervals, and 600-1000 Hz with 20 Hz component intervals. The cosine phase further offers a steep envelope which may provide an additional ITD cue. The cosine phase also offers the interpretation of this stimulus class as filtered click-trains.

Previous studies did not systematically investigate this stimulus type. The three different complexes were chosen to cover the complete range of temporal fine-structure (TFS) ITD sensitivity (up to 1400 Hz) or just the range of best ITD sensitivity (Brughera et al. 2013). In terms of the latter 600-1000 Hz range, there were two different conditions: one with 100 Hz component intervals spacing and one with 20 Hz spacing. With 100 Hz spacing, each component stimulates independent filters and information may be integrated across filters for better performance compared to pure tones. With 20 Hz component intervals, a very homogenous spectral excitation in the most sensitive frequency region is provided, like noise, but still with a deterministic waveform. We hypothesized that either feature may provide very good ITD sensitivity.

### *Noise*

The third stimulus type was noise. Five different kinds of noise were tested in this experiment: 600-1000 Hz band-pass, 750-850 band-pass, 20-1400 Hz band-pass, 20-20,000 Hz broadband white noise, and 20-20,000 Hz broadband pink noise.

The band-pass filter frequencies were chosen like how the frequency ranges were chosen for tone complexes. Again, the 600-1000 Hz frequency range was chosen because this is the frequency region with the highest ITD sensitivity (Brughera et al., 2013), and 20-1400 Hz was chosen because it covers the complete fine-structure sensitive region. In addition, a 750-850 Hz band-pass was chosen because this approximates a single auditory filter centered near the most sensitive region. Lastly, two conditions covering the complete audible spectrum (20-20,000 Hz) were also chosen for this experiment: Firstly 1/f noise (or pink noise) provides an equal amount of energy per octave and therefore a relatively homogeneous excitation of all auditory filters. Surprisingly, to our knowledge, pink noise has not been used in previous studies on ITD sensitivity. White noise, on the contrary, gives a large amount of energy to the high frequency filters which are not expected to be the most ITD sensitive because of the lack of TFS ITD.

For all three stimulus types, the default level was 70 dB SPL, default duration was 0.5 s including 50 ms squared cosine onset and offset gating, and the default inter-stimulus pause duration was 0.3 s. The ITD was applied either prior to gating (excluding onset and offset ITD: default) or after gating (included onset and offset ITD). During generation, stimuli were sampled with a rate of 1 MHz to allow for an ITD precision of 1  $\mu$ s and then down-sampled to 48 kHz for presentation.

### 2.2.4 Procedure

The default procedure was a two-interval two alternative forced choice task (Two-Interval 2 AFC). In a 2 AFC task the subject is forced to choose between one of two choices, one of which is the correct response.

In each trial the subjects were asked “Which interval was perceived the most toward the right-hand side.” Therefore, the participant would be forced to determine whether the target stimulus (right ear leading in time) appeared in the first or second interval. Subjects responded by pressing the corresponding target interval number on a standard computer keyboard. Visual feedback was provided after each trial. The target interval always had a right leading ITD that was half of the nominal ITD whereas the reference interval had a left leading ITD that was half of the nominal ITD. The symmetric presentation minimizes any potential hemispheric effects and ensures that the subject cannot do the task based on interaural coherence (Dietz et al., 2012).

An adaptive transformed up-down staircase procedure was chosen. Specifically, a ‘three-down one-up’ rule was selected where the ITD was decreased after three correct responses and increased after one wrong response, which is designed to estimate the 79.4% correct level on the psychometric function (Levitt, 1971). The ‘three-down one-up’ was chosen because of the higher precision, time effectiveness, and converges on a different threshold compared to the two-down one-up procedure (Kollmeier, Gilkey & Sieben, 1988). Each adaptive track started at an ITD of 40  $\mu$ s which was expected to be above threshold. The initial step-size was a factor of 2, which was reduced to 1.414 and 1.189 after the first and second “down-up reversal” respectively. An adaptive track was terminated after six reversals at the minimum step-size. The factorial step-sizes were

employed, because it has been shown that threshold distributions are approximately Gaussian on the logarithmic ITD scale (Yost et al., 1974; Saberi, 1995).

The first procedural comparison was between the default adaptive staircase procedure and a constant stimulus procedure. For the latter, eight fixed ITDs (2.5 to 28.28  $\mu$ s in half-octave step sizes) were presented 100 times each. Presentation was in four blocks, with each block consisting of 25 presentations at the same ITD, followed by the next smaller ITD. The constant stimulus procedure has been utilized in the above-mentioned 1950s studies. Potentially this may result in better performance compared to the adaptive staircase procedure, however, it was shown not to make a difference in binaural detection tasks (Trahiotis et al., 1990).

The second procedural comparison was between the default two-interval 2 AFC and a four-interval 2 AFC task (Bernstein & Trahiotis, 1993). In the four-interval 2 AFC task, the target ITD was presented in either the second or third interval, while the first and fourth intervals had zero ITD (“cuing intervals”). Bernstein & Trahiotis (1993) reported that the four-interval method was more reliable, at least in cases of target uncertainty. On the other hand, the two-interval method is twice as fast in terms of the presentation time. Furthermore, L/R discrimination is commonly performed as a motion task, if there is more than one interval (Yost et al., 1974). For a motion task, a two-interval procedure may be more natural, because it simplifies the task to essentially discriminating rightwards from leftwards movement. The four-interval procedure does not allow for this simplification. It remains to be shown which procedure results in lower threshold ITDs. For the four-interval task a hemispherically balanced presentation as in the two-interval

procedure is not possible in the same way. Therefore, the ITD was applied in full to the target interval (always right leading) whereas the other three intervals were diotic.

In the third comparison, the stimulus level was varied. Levels of 60, 70, 80 dB SPL were chosen, because this range was previously reported to yield the lowest threshold ITDs (Zwislocki and Feldman 1956).

The fourth comparison observed the influence of stimulus duration. The recent standard is 0.3 s (e.g. Bernstein & Trahiotis, 2009) to 0.5 s (e.g. Brughera et al., 2013). In contrast, Klumpp and Eady (1956) used 2 s. It is possible that this longer duration is one of the reasons for the lower threshold reported by Klumpp and Eady. In pilot experiments, we compared 0.5 with 2.0 s. As the two pilot subjects were slightly better in the 0.5 s condition and found the 2.0 s condition more exhausting, it was decided to compare 0.5 against 1.0 s in the formal experiment (1.0 s was also used by Zwislocki and Feldman, 1956). We speculated that a duration longer than 0.5 s would not result in lower thresholds.

Comparison number five tested whether the inclusion of stimulus onset and offset ITDs using 50 ms squared cosine onset and offset gating improved performance. Almost all studies on the subject from the last decades excluded onset and offset ITD, because it isolates the ongoing TFS ITD cue from the transient envelope ITD cue. A mixing of cues is not good to understand a system. Buell and colleagues (1991) showed that ongoing TFS ITD typically dominates perception. All this speaks in favor of excluding onset ITD and on reporting lowest TFS ITD thresholds. On the other hand, if there was any influence of adding an onset ITD to an ongoing ITD it can be expected to be a small improvement. Klumpp and Eady (1956) also included onset and offset ITD but their even

longer gating times of 0.3 s, likely rendered the transient ITD information very weak. Nevertheless, this condition was included for the sake of completeness, and it was assumed that the onset ITD included condition was equally good or marginally better. In theory, a short steep onset can be expected to yield the strongest improvement. However, with our focus on ongoing (TFS) ITD we refrained from systematically changing different onset parameters.

In the last comparison, the inter-stimulus pause duration was varied. While 0.3 s is a typical value for this parameter, in our pilot experiments we got the impression that a shorter pause may result in a better sensitivity. We therefore included a short 0.05 s pause condition to our test battery.

The eleven different waveform conditions were measured in six runs in randomized order. The second run of any condition could only appear after the first run was finished for all conditions. After the first six of the nine subjects finished measuring the eleven stimuli, the two stimuli yielding the lowest thresholds were selected as “presumably optimal” because their threshold ITD only differed by 0.2  $\mu$ s.

For the second part of this experiment, the six other parameters were tested one at a time. The six default settings for these parameters were (1) two-interval 2 AFC, (2) adaptive stair case, (3) 70 dB SPL, (4) 0.5 s stimulus duration, (5) excluded onset and offset ITD, and (6) 0.3 s inter-stimulus pause duration). The default condition, where all six parameters were at default, was identical to part 1, but tested again – in combination with the other two non-default levels (60 and 80 dB SPL). The non-default values of the other five parameters were each measured in separate tests, alternating between the two different stimulus waveforms. The order was (1): inclusion of onset and offset ITD, (2)

stimulus levels (60, 70, 80 dB SPL), (3) constant stimulus procedure, (4) stimulus duration (1 s), (5) inter-stimulus pause duration (0.05 s), and (6) four-interval 2 AFC procedure. After the six parameters were tested for three runs, an additional three runs were measured in reversed order (6 to 1).

The participants were trained by giving practice blocks identical to the actual experiment to avoid large training effects during the actual data collection. During the first session, subjects received at least 30 minutes of training before the formal data collection began. In all subsequent sessions, participants were given one practice run before continuing the formal data collection.

### 2.2.5 Data Analysis Methods

Individual thresholds were derived from reconstructing the psychometric functions from the adaptive tracks and subsequent fitting. The reason for using psychometric fits over the commonly used adaptive track reversal average was because reversals are prone to some substantial bias and less precision (García-Pérez, 1998; Schlauch & Rose, 1990). For comparison, we also included the conventional reversal analysis later in experiment two, where the bias becomes evident (see Table 1 discussed in Chapter 4). Psychometric functions were estimated using a parametric fit of a Weibull function. Specific for a 2 AFC procedure with 50% chance level and threshold  $T$  defined at the 79.4% correct level, the estimated correct rate ( $y$ ) can be expressed as a function of ITD:

$$y(\text{ITD}) = 1 - \frac{1}{2} e^{-0.8853 \times \left(\frac{\text{ITD}}{T}\right)^s}$$

The two free parameters were the slope ( $s$ ) and threshold ITD ( $T$ ). The constant 0.8853 is a result of the specific chance and threshold levels. The maximum likelihood fit was

derived by a 2-dimensional “brute-force search”. Thresholds were sampled with a  $0.25 \mu\text{s}$  grid and slopes with 0.1.

Across-subject averages were derived through geometric mean and geometric standard deviation. Accordingly, all analyses of variance (ANOVA) were conducted on the logarithm of the individual threshold ITDs.

## 2.3 Results

### 2.3.1 Stimulus Waveform

Geometric mean threshold ITDs were derived from the individual thresholds for each of the eleven stimulus waveforms (Fig. 7). Note that the threshold ITD ordinate in Fig. 7 is logarithmic, as a consequence of the threshold ITD distributions being approximately Gaussian on a logarithmic scale (Saberi, 1995).

The three pure tone stimuli had the highest threshold ITDs (Fig. 7) with averages between  $22 \mu\text{s}$  (800 Hz) and  $27 \mu\text{s}$  (600 Hz). The 600-1000 Hz noise and 20-1400 Hz noise had the lowest threshold ITDs with  $10.0 \mu\text{s}$  and  $10.7 \mu\text{s}$  respectively. Both narrower and wider bandwidths resulted in higher thresholds. ITD sensitivity to tone complexes was better than for pure tones but worse than for noise with the same bandwidth. Best threshold ITDs for this stimulus class were  $14 \mu\text{s}$  for both stimuli with  $f_0 = 100 \text{ Hz}$ .

A repeated measure one-way analysis of variance (ANOVA) on the log-scaled ITD data revealed a significant main effect of stimulus waveform [ $F(10,88) = 11.48$ ;  $p < 0.001$ ]. A post hoc pairwise comparison (Tukey) revealed a significant difference (assuming  $\alpha = 0.05$ ) between threshold ITDs for the two pure-tone stimuli with the highest thresholds (600 Hz and 1000 Hz) and all stimuli from the other two classes. Thresholds for the 800 Hz pure tone were significantly higher than for the two-tone complexes with

$f_0 = 100$  Hz and the 600-1000 Hz and 20-1400 Hz noises. No other pairs differed significantly.

Since the conservative ANOVA post-hoc test did not reveal any 1, 2, or 3 most ITD sensitive conditions with statistical significance, a rank comparison was conducted to move forward. For 8 of 9 subjects 600-1000 Hz noise was among the 2 most sensitive conditions and for 7 of 9 subjects 20-1400 Hz noise. That means that only in 3 of 18 instances any of the other 9 conditions was among the 2 most sensitive. For all 9 subjects one of the two conditions was among the two most sensitive. We therefore moved on to test the other parameters with these two stimuli.

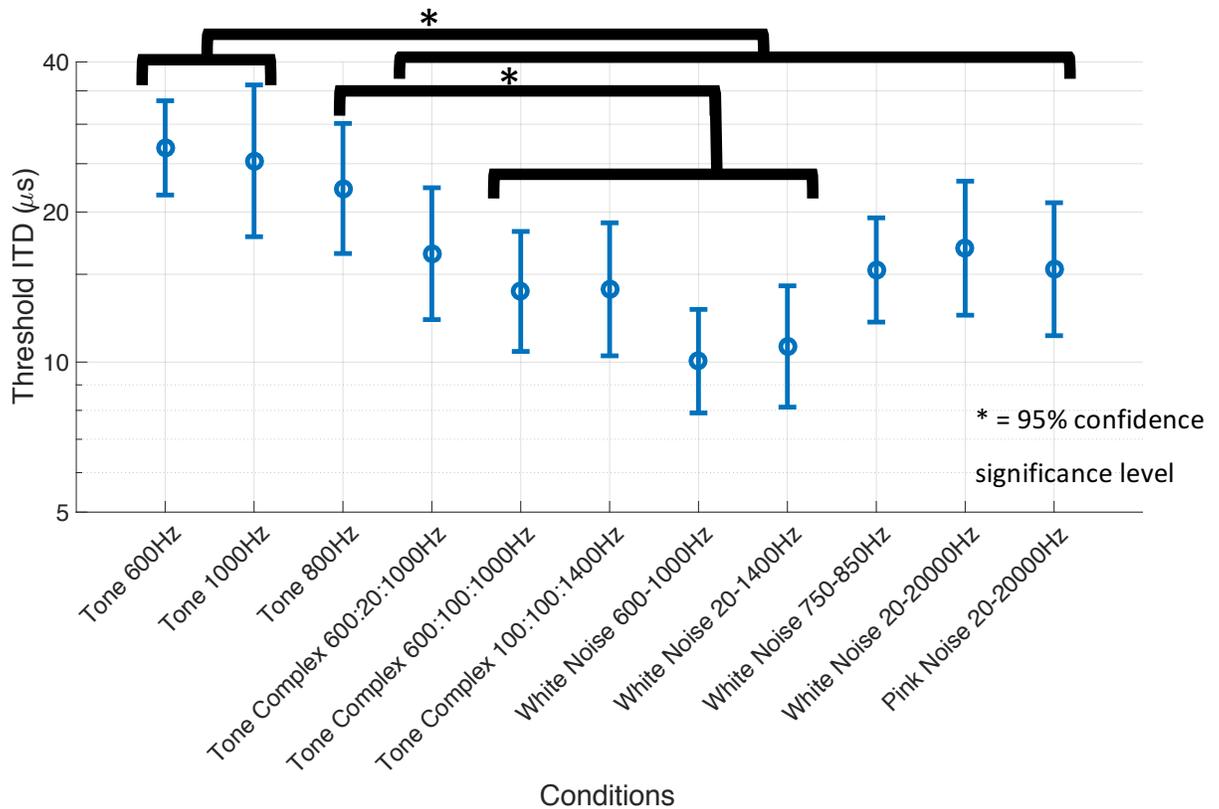


Figure 7. Threshold ITDs for the eleven different stimulus waveforms using a stimulus level of 70 dB SPL, stimulus duration of 0.5s, inter-stimulus pause duration of 0.3, two-interval paradigm, three-down one-up adaptive procedure, and excluded onset and offset ITD. The data points indicate the geometric mean across the nine participants and the error bars indicate the geometric standard errors.

### 2.3.2 Other parameters

In this section, the isolated influence of the other test parameters and procedural differences on threshold ITD is analyzed. Figures 8 to 12 show individual threshold ITDs together with the across-subject geometric means for the two best stimuli from sub chapter 2.3.1. The default parameters were the same as in sub chapter 2.3.1 and only one parameter was changed from default at a time. The default condition itself was simply re-measured from the stimulus waveform parameter test. When compared to the previous measurement, thresholds for the 600-1000 Hz noise increased by 1  $\mu$ s whereas thresholds for the 20-1400 Hz noise decreased by 1  $\mu$ s. As said, this default condition was integrated in the level test (70-dB condition; Fig. 8). For figures 9-12 the default condition data is reused.

First, the influence of stimulus level (60, 70, 80 dB SPL) on threshold ITD is reported (Fig. 8). While threshold ITDs at 70 dB SPL were marginally lower than at 60 and 80 dB SPL, a repeated measure two-way analysis of variance (ANOVA) on the log-scaled ITD data revealed no significant main effect of level [ $F(2,48)= 0.52$ ;  $p=0.599$ ] and noise stimulus type [ $F(1,48)= 0.18$ ;  $p=0.669$ ]. There was no interaction between level and noise stimulus type [ $F(2,48)= 0.12$ ;  $p=0.888$ ].

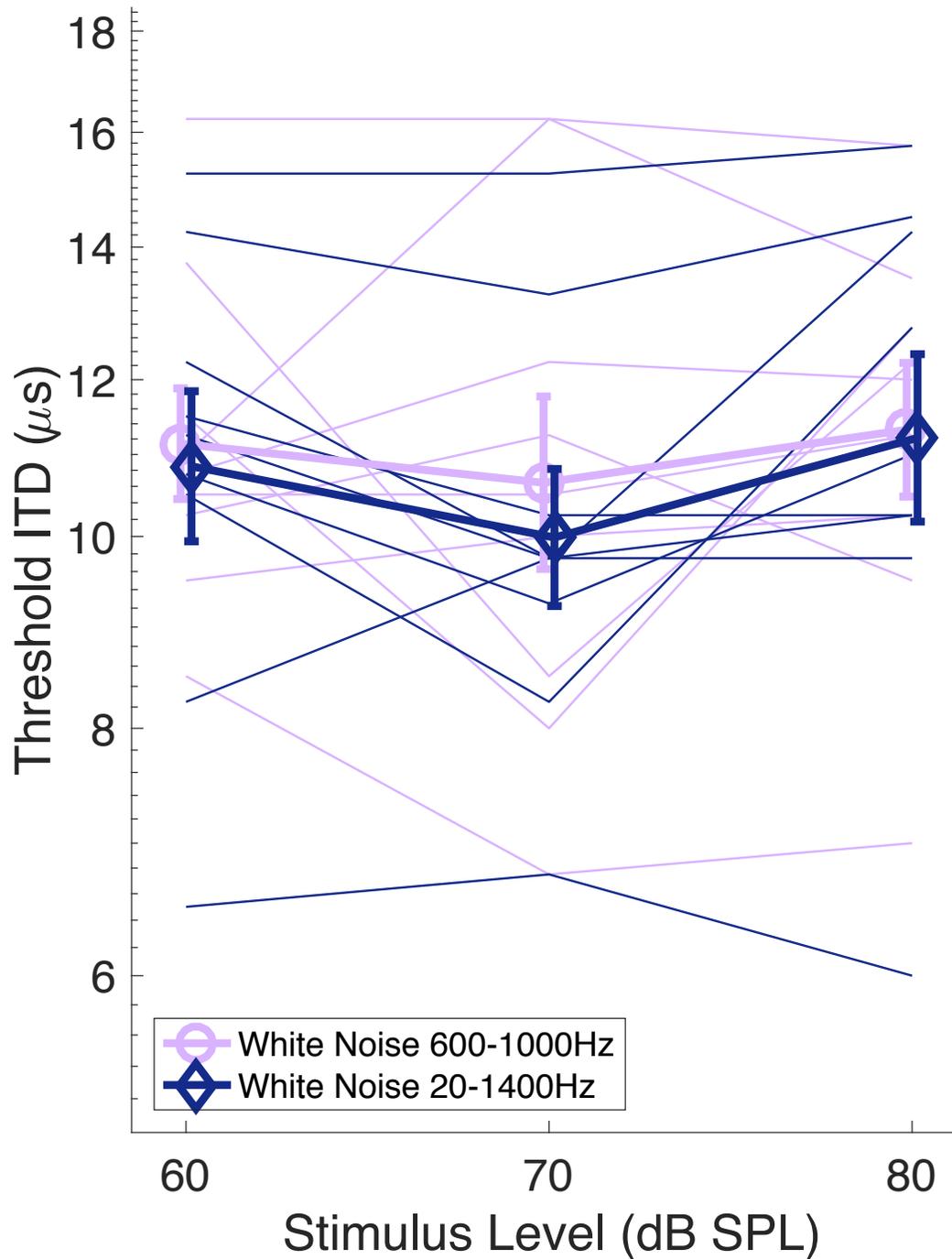


Figure 8. Threshold ITD for the two most ITD sensitive stimuli as a function of stimulus level. The 600-1000 Hz noise is plotted with the lighter lines and circles. The 20-1400 Hz noise is plotted with the darker lines and diamonds. The symbols indicate the geometric mean across the nine participants and the error bars indicate the geometric standard errors. Individual data are plotted as thin lines.

Next, we investigated whether thresholds change when adding onset and offset ITDs (Fig. 9). Both visual inspection and an ANOVA on the log-ITD data revealed no significant main effect of onset and offset ITD excluded versus included [ $F(1,32)= 0.04$ ;  $p=0.846$ ] or noise stimulus type [ $F(1,32)= 0.52$ ;  $p=0.477$ ], as well as no interaction [ $F(1,32)= 0$ ;  $p=0.948$ ].

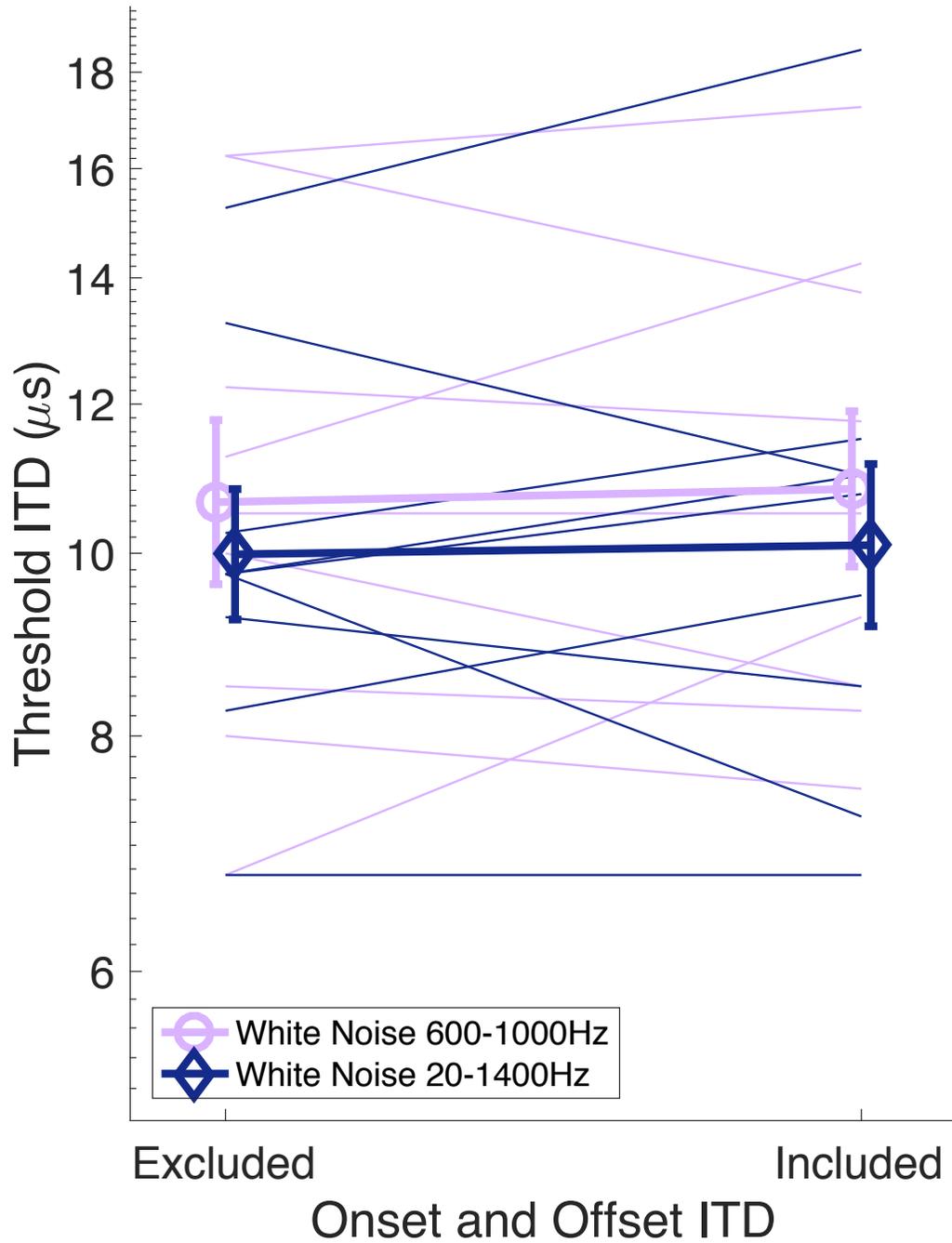


Figure 9. Influence of including versus excluding transient onset and offset ITDs. Same format as Fig. 8.

Third, a potential influence of stimulus duration was investigated (Fig. 10). For the longer 1 s stimulus duration, average thresholds increased by 1.5  $\mu$ s for the 20-1400 Hz noise and by 0.91  $\mu$ s for the 600-1000 Hz noise. An ANOVA on the log-scaled ITD data revealed neither a significant main effect of stimulus duration [ $F(1,32)= 1.36$ ;  $p=0.252$ ], nor of noise stimulus type [ $F(1,32)= 0.24$ ;  $p=0.625$ ], and there was no significant interaction [ $F(1,32)= 0.08$ ;  $p=0.777$ ].

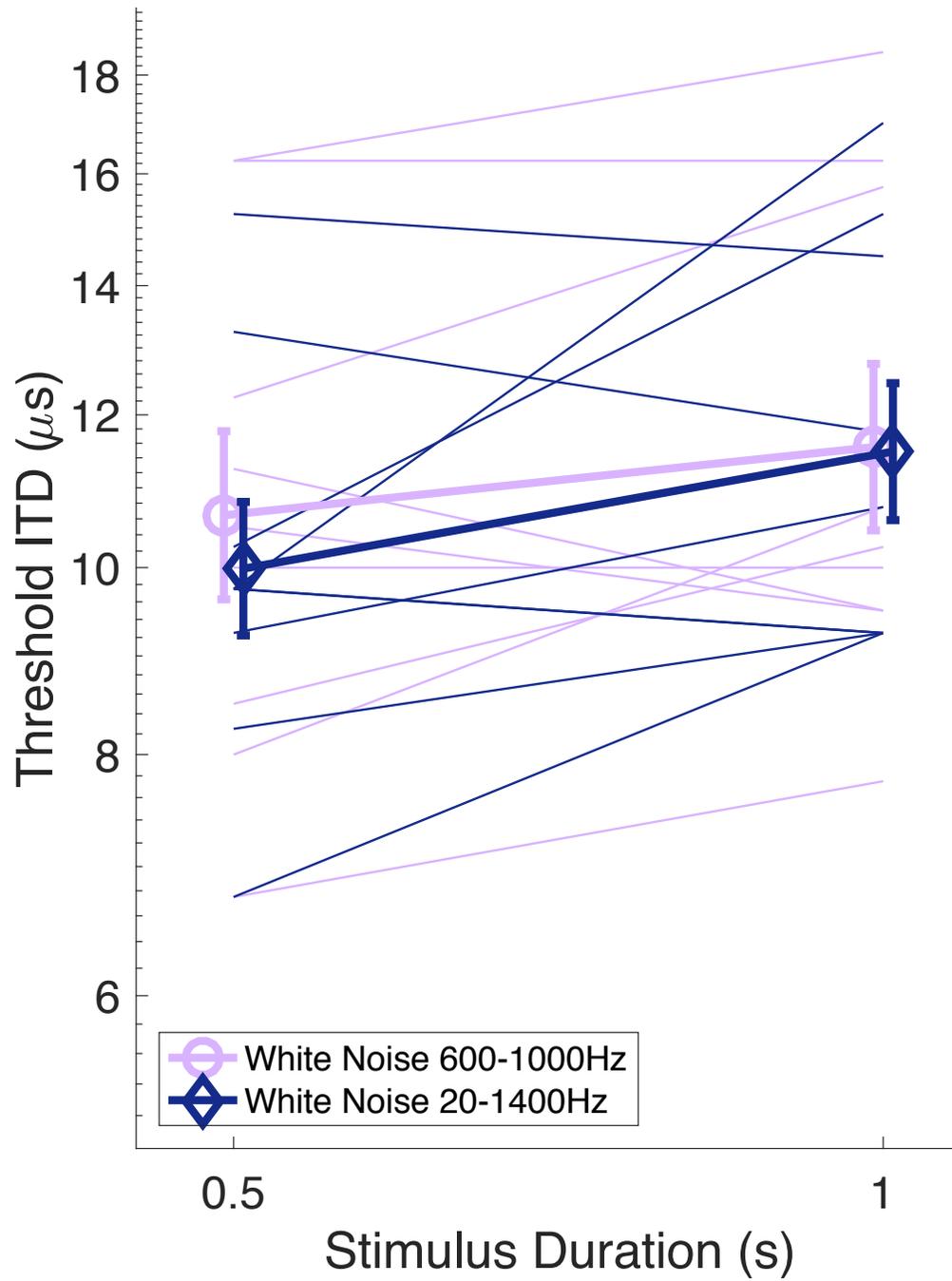


Figure 10. Comparison between a longer and shorter stimulus durations. Same format as Fig. 8.

Fourthly, we examined whether the addition of cuing intervals influenced threshold ITDs. Fig. 11 reveals that the cuing intervals increased threshold ITDs by 1.7  $\mu$ s for the 600-1000 Hz noise and by 3.9  $\mu$ s for the 20-1400 Hz noise. An ANOVA revealed a significant main effect of the number of intervals [ $F(1,32)= 5.31$ ;  $p=0.028$ ], but not of noise stimulus type [ $F(1,32)= 0.01$ ;  $p=0.941$ ], as well as no interaction [ $F(1,32)= 0.4$ ;  $p=0.532$ ].

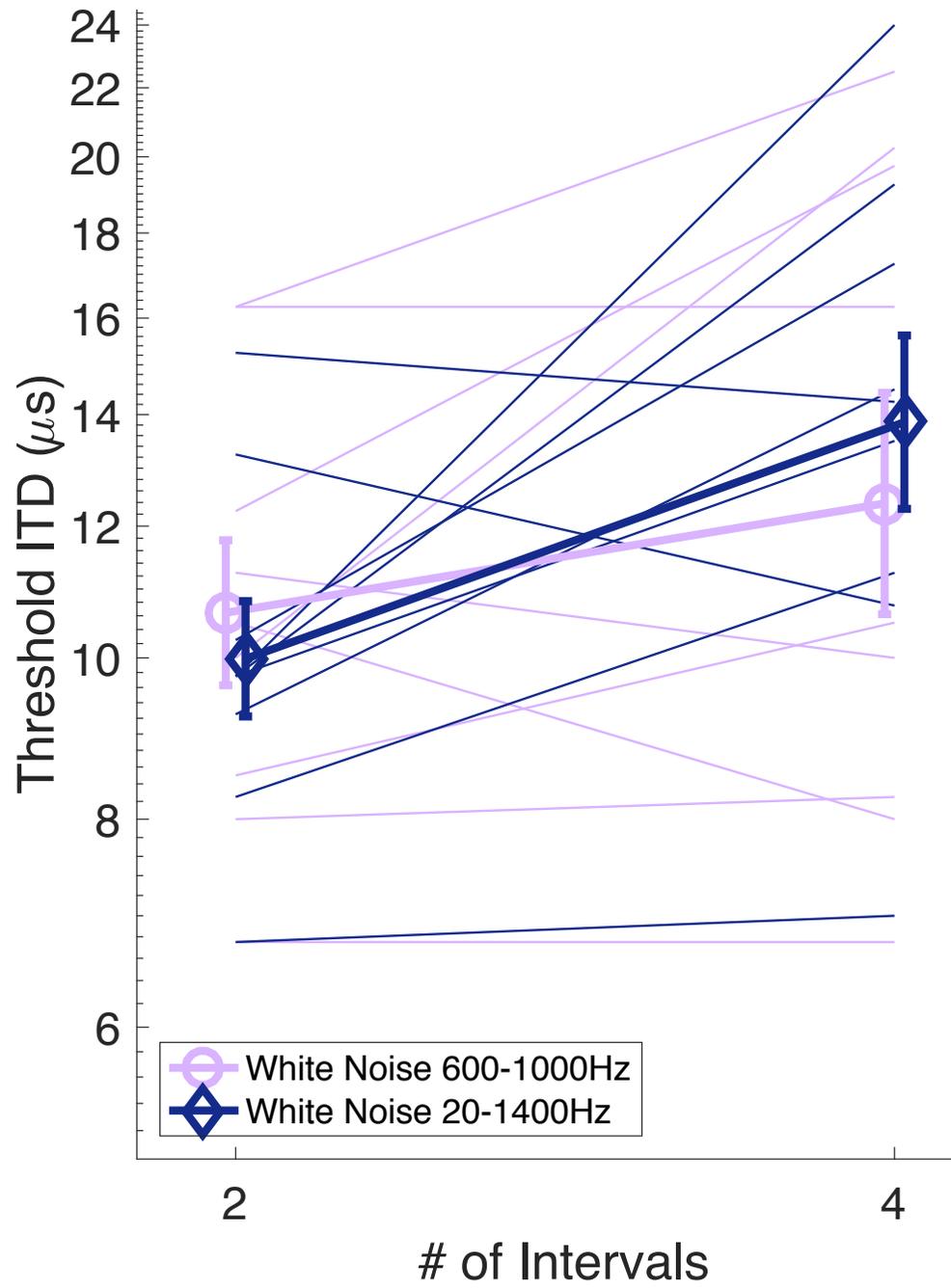


Figure 11. Comparison between two-interval and a four-interval 2 AFC tasks. Same format as Fig.8.

The influence of a shorter inter-stimulus pause duration on threshold ITDs is shown in Fig. 12. An ANOVA revealed no significant main effect of inter-stimulus pause duration [ $F(1,32)= 0.16$ ;  $p=0.691$ ]. The influence of noise stimulus type [ $F(1,32)= 0.21$ ;  $p=0.648$ ], and the two-factor interaction [ $F(1,32)= 0.19$ ;  $p=0.669$ ] were also not significant.

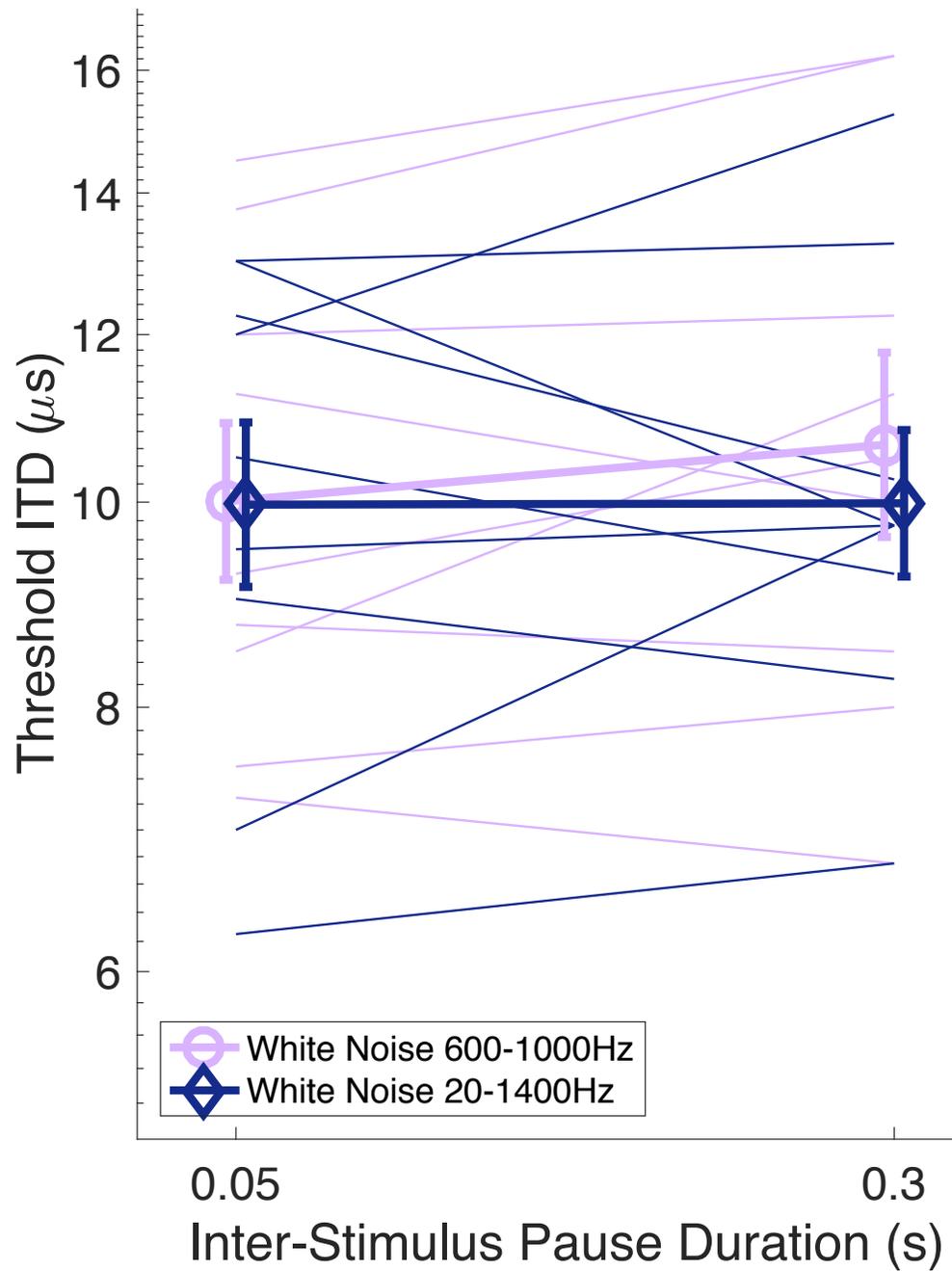


Figure 12. Influence of a shorter and longer inter-stimulus pause durations. Same format as Fig. 8.

Finally, a constant stimulus procedure was tested with default parameters: stimulus level of 70 dB SPL, stimulus duration of 0.5 s, inter-stimulus pause duration of 0.3 s, two-interval paradigm, 2 AFC procedure, and excluded onset and offset ITD. The eight fixed ITD values' (2.5 to 28.28  $\mu$ s in half-octave step sizes) correct rates were averaged across nine participants for the two noise stimuli (Fig. 13). For the 600-1000 Hz noise, ITDs of 6, 8, and 10  $\mu$ s resulted in 70%, 76%, and 79% respectively. The corresponding correct rates for the 20-1400 Hz noise were 70%, 75%, and 78%. Thus, for both noises 6  $\mu$ s would be virtually identical to a 70.7% 2-down 1-up threshold and 10  $\mu$ s to the 79.4% correct rate threshold from a 3-down 1-up procedure. The latter is almost identical to the 79.4% correct threshold ITDs obtained from the adaptive procedure (e.g. Fig. 8, 10  $\mu$ s at 70 dB SPL).

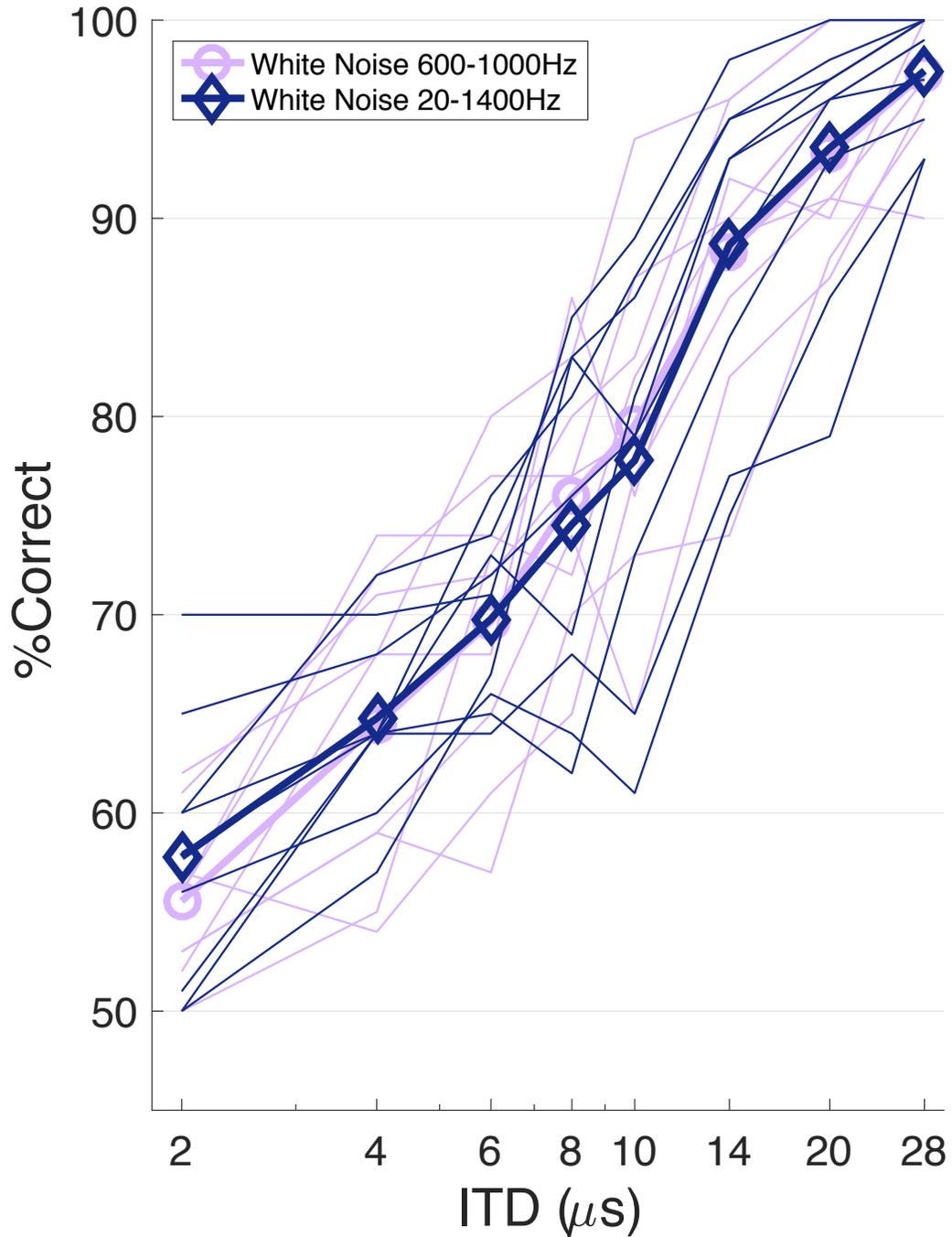


Figure 13. Percent correct for the two most ITD sensitive stimuli as a function of ITD obtained from a constant stimulus procedure. The 600-1000 Hz noise is plotted with the lighter lines and circles. The 20-1400 Hz noise is plotted with the darker lines and diamonds. Individual data are plotted as thin lines.

Visual inspection of the complete psychometric functions obtained with the adaptive (three-down one-up, 2 AFC) and constant stimuli procedures (Fig. 14), revealed no systematic differences. One subject (S6) appears to perform better with the adaptive procedure, while S7 is the other way around.

In this figure, the adaptive procedure has error bars that denote the 95% confidence level derived from the binomial distribution. Confidence interval size therefore depends on the average %-correct and on the number of times measured. Only data from ITDs presented at least 15 times during the adaptive track are plotted. For the constant stimulus procedure, the size of the error bar does not depend on the number of presentations because it is constant 100. To avoid overcrowded panels the error bars for constant stimulus procedure are not plotted. The constant stimulus procedure's error bars increase from plus/minus 5% (at 90% correct rate) to plus/minus 8% (at 50% correct rate).

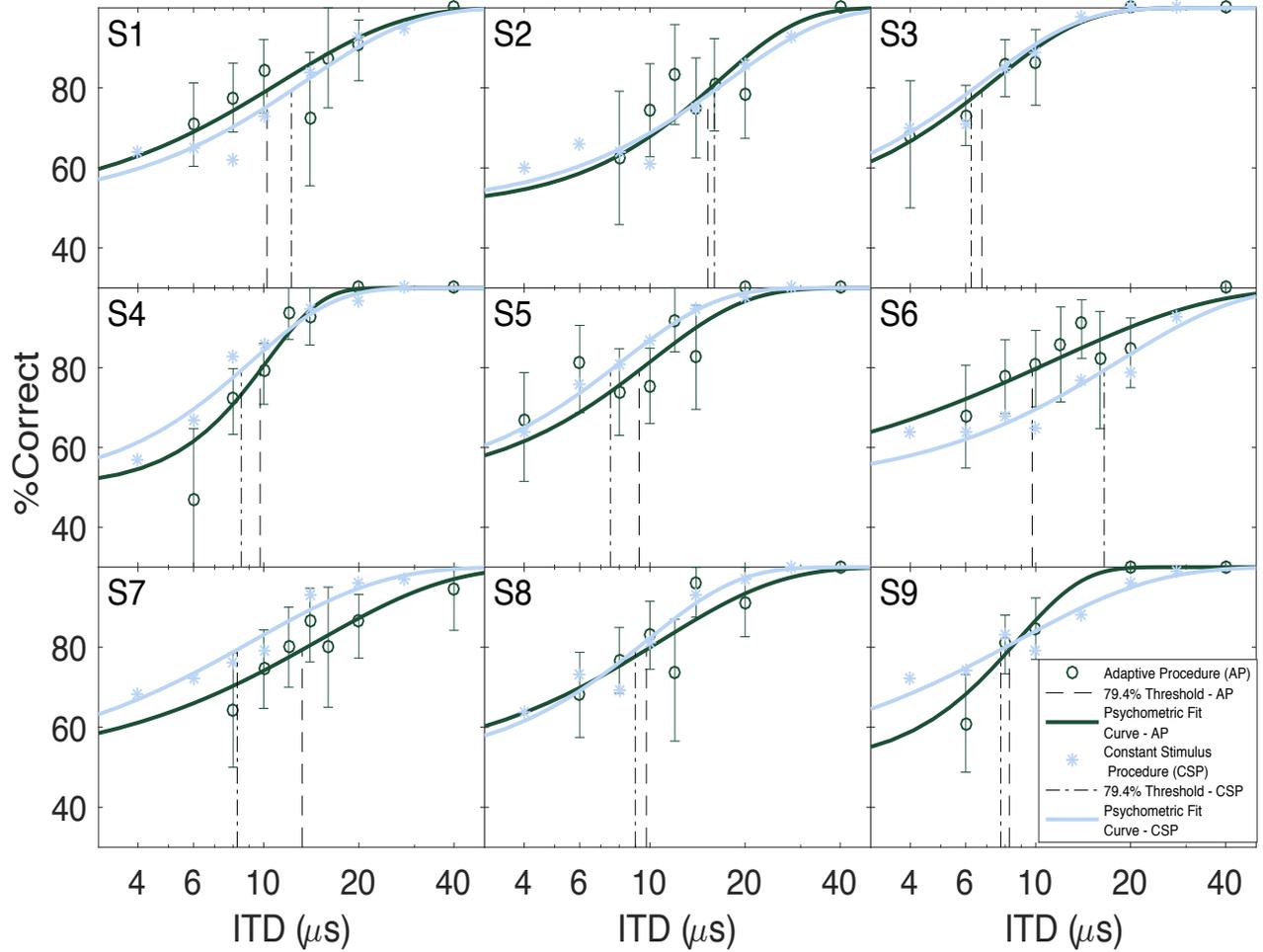


Figure 14. Psychometric functions for the two different types of procedures (adaptive and constant stimulus). Data are only shown for the 20-1400 Hz noise. The nine panels portray individual data of the nine participants (S1-S9).

## 2.4 Discussion

The objective of Experiment 1 was to determine the stimulus and method that yielded the smallest threshold ITD, i.e. the maximum ITD sensitivity. Klumpp and Eady (1956) and Zwillocki and Feldman (1956) did something similar for some ad-hoc choices of stimuli. The current experiment was created to revisit the two studies more systematically and extensively, as well as with methods that were more commonly used in the last 20-30 years.

The only statistically significant influences on threshold ITD were found when changing the stimulus waveform and when adding the cuing intervals. In line with the weak evidence from Klumpp and Eady (1956), pure tones do not produce the lowest possible thresholds. Differences are even more pronounced in the current study. Stimuli with a broader spectrum covering several auditory filters including the 800-Hz region resulted in a significantly better sensitivity. As all other differences were not significant at an  $\alpha = 0.05$  level, some of the trends will be briefly discussed:

Participants performed slightly better with tone complexes than with the pure tones with the averages across the nine participants well-below 20  $\mu$ s. It was expected that the three tone complexes would provide very good ITD sensitivity, because they cover all the most ITD sensitive frequency bands, not just one. It was unclear if the deterministic, tonal nature was going to be an advantage to noise or not. As it turned out, the average thresholds were slightly worse than for the corresponding noise.

When comparing the different noises with each other, the narrow-band noise with one filter at 750-850 Hz, near the most ITD sensitivity region, did not produce the lowest

thresholds. Potentially, maximum sensitivity requires integration of information across independent filters.

The two broadband noises resulted in higher threshold ITDs compared to the two intermediately broad low-frequency noises. We speculate that including frequency regions without TFS ITD sensitivity reduces performance, which would be in line with the variance-valued frequency integration hypothesis (this hypothesis states combining interaural information of targets and distractors lowers performance) (Buell & Hafter, 1991). Also, in line with this speculation, pink noise resulted in slightly better thresholds compared to white noise, likely because it contains more energy in low-frequency regions and less high-frequency energy. Taken together it appears as if a certain bandwidth including the frequency range of maximum pure-tone ITD sensitivity is required to produce the lowest thresholds.

The similarity between the 600-1000 Hz and the 20-1400 Hz conditions hint that TFS sensitive frequencies outside of the 600-1000 Hz region neither harm nor substantially improve ITD sensitivity. Across all conditions and secondary parameters tested, on average, subjects had slightly lower thresholds with the 20-1400 Hz noise. The possibility remains that some bandwidth intermediate to the two tested conditions produces the lowest thresholds. Dedicated high precision measurements with many subjects would be required to measure these sub-microsecond differences.

Somewhat expectedly, both including and excluding onset and offset ITD resulted in equally good sensitivity. We speculate that shorter gating ramp times might potentially improve sensitivity, but not substantially (see e.g., Buell et al. 1991). Because of our focus on ongoing TFS ITD, we leave the discussion of this parameter with this short note.

A less expected outcome was the worsening of performance when including the cuing intervals (Fig. 11). Bernstein and Trahiotis (1993, 2009, 2016) routinely add the cuing intervals, likely because they improve thresholds in case of stimulus uncertainty (Bernstein and Trahiotis, 1993). Stimulus uncertainty was not expected here, so the hypothesis was that the cuing intervals are not going to improve the thresholds – but also not to worsen them. A possible explanation for the significantly higher threshold ITDs with cuing intervals in the present study is that ITD discrimination can be measured with high performance by proxy of a L/R motion task (Yost et al., 1974). It appears plausible that a L/R motion discrimination task is most directly designed as a two-interval procedure. The concept of movement perception was discussed by Yost and colleagues (1974). They observed that a two-interval 2 AFC task was the most sensitive paradigm for ITD perception and that listeners appear to have exploited a lateral movement cue. Our study used two-intervals as the default, therefore, this concept of perception of movement could have been utilized by participants while they were doing the task. The worse sensitivity in the 4-interval paradigm could be caused by a reduced ability to exploit the movement cue, and thus supports the conclusions from Yost and colleagues. This argument notwithstanding, there is a potential small confound in that our participants were more familiar with the two-interval procedure. Therefore, we tested the four-interval procedure last before testing runs 4-6 in reversed order. In that way, the four-interval procedure was measured in 6 consecutive runs and subjects did not have to switch back and forth. In our N=2 pilot experiments, the situation was, however, reversed. We started with the four-interval procedure as default and threshold ITDs decreased after leaving out the cuing intervals.

Regarding stimulus duration, McFadden and Sharpley (1972) reported threshold ITDs to improve up to about 500 ms. Accordingly, our longer stimulus duration of 1s did not result in lower threshold ITDs in comparison to the shorter duration of 0.5 s.

With respect to the more or less absent dependence on level, the results are in line with Zwislocki and Feldman (1956).

With the constant stimulus procedure, subjects' performance was virtually identical to the adaptive procedure, which is in line with Trahiotis et al. (1990).

The shorter inter-stimulus pause duration yielded marginally lower thresholds. The effect is not only not significant on the 0.05 level, but with  $p = 0.69$ , the product of chance is even larger than that there is an underlying effect. Nevertheless, if the weak trend is not a product of chance, it could be explained by means of the motion concept detection hypothesis (Yost et al., 1974): With a shorter pause duration, the motion percept appears to be more pronounced. Conversely, minimum audible movement angles are lowest at low velocities (Chandler & Grantham, 1992).

## Chapter 3

### 3 Experiment 2: Accurate Measure of Threshold ITD

#### 3.1 Objective and Approach

The purpose of this experiment was to obtain an accurate measure of threshold ITD from the chosen condition identified in the previous experiment. Thresholds were reported for both trained and untrained normal hearing listeners.

It could be argued that for the trained listeners, we already have the data from Experiment 1. On the other hand, when the study was designed it was not clear if several deviations from default would result in lower thresholds and we would then measure a new combination of parameters here that was not tested before. Furthermore, Experiment 1 was very long and somewhat tedious for the subjects. While in Experiment 1 we took good care to average out any order, training, or fatigue effects, it cannot be claimed that subjects cannot do even better when they are fully trained and only perform one short measurement.

#### 3.2 Methods

##### 3.2.1 Participants

In this experiment, there were two pools of participants. The first pool were the nine trained normal hearing listeners from Experiment 1. The second pool were 53 untrained normal hearing listeners aged between 18 and 39 years (avg. age = 25,  $F=33$ ,  $M=20$ ) who participated in the experiment for approximately 30 minutes. A less restrictive inclusion criterion was chosen for the untrained listeners: Equal or less than 20 dB HL for 750 and 4000 Hz in each ear. 750 Hz was chosen, because it is close to the best ITD sensitivity of 800 Hz (Brughera et al., 2013). 4000 Hz was chosen, because it is

more indicative of hearing loss. One of the 54 subjects that wanted to participate were excluded because of this criterion. The participants performed the entire experiment in one session and were compensated at the end of the experiment. To our knowledge all participants for this experiment were university students and had not participated in any binaural hearing tests before.

### 3.2.2 Apparatus and Stimuli

The apparatus was the same as in Experiment 1.

The stimulus utilized in this experiment was the 20-1400 Hz band-pass noise.

This stimulus was selected because it produced the lowest thresholds throughout Experiment 1, although not in the stimulus waveform parameter part of the experiment.

The stimulus was presented at 70 dB SPL with an interval duration of 0.5 s, and the short 0.05 s inter-stimulus pause, using the 2-interval procedure and excluding onset and offset ITD.

To provide a higher ITD presentation accuracy, the internal sampling rate was increased to 6.144 MHz, allowing for a nominal ITD step size of 0.16  $\mu$ s. The stimulus was presented with a 96 kHz sampling rate.

### 3.2.3 Procedure

A two-interval two alternative forced choice task (Two-Interval 2 AFC) was employed, identical to Experiment 1. The only parameter that was changed was the starting value. Rather than 40  $\mu$ s it was now 41.67  $\mu$ s, corresponding to exactly 4 samples at 96 KHz.

The trained listeners tested this condition for nine adaptive runs after two practice runs that were identical to the actual experiment. Training was included, because for

some subjects there was a break of several weeks after Experiment 1. Subjects were instructed that this was a final test in which we assume that thresholds are going to be very small. They were given the option of seeing their threshold after each run and to compare that to their personal threshold from Experiment 1. All subjects opted to see their thresholds. By seeing their thresholds after each run and testing this final experiment may promote the motivation and potentially reduce the thresholds obtained from Experiment 1. The duration of this single session was always less than one hour.

For the untrained listeners, the approach was to explicitly avoid training in ITD discrimination prior to data collection. They were given one run of a threshold ILD (interaural level difference) task to get accustomed to the two-interval 2 AFC adaptive procedure and to left-right discrimination. The only method difference was a factor of 2 increase in the start ITD. They were tested for only five runs to make sure that the whole data was collected before they even had 30 minutes of experience in the task.

### 3.3 Results

#### 3.3.1 Trained Listeners

A Weibull function was fitted to the data in the same way as in Experiment 1. Data are shown together with the fits in Fig. 15 and summarized in Table 1. It can be seen that the most ITD sensitive subject (S8) responded to an ITD of 5.2  $\mu$ s with 80% correct (44 out of 55 presentations). At the same ITD S6 responded with 65% correct.

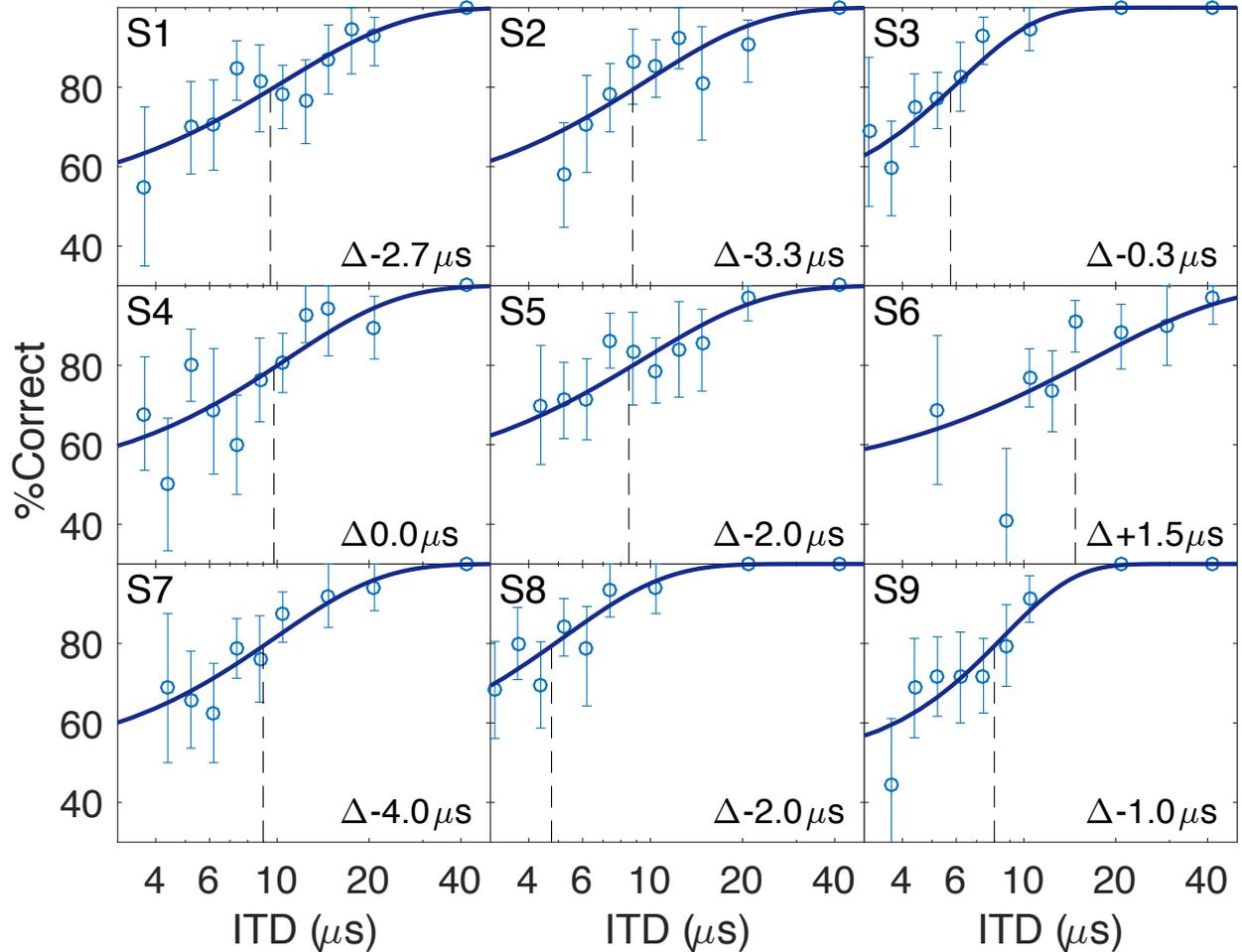


Figure 15. Left-right discrimination as a function of ITD for the 20-1400 Hz noise with an inter-stimulus pause duration of 0.05s. The nine panels portray individual data of the nine participants (S1-S9). The darker colored curve is the psychometric fit curve and the lighter colored circles are percent correct rates at ITDs that were presented at least 15 times. The error bars denote the 95% confidence level, which decreases with the number of presentations and with increasing correct rate. The vertical dashed line indicates the threshold ITD at the 79.4% correct rate. The performance change (Experiment 2 threshold minus Experiment 1 threshold) is indicated at the lower right corner of each panel.

Threshold ITDs at four different percent correct rates were derived from the fitted psychometric function (Table 1) for the nine participants: 70.7% correct rate for comparison with the many studies that used a 2-down 1-up procedure, 75% for comparing with most of the historic thresholds (especially Klumpp and Eady, 1956; Zwislocki and Feldman, 1956) and for reporting the middle between chance level and perfect performance; 76% which corresponds to  $d' = 1$  (e.g., Colman, 2009); and 79.4% for a comparison with 3-down 1-up data, including the internal comparison with the reversal data. Note that the average threshold from the reversals is 7.3  $\mu\text{s}$ , which is supposed to reflect the 79.4% correct level. In contrast, the fit results in 8.4  $\mu\text{s}$  at 79.4% correct and 7.3  $\mu\text{s}$  rather corresponds to 76% correct.

The relative standard error of the mean was always between 9 and 12%. Due to the geometric averaging only a relative error can be stated precisely. A conservative transformation into  $\mu\text{s}$ , by using the larger upper portion of the confidence interval, translates into a standard error smaller than 1  $\mu\text{s}$  at all percent correct levels stated in Table 1.

Across the nine participants, a 1%-point difference in correct rate (between 75% and 76%) corresponded to an increase in threshold ITD of 0.31  $\mu\text{s}$ . The other way around, a difference of 1  $\mu\text{s}$  ITD, on average caused the percent correct rate to change 3% points near the steepest slope, e.g. from 75% to 78%.

Subject #	Threshold ITD ( $\mu\text{s}$ )					Inverse slope (76% threshold - 75% threshold) in $\mu\text{s}$	Slope (%-correct change per $\mu\text{s}$ )	% correct at 10.4 $\mu\text{s}$
	@ 70.7%	@ 75%	@ 76% ( $d'=1$ )	@ 79.4%	From reversal			
1	6.1	7.7	8.1	9.5	9.3	0.44	2.3	81
2	5.8	7.1	7.5	8.7	8.8	0.34	3.0	83
3	4.6	5.3	5.4	6.0	5.1	0.19	5.4	96
4	6.3	7.8	8.2	9.5	7.8	0.37	2.7	81
5	5.6	6.9	7.2	8.5	8.0	0.33	3.0	83
6	8.5	11.2	11.9	14.5	10.8	0.67	1.5	73
7	6.2	7.5	7.8	9.0	7.6	0.28	3.6	83
8	3.5	4.2	4.4	5.0	4.2	0.19	5.2	96
9	6.3	7.1	7.3	8.0	6.6	0.19	5.4	88
<b>Average</b>	5.7	7.0	7.3	8.4	7.3	0.31	3.6*	85*
<b>Relative Standard Error (%)</b>	9.3	10.5	10.7	11.7	11.5	18.0	13.5	2.9
	<b>Untrained Listeners</b>							
<b>Average</b>	14.3	17.7	18.6	21.7	19.6	0.81	1.4*	
<b>Relative Standard Error (%)</b>	8.2	7.7	7.6	7.4	7.7	8.9	15.8	

Table 1: Summary of threshold ITDs from the fitted psychometric functions at different percent correct rates and slopes. In addition, conventionally calculated geometric means of the reversals and the %-correct rate at 10.4  $\mu\text{s}$  ITD (1 sample @ 96 KHz) are shown. The latter is only shown for trained subjects, because for most untrained listeners the adaptive procedure did not collect enough data at this small ITD. By default, averages are geometric mean. Arithmetic means are denoted by an asterisk.

### 3.3.2 Untrained Listeners

Out of the 53 untrained listeners tested, 52 participants' threshold ITDs were derived from Weibull fits at the 79.4% correct level (Fig.16) for the 20-1400 Hz noise stimulus described in sub chapter 3.2.2. The average (geometric mean) threshold ITD at the 79.4% correct level across 52 participants is 22  $\mu$ s. One subject was not included in the average, because run #5 was terminated after the adaptive variable exceeded 600  $\mu$ s. This is surprising, because for the first four runs the subject had an average threshold ITD of 18.2  $\mu$ s.

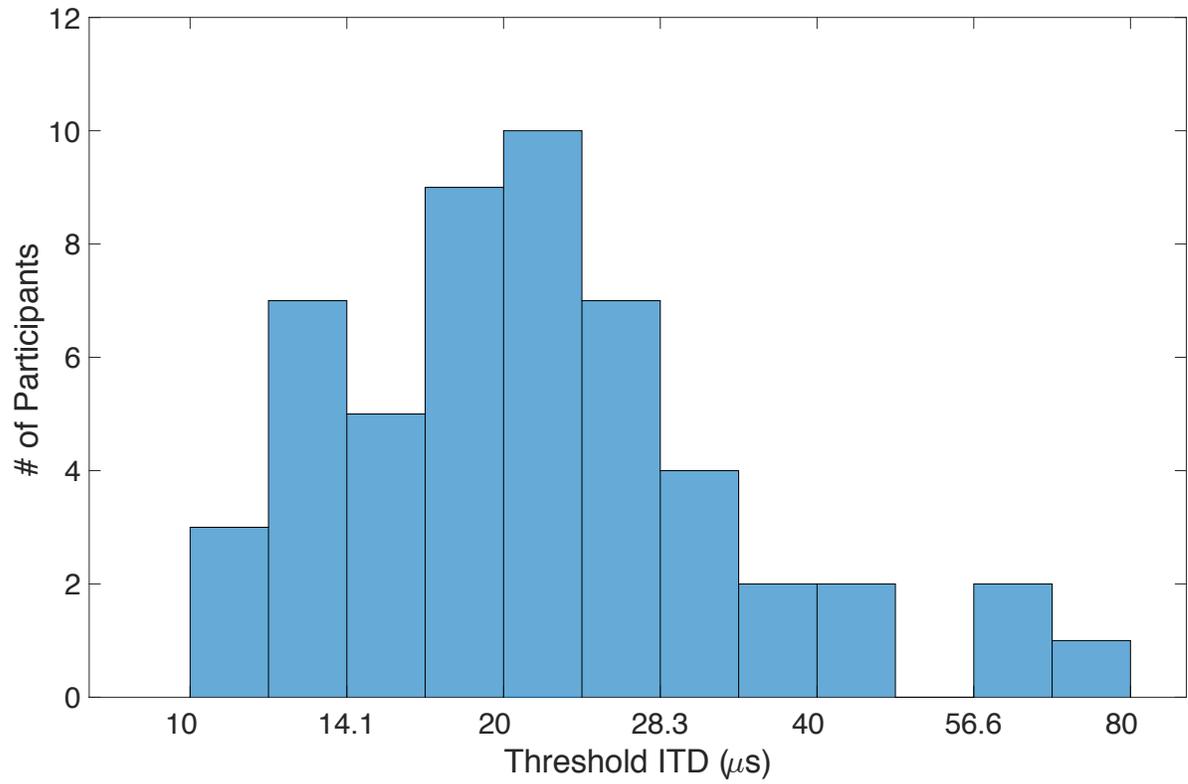


Figure 16. Histogrammic representation of threshold ITD for 52 untrained participants using the chosen condition (20-1400 Hz noise with an inter-stimulus pause duration of 0.05s).

### 3.4 Discussion

The objective of Experiment 2 was to determine accurate threshold ITDs for both trained and untrained normal hearing listeners.

In this experiment, the condition from Experiment 1 that yielded the smallest threshold ITD was utilized to obtain an accurate threshold ITD value for both trained and untrained listeners. The chosen condition was the 20-1400 Hz band-pass filtered noise presented at 70 dB SPL with a short inter-stimulus pause of 0.05s; which yielded the lowest threshold ITD of 10.0  $\mu$ s at 79.4% correct level in Experiment 1. This condition was repetitively measured by the trained listeners in the shorter and more dedicated Experiment 2, resulting in average threshold ITDs of 8.4  $\mu$ s at 79.4% correct level. When comparing to the historic data it is prudent to rather use the 7.0 ( $1 \pm 10.5\%$ )  $\mu$ s at the 75% correct level. This threshold is 30% below the referenced threshold of 10  $\mu$ s (Mills, 1958; Zwislocki & Feldman, 1956) and still 22% below the lowest trustworthy reported threshold of 9  $\mu$ s by Klumpp & Eady (1956).

To report this study's threshold ITDs we used geometric means to calculate the averages across subjects. This is meaningful when assuming a Gaussian distribution of log threshold ITD. Previously published data strongly hint at such a distribution (e.g. Yost et al. 1974, Saberi 1995), as does the present data from the 52 untrained listeners (Fig. 16). Henceforth, geometric averaging has become common practice. However, the studies from 1950s (Klumpp and Eady, 1956; Zwislocki & Feldman, 1956) used arithmetic means. As no distribution or single subject data is reported, we can only speculate that their distribution is similar to ours. In that case, the difference between the two means is approximately 3-4%, i.e. their geometric mean can be expected to be 0.3-0.4  $\mu$ s lower than their reported mean.

## Chapter 4

### 4 General discussion

The comparison to historic data from the previous chapter is also the focus of this general discussion. Presumably, the 20-30% (2-3  $\mu$ s) lower threshold ITDs reported here were caused by several factors. We speculate that the most critical factor was the factor “subjects”. The 1950s studies did not report if subjects underwent audiometric testing and if they were clinically normal-hearing. Recent work has shown that factors such as age (Goupell et al., 2017) and slight sub-clinical hearing loss (Bernstein & Trahiotis, 2016) critically influence binaural perception. Especially, subject related factors such as motivation, training, or fatigue cannot be easily quantified but can be expected to be important, as evidenced by the 16% performance difference between Experiment 1 and 2 for the same stimulus and for the same subjects. With respect to the stimuli it is noteworthy that our most sensitive stimulus is very similar to the stimulus that resulted in the lowest thresholds in the Klumpp and Eady (1956) study (150-1700 Hz band-pass filtered noise). We now know that the upper frequency limit for TFS ITD is very close to 1400 Hz (Brughera et al., 2013). This helped us set the upper frequency limit and may have resulted in a marginally better sensitivity. Finally, the possibility remains that reducing the inter-stimulus pause from 0.3 to 0.05 s has helped to bring down the average thresholds between 0 and 1  $\mu$ s. The historic studies employed even longer inter-stimulus pause durations, e.g. 1 s (Zwislocki & Feldman, 1956), giving potential rise to an even larger contribution to the threshold difference between the studies.

While it may seem trivial upon completion, the measurement of threshold ITDs has always been a significant methodologic challenge. Klemm’s (1920) tremendous

engineering skills first allowed the generation of controlled ITDs as small as 2  $\mu$ s. According to his report, at that time no other scientific discipline used such a small time difference in their experiments. Levitt's (1971) seminal paper on adaptive methods for psychophysics, was originally developed for a L/R ITD detection experiment and is now a standard in various scientific disciplines. In addition to these challenges that have been described in the method sections, we have identified an additional methodologic challenge: When comparing the preliminary data from the reversals of the adaptive tracks with the constant stimulus data, we found the reversal average to correspond to the 75-76% correct value rather than to the 79.4% correct value. To clarify if the subjects performed differently or if there was an analysis confound, we reconstructed psychometric functions from the adaptive tracks. As Fig. 14 clearly shows, there is no subject bias. We rather found that the bias of the reversal averaging was as large as 4%-points or 1-2  $\mu$ s in threshold ITD. The alternative analysis method through the fitting of the psychometric function offered the additional advantage that we can report different %-correct thresholds and the slope. We were also able to include all experimental trials into the calculation of the threshold, which resulted in a higher precision.

There were two possible strategies with which subjects solved the task. One possible approach was mapping each interval on a lateralization axis and then decide for the one most to the right. An alternative was a direct focus on the movement of the percept and effectively discriminate between a L/R from a R/L movement.

Finally, the intention of this experiment is to provide accurate reference values for the two different groups of subjects that can be utilized by different research disciplines. The trained subjects' average threshold value can be used by hearing researchers and

neuroscientists to determine how accurate neurons can code (highest temporal resolution of neural coding). The untrained subjects' average threshold value can be used by hearing aid manufactures and sound engineers for spatial (3D) auditory systems.

## Chapter 5

### 5 Summary

From the stimuli and methods tested in this study, best ITD sensitivity in trained young normal-hearing listeners can be obtained with 20-1400 Hz band-pass filtered noise, in a two-interval L/R discrimination paradigm with a short inter-stimulus pause.

The average threshold ITD across nine trained listeners in a two-alternative forced choice task is 7.0  $\mu\text{s}$  for this stimulus at the 75% correct level (50% chance level). The experimental accuracy of this value estimated from the 10.5% relative standard error of the mean is 0.7  $\mu\text{s}$ . Alternatively, for a  $d'=1$  (76% correct) an ITD of 7.3  $\mu\text{s}$  is required and for the 79.4% correct level the ITD has to be 8.4  $\mu\text{s}$ . Two of the nine listeners performed significantly above chance at an ITD as small as 3.7  $\mu\text{s}$ .

For 52 untrained listeners, the average threshold ITD is 17.7  $\mu\text{s}$  at the 75% and 21.7  $\mu\text{s}$  at the 79.4% correct level.

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# Appendices

## Appendix A: Ethics Approval Notice



**Western  
Research**

**Western University Health Science Research Ethics Board  
HSREB Delegated Initial Approval Notice**

**Principal Investigator:** Dr. Mathias Dietz

**Department & Institution:** Health Sciences\Communication Sciences & Disorders, Western University

**Review Type:** Delegated

**HSREB File Number:** 108836

**Study Title:** Just Noticeable Interaural Time Difference under Optimal Conditions'

**Sponsor:** Canada Research Chairs

**HSREB Initial Approval Date:** March 23, 2017

**HSREB Expiry Date:** March 23, 2018

**Documents Approved and/or Received for Information:**

Document Name	Comments	Version Date
Revised Western University Protocol		2017/03/13
Revised Letter of Information & Consent	Study 1	2017/03/10
Revised Letter of Information & Consent	Study 2	2017/03/10
Recruitment Items	Poster - Study 1	2017/03/22
Recruitment Items	Poster - Study 2	2017/03/22
Other	Email Script - Study 1	2017/03/22
Other	Email Script - Study 2	2017/03/22

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Ethics Officer, on behalf of Dr. Joseph Gilbert, HSREB Chair

EO: Erika Basile \_\_\_ Nicole Kaniki \_\_\_ Grace Kelly \_\_\_ Katelyn Harris \_\_\_ Nicola Morphet \_\_\_ Karen Gopaul \_\_\_

Western University, Research, Support Services Bldg., Ste. 5150  
London, ON, Canada

www.westernu.ca/research

## Appendix B: Information and Consent Forms – Trained Listeners



### Project Title

Just Noticeable Interaural Time Difference under Optimal Conditions

### Principal Investigator:

Mathias. Dietz, National Centre for Audiology, Western University

### Study Sponsors

Canada Research Chair in Binaural Hearing. CRC Admin Account

## LETTER OF INFORMATION

### Invitation to Participate

Since you have responded to our advertisement, you are being invited to participate in a research study that measures your ability to discriminate sounds based on their source location. This letter is intended to provide you with the information you require to make an informed decision on participating in this research. Please take the time to read this information and feel free to ask questions if there is anything unclear to you.

You will be given a copy of this letter for your records.

### Summary and Purpose of Research

The purpose of this experiment is to measure how well humans with normal hearing can discriminate sounds based on the sound source location.

Artificial sounds, such as tones and noises, will be presented over headphones. For some sounds the left and the right headphone output will be identical, simulating a sound from straight ahead. For other sounds, however, there will be a small difference between the ears, simulating a sound that comes from either the left or right. These latter sounds are the target sounds, which have to be identified.

Several properties of the sound will be changed, such as pitch or loudness or duration. Further, some details of the methods will be changed, such as number of sounds presented.

### Eligibility to Participate

You can participate in this study if you:

- are between 18 and 40 years old
- have normal hearing (No history of hearing difficulties and/or neurological disorders) At the beginning we will measure your hearing ability with the so-called 'audiogram'. If your audiogram does not meet the experiment's desired criterion (10 dB HL), this does not mean that you are hearing impaired by the clinical definition, but you cannot participate in the current study and will only receive \$10 compensation for your first appointment.
- are able to understand the instructions of the tasks involved

### Procedure

The study will take **20 to 30 hours** with **multiple** experimental appointments. You will perform left/right sound discrimination tasks in a sound booth. This means, that you will be presented 2-4 sound intervals and you have to decide by the press of a button which of these stimuli (sounds) came from the

right (or left) ear. On the first experimental appointments you will first do a hearing threshold test (audiogram) and a practice block of trials and then do the experimental blocks of trials. In both the practice and experimental blocks of trials, you will be given a feedback after each trial. If you respond correctly, the feedback would say “Correct” otherwise the feedback would say “Wrong.”

### **Information and Consent**

We will explain and display what you will be asked to do in the study. We will obtain your written informed consent.

### **Laboratory sessions**

You will be seated in the sound booth and will be given insert earphones that connect to the experimental computer sound program in a laboratory at the National Centre for Audiology (Elborn College), Western University. You can decide how long you would like to measure for each appointment with a maximum of 105 min and minimum of 50 min per appointment. The recommended time span for each experimental session is 70-90 minutes including breaks. Breaks are encouraged and will be offered as requested.

### **Estimated Time**

The study's duration is approximately 20 to 30 hours and will be divided and completed over multiple time-slotted days/appointments.

### **Location**

The laboratory sessions will be completed at the National Centre for Audiology, Elborn College room EC 2236 Western University, London, ON, Canada

### **Potential Risks, Discomforts, and Inconvenience**

Overall risks of the procedure are minimal. We make sure that the sound will be within the not harmful and not uncomfortable sound level range. Levels are typically 60-80 dB SPL (sound pressure level), which is between the sound level of light traffic (50 dB SPL) and the sound level of a hair dryer (80 dB SPL). Levels may go up to 90 dB SPL for exceptional experimental conditions testing level dependence.

You can take off the headphones at any time if the sound is uncomfortable and take a break at any time. In particular you can skip the loudest 90-dB SPL condition.

### **Potential Benefits**

You may not benefit directly from participating in this study. However, you will likely improve your spatial hearing abilities. If you wish, you will also get information about binaural hearing and the test procedure and detailed purpose of the study after participation. The results of this study lead to a better understanding on how accurate spatial hearing can be performed by listeners under ideal conditions. The obtained results from are going to be benchmarks for hearing aid manufactures and sound engineers, when they decide on the required accuracy for spatial (3D) hearing systems. It is further of fundamental interest to hearing researchers, to better understand the processing of sound in our brain.

### **Participation and Withdrawal**

Participation in this study is voluntary. You may refuse to participate, refuse to answer any questions, or withdraw from the study at any time with no effect on your future treatment, employment, or academic status. We may withdraw you from the study if you are unable to perform the required tasks.

### **Anonymity and Confidentiality**

Your data will be stored indefinitely but without using your name or any other identifiable information. The only personal information that is stored with the data is your age and your gender. If the results of the study are published, your name will not be used and no information that reveals your identity will be released or published. We will use 8 random letters as filename for your data.

We will collect personal information to contact and pay you and to link your name to the 8 random letters for the duration of your participation. This information will be stored in locked offices as hardcopy only, and separately from your experimental data. It is only to the investigators. However, representatives of the University of Western Ontario Research Ethics Board that oversees the ethical conduct of this study may request access to this information.

After your last appointment we will ask for your permission to retain and use your contact information (separately from your results) so that you can be contacted in the future about similar experiments. See form at the end of this document. If you decline permission, your contact information and records linking your identity to your data will be destroyed. Your de-identified data will be securely stored indefinitely. If the results of the study are published, your name will not be used and no information that reveals your identity will be released or published.

### **Compensation**

You will receive \$15 per hour in several payments that can be flexibly arranged (e.g. after every 5th appointment). You will also receive \$10 as a small additional incentive for the final session in addition to your hourly compensation. Each appointment's duration depends on the participant, but the recommended duration is 70-90 minutes. If you do not complete the study, you will be paid for the appointments completed. This study might result in the creation of new tests or other intellectual property that may be worth some money, even though this is not foreseen right now. Although we might make money from these findings, we cannot give you any of this money now or in the future because you took part in this study.

### **Legal Rights**

Your participation in this study is voluntary. You may decide not to be in this study. Even if you consent to participate you have the right to not answer individual questions or to withdraw from the study at any time. If you choose not to participate or to leave the study at any time it will have no effect on your employment or academic standing.

We will give you new information that is learned during the study that might affect your decision to stay in the study.

You do not waive any legal right by signing this consent form.

### **Publications of Results**

If you would like to receive a copy of the overall results of this study, please provide your name and contact information to the investigator.

### **Contact Persons**

If you have any questions about this study, please contact the principal investigator (contact information can be found on the first page of this letter). You may also contact the Office of Research Ethics at Western University if you have questions related to your rights as a research subject.

**Consent Form**

**Project Title:** Just Noticeable Interaural Time Difference under Optimal Conditions

**Study Investigator's Name:** Mathias Dietz

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

Participant's Name (please print): \_\_\_\_\_

Participant's Signature: \_\_\_\_\_

Date: \_\_\_\_\_

Person Obtaining Informed Consent (please print): \_\_\_\_\_

Signature: \_\_\_\_\_

Date: \_\_\_\_\_

**Project Title:** Just Noticeable Interaural Time Difference under Optimal Conditions

**Consent to be contacted for future studies and to keep a record linking my name to my data.**

Typically, your personal information is destroyed after the study, maximizing your anonymity.

You can allow us to keep the letter which contains your personal information. This letter also contains the information, which dataset is yours. It will help us to relate any future data from you, to your data from the current study.

**This consent is not relevant for participation.** You can withdraw your consent at any time.

If you do not give your consent we will shred your personal information after the last experiment. If you give us your consent to keep the personal information, we will keep it for a maximum of 5 year and then shred it.

Participant's Name (please print): \_\_\_\_\_

Participant's Signature: \_\_\_\_\_

Date: \_\_\_\_\_

## Appendix C: Information and Consent Forms – Untrained Listeners



### Project Title

Just Noticeable Interaural Time Difference under Optimal Conditions

### Principal Investigator:

Mathias. Dietz, National Centre for Audiology, Western University

### Study Sponsors

Canada Research Chair in Binaural Hearing, CRC Admin Account

## LETTER OF INFORMATION

### Invitation to Participate

Since you have responded to our advertisement, you are being invited to participate in a research study that measures your ability to discriminate sounds based on their source location. This letter is intended to provide you with the information you require to make an informed decision on participating in this research. Please take the time to read this information and feel free to ask questions if there is anything unclear to you.

You will be given a copy of this letter for your records.

### Summary and Purpose of Research

The purpose of this experiment is to measure how well humans with normal hearing can discriminate sounds based on the sound source location.

Artificial sounds, such as tones and noises, will be presented over headphones. For some sounds the left and the right headphone output will be identical, simulating a sound from straight ahead. For other sounds, however, there will be a small difference between the ears, simulating a sound that comes from either the left or right. These latter sounds are the target sounds, which have to be identified.

### Eligibility to Participate

You can participate in this study if you:

- are between 18 and 40 years old
- have normal hearing (No history of hearing difficulties and/or neurological disorders)
- are able to understand the instructions of the tasks involved

### Procedure

The study will take approximately **30 minutes** to complete. You will perform left/right sound discrimination tasks in a sound booth. This means, that you will be presented 2-4 sound intervals and you have to decide by the press of a button which of these stimuli (sounds) came from the right (or left) ear. If you respond correctly, the feedback would say "Correct" otherwise "Wrong."

### Information and Consent

We will explain and display what you will be asked to do in the study. We will obtain your written informed consent.

**Laboratory sessions**

You will be seated in the sound booth and will be given insert earphones that connects to the experimental computer sound program in a laboratory at the National Centre for Audiology (Elborn College), Western University.

**Estimated Time**

The study's duration is approximately 30 minutes and will take one appointment to complete it.

**Location**

The laboratory sessions will be completed at the National Centre for Audiology, Elborn College room EC 2236 Western University, London, ON, Canada

**Potential Risks, Discomforts, and Inconvenience**

Overall risks of the procedure are minimal. We make sure that the sound will be within the not harmful and not uncomfortable sound level range. Levels are equal or below 80 dB SPL (sound pressure level). The highest possible level of 80 dB SPL corresponds to the sound level of a hair dryer. You can take off the headphones at any time if the sound is uncomfortable.

**Potential Benefits**

You may not benefit directly from participating in this study. The results of this study lead to a better understanding on how accurate spatial hearing can be performed by listeners under ideal conditions. The results are going to be a benchmarks for hearing aid manufactures and sound engineers, when they decide on the required accuracy for spatial (3D) hearing systems. It is further of fundamental interest to hearing researchers, to better understand the processing of sound in our brain.

**Participation and Withdrawal**

Participation in this study is voluntary. You may refuse to participate, refuse to answer any questions, or withdraw from the study at any time with no effect on your future treatment, employment, or academic status. We may withdraw you from the study if you are unable to perform the required tasks.

**Anonymity and Confidentiality**

Your data will be stored indefinitely but without using your name or any other identifiable information. The only personal information that is stored with the data is your age and your gender. If the results of the study are published, your name will not be used and no information that reveals your identity will be released or published.

**Compensation**

You will receive \$10 for participation at the end of the experimental appointment. If you do not complete the study, you will be paid for the appointment. This study might result in the creation of new tests or other intellectual property that may be worth some money, even though this is not foreseen right now. Although we might make money from these findings, we cannot give you any of this money now or in the future because you took part in this study.

**Legal Rights**

Your participation in this study is voluntary. You may decide not to be in this study. Even if you consent to participate you have the right to not answer individual questions or to withdraw from the study at any time. If you choose not to participate or to leave the study at any time it will have no effect on your

employment or academic standing.

We will give you new information that is learned during the study that might affect your decision to participate.

You do not waive any legal right by signing this consent form.

**Contact Persons**

If you have any questions about this study, please contact the principal investigator (contact information can be found on the first page of this letter). You may also contact the Office of Research Ethics at Western University if you have questions related to your rights as a research subject.

**Consent Form****Project Title:** Just Noticeable Interaural Time Difference under Optimal Conditions**Study Investigator's Name:** Mathias Dietz

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

Participant's Name (please print): \_\_\_\_\_

Participant's Signature: \_\_\_\_\_

Date: \_\_\_\_\_

Person Obtaining Informed Consent (please print): \_\_\_\_\_

Signature: \_\_\_\_\_

Date: \_\_\_\_\_

## Curriculum Vitae

**Name:** Sinthiya Thavam

**Post-secondary Education and Degrees:** University of Waterloo  
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2012-2016 H.B.Sc.

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**Honours and Awards:** Western Neuroscience Graduate Travel Awards  
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### Conference Presentations:

**Thavam, S.\* & Dietz, M.** (2018). Threshold Interaural Time Differences Under Optimal Conditions. Poster presented at the London Health Research Day 2018, London, ON, Canada.

**Thavam, S.\* & Dietz, M.** (2018). Threshold Interaural Time Differences Under Optimal Conditions. Poster presented at the 41st Association for Research in Otolaryngology (ARO) Annual Mid-Winter Meeting, San Diego, CA, U.S.A.