TONAL DETECTION THRESHOLDS IN THE PRESENCE OF LOUD (80 dBA) NOISE: AN EMPIRICAL AND COMPUTATIONAL ERGONOMICS STUDY

by

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03 August 2015

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This is to certify that I have examined the above PhD thesis
and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by
the thesis examination committee have been made.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Tonal Detection Thresholds in the Presence of Loud (80 dBA) Noise: An Empirical and Computational Ergonomics Study

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Abstract

In a recent industrial consultation study, the author observed that workers could easily detect a 59 dBA train alarm in the presence of 77 dBA train noise; a signal-to-noise ratio (SNR) of -18 dB. A literature review indicated that little is known about alarm detection with SNRs of -18 dB or below. The first experiment of this study was designed to repeat the observations with 12 participants. Four stimuli conditions with alarms at -18, -21, -24 and $-\infty$ dB SNRs were studied. The train alarm (2 kHz with harmonics at 4 kHz, 6 kHz, 8 kHz and 12 kHz) and the train noise (with pink spectrum) were similar to the observed signals. Results indicated that the subjects were able to detect the train alarm with -24 dB SNR and the perceived loudness of the train alarm was significantly different among all four conditions. The SNR level of -24 dB was further reduced to -28 dB (median value) in the second experiment with sixteen participants using a two interval forced choice (2IFC) testing protocol. This was referred to as the alarm-in-noise (AIN) detection threshold. In addition, results indicated that if free-field spatial information was removed by presenting the train alarm and the train noise monaurally and diotically, the median AIN levels raised back to -13 dB and -14.3 dB, respectively. There was a statistically significant difference between the detection thresholds collected at the monaural and free-field conditions ($p<0.05$). In the second experiment, train alarms of different durations were tested and found to have no significant effect on the detection thresholds. A large inter-subject variability was also observed ranging from -9 dB to -46 dB SNR. In an attempt to uncover the mechanism behind an AIN detection threshold of -28 dB SNR (or -46dB in one listener), a customized biologically inspired model for hearing was constructed. The model was based on the existing Matlab Auditory Periphery (MAP) model developed by Meddis (2006). It contains basic modules to simulate and predict sound transmission from the pinna to the middle ear, the cochlea and the subsequent excitations of auditory nerves. The simulation results of the initial model indicated subtle but repeatable changes in the basilar membrane (BM) displacements and auditory nerve firing patterns related to the stimuli conditions of the experiments. In particular, the effects of efferent feedback of the medial olivocochlear system (MOCS) were simulated because this type of efferent feedback had been shown to improve speech intelligibility in noise. A third experiment was conducted to test the hypothesis that the MOCS efferent feedback would help the detection of train alarm in loud train noise. Subjects of the second experiment were tested for their strength of efferent feedback in terms of their contralateral suppression of the transient-evoked otoacoustic emissions (TEOAEs). To our surprise, correlation analysis indicated a significant ($p<0.05$) but negative correlation between contralateral suppression of TEOAEs and masked detection thresholds. This implied that stronger MOCS efferent feedback worsens the detection performance in negative SNR conditions. The fourth experiment verified and confirmed that the negative SNR levels of AIN also held for tone-in-noise (TIN) detection thresholds (1 kHz and 2 kHz). The thesis contains novel and original results that are beneficial for both industrial and academic purposes. The customized and calibrated biologically-inspired MAP models can be a useful platform for testing and developing future auditory alarms in noisy environments.

CHAPTER 1: INTRODUCTION

Summary

This chapter introduces the current study by presenting the research problem and corresponding research questions. It also includes definitions for important terms that are used in the current study.

1.1 Introduction, Motivation and Research Questions

Hearing is an “everyday miracle”, even though effortlessly done, involves procedures with staggering complexity (Schnupp *et al*., 2011). We hear and respond to sounds every day, from birth to death; barring persons with hearing impairments leading to deafness. The common types of sounds; speech, screams, music, noise etc. vary largely in loudness, pitch and quality. Out of the many sounds that we hear, detection of some is more important than others. Auditory warning signals, such as alarms and horns are commonly used in this day and age; the detection of those is critical in ensuring safety, especially in industrial environments.

According to data collected from a field study, even when a train alarm was with a signal-to-noise ratio (SNR) of -18 dB; listeners were able to successfully detect the alarm (So and Karunarathne, 2012). Therefore the idea of determining the negative boundary of SNR level in which listeners start failing to detect the signals, formed the motivation of this study.

This study attempts to investigate and answer two questions; how and why listeners with normal hearing are able to detect tonal signals at -18 dB SNR or below. Originating with experimental procedures and results, this study further investigates the underlying biological processes related to detecting sounds in the presence of loud noise.

1.2 Definitions

Sound Intensity: Rate at which the sound power falls on an imaginary surface of unit area in a direction perpendicular to the surface. (Crocker, 1998: 6). SI Unit: W/m^2

Sound Intensity Level (SIL): Logarithmic measure of the sound intensity of a sound relative to a reference sound intensity.

$SIL = 10log_{10}(\frac{I}{I_0})dB$, where I=sound intensity and I_0=reference sound intensity

Derived from relationships in Crocker (1998): 10,11.

Sound Pressure (Acoustic Pressure): Local pressure deviation from the ambient atmospheric pressure caused by a sound wave (Truax, 1999). SI unit: Pascal (Pa).

Sound Pressure Level (SPL): Logarithmic measure of the effective pressure of a sound relative to a reference sound pressure. SI unit: decibels (dB)

$SPL = 20log_{10}(\frac{p}{p_0})dB$, where p=sound pressure and p_0=reference sound pressure

Derived from relationships in Crocker (1998): 10,11.

Signal-to-Noise Ratio (SNR): The ratio of signal power to the noise power.

$SNR = \frac{P_{Signal}}{P_{Noise}}$, where P is average power.

Definition for sounds in decibels (dB)

$$SNR = \frac{P_{Signal}}{P_{Noise}} = \frac{I_{Signal}}{I_{Noise}} = \frac{p^2_{Signal}}{p^2_{Noise}}$$

$$SNR_{dB} = 10log_{10}(SNR)$$

$$SNR_{dB} = 20log_{10}\left(\frac{p_{Signal}}{p_{Noise}}\right) = 20log_{10}\left(\frac{p_{Signal}}{p_0} / \frac{p_{Noise}}{p_0}\right)$$

$$SNR_{dB} = 20log_{10}\left(\frac{p_{Signal}}{p_0}\right) - 20log_{10}\left(\frac{p_{Noise}}{p_0}\right)$$

$$SNR_{dB} = SPL_{Signal} - SPL_{Noise}$$

Derived from relationships in Crocker (1998): 8, 10, 11.

Power Spectral Density (PSD): Distribution of the power of the signal over frequency. (Hammond and White, 2008: 10). Figure 1.1 shows a PSD obtained by Welch's method (Welch, 1967).

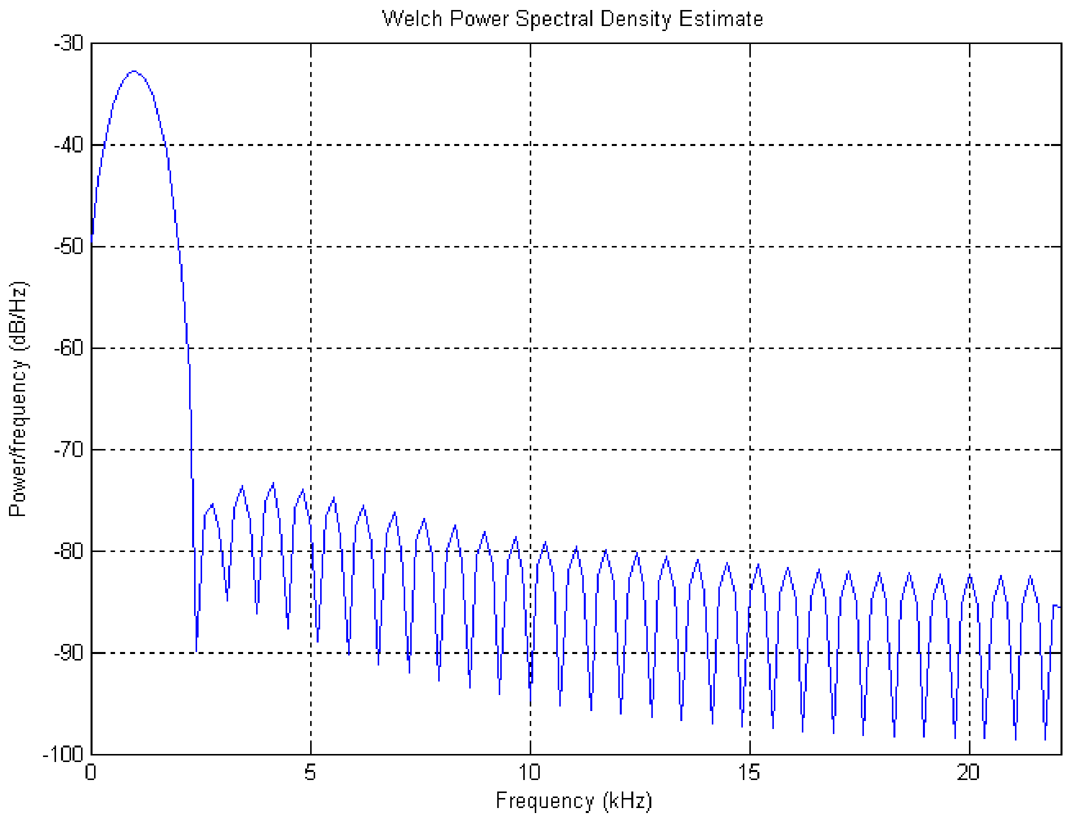

Figure 1.1 Welch PSD Estimate for a 1 kHz pure tone

Pink Noise: Signal or process with a frequency spectrum such that the power spectral density is inversely proportional to the frequency of the signal (1/f power spectral density, where f=frequency) (Vageshi, 2009: 43).

AIN: Alarm-In-Noise; this is a notation for train alarm in the presence of noise.

TIN: Tone-In-Noise; this is a notation for tone in the presence of noise.

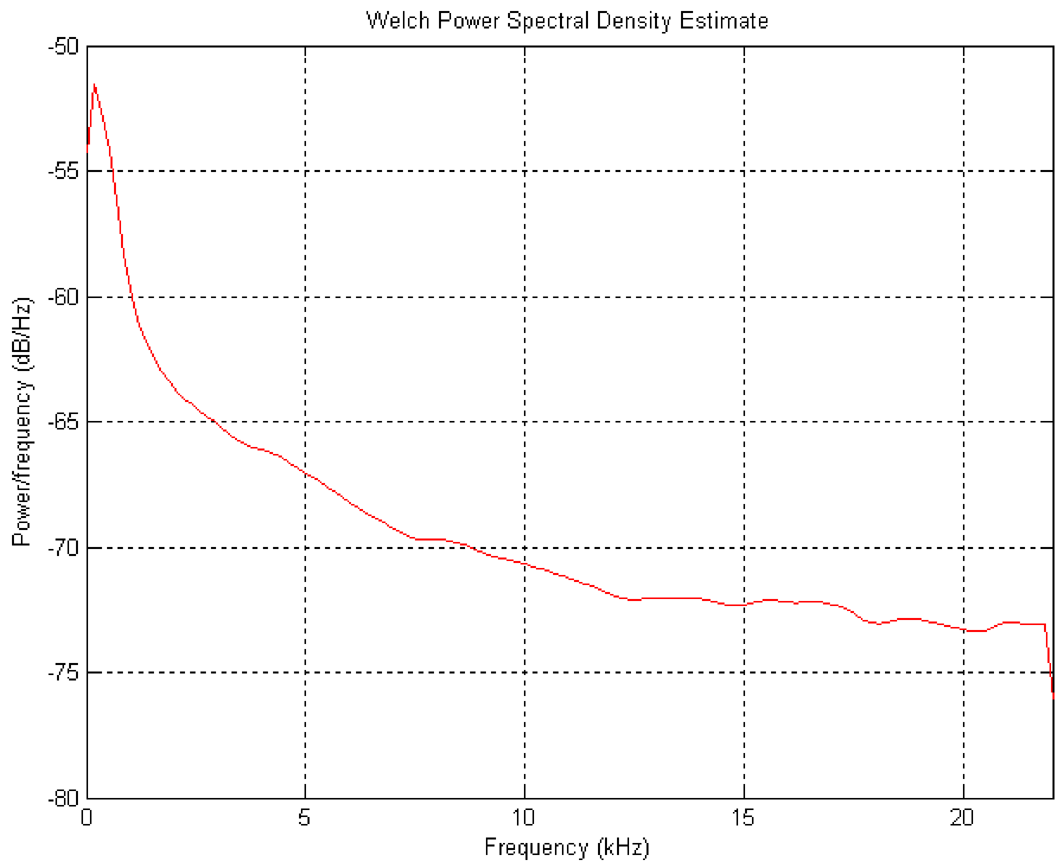

Figure 1.2 Welch PSD of pink noise used in this study

Detection Threshold: In this study, detection threshold is the minimum sound pressure level (in dB) of a signal (tone) that is audible as measured with an adaptive 2IFC procedure using the 3-down 1-up rule. The step size will initially be 5 dB and subsequently reduced to 1 dB after the first 4 reversals (adapted from Micheyl *et al.*, 1995). The threshold will be set at the average value of the last two reversals after 50 trials.

Basilar Membrane (BM): Basilar membrane is a structure inside the cochlea which divides the fluid-filled area inside the cochlea into upper compartments (scala vestibuli and scala media) and lower compartments (scala tympani) (Schnupp *et al.*, 2011: 55). Sensory cells of hearing (hair cells) use basilar membrane as the base.

Medial Olivocochlear System (MOCS): The efferent fibers of the cochlea, which are called olivocochlear neurons, are originated in the Superior Olivery Complex (SOC). One of the two kinds of efferents; medial olivocochlear system (MOCS) originates near the medial nucleus of the SOC and innervates Outer Hair Cells (OHCs) (Rossing, 2007: 436).

Otoacoustic Emissions (OAEs): Otoacoustic emissions (OAEs) are sounds of cochlear origin, which can be recorded by a microphone fitted into the ear canal. They are caused by the motion of the cochlea's sensory hair cells as they energetically respond to auditory stimulation (Kemp, 2002).

Efferent Feedback: Feedback signals within the auditory system which serves to suppress the transmission or perception of a loud sound. There are two types: (i) acoustic reflex (AR) – signals from the auditory nerves (ANs) with low spontaneous rates (about 10 spikes/s) processed in the brain stem and fed back to attenuate stapes and (ii) MOCS reflex from the ANs with high spontaneous rate (about 200 spikes/s) processed in the cochlea and fed back to attenuate responses at the basilar membrane (BM) (Guinan, 2006).

How loud is 'loud'? In this study, loud sound will be defined as a sound equal to or louder than 80 dBA. Noise levels of 80 dBA are studied because normal-hearing industrial workers have been observed to be able to detect a train alarm 18 dB lower than a train noise level of 77 dBA despite large individual differences (So and Karunarathne, 2012).

Normal-hearing listeners: In this study, a normal-hearing listener is defined as having (i) pure-tone thresholds less than or equal to 25 dB for frequencies 0.250 , 0.500, 1000, 2000, 4000 and 8000 kHz in both ears; and (ii) aged between 18 – 65 years.

1.3 Detection of tones in loud noise

Auditory alarms have a wide variety of applications and the "better safe than sorry" principle has discouraged the use of alarms with loudness lower than the background noise (i.e., with negative SNRs). Consequently, past studies on alarm perception with negative SNRs are few. On the other hand, after an alarm has been installed in the industry, levels of background noise could have increased over the years and gone beyond the original estimated levels resulting in negative SNRs.

Detecting an alarm in actual circumstances is a case of free-field spatial information configuration. Review of literature shows that most of the studies investigating tonal detection in the presence of noise has been carried out for monaural (Hawkins and Stevens, 1950; Bos and de Boer, 1966), binaural (diotic or dichotic) spatial information configurations (Gilkey *et al*., 1985, Evilsizer *et al*., 2001) or a combination of both (Henning and Zwicker, 1984; Isabelle and Colburn, 1990; Langhans and Kohlrausch, 1992). Therefore the need for investigating the differences between spatial information configurations is also highlighted. Detection at SNRs as low as -15dB has been reported (at 60dB noise: Leibold and Werner, 2006), but most studies have reported higher thresholds (-10dB SNR at 73dB noise: Langhans and Kohlrausch, 1992; -7dB SNR at 50dB noise: Viemeister 1983). Also most of the experimental work has used noise levels at or below 75dB (73dB: Langhans and Kohlrausch, 1992; 60dB: Patterson and Mayfield, 1990; Leibold and Werner, 2006).

Relationship between tonal detection thresholds and tonal duration has been studied (Plomp and Bauman, 1958; Florentine, 1986; Baer *et al*, 1999). The effect of tonal duration on tone-in-loud-noise detection requires further investigations.

1.4 Role of MOCS efferent feedback in detection in noise

The proposed functions of the MOCS are cochlear protection against loud sounds (Cody and Johnstone, 1982; Rajan and Johnstone, 1988), development of cochlea function (Liberman *et al.*, 1990) and detection and discrimination of sounds in noise (Dolan and Nuttal, 1988). Out of these, detection and discrimination of sounds in noise, falls in line with the scope of this study.

Garinis *et al*. (2011) indicated a negative correlation between the strength of MOC efferents and tonal detection threshold, while Bhagat and Carter (2010) found a positive correlation. Past studies have also looked into speech perception in noise and the role of efferent feedback. Brown *et al*. (2010) and Clark *et al*. (2012) have indicated the positive influence of MOCS efferent feedback in speech perception in noise. Why are the results contradicting? Can these phenomena be simulated and predicted using a biologically inspired auditory model? How can the individual differences in detection thresholds be explained? Answering these questions will benefit towards for a better understanding of the mechanism behind tonal detection in the presence of noise.

1.5 From Traditional Ergonomics to Computational Ergonomics

Ergonomics is the discipline that studies how human interacts with their environment and tools. The perspectives of ergonomics studies are spread across science, engineering, design, technology and management of human centered systems (Karwowski, 2012). The approach of the traditional ergonomics is to develop hypotheses and then test them through laboratory experiments. The experiments often have to use human subjects and the procedures are typically time-consuming.

The discipline of computational ergonomics tries to address this problem with the addition of biologically inspired computational models of the relevant human process (So and Lor, 2004). The ultimate objective is to develop computational models that can predict human responses to new stimuli and environment. If this can be achieved, computational simulations can be run to generate sets of predicted solutions and only selected conditions will be tested through time consuming empirical experiments.

The current study will present the details of experimental studies related to AIN and TIN detection performance of human subjects (Chapters 3, 4 and 6). Importantly the current study will also highlight the advantages of using an auditory neuroscience model (Chapter 5) for simulations and will suggest possible applications (Chapter 8).

1.6 Thesis Organization

This thesis was divided into 8 chapters. The chapters are summarized as follows.

Chapter 1 introduces the study by providing background details on tonal detection, biological process modelling and role of MOCS efferent feedback in TIN detection. It also provides definitions for the important terms that are used and discussed in this study.

Chapter 2 reviews the literature associated with TIN/AIN detection and the related studies that investigates the biological process behind human hearing. While analyzing the broad range of past studies on related topics, this chapter attempts to emphasize the importance of the current work.

Chapter 3 presents the detailed methodology and results of Experiment 1 of the current study, which re-constructed an actual industrial setting inside the laboratory to investigate the alarm-in-loud-noise detection. Promising results obtained in this experiment was an encouragement for the further investigations.

Chapter 4 presents the detailed methodology and results of the Experiment 2 that measured alarm-in-loud-noise thresholds and investigated the effects of spatial information and tonal duration on the thresholds.

Chapter 5 provides details about the usage of a biologically inspired model to simulate the results obtained in the experiments. Existing Matlab Auditory Periphery (MAP) model (Meddis, 2006a,b) was used to do the simulations. Also, the detailed methodology of Experiment 3 which measured TEOAEs and subsequent analysis is presented in this chapter.

Chapter 6 presents detailed methodology and results of the Experiment 4 which measured the tone-in-loud-noise detection thresholds for pure tones.

Chapter 7 discusses the results obtained in the current study and how the findings related to the existing literature.

Chapter 8 concludes the major findings and contributions of the current study. Limitations of the current study are also presented. A glimpse into the potential future extensions of this line of study is also introduced.

CHAPTER 2: LITERATURE REVIEW

Summary

This chapter presents and summarizes past studies related to the current work. Important studies related to tonal detection (Section 2.2), auditory modelling (Section 2.3) and MOCS efferents (Section 2.4) are reviewed.

2.1 Introduction

The curiosity on sounds and how we hear them originated many hundreds of years back; as early as in 6th century BC, Pythagoras explained sounds as vibrations in the air (Vogel *et al*., 2007). Examples of historical landmarks of hearing research include Hippocrates' clinical findings of hearing loss in 377 BC, Adreas Vesalius' descriptions of middle ear anatomy in 1543 and Gabriele Falloppio's discovery of the cochlea in 1561 (Vogel *et al*., 2007). In 1903, Max Wien introduced the "sensitivity curve", which is considered as the first attempt to relate hearing sensitivity to the frequency of sound (Vogel *et al*., 2007). Hearing research has been evolving, strengthened by the platform provided by the prominent research work in the past, and still continues to improve by exploring the finer details.

2.2 Tonal Detection

2.2.1 Detection and Masking

Sound detection under different circumstances has historically received significant attention. As early as in 1876, in a qualitative study, Mayer concluded that sounds of lower frequency may "obliterate" sounds of higher frequencies with considerable intensity but vice versa does not apply (Mayer, 1876). In 1924, Wegel and Lane studied the masking of a pure tone by another and its relation to the function of the inner ear (Wegel and Lane, 1924). Their study gave conclusive evidence that the effects of masking decreased as the target tone was removed, in frequency terms, from the masking sound. In a later study by Fletcher and Munson, they demonstrated similar behaviour for bands of noise and also introduced a prediction method for masking of tones in noise (Fletcher and Munson, 1937). Previously In 1933, Fletcher and Munson introduced a method for calculating the loudness of a complex tone from its frequency spectrum (Fletcher and Munson, 1933). Fletcher's work developed into the permanent work of critical bands and it is considered as one of the major milestones of the auditory masking theory. By means of experimental procedures, he demonstrated that a pure tone is masked only by noise components within a narrow range centered at the frequency of the target tone (Fletcher, 1940). This was called the critical band in auditory masking. It was also concluded that frequency components outside the critical band had no major effect in masking the tone and the masked threshold of the tone was reached when its intensity matched the intensity of the noise in the corresponding critical band (Fletcher, 1940). Further studies suggested that the masked threshold of a pure tone centered in a noise band which is narrower compared to the critical band, is reached when the tone level in approximately 1-2 dB lower than the noise level (Schafer *et al*., 1950).

2.2.2 Tone-In-Noise (TIN) Detection: factors other than effects of duration

Auditory detectability of pure tones as a function of frequency has been studied for continuous pure tones (Hawkins and Stevens, 1950) and pulsed pure tones (Green *et al*., 1959). The relationship of the detectability to the tonal frequency is important as it is used as a basis for investigating how the critical bands of the human auditory system vary with sound frequency (Green *et al*., 1959). Both studies mentioned above confirm the dependency of tonal detectability on the frequency.

Temporal aspects of masking have also received attention in the past. It has been shown that after having performed detection tasks in a single frequency for some time, listeners' ability of detecting a different tone with similar energy but different frequency will significantly reduce (Tanner *et al*., 1956; Greenberg, 1962).

Alterations of certain interaural parameters (eg. interaural phase) of both the target signal and the masker could significantly affect the detectability of the target signal in the presence of the masker (e.g., Hirsh, 1948; Licklider, 1948). Ahumada *et al*. (1975), Hanna and Robinson (1985), Gilkey and Robinson (1986) have attempted predicting monaural detection of individual target signals based on energy related parameters of the target signals. Gilkey *et al.* (1985) compared the diotic and dichotic conditions and showed that signal-to-masker phase had a large effect on the detectability under diotic condition and only a small effect under the dichotic condition. In a subsequent study in 1990, Isabelle and Colburn provided evidence of a small yet statistically significant effect of signal-to-masker phase in the dichotic condition. In this study, the signal-to-masker (noise) phase is kept constant.

Experimental work by Richards in 1992 has hinted that detection of a tone in noises of moderate bandwidth and duration depended on the noise bandwidth (Richards, 1992).Most models of tonal detection in the presence of noise assume that the change in power by the added tone is a critical factor affecting the detection of tone (e.g., Moore, 1988; Green and Swets, 1966). Apart from differences in level associated with the changes in the tone, there are few other cues that may be used by the listener when performing tone-in-noise tasks (Richards and Nekrich, 1993). For broad band noise (relative to critical bandwidth), across-frequency intensity differences (Green, 1988) and envelopes (Hall *et al*., 1984) have been studied. These differences may contribute to detection of tone in the presence of noise (Hall and Grose, 1988; Ahumada and Lovell, 1970; Gilkey and Robinson, 1986). In this study, the first two experiments adopted the "screw-shaped" envelope of the original alarm signals measured from the industry (see Figure 3.1, Chapter 3). In Experiment four, pure tones of constant sound level were used.

Free-field unmasking has been mainly studied for speech intelligibility improvements observed when the target and masker are in different spatial locations (Tonning, 1971; Plomp and Mimpen, 1981). Studies investigating this phenomenon for pure tones are also available in the current literature (Gatehouse, 1986, 1987; Santon, 1987; Saberi *et al*., 1991). Their results indicate that better detection performance is achieved for certain spatial locations of target tone and the masker. Gatehouse (1986, 1987) showed that for pure tones 1 kHz and 2.5 kHz, tonal detection performance was not necessarily poorest for the condition at which the target and the masker are spatially coincident. Santon (1987) showed similar results for 1.5 kHz. Gilkey and Good (1992) observed significant decreases in masking for free-field configurations (18dB when sound sources separated in the horizontal plane and 9dB for high frequencies when they were separated within the median plane). In our study, the effects of free-field, diotic, and monaural presentation are studied and the effects of spatial separation of the target sound and the noise sound are also examined. Discussions of how our findings are related to these studies can be found in Chapter 7.

Studies using dichotic presentations of stimuli over headphones have demonstrated that varying inter-aural time parameters of either the target tone or the masker can improve the detectability up to 15dB (Colburn and Durlach, 1965; Moore, 1989). Some past studies have also used head related transfer functions (HRTF: Wightman and Kistler, 1989; Carlile and Pralong, 1994) to create a "Virtual Auditory Space" to imitate the masking effects of a free-field configuration (Carlile and Wardman, 1996). Although we did not manipulate the interaural time parameters and did not apply HRTF filtering to the sounds used in this study, the spatial locations of the sound sources in Experiments 1, 2 and 4 had embedded these characteristics inherently. Discussions of how our findings are related to these studies can be found in Chapter 7.

Patterson studied about detection of tones in the presence of noise and found that repeated signals are more detectable in uncorrelated noise than in repeated noise when the target signal is at 1.6 kHz (Patterson *et al*., 1982). Studying about detection of auditory signals in the presence of noise, Pfaflin and Mathews identified that the main determinant of detection behaviour was the energy differences introduced by the signal (Pfaflin and Mathews 1965). In our study, the noise has a pink spectrum and is random in its statistical behaviour. The noise was chosen because it resembles background noise common found in workplaces.

Measuring tonal detection thresholds in the presence of noise is not new, but most previous studies used noise levels of 75dB or less and reported detection thresholds with positive SNRs (e.g., SNRs of 9 to 32dB with a noise level of 30dB (Penner and Viemeister, 1973); SNRs of 8 to 15dB with a noise level of 40dB (Schooneveldt and Moore, 1989); a SNR of 20dB with 60dB noise (Patterson and Mayfield, 1990)). As the level of noise increased, a trend can be observed for the SNRs of detection thresholds to reduce (Bos and de Boer, 1966). It is important to note that tone detection with a negative SNR in the presence of noise has been reported, but only up to around -15dB SNR. In this study, tone-in-noise detection conditions with SNRs smaller than -15dB are examined.

2.2.3 Effects of Tonal Duration on Detection Thresholds

In 1946, Hughes conducted experiments to test effect of durations of the target tone on the detectability (under absolute threshold conditions) using six different durations ranging from 63ms-739ms and five frequencies (Hughes, 1946). The data from this study fitted the following equation.

$$\frac{I}{I_0} = b + \frac{a}{t}$$

Where, I is the threshold intensity of the target tone of duration t, I_0 is a constant intensity (which is the threshold intensity of the shortest target tone duration) and a, b are constants for the given frequency (Hughes, 1946). Assuming that the relationship holds for continuous presentation of the tone ($t \rightarrow \infty$), and that the threshold intensity is then I_∞,

$$I_\infty = bI_0 = C$$

Where C is a constant.

Garner and Miller (1947) suggested a similar relationship based on the data obtained by their experiments which used eight durations ranging from 12.5ms to 2000ms and measured masked tonal detection thresholds.

Hughes (1946) further suggested that,

$$I = I_\infty \left(1 + \frac{a}{bt}\right) = I_\infty (1 + \tau t)$$

Where τ is a constant of the dimensions of time.

Effect of signal duration on critical bandwidth measurements has been studied (Hamilton, 1957; van den Brink, 1964). Hamilton's findings suggested a widening of the critical bandwidth from 150 Hz to 200 Hz and 500 Hz as the tonal duration reduced from 400ms to 50ms and to 25ms, respectively. The conclusions are based on thresholds ratios of signal power to noise power density for a range of external filter widths and tonal durations for target tone of 800 Hz. van den Brink (1964) also reported similar findings. Studies of temporal integration at masked threshold also suggested changes in thresholds with tonal duration (Plomp and Bouman, 1959; Florentine *et al*., 1988).

Using target frequencies 250, 1000 and 4000Hz, Baer *et al*. (1999) concluded that detection thresholds either in quiet or in pink noise (spectrum level at 1000 Hz 15 or 40 dB), declined with increasing duration at a rate of approximately 3 dB per doubling duration.

Meddis and Lecluyse (2011) defined a probabilistic approach to investigate detection thresholds and tonal duration. The psychometric function was defined as,

$$\Psi = 1 - \exp\left(-d(GP - A)\right)$$

where Ψ is the probability that at least one detection will occur between the beginning and the end of the tone, P is the peak pressure of a pure tone (µPa), G is a free parameter representing the gain of the system and A is a rate of events below which the system does not ever respond.

Threshold/duration function was defined as,

$$P_{thr} = (\frac{0.69}{d} + A)/G$$

where P_{thr} is the peak pressure at threshold (µPa) and d is the duration of the tone (in seconds) (Meddis and Lecluyse, 2011). These derived equations were backed up by the experimental data collected for both normal hearing and hearing-impaired listeners.

In summary, duration of tone is likely to affect the detection thresholds of tone-in-noise performance. In Experiment 2 of this study, the effects of tone duration are investigated.

2.2.4 Alarm-In-Noise (AIN) detection

Alarm perception has been the subject of many studies. Guillaume *et al*. (2002) reported that a loud alarm is not necessarily a good alarm. Edworthy, Hellier and their colleagues investigated the effects of acoustic properties, such as pitch and harmonics on levels of perceived urgency of alarm in the absence of loud noise (Edworthy *et al*., 1991, Hellier *et al*., 1993). Carter and Beh (1987) reported that high level of background noise (92dBA) has adverse effects on performance of vigilance tasks.

Alali and Casali (2011) investigated vehicle backup alarm localization and related factors affecting it using pink noise levels of 60 dBA and 90 dBA. The study showed that localization performance degraded significantly when the noise was increased from 60 dBA to 90 dBA. Backup alarm signal type also had a significant main effect on the localization performance. Their results also suggested that wearing augmented hearing protectors did not improve the localization ability of the listeners (Alali and Casali, 2011). Casali *et al*. (2004), used noise levels of 85 dBA and 100 dBA to compare alarm detection performance when wearing different types of hearing protectors. Their results revealed statistical significance between hearing protection devices for both 85 dBA and 100 dBA noise conditions. Another important finding was that for 85 dBA condition masked thresholds with hearing protection was significantly lower than masked thresholds without hearing protection (open-ear) (Casali *et al.*, 2004). It is important to note that in these experiments, the masked thresholds reported for open-ear conditions were higher than -15 dB SNR (at 85 dBA noise level).

In summary, alarm signal detection in noise with positive SNRs has been the subject of many studies. However, studies focusing on the vigilance of alarms with negative SNRs in the presence of loud (80 dBA or above) background noise are not common and the only related studies using noise level greater than 80 dBA only reported a SNR level of -5 dB in alarm-in-noise detection (Casali *et al.*, 2004). This is 13 dB higher than -18 dB that was observed in the industrial study reported in Chapter one. Therefore it is important to conduct more experiments on perception of alarms with negative SNRs. Data collected would be vastly useful in establishing the threshold boundaries within which an alarm is detectable in the presence of loud (80 dBA) noise.

2.3 Matlab Auditory Periphery (MAP) Model

MAP is a computer model which takes arbitrary sound stimuli as input and provides a range of spiking events in one or more parallel auditory nerve (AN) fibers (Meddis, 2006). The main stages of the output of the model can be listed as follows.

- Stapes velocity
- Basilar Membrane (BM) velocity
- Inner Hair Cell (IHC) receptor potential
- IHC presynaptic calcium currents
- Transmitter release events at the IHC-AN synapse
- AN spiking response including refractory effects

(Meddis, 2006).

Notable later additions to the model are representations for acoustic reflex and medial olivocochlear effects. Another important change to the model is the usage of displacements for calculations rather than velocities (Hearing Research Lab, 2011).

MAP was identified as a sophisticated model which simulates the complex biological process in the auditory system. In this study MAP is used to generate simulations for the stimuli that are used in the laboratory experiments.

2.4 Role of Medial Olivocochlear System (MOCS) Efferents

The olivocochlear bundle (OCB) comprises of a lateral and a medial part; both parts consist of crossed and uncrossed fibers (Warr and Guinan, 1979). Lateral neurons synapse with afferent fibers of the inner hair cells while Medial olivocohlear (MOC) efferents terminate directly on the outer hair cells (Wagner *et al.*, 2008). Evidence on MOCS efferents' relationship with cochlear function is presented in many studies (Fex, 1967; Francis & Nadol, 1993; Mountain, 1980).

By means of electrophysiological studies in animals, attempts have been made to understand the role of the olivocochlear bundle. Works by Galambos, 1956, Buno 1978 and Liberman, 1989 have demonstrated reductions in compound action potential. Furthermore reductions in auditory nerve fiber discharge rate have also been identified (Wiederhold and Kiang, 1970). These findings suggest an inhibitory role which implies a protective action (Cody and Johnstone, 1982). Anti-masking role for the OCB was also suggested (Nieder and Nieder, 1970; Dolan and Nuttal, 1988).

Dewson (1968) suggested that efferents played a part in discriminating complex sounds in noise. But, later studies which used transection of the olivocochlear bundle initially suggested that auditory efferents did not play a role in detection of simple signals in noise (Trahiotis and Elliott, 1970; Igarashi *et al.*, 1972). Further investigations on the properties of efferent fibers indicated that they could be involved in detecting signals in the presence of noise (Liberman, 1988; Langhans and Kohlrausch, 1992). Psychoacoustic studies also suggested a relationship between efferents tone-in-noise detection in humans (Langhans and Kohlrausch, 1992).

MOC unmasking: increase of the effective signal-to-noise ratio in the auditory nerve response (which improves the perception in noise) is hinted (Guinan, 2006; 2010; Kujawa & Liberman, 2001). Animal studies have suggested that MOC activity improves the auditory nerve's response to the background noise (Kawase *et al*., 1993; Winslow & Sachs, 1988) and thereby shifts the dynamic range of hearing (Dolan & Nutall, 1988; Kawase *et al*., 1993; Kujawa & Liberman, 2001).

Study on Guinea pigs has suggested auditory efferent feedback may help inhibit perception of continuous noise and increase the probability of transient noise (Liberman and Guinan, 1998; Dolan and Nuttall, 1988). Studies of Giraud *et al*. (1997), Kumar and Vanaja (2004) have indicated that efferent feedback could improve speech perception in noise. Brown *et al*. (2010) and Clark *et al*. (2012) have successfully simulated and predicted the benefits of efferent feedback on speech perception in noise. Moreover free-field and monaural presentations seemed to affect the benefits of efferent feedback (free-field: Wagner *et al*., 2008; monaural: Kumar and Vanaja, 2004). Mixed relationships between OAE suppression and detection thresholds have been reported (correlated: Micheyl and Collet, 1996; uncorrelated: Wagner *et al*., 2008).

In summary, the physiology and the behaviour of MOCS efferents has been subject to many studies in the past. However its role in detecting tones or speech in the presence of noise has not been well established. In this study we focus on studying the role of MOCS efferents on the detection of tonal stimuli in negative SNR conditions in the presence of 80 dBA noise.

2.5 Otoacoustic Emissions (OAEs)

2.5.1 A Brief Introduction

First hypothesized by Thomas Gold in 1948, OAEs were discovered by David Kemp in 1977 by means of laboratory experiments (Kemp, 2003). Spontaneous OAEs can be regarded as a natural by-product that is generated in the inner ear while processing the received sound information to be sent to the brain for identification (Kemp, 2003). OAEs can be evoked in two main methods; transient-evoked (or click-evoked) termed as TEOAEs and distortion product termed as DPOAEs (Kemp, 2003). These two techniques complement each other. DPOAEs are credited for offering a wider range of frequency (above 10 kHz), but they do not provide greater frequency selectivity than TEOAEs (Kemp, 2002).

2.5.2 Importance of OAEs

Activation of the MOCS by acoustic stimulation results in amplitude changes in otoacoustic emissions; this process is called MOC reflex (Puel and Rebilliard, 1989). The reduction of the amplitude of evoked OAEs in one ear upon stimulation of the opposite ear is termed contralateral suppression effect (Micheyl *et al*, 1995). This effect has been used to investigate the function of the MOCS in many studies (Collet *et al*., 1990; Veuillet *et al*., 1991; Micheyl *et al*., 1995).

In summary, many studies in the past have used contralateral suppression of evoked OAEs as an indication of the MOCS efferent feedback strength. In this study we use the contralateral suppression of TEOAEs as the measure of the MOCS efferent feedback strength of the human subjects.

2.6 Research Gaps

In Chapter one, the discovery of a -18 dB SNR level of alarm-in-noise detection is reported. A review of literature indicates that such a low SNR level is unusual. In the light of the literature review, the following research gaps are established for the present study:

Gap 1: How is tone-in-noise detection at very low SNRs (-18 dB and below) possible?

(a) Alarm-in-loud (>=80 dBA)-noise detection thresholds are not well established.
(b) Effects of alarm duration on alarm-in-noise detection thresholds are likely to be significant but not established with noise of 80 dBA.
(c) Effects of spatial information of the tonal presentation (free-field/diotic/monaural) on alarm-in-noise thresholds are likely to be significant but not established with noise of 80 dBA

Gap 2: Why is tone-in-noise detection at very low SNRs (-18 dB and below) possible? In particular, there is a lack of details on the underlying biological process of the tone-in-noise detection.

CHAPTER 3: EXPERIMENT ONE: VERIFYING RESULTS OF THE INDUSTRY CONSULTATION STUDY BY MEANS OF LABORATORY EXPERIMENTS

Summary

This chapter presents the results of Experiment one conducted to investigate the detectability of a train alarm sound in the presence of loud (80 dBA) train noise. The setting of the experiment replicated an industrial setting at which the author first observed the detection of a quiet train alarm in the presence of 77 dBA train noise. Listeners with normal hearing participated in the experiment. Different levels of train alarm (SNRs of -18, -21, -24 and -∞ dB) were presented. The main finding was that the listeners were able to detect the alarm sound even at the level of -24 dB SNR and they were able to differentiate the four alarm conditions. The results replicated the industrial observations and motivated the rest of the study to investigate AIN and TIN detectability in the presence of loud noise. Preliminary results of this experiment were published in Karunarathne *et al*. (2014).

3.1 Introduction

During a field study, the author observed that workers were able to detect a train alarm sound of SPL 18 dB below the train noise of 77 dBA in a free-field configuration (So and Karunarathne, 2012). This interesting observation formed the basis of this experiment. The initial task was to reproduce and substantiate the observations in a controlled laboratory setting. Since there was the prior knowledge that -18 dB SNR train alarm was detected successfully, this experiment was designed to explore SNR levels lower than -18dB.

3.2 Hypothesis

Listeners with normal hearing were hypothesized to be able to detect and differentiate train alarms of 62 dBA, 59 dBA and 56 dBA presented in the presence of 80dBA train noise.

3.3 Design of Experiment

3.3.1 Stimuli

3.3.1.1 Loudness Conditions

There were four stimuli loudness conditions: (i) train alarm at 62 dBA in 80 dBA train noise (SNR = -18dB); (ii) train alarm at 59 dBA in 80 dBA train noise (SNR = -21 dB); (iii) train alarm at 56 dBA in 80 dBA train noise (SNR = -24 dB); and (iv) 80 dBA train noise only (control condition with SNR = $-\infty$ dB). Levels of dBA were measured by a sound level meter (Model 3000 from QUEST Inc.)

Length of each stimulus was 5 seconds. All the four conditions were repeated 12 times. These 48 stimuli were presented in random order without breaks in between. The total duration of the presentation for each subject was 240 seconds [5 seconds x (4 train alarm conditions x 12 repeats)]).

3.3.1.2 Temporal Characteristics

The alarm and noise used in this experiment had similar characteristics to a train alarm and a train noise recorded in an industrial consultation study, So and Karunarathne (2012). The full recording contained various unwanted background sounds (e.g. speech, clicking sound of switches, isolated loud sounds). During the extraction procedure, I made sure that these unwanted background sounds were not included in the stimuli used in the experiments.

Figure 3.1(a) and 3.1(b) shows the waveform of the train alarm and train noise respectively. The rise time of the train alarm was approximately 20ms. The initial part of the envelope has the shape of a cone. After about 200ms it levels up and takes a cylindrical shape. The high sound level at the start could have been an attempt to grab the attention of the listener instantly and thereafter reduce the levels in order not to expose the listener to loud sounds for a longer period. Since this research is an ergonomics study to examine the detection of train alarm in the presence of train noise, real sound recordings were used. It is worth noting that in the last experiment, the recorded alarm and noise were replaced by pure tones and computer generated pink noise in order to generalize the results.

The noise level of 80 dBA was comparable to the background noise in the actual setting that was tested in So and Karunarathne (2012).

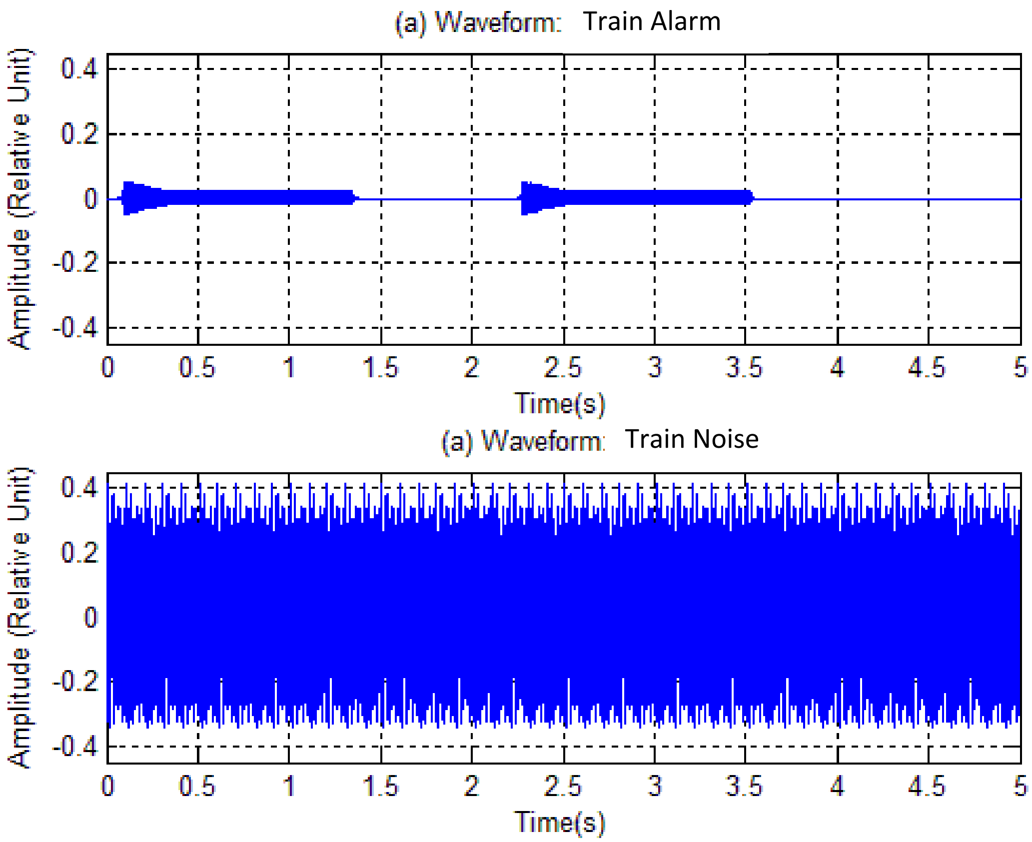

Figure 3.1 Temporal characteristics of the train alarm and train noise

3.3.1.3 Spectral Characteristics

Figure 3.2 shows the Welch power spectral density (PSD) plots for the train alarm and the train noise. Train alarm sound has the highest power at around 2 kHz. The power of the alarm is always less than that of the noise for all the three conditions -18 dB, -21 dB and -24 dB SNR. The spectral characteristics of the train noise recorded in the industrial consulting project are similar to that of a pink noise.

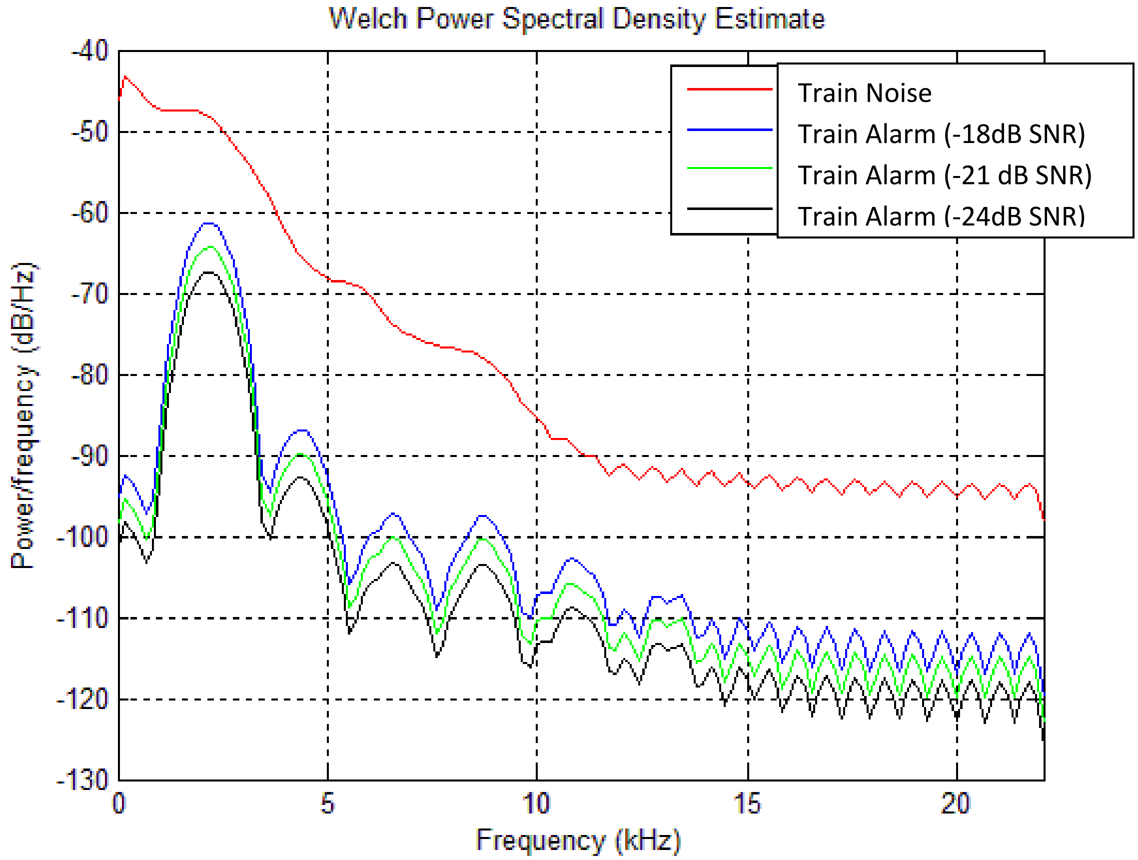

Figure 3.2 Spectral characteristics of the train noise and train alarm (at -18dB, -21dB and -24dB SNR)

3.3.2 Sound Calibration

Sound pressure levels of the train alarm sound and train noise were measured at the subject's ear level using the QUEST 3000 Sound Level Meter. The calibration was a three step process. First step was to measure the sound pressure level generated by the raw sound file (.wav). And then the volume of the sound file was adjusted using Goldwave^{TM} software by altering the amplitude of the waveform. The third step was to measure the sound pressure level generated by the adjusted wave file to ensure the required level is obtained. If further adjustments were needed, steps 2 and 3 were repeated. Calibrations were initially done with a human listener sitting at the experiment set up. Later the same calibrations were done using a mannequin placed instead of the subject (Figures 4.5a, b). Differences of results were insignificant. The effect of the pointing direction of the Sound Level Meter also proved to be insignificant. The raw calibration data are documented in Appendix 7.1.

3.3.3 Task and Apparatus

The experiment was conducted inside an acoustic chamber (a 1400-A-CT chamber custom-built by the Industrial Acoustics Company Ltd.).

Subjects were instructed to sit in front of a computer screen and listen to the audio clip presented. Their task was to listen to the stimuli sequence, and use the hardware slider bar (Figure 3.3) to rate the perceived loudness of the train alarm in a scale from 0 to 100. Phidget® system was used to sample the position of the slide bar at 10 Hz. The train alarm signals changed once every 5s (i.e., 0.2Hz). Therefore 10 Hz sampling rate was used as it should be sufficient to measure the perceived changes of loudness as represented by positions on the sliding bar.

Prior to the experiment, subjects were trained to anchor the 0 position to noise only (-∞ dB SNR) condition and the 100 position to the 62 dBA train alarm in 80 dBA noise (-18 dB SNR) condition. The computer screen was used to provide a visual representation of the slider bar position.

As shown in Figure 3.4 experimental setup used three speakers to present the audio stimuli. Two speakers placed on the left and right sides played the 80 dBA noise and the third speaker in the front-left played the alarm signal. This positioning of the speakers was used to mimic one of the real testing conditions in So and Karunarathne, 2012 which resulted in successful detectability at -18dB SNR. The importance of this setting is related to the ergonomic aspect of this study. I attempted as much as possible to re-create the setting inside a train driver's cabin.

Figure 3.3 Hardware slider for user response

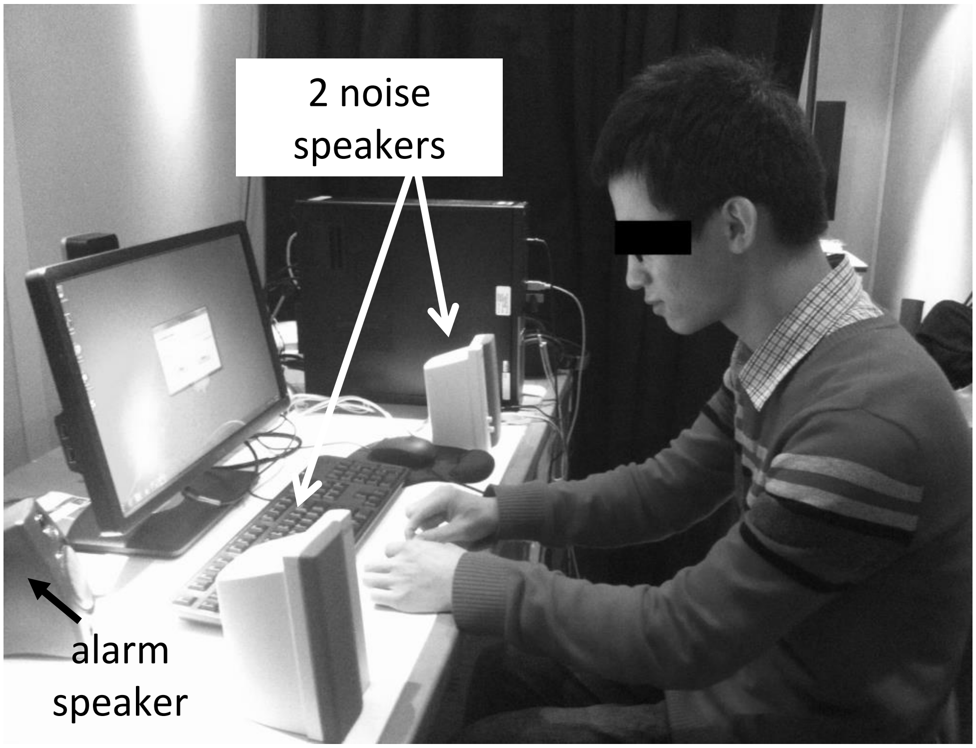

Figure 3.4 Experiment setup inside the acoustic chamber

3.3.4 Subjects

In total twelve subjects (8 male and 4 female) participated in the experiment. They had no known history of hearing impairments. Their average age of the subjects was 25 years and ranged from 20 years to 31 years.

The subjects underwent audiometric testing at 500 Hz, 1 kHz and 2 kHz for both ears. Their pure-tone hearing thresholds were 20dB or below for all three frequencies. For all subjects the deviation of hearing thresholds of both ears was no more than 5 dB.

3.4 Results and Data Analyses

3.4.1 Response Times

Figure 3.5 shows the average positions of the slide bar during the 5 second presentation of each of the four conditions. The starting positions for each condition were different as the 60 stimuli were presented continuously without breaks in between. Therefore the starting position of the slider position for each stimulus is the ending position of the immediate preceding stimulus.

The train alarm contained two similar segments, each 1.25s in length and separated by approximately 0.9s. In all the stimuli presentations the first segment started after a 0.1s silent period. The second segment started at 2.25s from the beginning of the stimuli. From Figure 3.5 it can be observed that subjects decided the perceived loudness and started responding to the stimuli before the 2.25s mark. This implied that they did not have to consider the second segment when providing a response. This is an important point for the design of the next experiments which will be described in chapters 4 and 6.

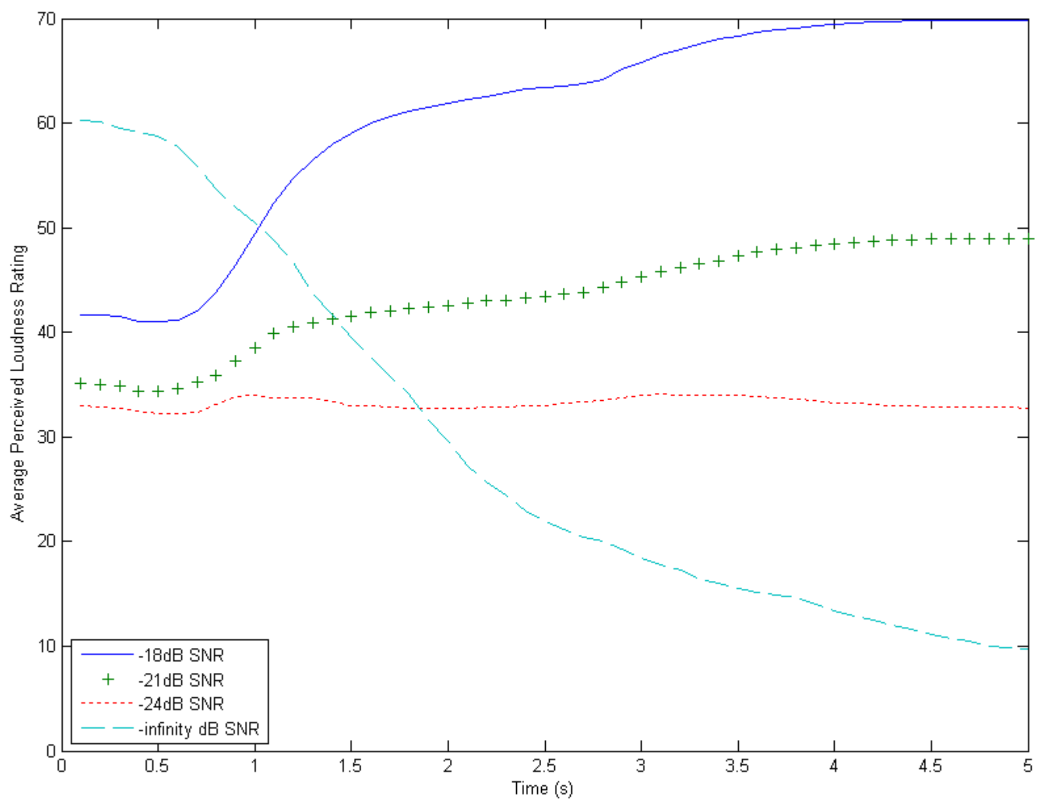

Figure 3.5 Average changes of slider positions (step responses) during the 5 second train alarm stimulus at SNR levels of -18 dB, -21 dB, -24 dB and -∞ dB

3.4.2 Effect of time segments

Inspections of Figure 3.5 show that the slider positions for each condition asymptotically approached a final level. Average slider positions measured within each 0.5 second segments were extracted and compared using Friedman tests and Wilcoxon signed ranked tests to test the effects of convergence. Non-parametric tests were used since the data was not normally distributed ($p<0.05$, Shapiro-Wilk).

Data collected in different time segments from the same subjects were directly compared with each other using the non-parametric tests. Results of Friedman tests indicated that, for SNR levels -∞ dB, -18 dB and -21 dB, time of measurement (within the 5 second measurement period) had significant main effects on the slider positions (perceived loudness rating) (Chi-square=94.484, p=0.000; Chi-square=106.238, p=0.000; Chi-square=74.247, p=0.000; respectively). For SNR level -24dB the time of measurement did not have a significant effect (Chi-square=2.210, p=0.988, Freidman). This result is consistent with Figure 3.5.

Subsequent Wilcoxon tests indicated that the slider positions collected in the last 0.5 second period were not significantly different from those collected between 4 and 4.5 seconds for SNR levels -18 dB and -24 dB (Z=-1.127, p=0.260; Z=-0.764, p=0.445; respectively). This suggests that the slider positions had reached their asymptotical steady levels in the last one second in these SNR levels. However for SNR levels -∞dB and -21dB slider positions in these two time segments were significantly different (Z=-2.197, p=0.028; Z=-2.023, p=0.043; respectively, Wilcoxon). The result is consistent with Figure 3.5.

3.4.3 Effect of SNR Levels

Subsequently, the slider positions of the last one second were extracted to determine the effects of SNR levels. Average perceived loudness ratings as a function of SNR levels is shown in Figure 3.6.

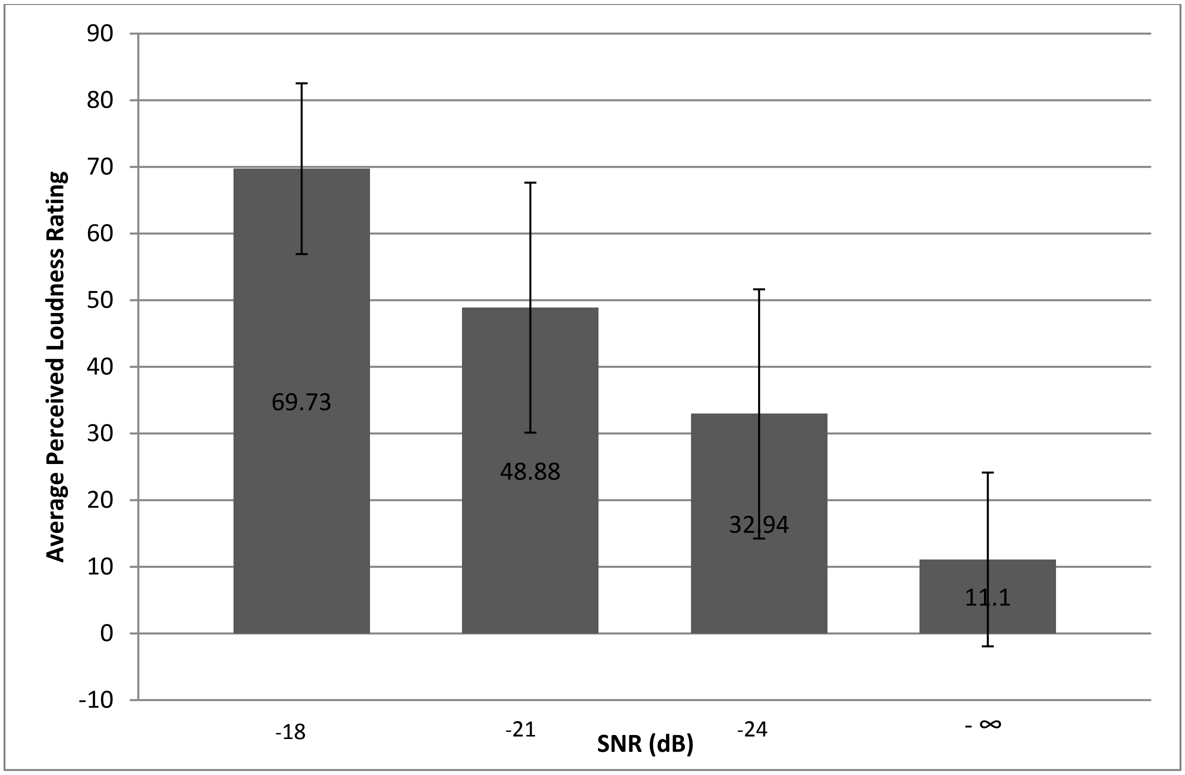

Figure 3.6 Average perceived loudness ratings as measured by the averaged slider positions in the last second of the 5 second measurement period as a function of different SNR levels (-18 dB, -21 dB, -24 dB and -∞ dB)

A Friedman test was carried out to analyze the main effects of four SNR levels on the averaged slider positions during the last second of the stimuli. The result showed that the effect of SNR levels was statistically significant (Chi-square=32.700, p=0.000, Friedman). Subsequent Wilcoxon signed rank tests indicated that data from all four SNR levels were significantly different from each other ($p<0.05$, Wilcoxon).

3.5 Discussion & Conclusion

This experiment used a non-conventional method to obtain time history data of perceived loudness of a train alarm presented in the presence of train noise. Collecting time history data had both advantages and disadvantages. On the positive side, the time history data was helpful in determining that subjects did not have to listen to the second segment of the alarm to decide on the perceived loudness. Therefore in the subsequent experiments only one segment of the train alarm/tone stimuli was used.

On the negative side, even though each stimulus was 5 seconds long, actual usable data contained were collected in the last one second. In the first 4 seconds, the subjects were in the process of moving the slider to their preferred position to rate the perceived loudness. This was overcome in the analysis by extracting and using the data only collected during the last one second for all the subjects.

We acknowledge that the experiment was conducted using a fixed sample of train noise. Therefore the effect of 'frozen noise' has not been taken into account. But it is also important to note that past studies have also used similar methods (e.g. Casali et al., 2004; Alali and Casali, 2011).

In summary the work of this chapter suggests that, subjects with normal hearing were able to detect a train alarm with SNR of -24dB and discriminated the presence of the alarm from the absence of the alarm in the presence of 80dBA train noise. This corroborated the findings of So and Karunarathne, 2012 and provided further motivations to investigate the AIN and TIN detection thresholds which will be presented in Chapters 4 and 6.

CHAPTER 4: EXPERIMENT TWO: EFFECTS OF TARGET TONE DURATION AND SPATIAL INFORMATION ON ALARM-IN-NOISE (AIN) DETECTION THRESHOLDS

Summary

This chapter presents the details of the methodology and results of the second experiment. In Experiment 1, participants were able to detect a 56 dBA train alarm in the presence of 80 dBA train noise. The signal-to-noise ratio (SNR) was -24 dB which was much lower than the -15 dB SNR level what had been reported in the literature (see Chapter two). In Experiment 2, the effects of alarm duration and spatial information on the alarm-in-noise (AIN) detection thresholds were studied. The standard way to measure the detection thresholds were adopted from Micheyl *et al.* (1995). Median alarm-in-noise thresholds of -28 dB SNR and -13 dB SNR were observed for free-field and monaural spatial information conditions respectively. Increasing the alarm duration from 100ms to 500ms did not significantly affect the detection thresholds.

4.1 Introduction

In Experiment 1, listeners were able to detect a train alarm (energy centered at 2 kHz) immersed in train noise with a negative SNR of -24 dB. In that experiment, the train alarm and the train noise were broadcasted from different locations using different loud speakers. A review of literature suggests that the binaural unmasking effect where the target tone and the masker are broadcasted from different spatial locations has been the subject of many studies (Gatehouse, 1986, 1987; Santon, 1987; Saberi *et al*., 1991). Gilkey and Good (1992) reported significant reductions in the noise masking effect when the target tone and the noise were broadcasted from different locations (referred to as the free-field configurations). The unmasking effect could be as large as 18 dB when the sources were separated in the horizontal plane. However, the past studies mostly examined listening conditions with positive SNRs. Consequently, there is a need to investigate the effects of spatial information. In this experiment, the effects of three different spatial configurations were used: free-field, monaural and diotic.

Data collected during the preliminary tests of the experiment suggested that the duration of the target stimuli may have a significant effect on the alarm-in-noise detection thresholds. Past studies also suggest that there might be a significant relationship between the two factors (see Section 2.2.3).

In summary, the objectives of this experimental procedure were to investigate the effects of (i) alarm duration and (ii) spatial information on the detection thresholds of a train alarm in the presence of 80 dBA train noise.

4.2 Hypotheses

It was hypothesized that the Alarm-In-Noise detection thresholds of listeners will be significantly affected by the alarm duration and the spatial configuration between the train alarm and the train noise.

4.3 Design of Experiment

The experiment had two parts. In part one, the effects of time duration and spatial information were studied. Part two further investigated the effects of spatial configurations.

4.3.1 Experiment 2 Part 1: Effects of Target Duration and Spatial Configurations

4.3.1.1 Variables

The independent variables were stimuli duration (4 levels) and spatial configurations (2 levels). A full factorial design with 8 conditions was used.

Control variables included alarm spectrum, noise spectrum, and the sound pressure level of the noise (80 dBA).

4.3.1.2 Stimuli

The train alarm and train noise used in this experiment were the same as those used in Experiment 1 (Chapter 3). The duration of the alarm was shortened, deleting from the end, to achieve the designed levels of alarm duration. The temporal and spectral characteristics of the train alarm and train noise are presented in Figure 4.1 and Figure 4.2 respectively. The duration of the train alarm illustrated in the Figure 4.1 is 500ms, which is the longest alarm signal that will be used in the experiment. In the cases where shorter alarm signals were required (100ms and 300ms), they were extracted from the same waveform keeping time zero as the starting point.

The noise used had the same characteristics as a recording of the background noise inside a train cabin and its characteristics approximately resembled pink noise. The sound pressure level of the noise was fixed at 80 dBA. The alarm had the same characteristics of an alarm inside a train cabin.

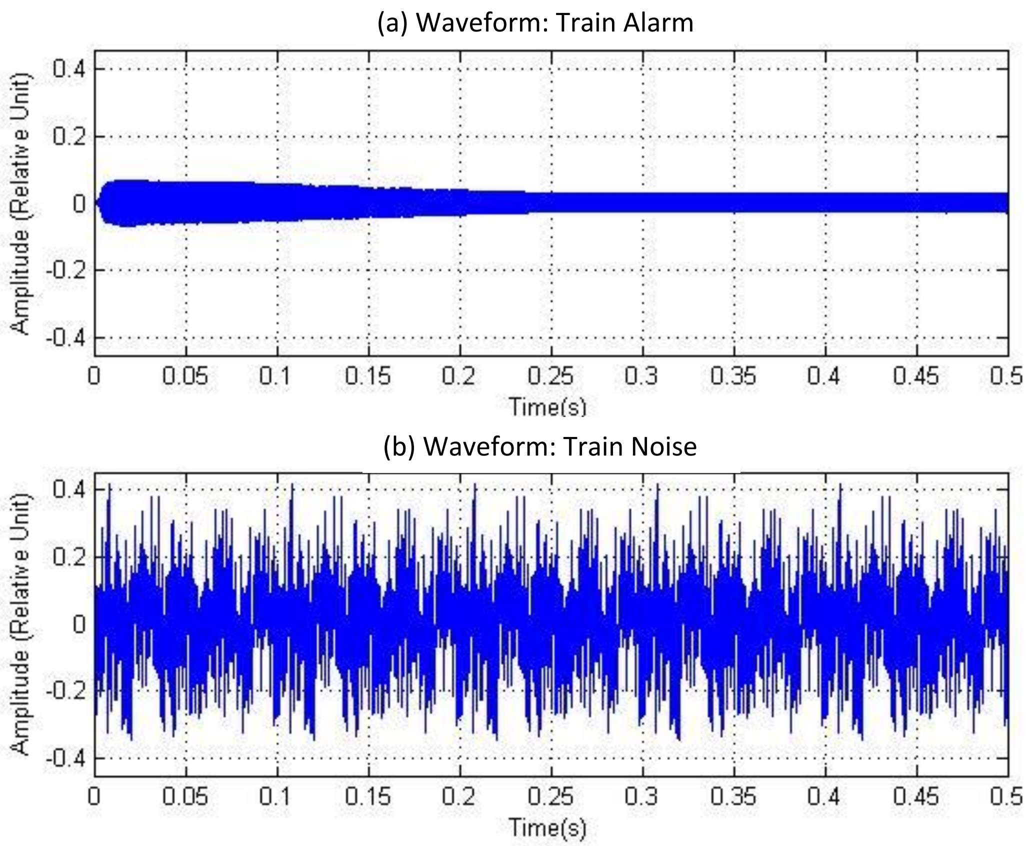

Figure 4.1 Temporal characteristics of the train alarm (target) and train noise

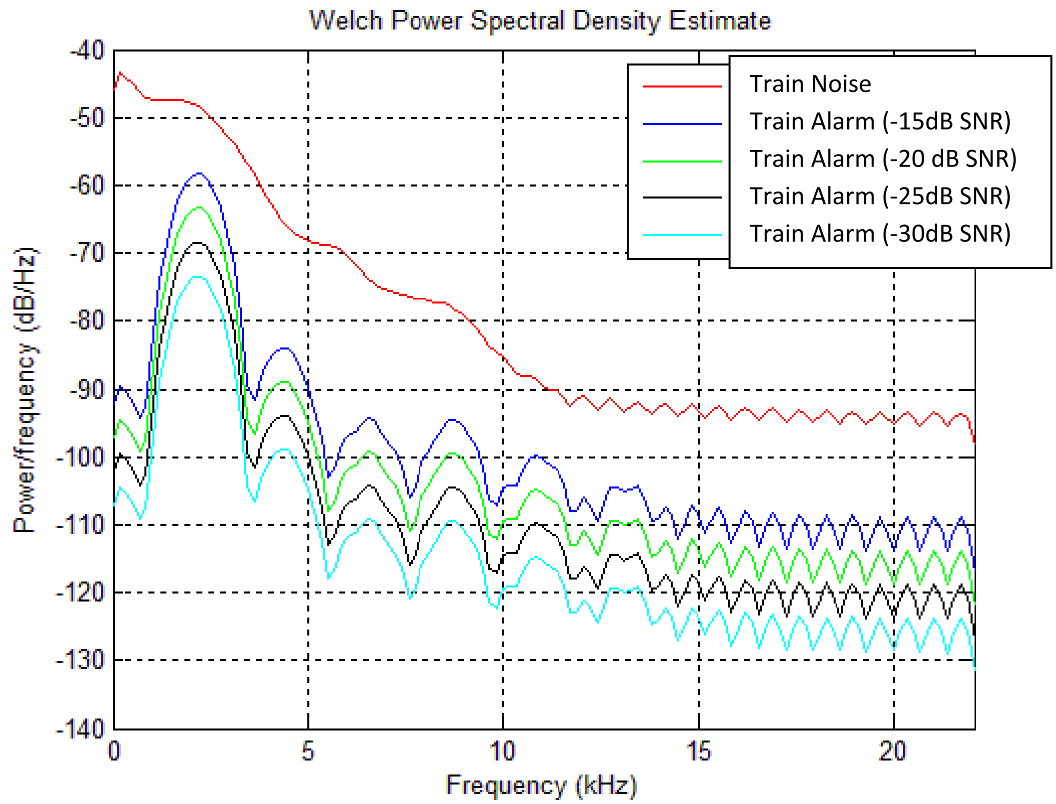

Figure 4.2 Spectral characteristics of the train noise and the train alarm (at -15, -20, -25 and -30dB SNR)

4.3.1.3 Method to Determine the AIN Thresholds

Thresholds were determined based on the 79.4% points on the psychometric functions by means of an adaptive Two Interval Forced Choice (2IFC) method (Levitt, 1971) with a 3-down 1-up rule. Initial step size was 5dB, and it was reduced to 1 dB after the first four reversals. Each run consisted of 50 trials. Past studies widely used 2IFC method for threshold estimation (e.g. Saberi *et al.*, 1991; Richards, 1992; Micheyl *et al.*, 1995).

The experiment method was implemented using a Matlab® (Version R2012a) program written by the author. Figure 4.3 illustrates a typical user response for a thresholds measurement using 2IFC method.

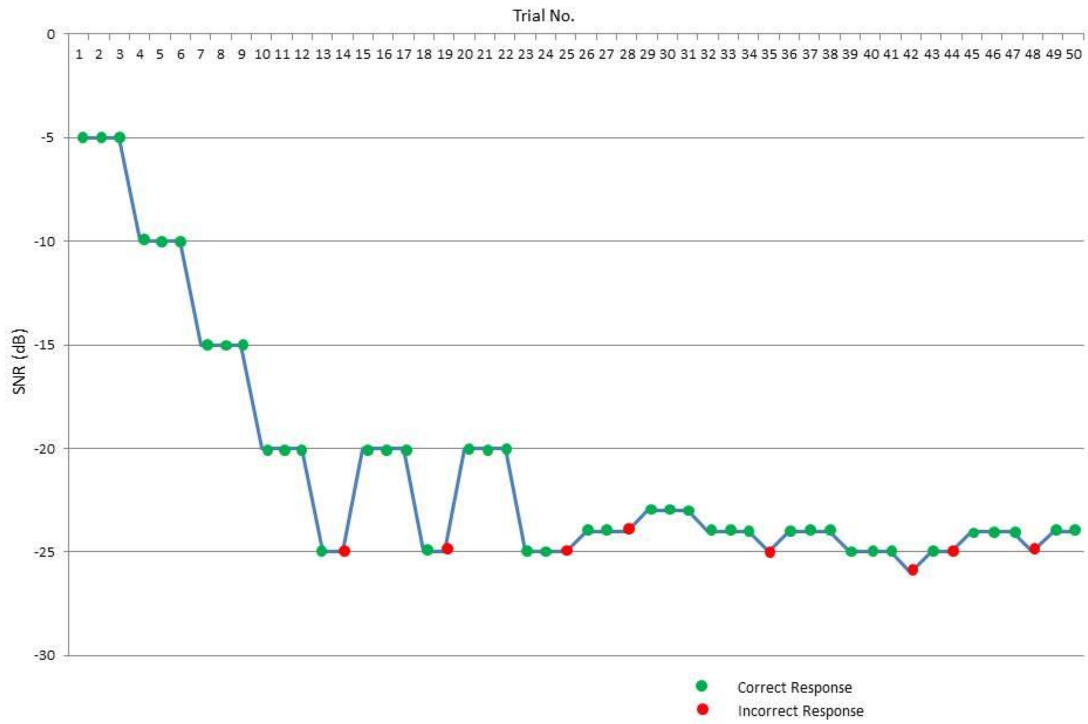

Figure 4.3 A sample result of adaptive 2IFC method with 3-down 1-up rule

4.3.1.4 Stimuli Conditions

One trial consisted of two segments separated by a 500ms silent period. Only one segment contained the train alarm (target) and the subject's task was to identify which of the two segments did contain the alarm. There were four pairs of segments representing the four train alarm (target) duration conditions: (i) 400ms train noise Vs (200ms train noise + 100ms train noise and target + 100ms train noise); (ii) 800ms train noise Vs (200ms train noise + 100ms train noise and target + 500ms train noise); (iii) 800ms train noise Vs (200ms train noise + 300ms train noise and target + 300ms train noise); (iv) 800ms train noise Vs (200ms train noise + 500ms train noise and target + 100ms train noise). In condition (i) the total duration of a segment was 400ms. In conditions (ii), (iii) and (iv), they were 800ms. All stimuli had 20ms cosine ramps. Duration condition (i) was adopted from Micheyl *et al*. (1995).

Table 4.1 Notations for conditions based on target duration (the suffix ‘4’ and ‘8’ indicate the total duration of 400ms and 800ms for the whole segment, respectively

Target/Masker Duration	Notation
100ms/400ms	100_4
100ms/800ms	100_8
300ms/800ms	300_8
500ms/800ms	500_8

The two spatial information settings were monaural (MN) and free-field (FF). Monaural presentation was done using Sennheiser HD600 headphones (Figure 4.4), only to the right ear. Free-field presentation was done using a speaker arrangement which can be seen in Figure 4.6. The two speakers at the left and right sides played the noise. The alarm speaker was at front-left (45 degrees relative to the subject’s position). This setting is similar to the free-field setting used in Experiment 1 (see Figure 3.4 in Chapter 3). In that condition, the subjects were asked to use the chin rest in order to control the location of the head. For the same condition, the speaker system was calibrated to generate the desired sound pressure level at the approximate location of the subject’s ears. Similar to Experiment 1, both a real person (with real torso) and a mannequin were used in the sound calibrations and the results were similar. Whereas for the monaural condition, the headphones were calibrated using the mannequin head (Figure 4.5a). QUEST 1800 Sound Level Meter was used for all the calibration measurements. The raw calibration data are documented in Appendix 7.2.

Figure 4.4 Sennheiser HD600 Headphones

Figure 4.5a Mannequin head used for sound calibrations

Figure 4.5b Silica pinna inserted in the mannequin head during sound calibrations

Figure 4.6 The experiment set-up inside the acoustic chamber. The speaker configuration for free-field presentation, the computer system for subject response and the chin rest are visible

4.3.1.5 Subjects

Sixteen subjects (12 male, 4 female) with no history of hearing impairments participated in the experiment. Their hearing thresholds were measured using a Madsen Itera II Audiometer. They had hearing thresholds at 20 dB or below at 0.25, 0.5, 1, 2, 4, 6, and 8 kHz. The deviation of hearing threshold of both ears was 5 dB or less for all subjects. The average age of the subjects was 26.4 years and the ages ranged between 20-31 years.

4.3.2 Experiment 2 Part 2: Effects of Spatial Configuration

4.3.2.1 Variables

The independent variable was the spatial configuration (4 levels) and the dependent variable for this part was the alarm-in-noise detection threshold.

Alarm duration was controlled to be 100ms and the whole duration of each sound segment was controlled to be 400ms.

4.3.2.2 Stimuli

Stimuli 100_4 (Table 4.1) was used. The sound pressure level of the train noise was fixed at 80 dBA.

4.3.2.3 Spatial Configurations

Four configurations were used. Monaural (MN) (identical to the monaural condition in part one) and diotic (DT) conditions were presented using Sennheiser HD600 headphones. Two free-field (FF) conditions were used. In FF-multi-speaker condition, the train alarm and the train noise were presented using different speakers (similar to part one but this time the target speaker is in front of the subject, at 0 degrees relative to the subject's position). In FF-same-speaker condition both the alarm and noise were presented by the same speaker which was placed in front of the subject.

Table 4.2 Notations for conditions based on spatial information configuration

Spatial Information Configuration	Notation
Monaural (Right Ear)	MN
Diotic	DT
Free-Field (target and noise from different speakers)	FF-multi-speaker
Free-Field (target and noise from same speaker)	FF-same-speaker

4.3.2.4 Subjects and Threshold Measurements

The same sixteen subjects as in part one were used and the same procedure for threshold estimation was used.

4.4 Results and Data Analyses

4.4.1 Results of Part 1: Interacting effects of alarm duration and two spatial configurations (free-field vs. monaural)

Median AIN detection thresholds of the sixteen subjects are illustrated in Table 4.3 and plotted in Fig. 4.7. The units of thresholds are SNR values (in dB) relative to the 80 dBA fixed noise level.

Table 4.3 Median AIN Thresholds – Experiment 2 Part 1

Condition	Median AIN Threshold (dB SNR)
MN100$_4$	-13.0
MN100$_8$	-12.8
MN300$_8$	-14.3
MN500$_8$	-13.5
FF100$_4$	-28.0
FF100$_8$	-28.5
FF300$_8$	-28.5
FF500$_8$	-28.8

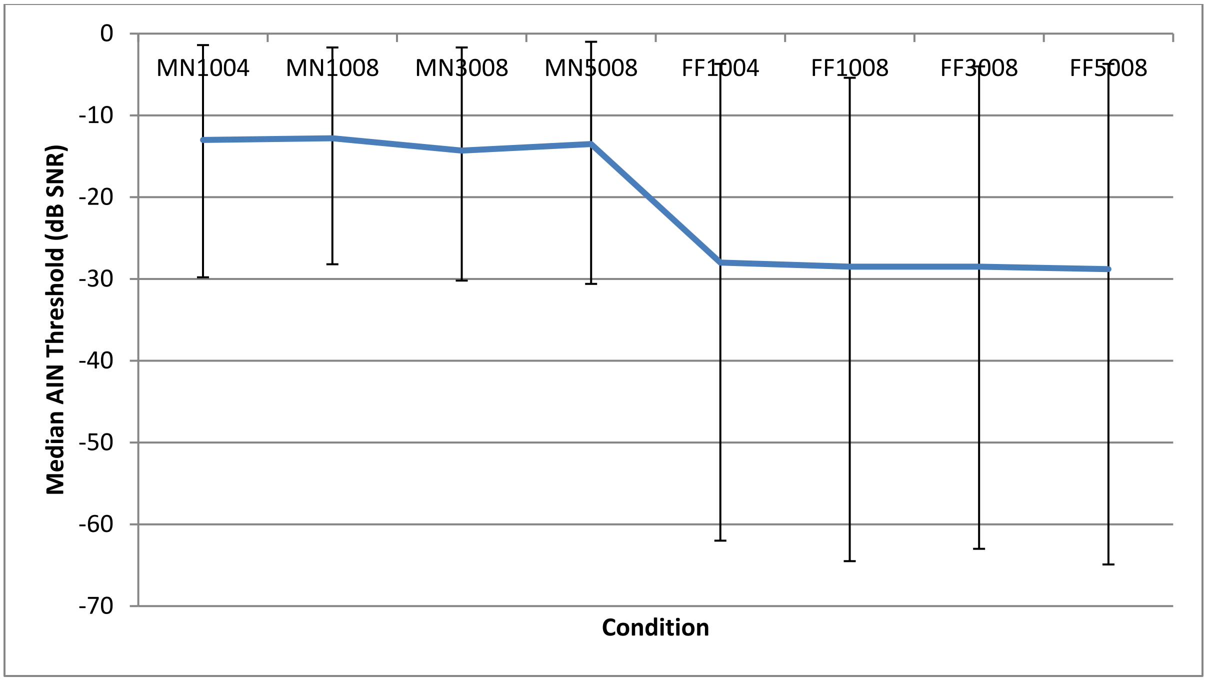

Figure 4.7 Median AIN detection thresholds for all conditions. MN – Monaural, FF – Free-Field

For the monaural condition median detection threshold was -13 dB SNR, whereas for the free-field condition it was as low as -28 dB SNR. Some individuals obtained thresholds below -35 dB SNR with one achieving -46 dB. From Figure 4.7 it is visually observable that there is a clear difference between the monaural and free-field conditions.

The data set was tested for normality using Shapiro-Wilk test. Since the data set showed a significant deviation from normality ($p<0.05$, Shapiro-Wilk), non-parametric tests were employed. Friedman tests showed that for both monaural and free-field conditions, the effect of the target duration was not significant (Chi-square=4.272, $p=0.234$; Chi-square=1.689, $p=0.639$; respectively).

Furthermore Wilcoxon signed rank tests revealed that for each duration condition, the effect of the spatial information was significant (MN100$_4$ vs FF100$_4$: $Z=-3.517$, $p=0.000$; MN100$_8$ vs FF100$_8$: $Z=-3.517$, $p=0.000$; MN300$_8$ vs FF300$_8$: $Z=-3.517$, $p=0.000$; MN500$_8$ vs FF500$_8$: $Z=-3.517$, $p=0.000$).

Analysis of the AIN detection thresholds for individual subjects revealed substantial amount of individual variability.

Figure 4.8 and 4.9 show the individual detection thresholds for monaural and free-field conditions respectively.

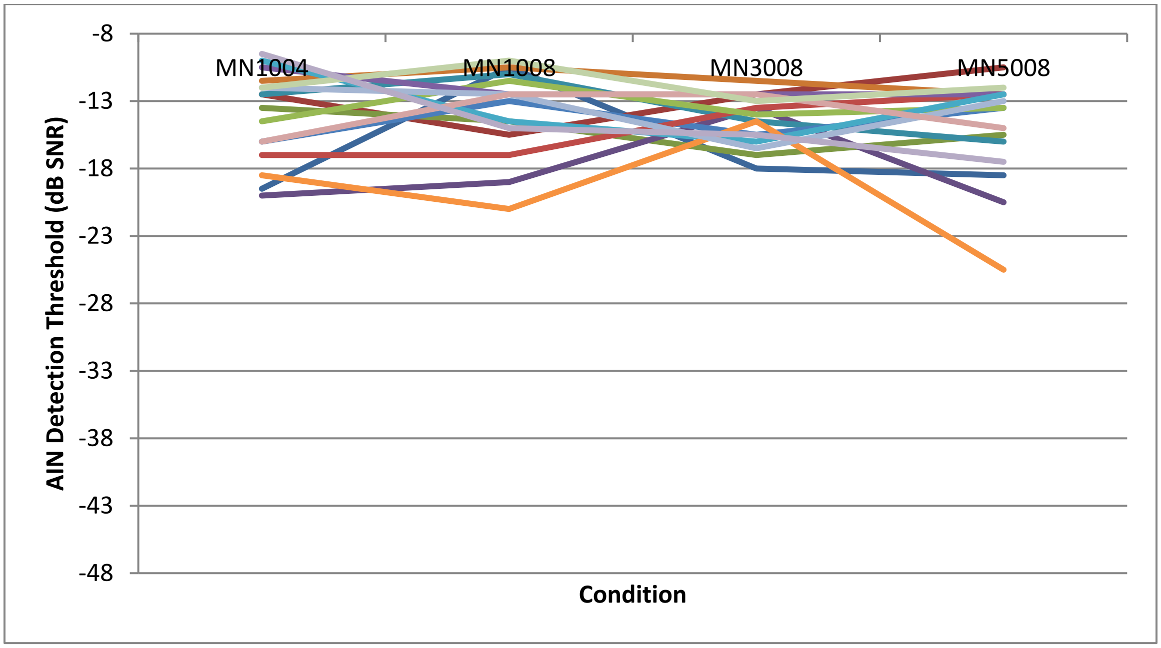

Figure 4.8 Individual variability in MN conditions

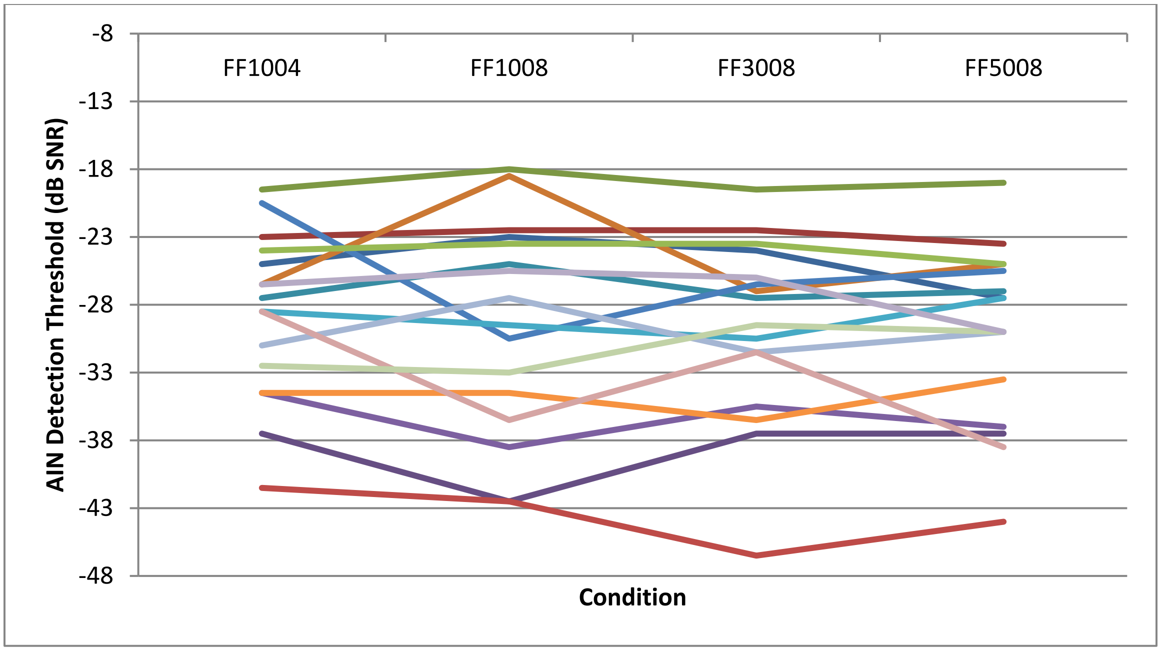

Figure 4.9 Individual variability in FF conditions

For the FF conditions there was a larger individual variability (ranging from -18 dB to -46 dB) compared to MN conditions (ranging from -9 dB to -25 dB).

4.4.2 Results of Part 2: main effects of spatial configurations

Median values of AIN detection thresholds are given in Table 4.4 and the corresponding plot is given in Figure 4.10.

Table 4.4 Median AIN Thresholds – Experiment 2 Part 2

Condition	Median AIN Threshold (dB SNR)
MN	-12.5
DT	-14.3
FF-multi-speaker	-24.0
FF-same-speaker	-16.0

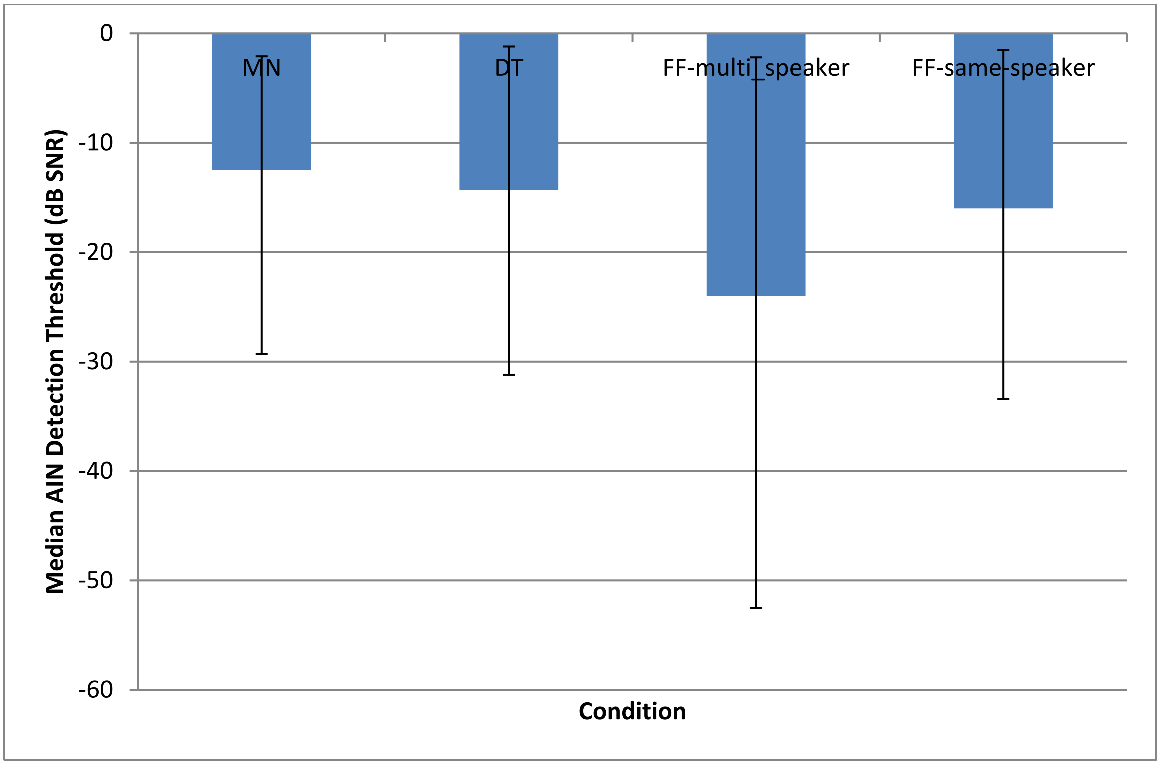

Figure 4.10 Median AIN detection thresholds for all conditions

Results of Friedman two-way ANOVA indicated that the spatial information configuration had a significant main effect on the AIN detection threshold (Chi-square=32.694, p=0.000).

Subsequent Wilcoxon signed rank tests revealed that detection thresholds for MN and DT conditions were not significantly different (Z= -0.777, 0.437). Detection thresholds for MN condition were significantly different from that of free-field conditions (MN vs FF-multi-speaker: Z=-3.520, p=0.000; MN vs FF-same-speaker: Z=-2.761, p=0.006). Similarly the thresholds for DT condition were significantly different from that of free-field conditions (DT vs FF-multi-speaker: Z=-3.518, p=0.000; DT vs FF-same-speaker: Z=-2.328, p=0.020). Interestingly, the detection thresholds for the two free-field conditions were also significantly different (FF-multi-speaker vs FF-same-speaker: Z=-3.518, p=0.000).

Further Wilcoxon signed rank tests showed that detection thresholds in the MN1004 condition (part one) was not significantly different from MN detection thresholds in part two (Z=-1.168, p=0.243). This result confirmed the results in part1 and provided evidence on the repeatability of the experimental data. Interestingly, the detection thresholds in FF100$_4$ condition significantly differed from that of FF-multi-speaker condition (Z=-3.130, p=0.002). Both conditions used the same alarm speaker and the same noise speakers and the only difference was the positioning of the alarm speakers.

4.5 Discussion and Conclusion

The most striking result of part one of this experiment is the substantial difference in AIN detection thresholds for monaural (right ear: c.f. Micheyl et al., 1995) and free-field conditions. On average there was a 15dB masking level difference between the two spatial information configurations. This result provides evidence that the spatial location of the sources of the target and noise have an effect on the masking. Also, it was observed that the duration of the target (above 100ms) did not have a significant effect on the detection thresholds. This was a useful result for the design of the next experiments of this study. The range of AIN thresholds reported was from -9 dB to -46 dB and such low values were new and original findings.

Part two of the experiment further investigated the effects of spatial configuration of the loud speakers on AIN detection thresholds. Significant differences were observed between MN/free-field conditions and DT/free-field conditions. The AIN detection thresholds for the FF-multi-speaker condition were significantly different from that of FF-same-speaker. These results further provide evidence of a relationship between the spatial localization of the sources and masking level. Separation of the sources of the target and the noise seems to reduce the masking, subsequently resulting in better detection thresholds. These results are consistent with the observations made in some of the past studies where much quieter noise was used (Gatehouse, 1986, 1987; Saberi *et al*., 1991; Gilkey and Good, 1992).

Another important observation from the results of part one is the large individual variability in the detection thresholds, especially for the free-field configuration. This formed the motivation for the next steps of this study to investigate the physiological process in hearing that is related to AIN detection.

One possible explanation for the significantly lower detection thresholds for the free-field condition would be the binaural directional sound cues introduced by the alarm and the noise. Interaural time differences (ITDs) and interaural level differences (ILDs) may possibly play a major part in improving the detection of the alarm in the free-field conditions. The fact that the two free-field conditions produced significantly different detection thresholds indicated the importance of the binaural directional sound cues. Also, in order for a listener to detect the alarm, he or she may not need to hear the full duration of the alarm. In other words, if the listener was able to hear and identify part of the alarm, that may be sufficient for them to detect the presence of that alarm. If there are dips in the noise waveform, that could be advantageous to the listener. Inspections of Figure 4.1 (and Figure 3.1) indicate that the amplitudes of the noise remained fairly constant and no observable dips of amplitude could be found. Furthermore, should there have been a dip in the noise amplitude, it would have occurred in all conditions and would not have contributed towards the differences between the free-field and the monaural conditions.

CHAPTER 5: COMPUTER SIMULATION AND THE ROLE OF MEDIAL OLIVOCOCHLEAR (MOCS) EFFERENT FEEDBCAK IN DETECTING TONAL STIMULI IN THE PRESENCE OF LOUD NOISE (EXPERIMENT THREE)

Summary

This chapter has two parts. Firstly, simulation results of the responses of the auditory system to the stimuli that were used in Experiments 1 and 2 are reported (Section 5.2). The Matlab Auditory Periphery (MAP) model (Meddis, 2006) was used. Secondly, inspired by the simulations, the role of the Medial Olivocochlear (MOCS) efferent feedback on the Alarm-In-Noise (AIN) detection thresholds was investigated and results are reported in the second part (Section 5.3).

5.1 Introduction

The empirical procedures discussed in Chapters 3 and 4 yield several interesting findings. Median masked detection thresholds as low as -13 dB and -28 dB SNR for monaural and free-field spatial information are reported, respectively. Substantial individual differences ranging from -9 dB to -46 dB SNR are also reported. In order to explain the findings, it is important to look into the underlying biological process. To do that, we used a sophisticated biologically inspired model, the Matlab Auditory Periphery (MAP). It is a computational neuroscience model developed to simulate and predict sound transmission from the pinna to the middle ear, the cochlea and the subsequent excitations of auditory nerves (Meddis, 2006).

The role of auditory efferent feedback of the medial olivocochlear system (MOCS) has been attributed to help speech perception in the presence of noise (Brown *et al.*, 2010; Clark *et al.*, 2012). However, whether it has similar effects on tonal detection tasks in the presence of noise is not clearly understood. Past studies yielded inconsistent results on the relationship between efferent feedback and tonal/speech detection thresholds (correlated: Micheyl and Collet, 1996; uncorrelated: Wagner *et al.*, 2008). In Experiment 3, the objective is to study the role of the MOCS efferents on tonal detection thresholds in the presence of noise.

It is not easy to measure the strength of MOCS efferent signals, several past studies have used contralateral suppression of evoked otoacoustic emissions (EOAEs) as a means of measuring the strength of auditory efferent feedback (e.g. Micheyl and Collet, 1996; Collet *et al*., 1990; Veuillet *et al*., 1991; Micheyl *et al*., 1995; Garinis *et al*., 2011). In this experiment, the contralateral suppression of transient evoked otoacoustic emissions (TEOAEs) were measured and used to indicate the strengths of MOCS in subjects. This chapter reports the procedures, data analysis and conclusions of Experiment 3.

5.2 Part I: Simulations of the AIN processes using the MAP

A customized version of the MAP model was used to facilitate the simulation. The customizable user program allows the modification of model parameters, model output type (full brainstem model or a shorter version that computes only up to auditory nerve), input signal type (tone signal or an audio file), root-mean-square sound pressure level of the input signal, and the range of best frequencies (Hearing Research Lab, 2011).

5.2.1 Outputs of the model

Outputs of the simulation model when the input was a 65 dBA 1 kHz pure tone are presented in Figures 5.1, 5.2 and 5.3.

Input signal amplitude, Stapes displacement, multi-channel Basilar Membrane (BM) displacement and Auditory Nerve (AN) spiking probability for the three AN fiber types are given in Figure 5.1. The three fiber types are High Spontaneous Rate (HSR), Medium Spontaneous Rate (MSR) and Low Spontaneous Rate (LSR) (Hearing Research Lab, 2011). This will be referred to as Model Output 1 in later analyses.

A three dimensional representation of HSR AN response is given in Figure 5.2. The x, y and z axes are time, Best Frequency (BF) and AN spiking rate, respectively. This will be referred to as Model Output 2 in later analyses.

Figure 5.3 shows the input signal amplitude, attenuation due to the acoustic reflex (AR) and multi-channel attenuation as a result of medial olivocochlear (MOC) reflex (Hearing Research Lab, 2011). This will be referred to as Model Output 3 in later analyses.

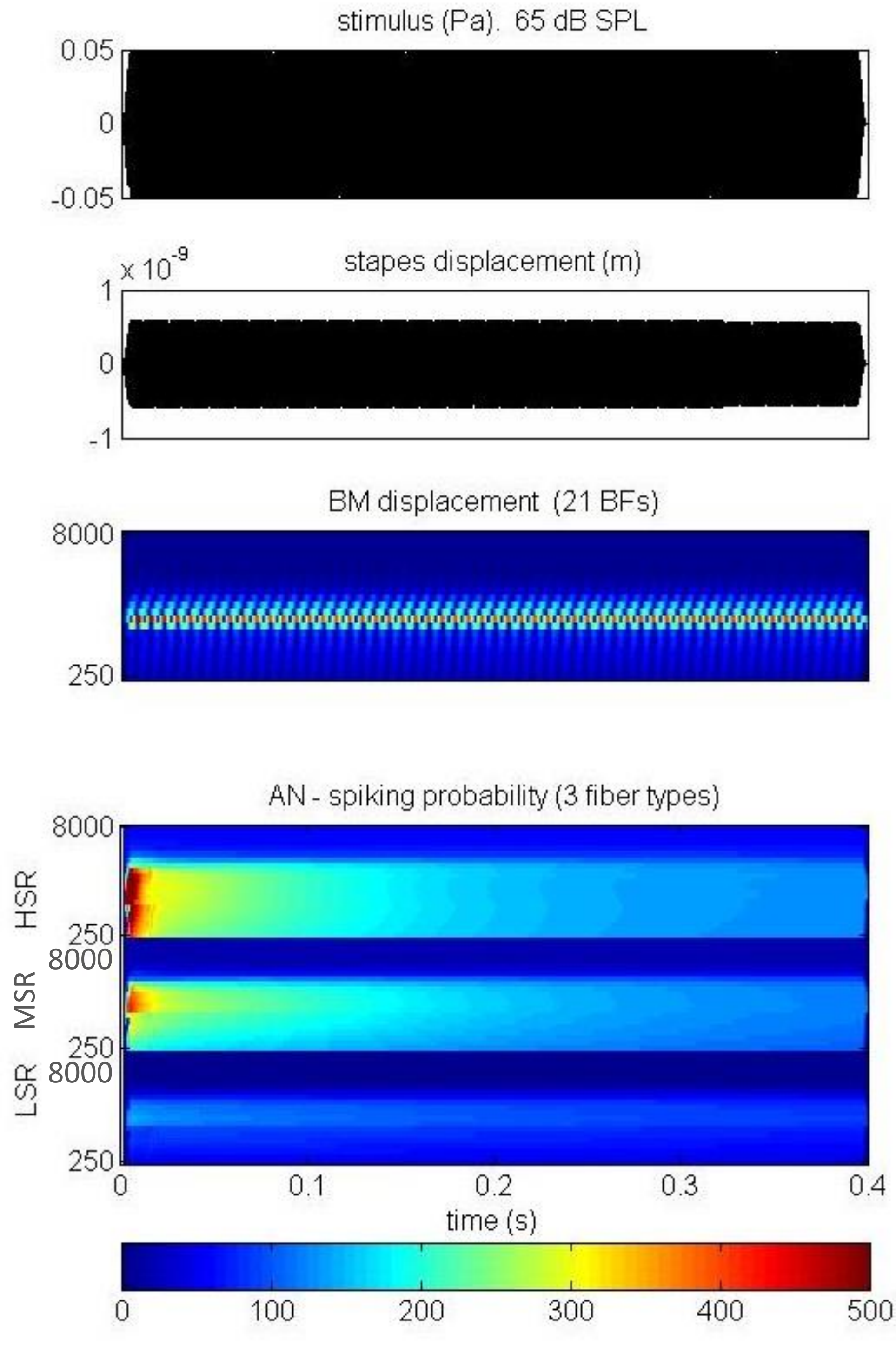

Figure 5.1 Sample Model Output 1 when 65dBA 1 kHz tone was used as the input signal (from top to bottom: Input signal amplitude, Stapes displacement, multi-channel Basilar Membrane (BM) displacement, and Auditory Nerve (AN) spiking probability)

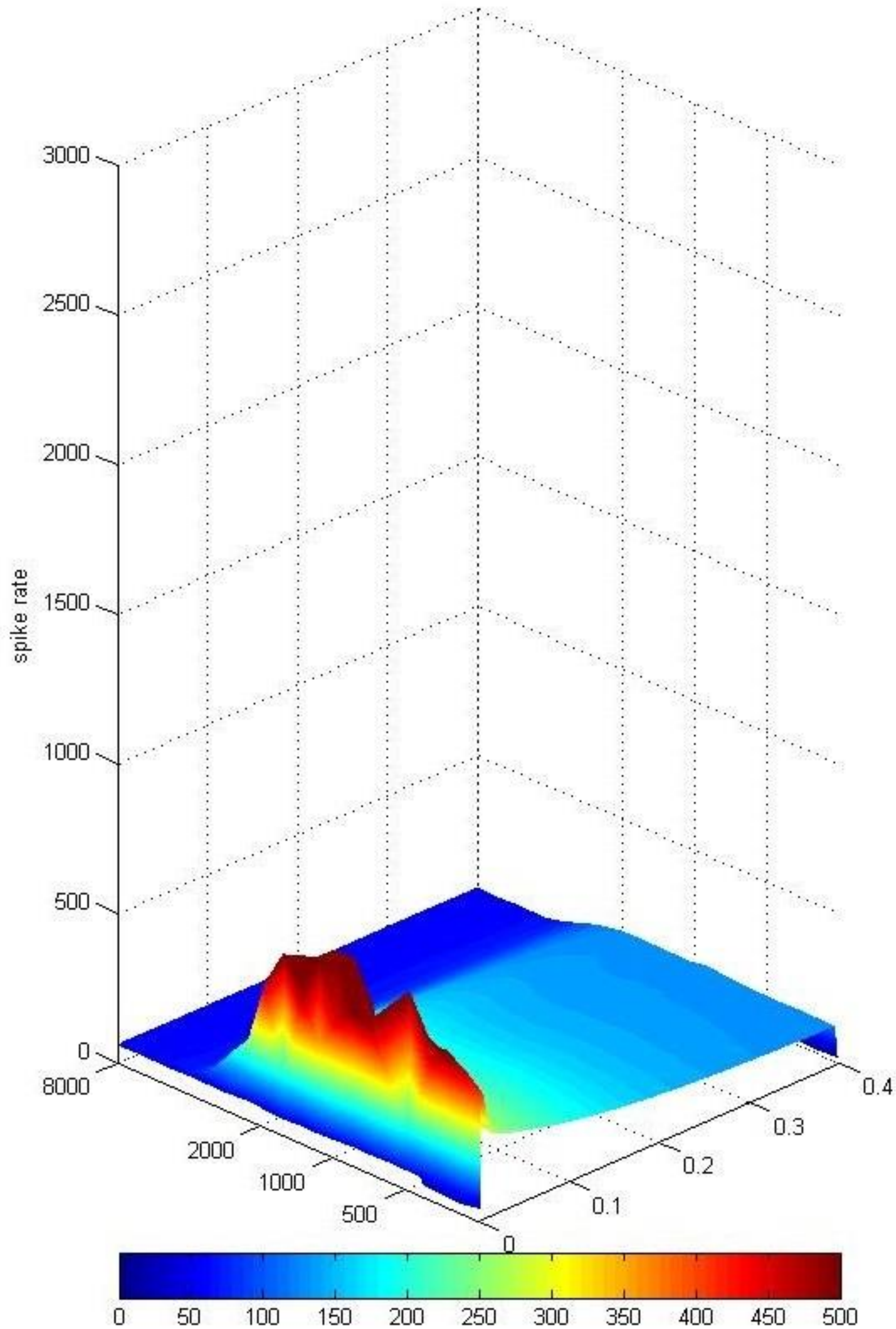

Figure 5.2 Sample Model Output 2 when 65dBA 1 kHz tone was used as the input signal (HSR AN spiking rates as functions of time and best frequencies)

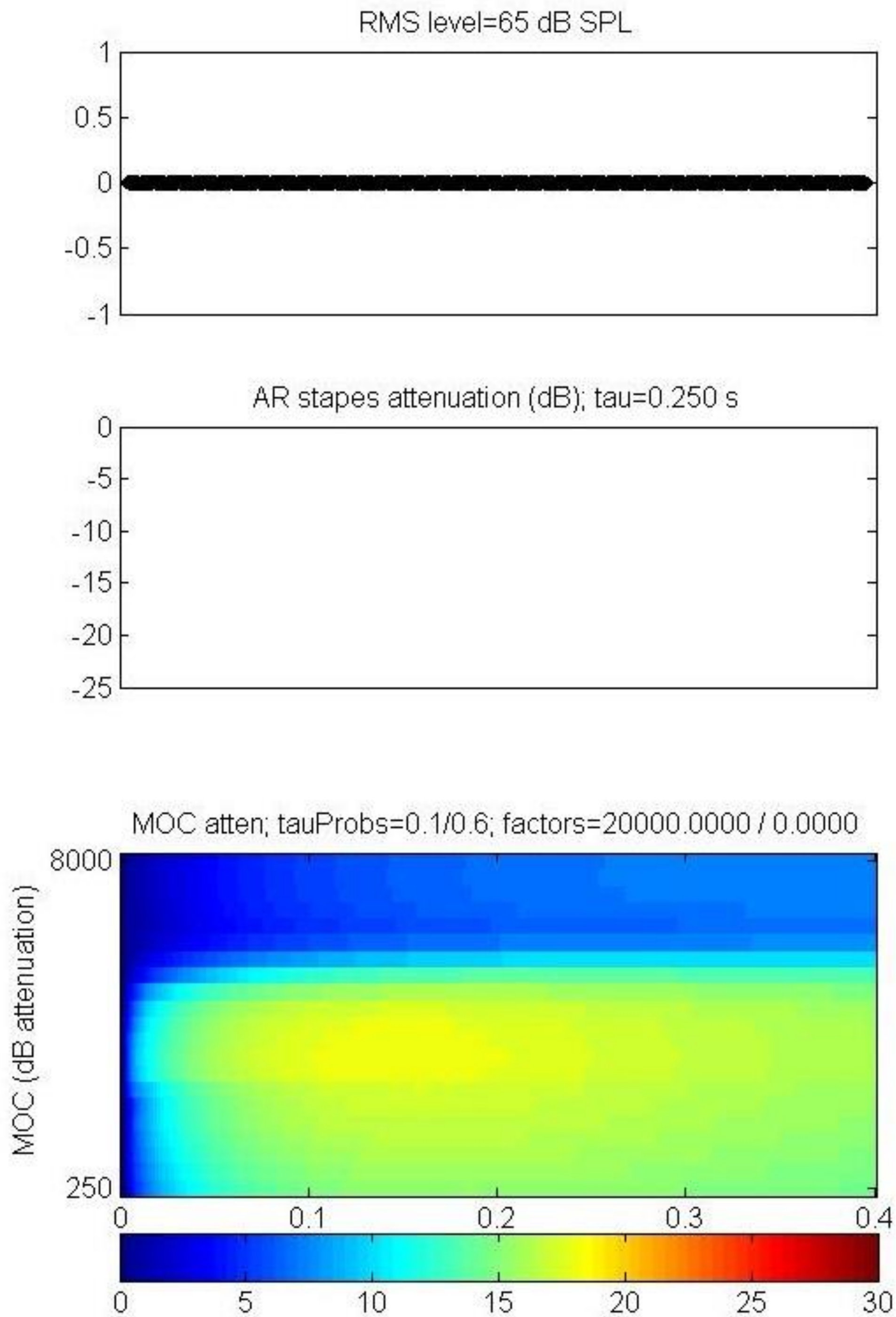

Figure 5.3 Sample Model Output 3 when 65dBA 1 kHz tone was used as the input signal (top: input signal amplitude, middle: attenuation due to the acoustic reflex (AR) and bottom: multi-channel attenuation as a result of medial olivocochlear (MOC) reflex)

5.2.2 Audio Stimuli used in the simulation

Samples of the stimuli used in Experiment 2 and 4 were used as the input signals to the model. Recommended parameters for normal hearing (Hearing Research Lab, 2011) were used for the simulations. Inputs of audio stimuli were in the form of .wav file format. 21 Best Frequency channels (250 – 8000Hz) were used and the channels were equally spaced in a log scale.

5.2.2.1 SNR Level of -20dB (60dBA Train Alarm in the presence of 80dBA Train Noise)

Simulations results of the train noise only and train noise + train alarm conditions are given in Figures 5.4.

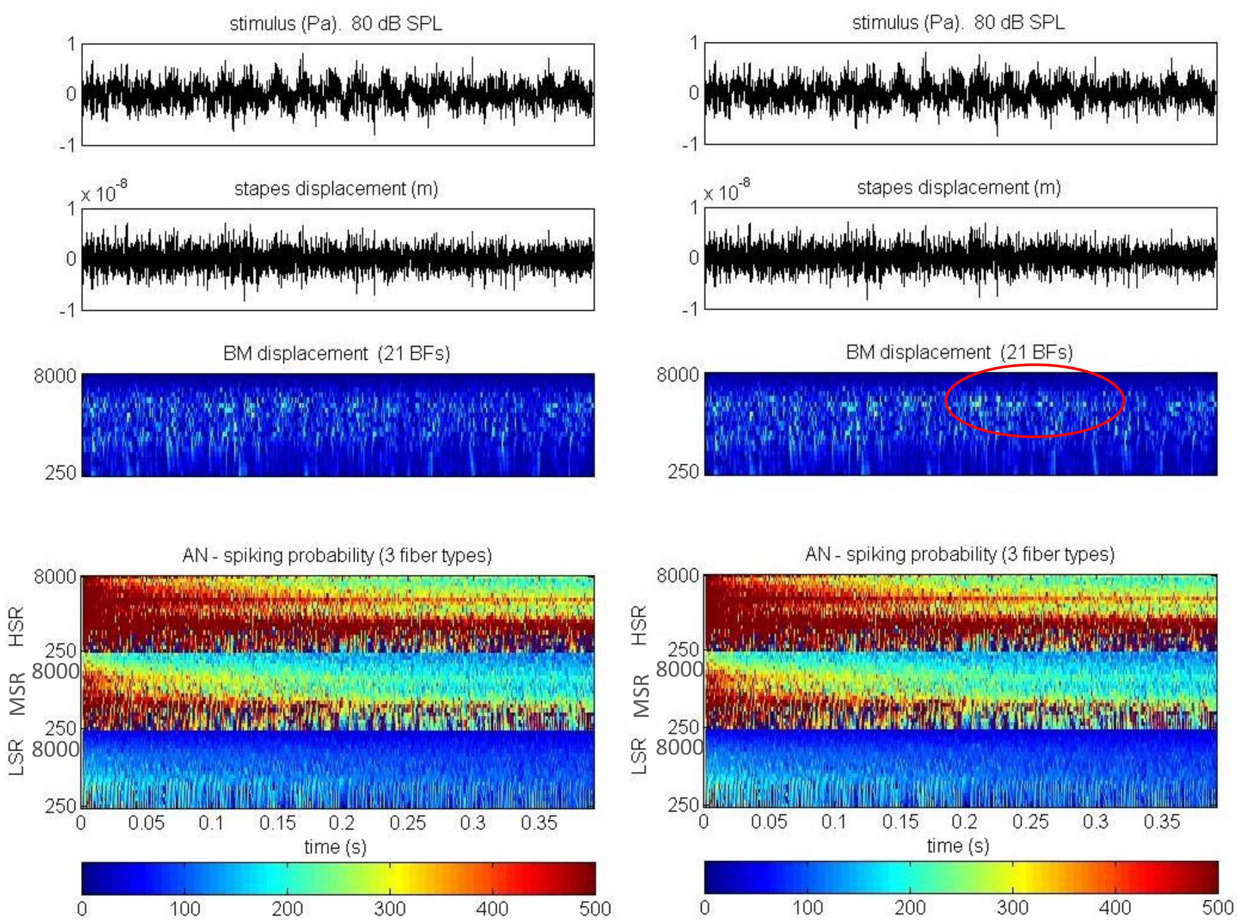

Figure 5.4 Left: 80dBA Train Noise only condition, Right: 60dBA Train Alarm in 80dBA Train Noise (-20dB SNR) Condition – Model Outputs 1 (from top to bottom: Input signal amplitude, Stapes displacement, multi-channel Basilar Membrane (BM) displacement, and Auditory Nerve (AN spiking probability)

Since the center frequency of the train alarm that was used in the experiments was 2 kHz, special attention was given to the best frequencies near 2 kHz during the initial analysis of the results. Visible changes in the BM displacement were observed in Figure 5.4. Therese changes start to appear in the 200ms timestamp. That was when the alarm sound started to play. But there was no visible evidence for the AN firing pattern changes between the two conditions. Inspections of Figure 5.4 indicate that the AN corresponding to the best frequency (BF) of 2 kHz was actually firing. This suggested that the noise has a concentration of energy at 2 kHz. Upon examination of the noise spectrum (Figure 3.2), it was confirmed that indeed the recorded train noise had a concentration of energy at 2 kHz. Given the fact that the train alarm also had a concentration of energy at 2 kHz, the recorded train noise and alarm paradigm could have made the AIN detection thresholds reported in Experiments 1 and 2 more conservative. In other words, one should expect an even lower AIN detection threshold if the 2 kHz energy was removed from the noise.

5.2.2.2 SNR Level of 0dB (65dBA Train Alarm in 65dBA Train Noise)

Since the simulation results for -20 dB SNR (80 dBA train noise) did not indicate observable differences in AN firing patterns, a new control condition of 0 dB SNR ratio was added to the simulation. This was not a condition that was tested in Experiment 1 or 2, but the evidence from those experiments imply that normal hearing listeners should be able to detect the train alarm at 0 dB SNR without difficulty. The condition had a 65 dBA train alarm of 100ms duration embedded in a 400ms noise clip of 65 dBA SPL. Same alarm and noise from the experiments 1 and 2 were used. The simulation results are presented in Figure 5.5.

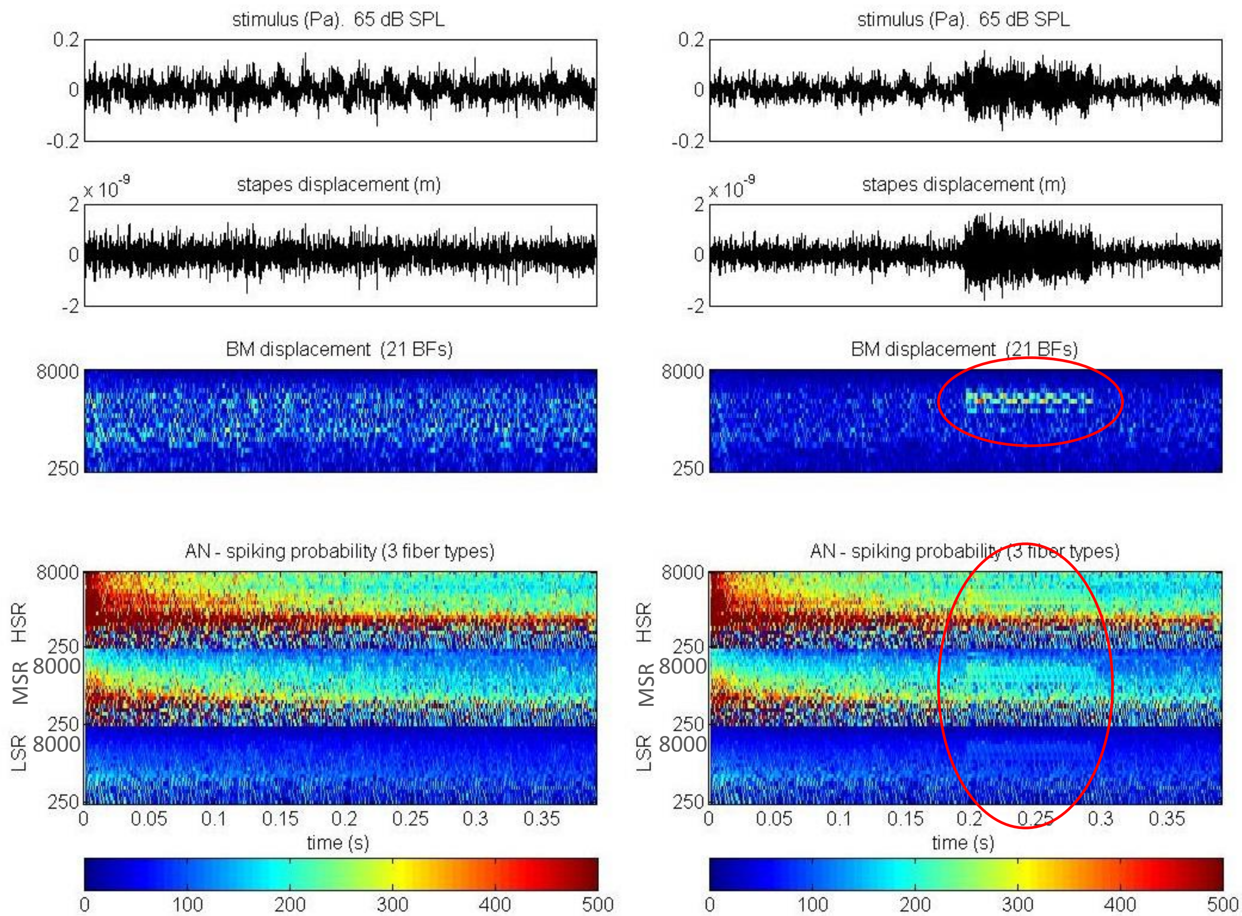

Figure 5.5 Left: 65dBA Train Noise only condition, Right: 65dBA Train Alarm in 65dBA Train Noise (0dB SNR) Condition – Model Output 1 (from top to bottom: Input signal amplitude, Stapes displacement, multi-channel Basilar Membrane (BM) displacement, and Auditory Nerve (AN) spiking probability)

Inspections of Figure 5.5 indicate that stapes displacements show major differences during the period 200ms - 300ms. BM displacement differences are observably large especially during the period where the train alarm is present. It is important to notice that BM displacements in the time segments before and after the train alarm during which only train noise was presented (Right Graph) are smaller in magnitude than those of Left Graph (train noise only in the whole condition).

Visible changes of the AN firing patterns were observed for all the three fiber types LSR, MSR and HSR, especially during the period where train alarm is present (200ms-300ms).

5.2.2.3 SNR Level of +5dB (65dBA Train Alarm in 60dB Train Noise)

Noise level was further reduced to 60dBA while keeping the alarm at 65dBA (SNR of +5dB) in order to further highlight the differences in BM displacements and AN firing patterns. Results of this simulation are given in Figure 5.6.

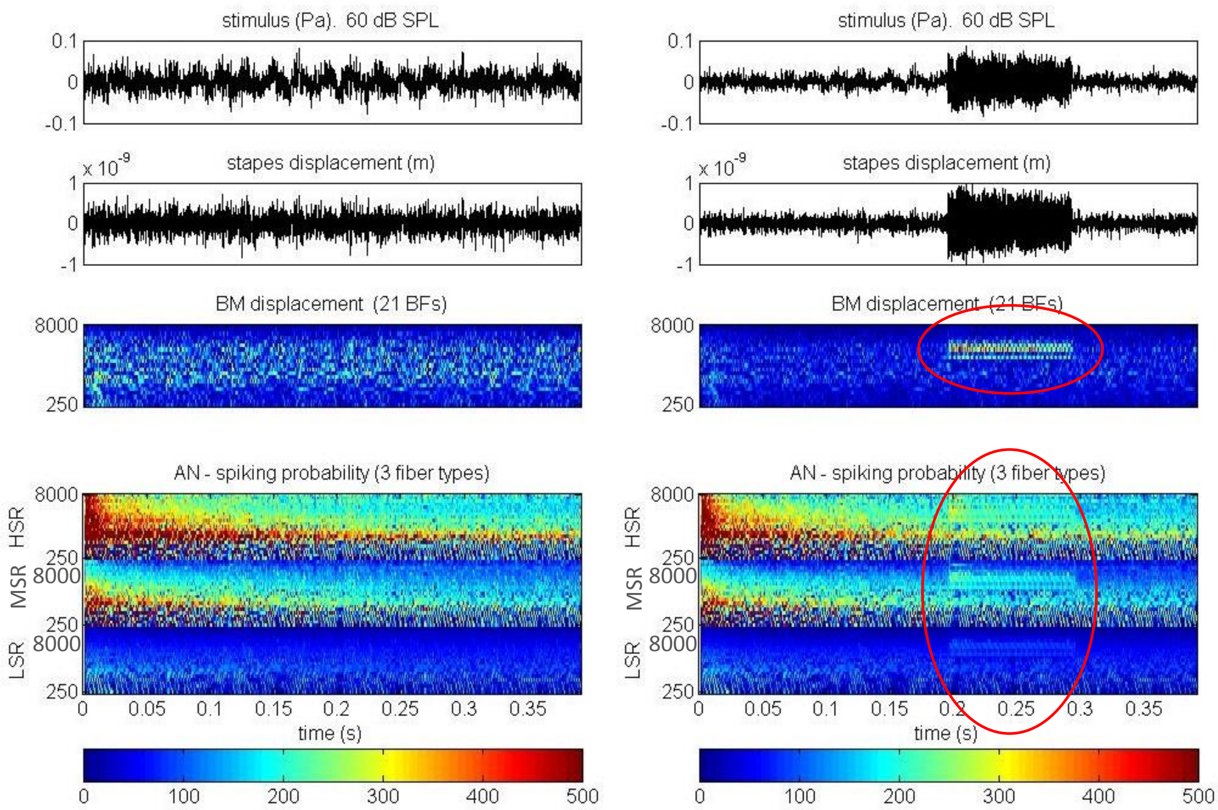

Figure 5.6 Left: 60dBA Train Noise only condition, Right: 65dBA Train Alarm in 60dBA Train Noise (0dB SNR) Condition – Model Output 1 (from top to bottom: Input signal amplitude, Stapes displacement, multi-channel Basilar Membrane (BM) displacement, and Auditory Nerve (AN) spiking probability)

5.2.2.4 SNR Level of -15dB (65dBA Train Alarm in 80dBA Train Noise)

Further simulations were conducted for the -15dB SNR condition. This simulation is important as the average monaural AIN detection thresholds observed in Experiment 2 (Chapter 4) is approximately at SNR of -15 dB.

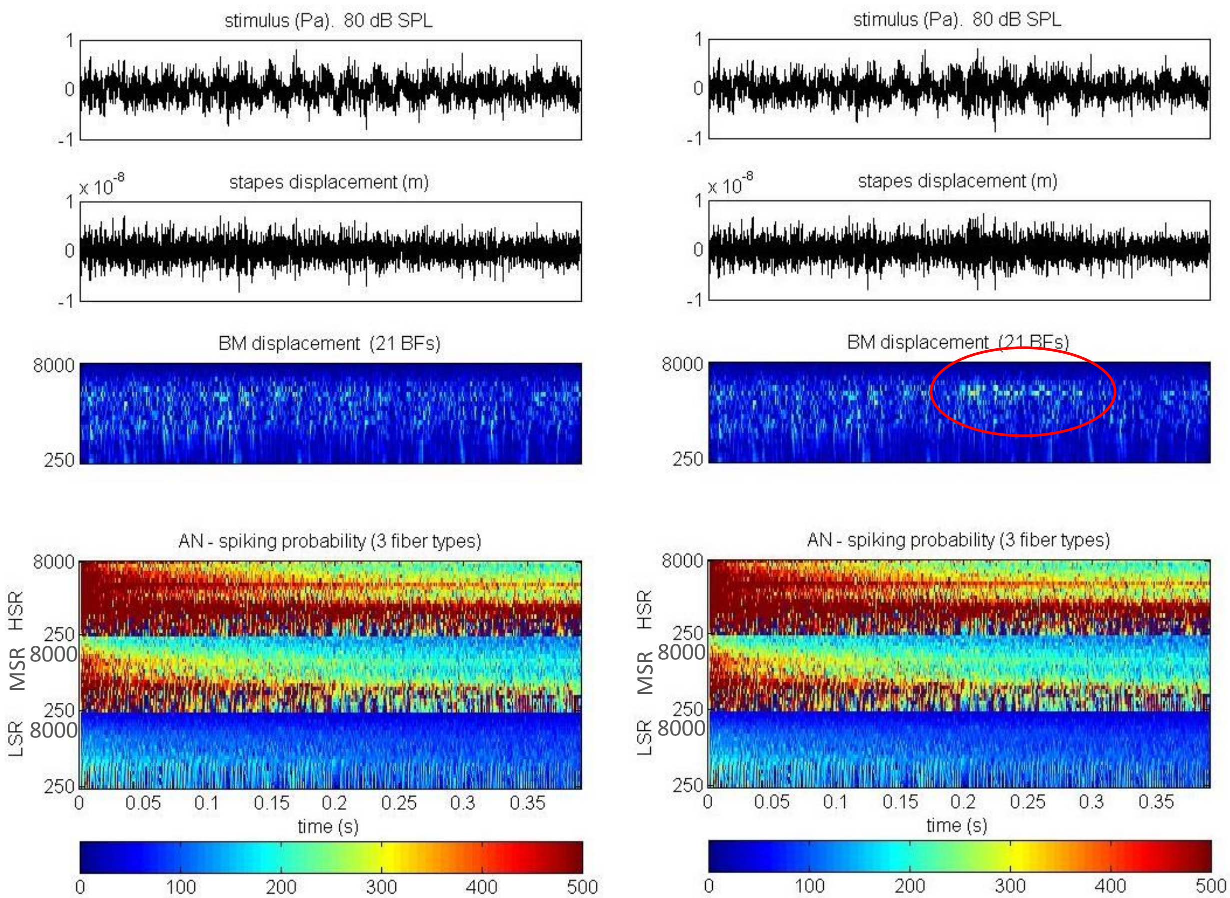

Figure 5.7 Left: 80dBA Train Noise only condition, Right: 65dBA Train Alarm in 80dBA Train Noise (-15dB SNR) Condition – Model Output 1 (from top to bottom: Input signal amplitude, Stapes displacement, multi-channel Basilar Membrane (BM) displacement, and Auditory Nerve (AN) spiking probability)

Visible changes in the stapes displacement and BM displacement can be observed in Figure 5.7. Especially when the train alarm is present (during 200ms-300ms) the differences around 2 kHz Best Frequency can be highlighted. In order to illustrate this further, the BM displacement data for 2 kHz Best Frequency were extracted from the model outputs.

Figure 5.8 presents the data for 2 kHz BF between 200ms-300ms. Figure 5.9 shows the data for 2 kHz BF between 200ms-224ms.

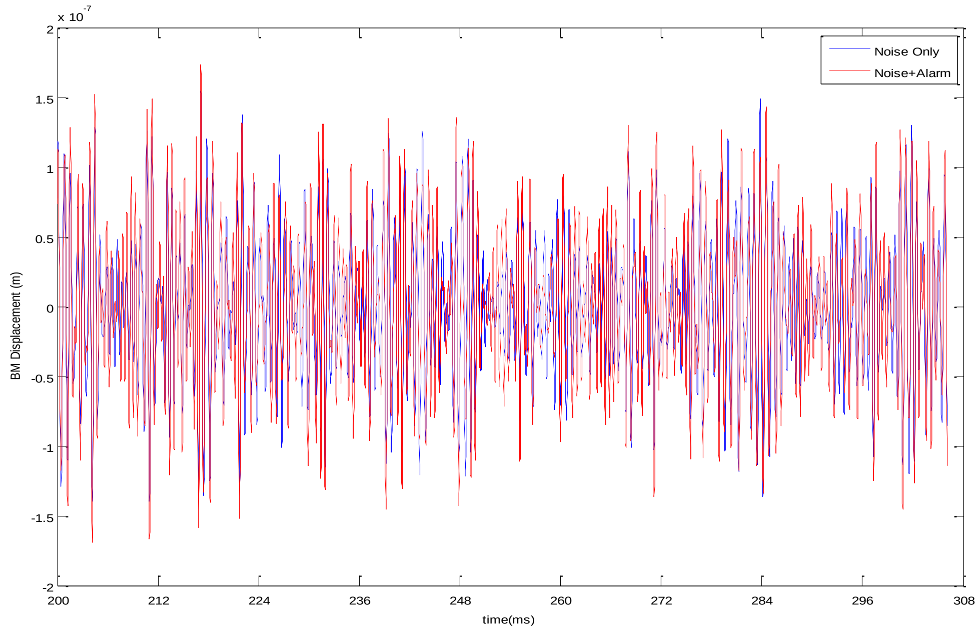

Figure 5.8 BM displacement data for 2 kHz BF during 200ms-300ms for conditions Noise Only (Blue) and Noise + Alarm (Red)

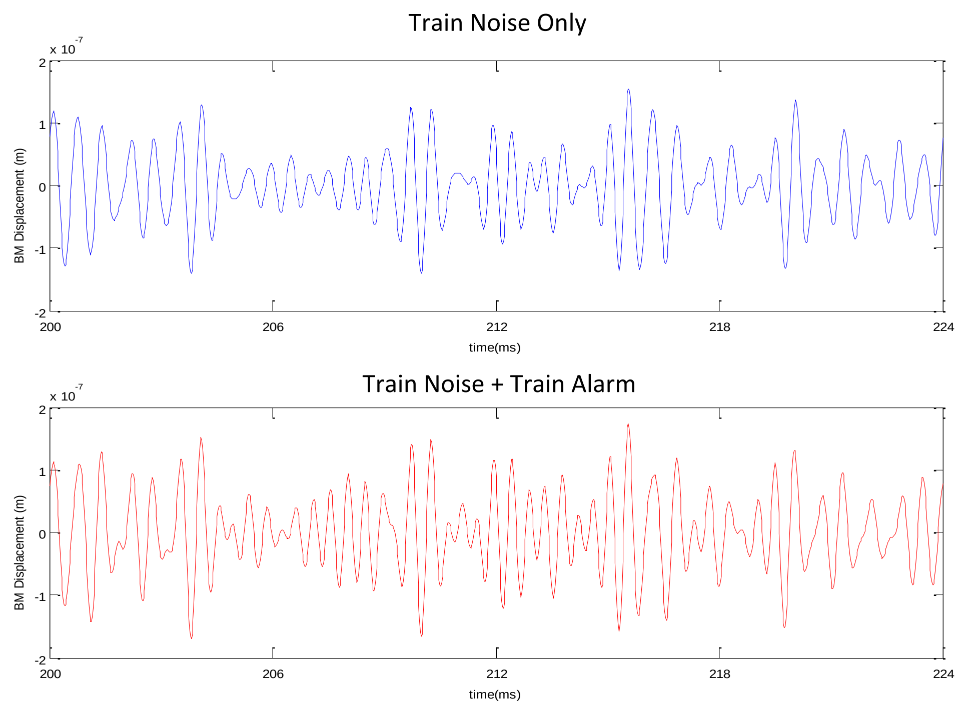

Figure 5.9 BM displacement data for 2 kHz BF during 200ms-224ms for conditions Train Noise Only (Upper) and Train Noise + Train Alarm (Lower)

Inspections of Figure 5.9 indicate differences in both the amplitude and the frequency components. Magnitude of BM displacement has increased in Train Noise + Train Alarm condition. Changes in waveform in terms of shape were also observed.

Upper graph of Figure 5.10 is a comparison of power spectral densities of stimuli before and after the introduction of the train alarm at 200ms. One can observe that the addition of the alarm caused an increase in the BM movements in the frequency range from 2 kHz to 3 kHz.

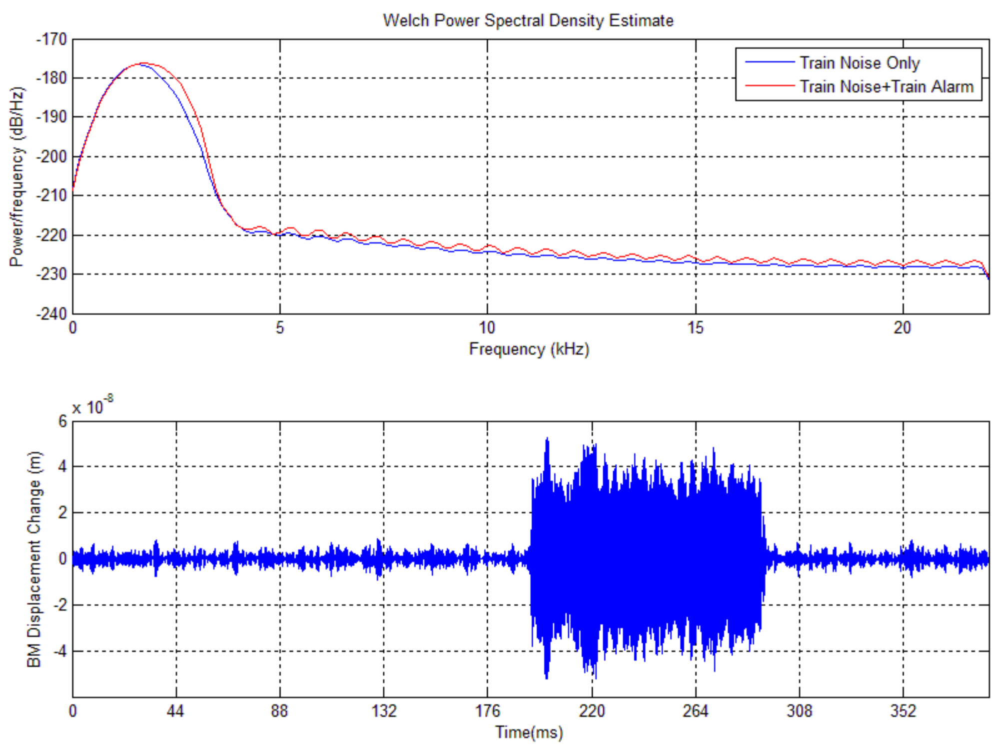

Figure 5.10 Upper: Welch power spectral density plot for Basilar Membrane (BM) displacements before and after the introduction of train alarm signal, Lower: Difference of BM displacement between Noise Only and Noise+Alarm conditions

Substantial difference of BM displacement can be observed in the lower graph of Figure 5.10, during 200ms-300ms. Results of paired T-Tests indicated that BM displacement difference during 200ms-300ms (during alarm) was significantly ($p<0.001$) higher compared to the durations 100ms-200ms (before alarm) and 300ms-400ms (after alarm).

However it should be noted that due to the high number of data points (excess of 4000) the p-value might have inflated. In order to negate that effect, the data set was down-sampled (44 data points) and the T-Tests were re-run. The results were similar. These results imply that the BM displacement differences (for negative SNR AIN detection) are quantifiable and may be used for possible development of prediction systems using biologically inspired MAP model.

5.2.2.5 SNR Level of -15dB (65dBA 1 kHz tone in 80dBA pink noise)

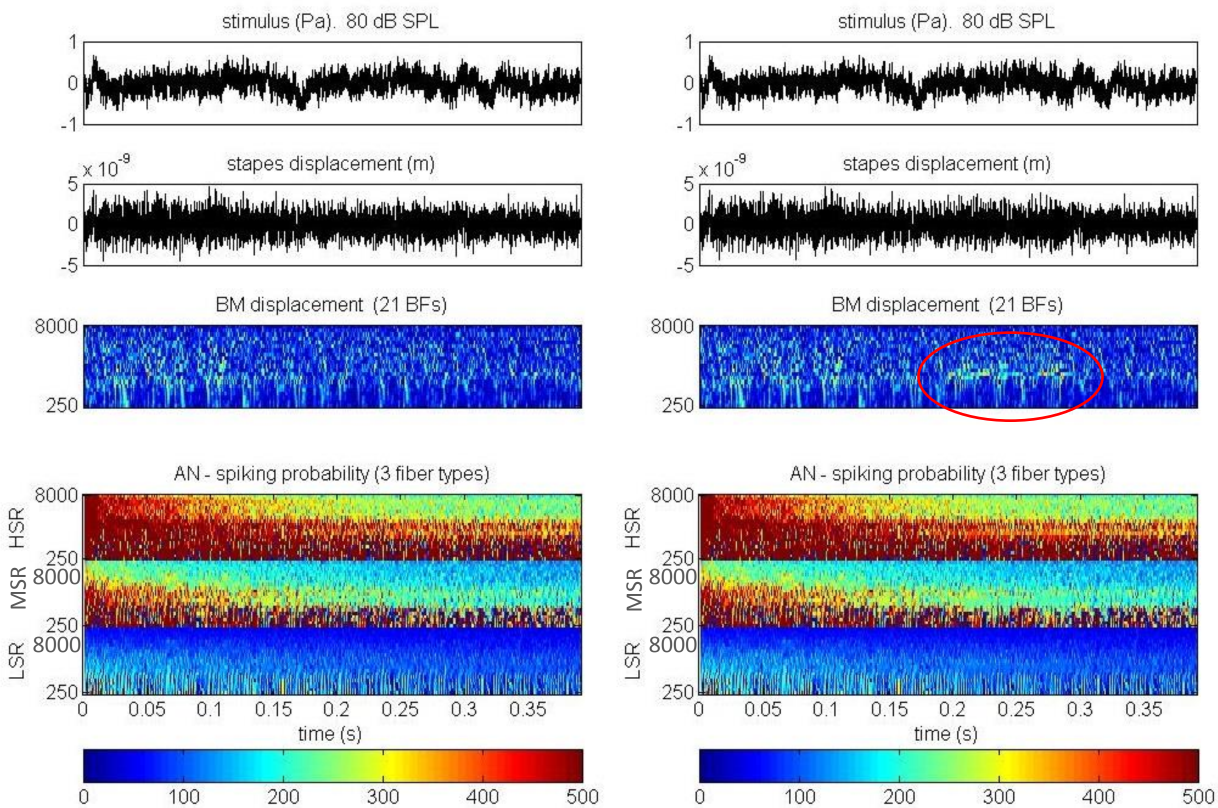

Figure 5.11 Left: 80dBA Pink Noise only condition, Right: 65dBA 1kHz Tone in 80dBA Pink Noise (-15dB SNR) Condition – Model Output 1 (from top to bottom: Input signal amplitude, Stapes displacement, multi-channel Basilar Membrane (BM) displacement, and Auditory Nerve (AN) spiking probability)

Inspections of Figure 5.11 indicate observable differences of BM displacements after introducing the tone, especially close to 1 kHz Best Frequency.

5.2.2.6 SNR Level of -15dB (65dBA 2 kHz tone in 80dBA pink noise)

Further simulations were done using the 2 kHz tone in the presence of pink noise. Results are given in Figure 5.12.

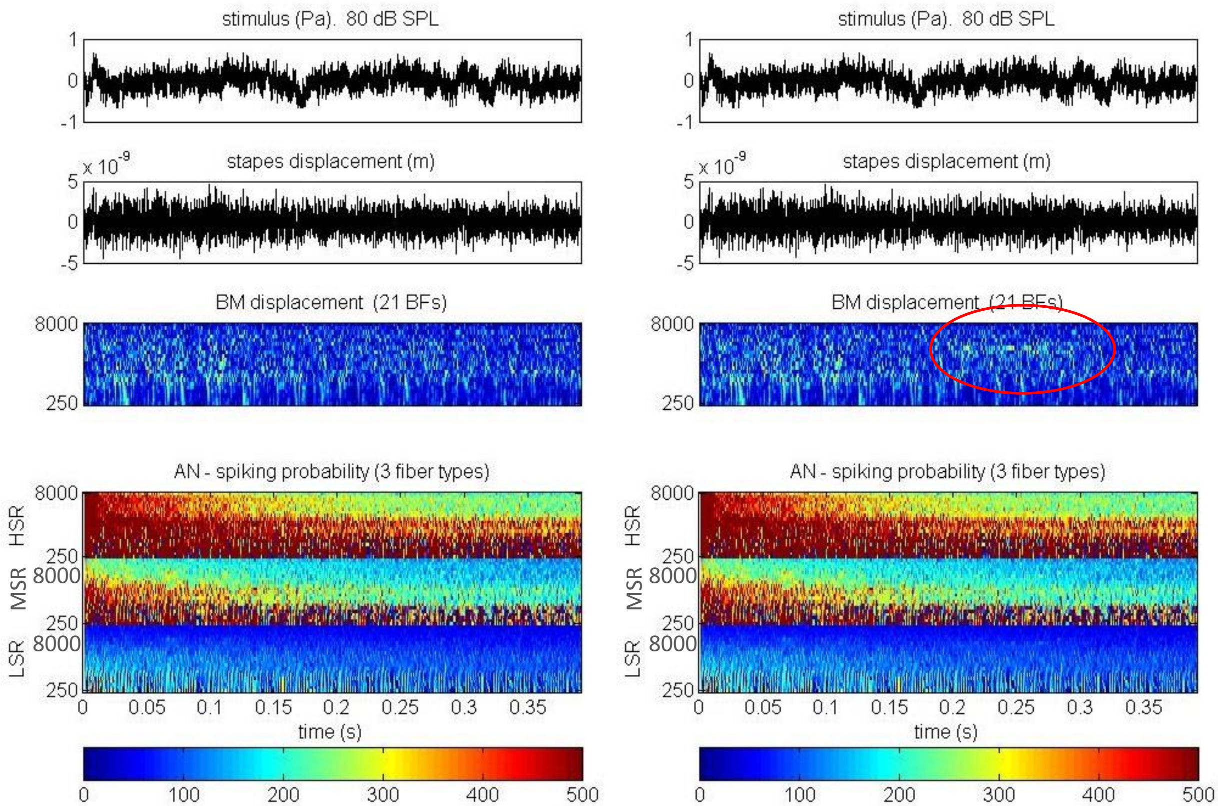

Figure 5.12 Left: 80dBA Pink Noise only condition, Right: 65dBA 2kHz Tone in 80dBA Pink Noise (-15dB SNR) Condition – Model Output 1 (from top to bottom: Input signal amplitude, Stapes displacement, multi-channel Basilar Membrane (BM) displacement, and Auditory Nerve (AN) spiking probability)

Inspections of Figure 5.12 indicate observable differences of BM displacements after introducing the tone, especially close to 2 kHz Best Frequency.

5.2.3 Discussion and summary of the simulation findings

From the model simulations, noticeable differences in BM displacement were observed for the -15dB SNR condition (Figure 5.7). This value was chosen as a benchmark because Experiment 2 yielded an average monaural AIN threshold of -15 dB SNR (-13 dB median value) in the presence of 80 dBA train noise. Differences for AN firing patterns were also observed in further analysis of data obtained from the MAP model simulations.

Since the MOCS efferents synapse on the Outer Hair Cells (OHCs) which are on the basilar membrane (Guinan, 1996), the importance of investigating the effects of MOCS was highlighted. Efferent inhibition of perception of continuous and transient noise has been reported (Liberman and Guinan, 1998; Dolan and Nuttall, 1988). Moreover, MOCS efferent feedback's role in perception of speech in noise has also been reported (Giraud *et al*., 1997; Kumar and Vanaja, 2004). More recently, studies by Brown *et al*. (2010) and Clark *et al*. (2012) reported that MOCS efferent feedback could enhance speech intelligibility in noise.

Subsequently, the next step of this study was to investigate the effects of MOCS efferent feedback on the detection thresholds of train alarm in the presence of loud train noise.

5.3 PART II: Experiment 3 studying the effects of MOCS efferent feedback

The objective of Experiment 3 was to test the hypothesis that MOCS efferent feedback can enhance the AIN detectability.

5.3.1 Design of Experiment

OAEs can be suppressed by contralateral noise stimulation. This suppression is a result of MOCS efferent feedback and the stronger the MOCS feedback, the larger the suppression. Therefore contralateral suppression of OAEs has been used as a measure of MOCS efferent feedback strength (e.g. Micheyl and Collet, 1996; Collet *et al*., 1990; Veuillet *et al*., 1991; Micheyl *et al*., 1995; Garinis *et al*., 2011). Therefore we decided to use a similar methodology to assess the MOCS feedback strength of our subjects who participated in Experiment 2.

5.3.1.1 Subjects

Fifteen out of the sixteen subjects that took part in Experiment 2 participated in Experiment 3. All subjects had normal hearing.

5.3.1.2 TEOAE Measurement

5.3.1.2.1 Location

TEOAE measurement was done inside an acoustic chamber in the Audiology Unit, Prince of Wales Hospital, Hong Kong (Figure 5.13).

Figure 5.13 Acoustic Chamber in the Audiology Unit in the Price of Wales Hospital, Hong Kong

5.3.1.2.2 Equipment

Otodynamics® Echoport ILO292-II equipment (Figure 5.14) was used to measure the TEOAEs of the subjects. The system used ILO V6 software provided by Otodynamics Ltd.

Figure 5.14 Left: Otodynamics ILO292-II running ILO V6 software, Right: Ear probe (Image source: www.otodynamics.com)

5.3.1.2.3 Measurement Settings

Linear clicks were used as the evoking stimuli at an SPL of 60 dB. Linear stimulus was selected as it was the best option for investigating effects of contralateral stimulation (Otodynamics Ltd., 2011). Broadband white noise at an SPL of 80dB was used as the contralateral noise because the apparatus does not have the option to generate pink noise.

Contralateral TEOAE suppression testing is done by making two separate OAE recordings. One type of recording is done when the masking noise is presented to the contralateral ear. The other type is recorded when the masker is absent. These two types of recordings are alternated regularly to minimize the effects of runtime changes in the measurement setting (Otodynamics Ltd., 2011).

5.3.1.2.4 Instructions to the Subjects

The subjects were asked to sit, wear the OAE probes and listen to the stimuli that were presented. Also they were instructed to make minimal movements and keep silent during the measurement procedure.

5.3.2 Results and Data Analyses

Contralateral suppression of TEOAEs was derived by calculating the differences between the two types of measurements mentioned in Section 5.3.1.2.3.

TEOAE contralateral suppression data and monaural AIN threshold data obtained in Experiment 2 (Chapter 4) were analyzed using the Pearson product-moment correlation analysis in order to determine any interesting and reliable relationships.

A statistically significant negative correlation was observed between the TEOAE contralateral suppression and AIN monaural detection thresholds ($r=-0.526$, $n=15$, $p<0.05$).

The corresponding data plot is given in Figure 5.15.

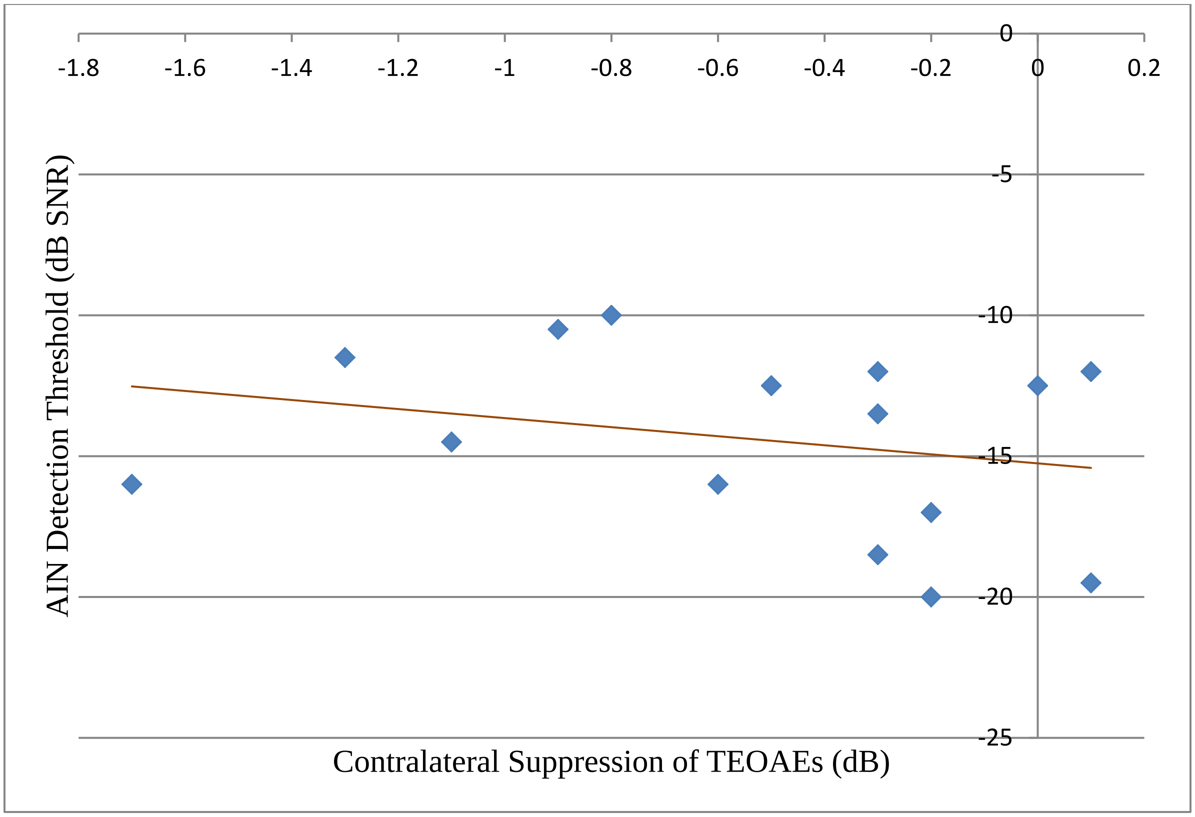

Figure 5.15 Relationship between Contralateral Suppression of TEOAEs and AIN Detection Thresholds (Monaural)

The results of the correlation analysis and inspections of Figure 5.18 imply a negative relationship between TEOAE contralateral suppression and AIN detection thresholds. In other words, subjects with higher MOCS feedback have higher AIN detection thresholds (worse detection performance).

5.4 Discussion & Conclusion

Results from this study indicate a significant negative relationship between the TEOAE contralateral suppression levels and the AIN detection thresholds. This supports the argument that MOCS efferent feedback worsens the detection performance of alarm in negative SNR conditions (in the presence of 80 dBA noise).

The equipment used for OAE measurements only supported broadband (white) or narrowband noise. Therefore it was not practically possible to use pink noise as the suppresser for OAE measurements. Broadband (white) noise is generally accepted as a more effective suppressor (Otodynamics Ltd., 2011). Therefore we used broadband (white) noise rather than narrowband noise as the suppressor. Usage of pink noise might reduce the overall levels of OAE suppression but it should not affect the correlation analysis.

This result disagrees with the positive correlation reported by Micheyl and Collet (1996); Bhagat and Carter (2010). This condition of negative SNR ratio may be a possible reason for the difference between the present result and results of the past studies. .Wagner *et al*. (2008) could not find a significant correlation using speech as target stimuli.

Further discussions on how the findings of this chapter relates to the past studies will be presented in Chapter 7. Suggestion of a possible reason for the negative correlation between MOCS efferent feedback strength and AIN detection thresholds in negative SNR will also be presented in Chapter 7.

CHAPTER 6: EXPERIMENT 4: TONE-IN-NOISE (TIN) THRESHOLDS

Summary

This chapter presents detailed methodology and results of Experiment 4. The experiment was designed to generalize and validate the findings of the Experiments 1 and 2 (described in Chapters 3 and 4). The findings of the experiment are in agreement with the previous experiments' findings and provide general validity and a solid foundation for the generalization of the findings.

6.1 Introduction

Results of Experiment one indicated that human were able to detect a train alarm sound in the presence of 80 dBA train noise at a SNR level of -24dB (Chapter 3). This finding was substantiated with Experiment two with median AIN detection thresholds as low as -28 dB SNR and -13dB SNR for free-field and monaural conditions, respectively (Chapter 4). However both experiments used train alarm and train noise segments with characteristics similar to those recorded in a real industrial situation (Chapter 3). This limits the findings of Experiments one and two as confounded with the characteristics of the alarm and the noise. At best, they are AIN and not tone-in-noise detection thresholds. The objective of Experiment four is, therefore, to study tone-in-noise (TIN) and extend the findings of Experiments one and two. Selected pure tones and pink noise are used and the effect of spatial presentation is investigated.

6.2 Hypotheses

It was hypothesized that (i) the negative SNR ratios for the AIN detection thresholds will also hold for TIN detection thresholds; and (ii) the spatial information and (iii) tonal frequency will affect the TIN detection thresholds.

6.3 Design of Experiment

6.3.1 Variables

The independent variables were spatial information (Diotic and Free-Field spatial configurations) and tonal frequency (1 kHz and 2 kHz). The dependent variable was TIN detection threshold. Noise spectrum and Noise SPL were controlled.

6.3.2 Stimuli and Presentation

1 kHz and 2 kHz pure tones were used in the experiment. The original train alarm has the highest energy concentration at 2 kHz (see Chapter 3, Figure 3.2). The 1 kHz was added as it is the common reference frequency. Both were generated using Matlab® . The SPL of the pink noise (also generated using Matlab®) was set to 80 dBA for all conditions. PSD of the pink noise is given in Figure 6.1 and it can be compared with the similar PSD shape of the original train noise spectrum (Figure 3.2, Chapter 3). Diotic and Free-Field spatial configurations were studied because they were shown to have significant influence on the AIN detection thresholds. The free-field configuration in this experiment is the same as Experiment 2 Part 1, where target and noise are presented by separate speakers and the target speaker was placed in front-left (45 degrees) with respect to the subject’s location.

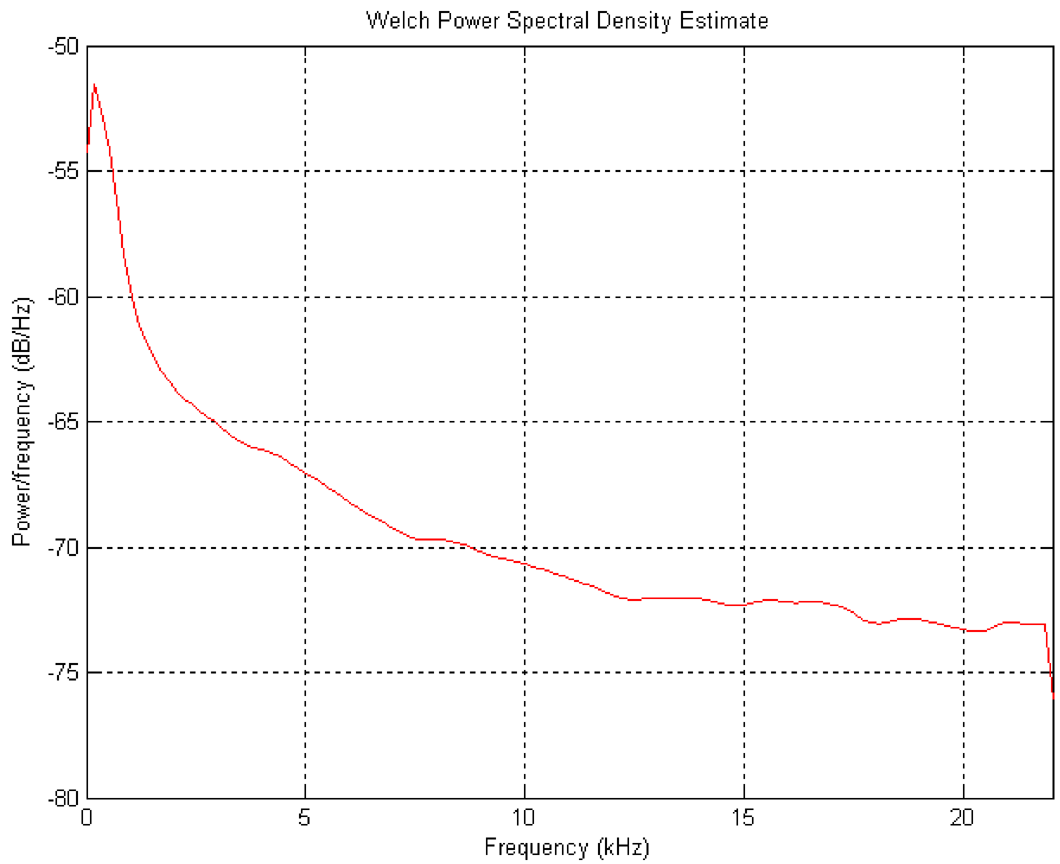

Figure 6.1 Welch Power Spectral Density graph for the pink noise used in the experiment

Similar to the conditions in Part 2 of Experiment 2, the duration of one noise segment was set to 400ms and target tone duration was 100ms. Target tone started 200ms after the noise and ended 100ms before the noise. The silent gap between the two segments was 500ms.

Table 6.1 Notations for conditions based on spatial information and tonal frequency

Spatial Information/Tonal Frequency	Notation
Diotic/1 kHz	DT1
Diotic/2 kHz	DT2
Free-Field/1 kHz	FF1
Free-Field/2 kHz	FF2

6.3.3 Equipment and Calibration

The same equipment used in Experiment 2 was used in this experiment. For diotic configuration, the Sennheiser HD 600 headphones were used. Calibration procedure was also similar to that of Experiment 2. Free-field calibrations were done at the subject's ear level and diotic condition calibration was done using the mannequin. QUEST 1800 Sound Level Meter was used for SPL calibrations. Matlab® program run on a Dell personal computer (64-bit Windows 7 Enterprise) system was used for the thresholds estimation procedures.

6.3.4 TIN Threshold Estimations

TIN threshold estimation was done using the same procedure as in Experiment 2 by an adaptive 2IFC method (see Chapter 4).

6.3.5 Subjects

Twenty-two subjects (20 male and 2 female) with normal hearing participated in the experiment. Their audiometric data was obtained using a Madsen Itera-II audiometer. The subjects were aged between 24 – 50 years.

6.4 Results and Data Analysis

6.4.1 Individual differences in TIN thresholds

Figures 6.2 and 6.3 illustrate the individual variability of the TIN detection thresholds for diotic and free-field spatial configurations respectively.

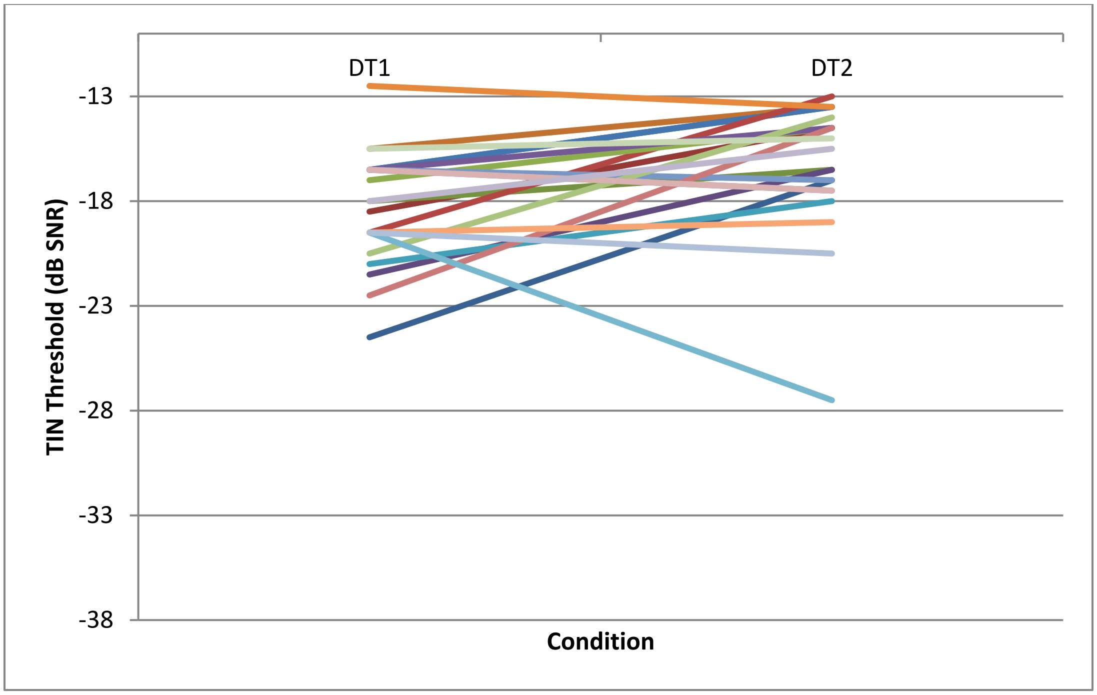

Figure 6.2 Individual differences of TIN thresholds for the diotic condition

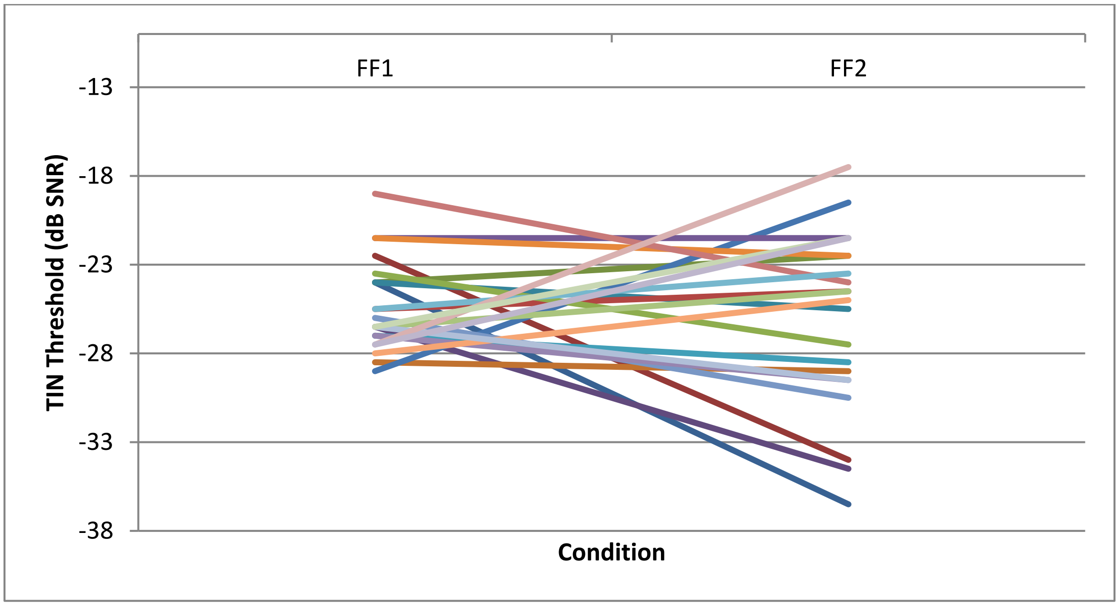

Figure 6.3 Individual differences of TIN thresholds for the free-field condition

TIN threshold ranges for the four conditions are summarized in Table 6.2

Table 6.2 Notations for conditions based on spatial information and tonal frequency (DT1 and DT2 are diotic conditions with 1 kHz and 2 kHz tones; and FF1 and FF2 are free field conditions with 1 kHz and 2 kHz tones)

Condition	TIN Threshold Range (dB SNR)
DT1	(-12.5) – (-24.5)
DT2	(-13.0) – (-27.5)
FF1	(-19.0) – (-29.0)
FF2	(-17.5) – (-36.5)

As illustrated by Figures 6.2 and 6.3, similar to the findings in AIN detection thresholds collected in Experiment 2, substantial individual differences were observed for TIN detection thresholds for all conditions.

6.4.2 Median TIN detection thresholds

Median TIN detection thresholds for the four conditions are given in Table 6.3 and the corresponding plot is given in Figure 6.4.

Table 6.3 Median TIN detection thresholds (DT1 and DT2 are diotic conditions with 1 kHz and 2 kHz tones; and FF1 and FF2 are free field conditions with 1 kHz and 2 kHz tones)

Condition	Median TIN Threshold (dB SNR)
DT1	-18.0
DT2	-15.2
FF1	-26.2
FF2	-24.8

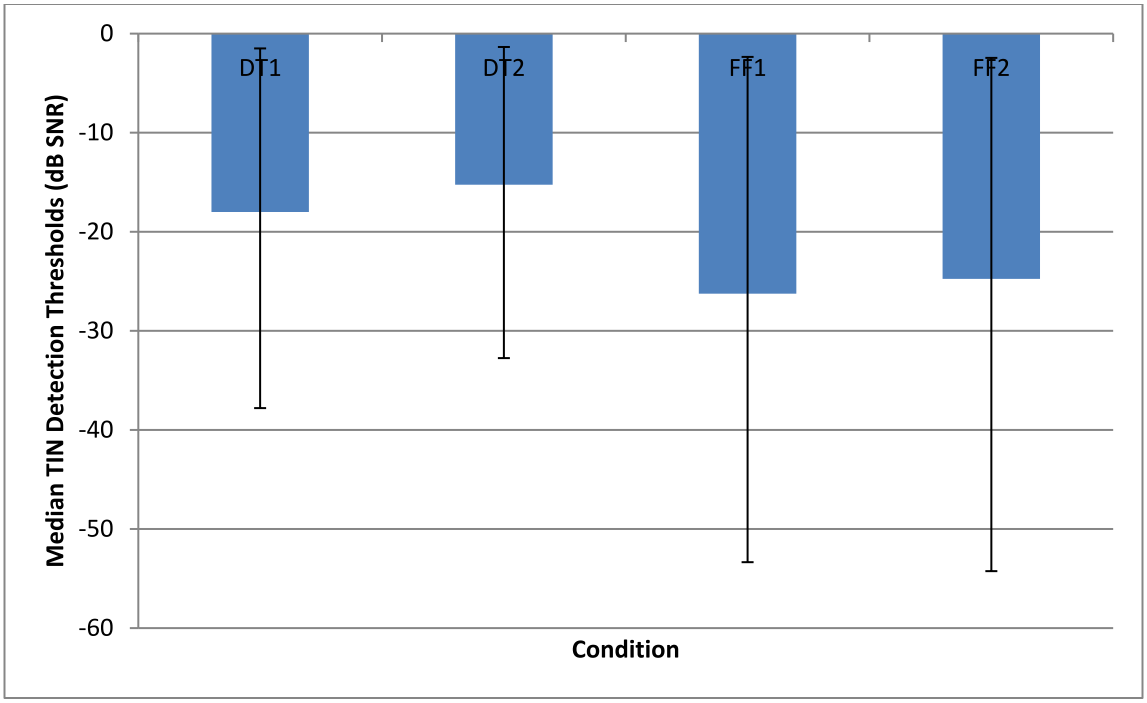

Figure 6.4 Median TIN Detection Thresholds (DT1 and DT2 are diotic conditions with 1 kHz and 2 kHz tones; and FF1 and FF2 are free field conditions with 1 kHz and 2 kHz tones)

6.4.3 Statistical Analysis

Since the Shapiro-Wilk normality tests indicated a significant deviation from normality ($p<0.05$, Shapiro-Wilk), non-parametric tests were employed.

Wilcoxon signed rank tests indicated that TIN thresholds between DT1 and FF1 were significantly different from each other ($Z=-4.016$, $p=0.000$). TIN thresholds between DT2 and FF2 were also significantly different from each other ($Z=-3.984$, $p=0.000$). These results indicate a significant effect of the spatial information on TIN detection thresholds. Inspections of the data indicated a lower TIN detection threshold for the free field condition (Figure 6.4).

TIN thresholds of DT1 and DT2 were significantly different from each other ($Z=-2.634$, $p=0.008$) while those of FF1 and FF2 were not significantly different ($Z=-0.522$, $p=0.602$). This indicates that for the diotic condition, effect of tonal frequency on the TIN detection threshold was significant but not for the free-field condition. With diotic presentation, 1 kHz has a lower TIN threshold than 2 kHz.

6.5 Discussion and Conclusion

For the diotic condition median TIN detection thresholds of -18.0 and -15.2 dB SNR were observed for 1 kHz and 2 kHz respectively. These values indicate an improvement in the TIN thresholds compared to the median AIN threshold of -14.3 dB SNR obtained in Experiment 2 Part 2. A pair-wise Mann-Whitney U test indicated that DT1 TIN thresholds were significantly different from diotic AIN thresholds (DT) in Experiment 2 Part 2 (U=50.5, p=0.003). Interestingly DT2 TIN thresholds were not significantly different from AIN (DT) thresholds (U=111, p=0.517). We acknowledge that the data for this statistical test were collected in different experiments and the results of the tests are of indicative value only.

In the free-field condition median TIN thresholds of -26.2 and -24.8 dB SNR were observed for 1 kHz and 2 kHz respectively. This implies a slight degradation of the average TIN thresholds compared to the value of -28.0 dB SNR obtained in Experiment 2 Part 1. Mann-Whitney U tests indicated that FF1 TIN thresholds were significantly different from AIN (FF100$_4$) thresholds (U=74, p=0.043). But again FF2 TIN thresholds were not significantly different from AIN (FF100$_4$) thresholds (U=108.5, p=0.462). It has been shown that a wider spectrum of sound are needed for human to facilitate the monaural spatial cue and this may be the possible reason why the train alarm (2 kHz and its harmonics at 4 kHz, 8 kHz) was associated with lower detection thresholds (So *et al.*, 2011).

The significant difference between the diotic and free-field conditions corroborates the findings of Experiment 2. This provides further evidence of a relationship between the spatial localization and the masking level suggested in the past studies (e.g. Gatehouse, 1986, 1987; Saberi *et al.*, 1991; Gilkey and Good, 1992). Significant effect of the tonal frequency on the TIN detection threshold was observed for the diotic condition. However this was not true for the free-field condition. Further studies may be required to verify the relationship. All in all, the most important findings are: (i) the -14.5 dB median AIN detection thresholds for the diotic presentation condition hold when the train alarm was replaced by 1 kHz and 2 kHz pure tones resulting in -18.0 dB and -15.2 dB median TIN thresholds, respectively; (ii) similarly, the -28.0 dB AIN detection thresholds for the free field presentation conditions hold when the train alarm is replaced by 1 kHz and 2 kHz pure tones resulting in -26.2 dB and -24.8 dB SNR TIN detection thresholds, respectively.

CHAPTER 7: SUMMARY OF RESULTS AND DISCUSSION

Summary

This chapter discusses the findings of the study and attempts to relate them to the existing literature. The organization of this chapter will follow two main research questions: (i) how is the detection of tonal alarms with very low SNR (-18 dB or below) affected by other factors such as individual differences, alarm duration and spatial configurations of loud speakers and (ii) why tone-in-noise detection is possible at very low SNR (-18dB and below) levels.

7.1 A summary of findings in the current study

In the first experiment, successful train alarm detection was reported at an SNR level of -24 dB. Later experiments (Exp. 2a and 2b) yielded median train alarm detection thresholds of -13 dB, -14 dB and -28 dB SNR for monaural, diotic and free-field configuration of loud speakers, respectively. Duration of the signal did not have a significant influence on the masked detection thresholds. These findings prompted the question why human listeners were able to detect tonal stimuli at such low SNR levels. Substantial individual differences among subjects were observed as well.

Computational simulations were conducted using the MAP to examine how the different stages of the auditory system responded when detecting an alarm at such a low level SNR level. Initial results indicated small but repeatable changes of AN firing patterns with regard to very low signal levels in the presence of high background noise. A review of literature suggested that the MOCS efferent feedback might be the reason for the ability to detect an alarm at such a low SNR level. To our surprise, results of the third experiment indicated a negative correlation between MOCS efferent feedback strength and the masked detection thresholds. This implied that stronger the efferent feedback, the weaker the ability to detect a quiet alarm in the presence of loud noise.

Experiments 1 and 2 in this study used alarm and noise with similar characteristics to those extracted in an industrial study (Chapter 3 and 4). This limitations were lifted in the fourth experiment when pure tons and Matlab® generated pink noise were used. Findings of detection thresholds of -18 dB or below still held.

7.2 How does alarm/tone-in-noise detection affected by alarm duration, spatial configurations of loudspeakers, and individual differences?

7.2.1 AIN Thresholds in loud (80 dBA or above) noise

Work of Casali *et al*. (2004) is closest to the current study. Casali and his colleagues focused on comparing the effects of electronic active noise reduction (ANR) and conventional hearing protection devices on the detection of alarms in the presence of noise. Their studies used 85 dBA pink noise and a vehicle back-up alarm (highest energy concentration at 1.25 kHz) which was played from behind the subjects. The noise was presented using a surround speaker system. Findings of Casali *et al*. (2004) yielded an average AIN detection threshold of -5.3 dB SNR. In contrast, the current study reported that successful detection at a level of -28 dB SNR. The most obvious reasons for the large difference would be (i) the spatial configurations of the alarm loudspeaker; and (ii) the frequency of alarm. Casali presented the alarm from the back and used alarm with main frequency at 1.25 kHz.

The current study investigated the effects of spatial configuration and indeed reported significant effects. In particular, AIN detection thresholds of -13 dB, -14dB and -28 dB SNR for monaural, diotic and free-field configuration of loudspeakers were reported. Our results indicate that the presence of spatial information (monaural and binaural) helped to lower the AIN detection threshold from -13 dB to -28 dB. This suggested that even in the absence of both monaural and binaural cues (our monaural presentation condition), the AIN detection threshold obtained in the current study (-13 dB) is much lower than that (-5.3 dB) reported in Casali *et al.* (2004). Since the alarm in the current study has most energy at 2 kHz which is higher than the 1.25 kHz used in Casali's study, the remaining possible reason could be due to the frequency of the alarm. Results of Experiment 4 yielded the free-field median tone-in-noise (TIN) detection thresholds of -26.5 and -24.8 dB SNR for 1 kHz and 2 kHz pure tones in the presence of 80 dBA pink noise, respectively. The current data suggested that the lowering of alarm frequency from 2 kHz to 1 kHz should make the alarm more detectable.

In summary, the current study has reported substantially low AIN detection thresholds (-28 dB SNR in free-field train alarm detection) in the presence of 80dBA train noise compared to the studies in the existing literature. The influence of tone frequency and spatial configurations of loudspeakers have also been investigated. See Section 7.2.3 for more discussion on the effects of spatial information.

7.2.2 Effects of alarm duration on AIN detection thresholds in 80 dBA noise

The relationship between tonal duration and tonal detection thresholds has been thoroughly studied (see Chapter 2 Section 2.2.3 for a review). Past studies suggested tonal detectability increased with the tonal duration.

However results of the current study indicated that there was no significant effect of the alarm duration (above 100ms) on AIN detection thresholds ($p>0.05$).

7.2.3 Effects of spatial information on AIN detection thresholds in 80 dBA noise

Effects of spatial configurations of loudspeakers on tone detection have been studied (Gatehouse, 1986, 1987; Santon, 1987; Saberi *et al*., 1991). The benefits of spatial information to lower the tone detection thresholds have been referred to as the 'unmasking' effects. The findings of these studies suggested a relationship between spatial location of the target tone and the noise sources. However, past studies mostly involved conditions with positive SNRs and conditions with SNRs lower than -15 dB in the presence of 80 dBA noise were not reported.

Consistent with past findings, the current study also reported significant effects of spatial information. In Experiment 2 Part 1, AIN thresholds between monaural condition and free-field condition were significantly different. In the monaural condition the train alarm and the train noise came from the same speaker of a headphone, while in the free-field condition they were separately broadcasted from different loudspeakers from different locations. There was an unmasking effect of 15 dB from the monaural condition to the spatial condition ($MN100_4$: -13.0 dB SNR; $FF100_4$: -28.0 dB SNR).

Free-field unmasking effect was evident in the findings of Experiment 2 Part 2 as well. Comparisons of the conditions in Experiment 2 and their unmasking values are summarized in Table 7.1.

Table 7.1 Free-field unmasking effect in conditions tested in Experiment 2

Condition Transition	Unmasking (dB)
MN100$_4$ → FF100$_4$	15.0
MN100$_4$ → FF-multi-speaker	11.0
MN100$_4$ → FF-same-speaker	3.0
FF100$_4$ → FF-multi-speaker	-4.0
FF100$_4$ → FF-same-speaker	-12.0
FF-multi-speaker → FF-same-speaker	-8.0

Inspections of Table 7.1 show that the largest unmasking occurs when comparing the monaural (MN100$_4$) and free-field separate source (FF100$_4$ and FF-multi-speaker) conditions. Because the source of the alarm and noise are the same in the FF-same-speaker condition, free-field unmasking effect is low. Unmasking effect of FF-same-speaker condition compared to MN100$_4$ condition is only 3 dB. Also it is important to note the 4 dB difference between the conditions FF100$_4$ and FF-multi-speaker. The only difference between these two conditions is the change of location of the target source (FF100$_4$: target speaker at front-left; FF-multi-speaker: target speaker at front). Separation of the sources of the target and the masker seems to be the vital factor for the unmasking effect.

Gatehouse (1986, 1987) hinted that tone-in-noise detection thresholds may not be the highest for the condition where the target and masker are spatially coincident. However current study does not corroborate that finding. In fact in the current study, the worst detection performance occurs when the two sources are spatially coincident.

Results of Experiment 4 indicate similar free-field unmasking effects for TIN detection thresholds. The unmasking values are summarized in Table 7.2.

Table 7.2 Free-field unmasking effect in conditions tested in Experiment 4

Condition Transition	Unmasking (dB)
DT1 → FF1	8.2
DT2 → FF2	9.6

For both 1 kHz and 2 kHz tones, free-field unmasking was observed but the magnitudes are lower compared to the results of Experiment 2.

When sources are separated in the horizontal plane, Gilkey and Good (1992) observed free-field unmasking of 18 dB. This level of unmasking benefit is more than the maximum value obtained in this study (15 dB, Table 7.1). The difference may be due to the fact that the current study involved conditions with SNRs in the range of -13dB to -28dB.

Past studies have demonstrated similar unmasking effects using dichotic presentations with headphones, suggesting up to 15 dB improvement of detectability by varying inter-aural parameters (Colburn and Durlach, 1965; Moore, 1989). This value of unmasking is consistent with the finding of the current study.

Carlile and Wardman (1996) implemented head related transfer functions (HRTF) to mimic the spatial separation of the target and masker sources. Even though the current study did not implement such methods, the variation of inter-aural parameters was introduced by changing the spatial configuration of the sources of the target and masker. Again, the current findings are consistent with those reported in the past studies but the data are new because they involved conditions with SNR levels ranging from -13 dB to -28 dB.

In summary the current study reported free-field AIN detection thresholds of -28 dB SNR and showed a maximum free-field unmasking value of 15 dB when compared to monaural AIN detection threshold of -13 dB SNR. The difference is mainly attributed to the inter-aural differences introduced by separation of target (alarm) and masker (noise) sources.

7.3 Why tone-in-noise detections at such low SNRs (-13dB to -28dB) are possible?

The current study attempts to answer the above question through the use of MAP model (Meddis, 2006). It is a biologically inspired model and was adopted and customized to simulate the conditions in Experiment 2.

Stimuli with very low SNR (e.g. -15 dB, -20dB) were used for the simulations, since the experimental results indicated that detection at such levels was still possible for the listeners with normal hearing. The objectives were to identify and determine at which stage of auditory responses that human was able to detect an alarm with SNRs of -15 dB and -20 dB.

With a train alarm at an SNR level of -15 dB, observable signatures in stapes displacements and basilar membrane (BM) displacements were found, but the firing patterns of AN did not show observable change. Further analyses of the time history data for AN firing patterns indicated subtle but repeatable changes in the AN firing patterns with regard to very weak (-15 dB SNR) train alarm in the presence of loud (80 dBA) train noise. Whether such a weak and repeatable difference can be picked up by the auditory cortex will be a desirable future study.

Many past studies have studied the physiology and the behavior of medial olivocochlear system (MOCS) and its efferent activities on unmasking in the presence of noise (for a review see Chapter 2 Section 2.4). The possibility that MOCS efferents might enhance the ability to detect a quiet alarm or tone in the presence noise was explored in Experiment 3. We hypothesized that the stronger the MOCS efferent feedback, the lower the AIN detection thresholds. To our surprise, the opposite was found. A review of literature indicates that different past studies have yielded contradicting results. A summary of the available literature on this topic is given in Table 7.3.

Table 7.3 Comparison of past studies and the current study on the relationship between MOCS efferents and tonal\speech detection in the presence of noise

Study	Target Stimuli Type	SNR	MOC-Threshold Relationship
Micheyl *et al*. (1995)	Tonal	Negative	Negative
Micheyl and Collet (1996)	Tonal	Negative	Positive
Wagner *et al*. (2008)	Speech	Negative	None
Bhagat and Carter (2010)	Tonal	Negative	Positive
Garinis *et al*. (2011)	Tonal	Negative	Negative
Current study	Tonal	Negative	Negative

Apart from Wagner *et al*. (2008), all the other studies listed above used tonal stimuli. And the detection thresholds in all the studies were at negative SNR. All studies used contralateral suppression of Evoked OAEs as a measure of the MOCS efferent feedback strength.

As summarized in Table 7.3, Micheyl and Collet (1996) and Bhagat and Carter (2010) reported a significant positive correlation between the tone-in-noise detection thresholds and MOCS efferent feedback strength. However, Wagner *et al*. (2008) did not find a significant correlation between speech-in-noise detection and MOCS efferent feedback strength. Furthermore, Micheyl *et al*. (1995) and Garinis *et al*. (2011) found a significant negative correlation between tone-in-noise detection thresholds and MOCS efferent feedback strength. The current study reported a significant negative correlation between the AIN detection thresholds and MOCS efferent feedback and thus supports the findings of Micheyl *et al*. (1995) and Garinis *et al*. (2011).

One major difference of this study compared to the related past studies is the usage of loud (80 dBA) noise level. Maximum noise level used in the past studies is 70 dB (used in Micheyl *et al*. (1995)). Therefore the current study contributes to substantiate the findings of Micheyl *et al*. (1995) and Garinis *et al*. (2011) for louder noise levels.

A negative correlation between AIN detection thresholds and MOCS efferent feedback strength indicate that a stronger MOCS efferent feedback is associated with weaker AIN detection performance.

A possible explanation for this phenomenon is suggested in Figure 7.1.

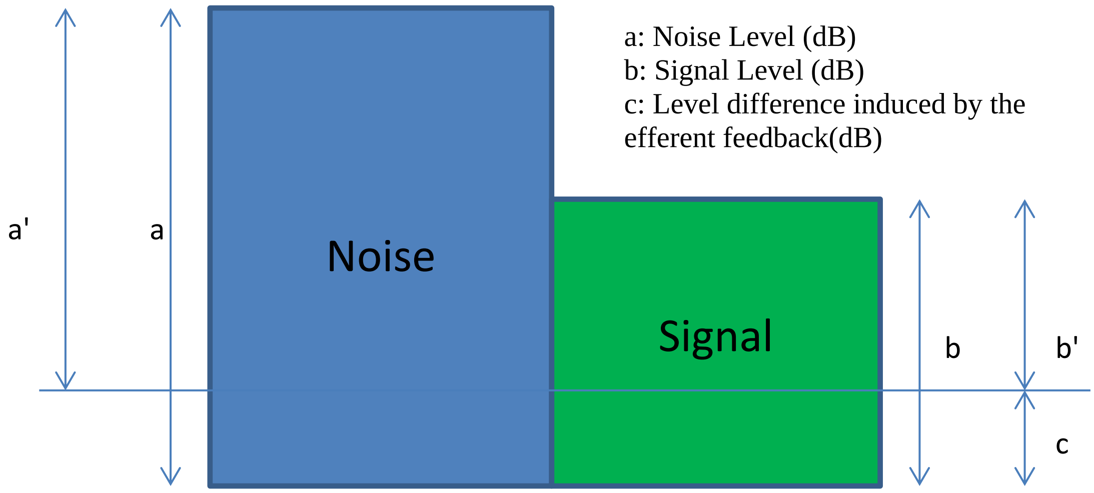

Figure 7.1 Possible explanation of the negative correlation between TIN thresholds and MOCS efferent feedback strength

As illustrated in Figure 7.1, we can derive the following expressions:

$$a' = a - c$$

$$b' = b - c$$

$$When\ a > b,$$

$$\frac{a}{b} < \frac{a'}{b'}$$

$$Thus,$$

$$\frac{b}{a} > \frac{b'}{a'}$$

These expressions imply that when the original SNR is negative (a>b) the MOCS efferent feedback results in a further reduction of the effective SNR, thus making the signal harder to detect.

In summary, finding of this study suggests that a person with stronger MOCS efferent feedback may find it harder to detect tones in the presence of noise in negative SNR conditions. This is also one possible factor to the large individual differences in AIN/TIN detection thresholds. Further research is desirable.

CHAPTER 8: CONCLUSIONS, LIMITATIONS AND FUTURE WORK

Summary

This chapter presents the conclusions drawn based on the findings of the current study. Limitations of the current study and possible future work are also presented.

8.1 Conclusions

Four experiments have been conducted to examine alarm-in-noise (AIN) / tone-in-noise (TIN) detection thresholds in the presence of 80dBA pink noise. The main research questions tackled were (i) how and (ii) why AIN / TIN could happen at very low (below -18dB) SNRs. Besides empirical experiments, computational simulations of the human auditory process by the Matlab Auditory Periphery (MAP) models have been conducted to explore the "why" question.

8.1.1 AIN detection thresholds in the presence of 80 dBA noise

Listeners with normal hearing successfully performed AIN detection at -24 dB SNR in 80 dBA train noise under a free-field listening condition. Median AIN detection thresholds in 80 dBA noise were reported to be -13 dB and -28 dB SNR for monaural and free-field listening conditions, respectively. These are new and original findings since past studies on AIN detection did not report detection thresholds below -15 dB SNR in the presence of loud (80 dBA or above) noise. The train alarm had most energy at 2 kHz.

The above findings have been successfully replicated using 1 kHz and 2 kHz tones. Median TIN detection thresholds of -18 dB SNR (1 kHz, diotic), -15.3 dB SNR (2 kHz, diotic), -26.2 dB SNR (1 kHz, free-field) and -24.8 dB SNR (2 kHz, free-field) have been found.

Implications of this finding are important in determining a minimal level of alarms that can still be reliably detected under noisy environments with 80 dBA noise with a pink spectrum.

8.1.2 Effects of alarm duration on AIN detection thresholds

Alarm durations of 100ms, 300ms and 500ms have been studied. Effects of alarm duration did not have a significant effect on the AIN detection thresholds. This finding is consistent in both the monaural and the free-field listening conditions. This finding is useful in optimizing the durations of future alarms.

8.1.3 Effects of spatial configuration of loudspeakers on AIN detection thresholds

Spatial configuration of loudspeakers significantly affected both AIN and TIN detection thresholds. Listeners have been shown to detect AIN and TIN at levels significantly lower in a free-field listening condition as compared to a monaural or diotic arrangement. A maximum free-field unmasking effect of 15dB from monaural to free-field is found (Table 7.1). Separating the physical locations of the alarm (target) and noise (the masker) has been shown to significantly reduce the AIN detection level by at least 8 dB in both AIN and TIN tasks (Tables 7.1, 7.2).

In most industrial settings, location of the alarm will be physically separated from the background noise. This 8 dB unmasking effect proven in both AIN and TIN with 1 kHz and 2 kHz are useful in determining the optimal level of alarm in the presence of noisy environment. While it is important for an alarm to be detected, it is also important not to add excessive sound exposure to the listeners. In other words, an alarm with excessive loudness is not desirable and this thesis provides useful data for determining the minimum alarm level in the presence of 80 dBA pink noise.

8.1.4 Simulation of underlying biological process of AIN/TIN detection

Computational simulations have shown clear and observable signatures in simulated basilar membrane displacements for a 65 dBA train alarm (centered at 2 kHz) in the presence of 80 dBA pink noise. Simulation was conducted using the MAP model by Meddis (2006). Although the signatures in auditory nerves firing patterns have been small, they are repeatable. The use of biologically-inspired computational models alongside the empirical study has great value in future development of a model to test and verify different types of alarms. This will save a lot of efforts in conducting experiments which are costly in both time and efforts.

8.1.5 Role of MOCS efferents in AIN/TIN detection

Strengths of individual MOCS efferent feedback have been estimated by measuring the contralateral suppression of Evoked OAEs. To my initial surprise, instead of improving the detection performance, MOCS efferent feedback actually degraded the AIN detection ability in the negative SNR conditions (in the presence of loud noise). This suggests that persons with stronger MOCS efferent feedback will have higher AIN detection thresholds. In this study, a larger inter-subject variability has been reported (from -9 dB to -46 dB SNR). Further work to examine whether MOCS efferent feedback is the sole contributor to the inter-subject variability is desirable.

8.2 Limitations & Future Work

For AIN testing, only one particular train alarm and train noise were used. Even though the findings were replicated for pure tones in pink noise, further studies with different types of alarms and noise are desirable.

Persons with normal hearing were only used as experiment subjects. It will be interesting to investigate applicability of the findings to persons with hearing impairments given the likelihood that long time exposure to noisy environment of about 80 dBA noise can cause hearing impairment.

The current study used a fixed noise level of 80 dBA due to ethical reasons in human experiments. Since the existence of work places with even louder continuous background noise (e.g. industrial premises), studies of TIN in the presence of higher background noise with carefully controlled daily exposure will be useful. Also future studies may investigate the effects of frozen noise on the AIN and TIN detection thresholds.

The current study used only two free-field configurations of the loudspeakers. Further studies to systematically examine the effects of alarm sources will be interesting.

The AIN and TIN detection tasks in the current study did not impose a time limitation pressure on the subject. Also, if the subject's task also requires indicating the direction (or location) of the target tone, he or she may be under further pressure. These are practical situations in some of the industrial environments. Further studies imposing time limitations and requiring subjects to localize the incoming directions of the alarms will be useful.

Computational neuroscience models like MAP could be customized and used as prediction platforms for AIN or TIN detection. Such simulation systems will be useful in the design of alarms.

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Appendix 3.1 Results of Shapiro-Wilk Normality Test – Time separated perceived loudness ratings

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the statistic and the second number is the p-value of the Shapiro-Wilk normality test (IBM SPSS Statistics 21).

Perceived Loudness Rating – Shapiro-Wilk Normality Test				
	SNR Level			
	-∞dB	-18dB	-21dB	-24dB
Time Segment 1	0.938	0.858	0.898	0.915
	0.476	0.046	0.150	0.248
Time Segment 2	0.974	0.881	0.940	0.905
	0.946	0.091	0.504	0.184
Time Segment 3	0.804	0.953	0.886	0.888
	0.010	0.681	0.105	0.110
Time Segment 4	0.949	0.969	0.876	0.823
	0.617	0.899	0.077	0.017
Time Segment 5	0.943	0.972	0.847	0.806
	0.537	0.928	0.034	0.011
Time Segment 6	0.903	0.965	0.844	0.797
	0.175	0.847	0.031	0.009
Time Segment 7	0.821	0.959	0.850	0.789
	0.016	0.767	0.036	0.007

Time Segment 8	0.736	0.961	0.847	0.810
	0.002	0.792	0.033	0.012
Time Segment 9	0.651	0.966	0.855	0.829
	0.000	0.859	0.043	0.020
Time Segment 10	0.588	0.970	0.861	0.824
	0.000	0.911	0.050	0.018

Appendix 3.2 Results of Friedman Test – Effects of time segments on the perceived loudness rating

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Chi-square value and the second number is the p-value of the Friedman test (IBM SPSS Statistics 21).

Perceived Loudness Rating – Results of Friedman Test			
SNR Level			
-∞dB	-18dB	-21dB	-24dB
94.484	106.238	74.247	2.210
0.000	0.000	0.000	0.988

Appendix 3.3 Results of Wilcoxon Signed Rank Test – Effects of time segments on the perceived loudness rating

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Z value and the second number is the p-value of the Wilcoxon signed rank test (IBM SPSS Statistics 21).

Perceived Loudness Rating – Results of Wilcoxon Signed Rank Test					
		SNR Level			
		-∞dB	-18dB	-21dB	-24dB
Time Segment 10	Time Segment 9	-2.197	-1.127	-2.023	-0.764
		0.028	0.260	0.043	0.445
Time Segment 10	Time Segment 8	-2.380	-2.624	-2.310	-1.423
		0.017	0.009	0.021	0.155

Appendix 3.4 Result s of Shapiro-Wilk Normality Test – Perceived loudness ratings – SNR Levels

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the statistic and the second number is the p-value of the Shapiro-Wilk normality test (IBM SPSS Statistics 21).

Perceived Loudness Rating – Shapiro-Wilk Normality Test	
-∞dB SNR	0.968
	0.888
-18dB SNR	0.858
	0.046
-21dB SNR	0.826
	0.019

-24dB SNR	0.616
	0.000

Appendix 3.5 Results of Friedman Test – Effects of SNR Level

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Chi-square value and the second number is the p-value of the Friedman test (IBM SPSS Statistics 21).

Perceived Loudness Rating – Results of Friedman Test
32.700
0.000

Appendix 3.6 Results of Wilcoxon Signed Rank Test – Effects of SNR Level

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Z value and the second number is the p-value of the Wilcoxon test (IBM SPSS Statistics 21).

Perceived Loudness Rating – Results of Wilcoxon Signed Rank Test		
-18dB	-21dB	-3.059
		0.002
-18dB	-24dB	-3.059
		0.002
-18dB	-∞dB	-3.059
		0.002
-21dB	-24dB	-3.059
		0.002

-21dB	-∞dB	-2.981
		0.003
-24dB	-∞dB	-2.589
		0.010

Appendix 4.1 Results of Shapiro-Wilk Normality Test – Alarm-In-Noise detection thresholds in four duration conditions

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the statistic and the second number is the p-value of the Shapiro-Wilk normality test (IBM SPSS Statistics 21).

Alarm-In-Noise Thresholds – Results of Shapiro-Wilk Normality Test				
	Tonal Duration Configuration			
	1004	1008	3008	5008
Monaural	0.933	0.917	0.964	0.853
	0.275	0.149	0.726	0.015
Free-Field	0.973	0.950	0.949	0.953
	0.882	0.484	0.467	0.537

Appendix 4.2 Results of Friedman Test – Effect of tonal duration on the Alarm-In-Noise detection thresholds for monaural condition

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Chi-square value and the second number is the p-value of the Friedman test (IBM SPSS Statistics 21).

Alarm-In-Noise Thresholds – Results of Friedman Test
4.272
0.234

Appendix 4.3 Results of Friedman Test – Effect of tonal duration on the Alarm-In-Noise detection thresholds for free-field condition

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Chi-square value and the second number is the p-value of the Friedman test (IBM SPSS Statistics 21).

Alarm-In-Noise Thresholds – Results of Friedman Test
1.689
0.639

Appendix 4.4 Results of Wilcoxon Signed Rank Test – Effects of spatial information on Alarm-In-Noise detection thresholds

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Z value and the second number is the p-value of the Wilcoxon test (IBM SPSS Statistics 21).

Alarm-In-Noise Detection Thresholds – Results of Wilcoxon Signed Rank Test		
MN1004	FF1004	-3.517
		0.000

MN1008	FF1008	-3.517
		0.000
MN3008	FF3008	-3.516
		0.000
MN5008	FF5008	-3.517
		0.000

Appendix 4.5 Results of Shapiro-Wilk Normality Test – Alarm-In-Noise Detection Thresholds

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the statistic and the second number is the p-value of the Shapiro-Wilk normality test (IBM SPSS Statistics 21).

Alarm-In-Noise Detection Thresholds - Shapiro-Wilk Normality Test			
Spatial Information Configuration			
MN	DT	FF-multi-speaker	FF-same-speaker
0.969	0.933	0.935	0.923
0.826	0.271	0.295	0.186

Appendix 4.6 Results of Friedman Test – Effect of spatial information on the Alarm-In-Noise detection thresholds

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Chi-square value and the second number is the p-value of the Friedman test (IBM SPSS Statistics 21).

Alarm-In-Noise Thresholds – Results of Friedman Test
32.694
0.000

Appendix 4.7 Results of Wilcoxon Signed Rank Test – Effects of spatial information on Alarm-In-Noise detection thresholds

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Z value and the second number is the p-value of the Wilcoxon test (IBM SPSS Statistics 21).

Alarm-In-Noise Detection Thresholds – Results of Wilcoxon Signed Rank Test		
MN	DT	-0.777
		0.437
MN	FF-multi-speaker	-3.520
		0.000
MN	FF-same-speaker	-2.761
		0.006
DT	FF-multi-speaker	-3.518
		0.000

DT	FF-same-speaker	-2.328
		0.020
FF-multi-speaker	FF-same-speaker	-3.518
		0.000

Appendix 4.7 Results of Wilcoxon Signed Rank Test – Effects of spatial information on Alarm-In-Noise detection thresholds

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Z value and the second number is the p-value of the Wilcoxon test (IBM SPSS Statistics 21).

Alarm-In-Noise Detection Thresholds – Results of Wilcoxon Signed Rank Test		
MN1004	MN	-1.168
		0.243
FF1004	FF-multi-speaker	-3.130
		0.002

Appendix 5.1 Results of Shapiro-Wilk Normality – Data for Contralateral Suppression of TEOAE

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the statistic and the second number is the p-value of the Shapiro-Wilk normality test (IBM SPSS Statistics 21).

Contralateral Suppression of TEOAE – Results of Shapiro-Wilk Test
0.789
0.003

Appendix 5.2 Results of Pearson's Correlation Analysis – Alarm-In-Noise detection thresholds and Contralateral Suppression of TEOAE

Note: Tuples which are shaded indicate statistical significance. The first, second and third numbers denote Pearson's correlation coefficient, p-value and the number of data points respectively.

Alarm-In-Noise Detection Thresholds and Contralateral Suppression of TEOAE
-0.526
0.044
15

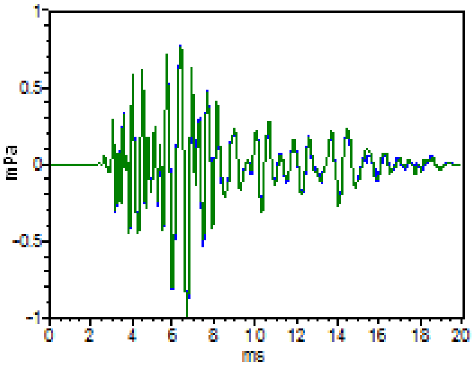
Appendix 5.3 TEOAE Measurement Result Sheet: Provided by ILOV6 – Otodynamics Echoport ILO292-II

TEOAE Test Report

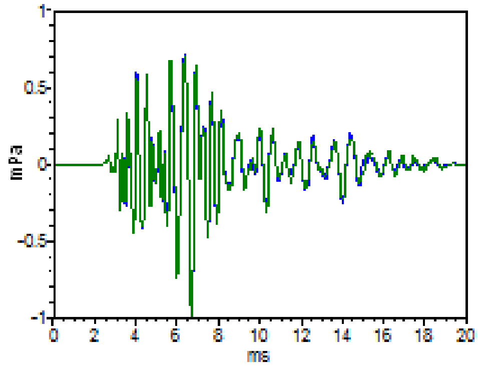
Family name: [redacted] First names: [redacted]
ID number: [redacted] Sex: Male Location: OutPatient
Date of birth: 16/03/1984 Report Mode: Bilateral pair

Left record		Right record	
Ear:	Right	Ear:	Right
Date/Time:	12/06/2014 15:15:54	Date/Time:	12/06/2014 15:15:54
Test type:	TE - Linear-Bilateral	Test type:	TE - Lin, mask=BB, 80dB SPL
Stimulus:	80.8dB pe SPL	Masker:	79.1dB SPL
Mode:	Gen Diag	Mode:	Gen Diag
Tester ID:	AUD	Tester ID:	AUD
Data file:	USIO6C84.DTA	Data file:	USIO6C85.DTA
Notes:		Notes:	

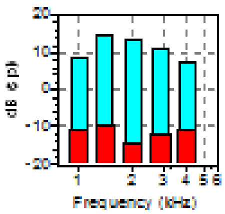
Response waveform (USIO6C84.DTA)



Response waveform (USIO6C85.DTA)

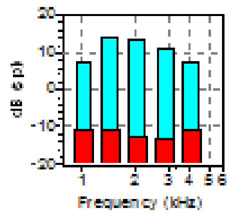


Half octave band OAE power (USIO6C84.DTA)



Freq (kHz)	Signal (dBspl)	Noise (dBspl)	SNR (dB)
1.0	9.0	-10.6	19.6
1.4	14.8	-8.8	23.7
2.0	14.0	-13.7	27.7
2.8	11.6	-11.8	23.4
4.0	7.8	-10.7	18.5

Half octave band OAE power (USIO6C85.DTA)

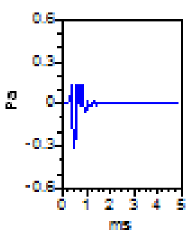


Freq (kHz)	Signal (dBspl)	Noise (dBspl)	SNR (dB)
1.0	7.7	-10.3	18.0
1.4	14.4	-10.4	24.7
2.0	13.5	-12.2	25.7
2.8	11.2	-12.7	23.9
4.0	7.2	-10.5	17.7

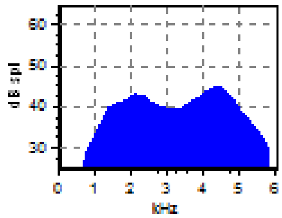
Test Summary (USIO6C84.DTA)
Total OAE response = 19.3dBspl Total Noise = -3.1dBspl

Test Summary (USIO6C85.DTA)
Total OAE response = 18.7dBspl Total Noise = -3.2dBspl

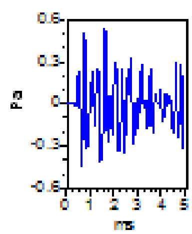
Check fit stimulus (USIO6C84.DTA)



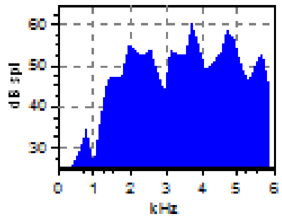
Ear canal response (USIO6C84.DTA)



Check fit stimulus (USIO6C85.DTA)



Ear canal response (USIO6C85.DTA)



Test Environment (USIO6C84.DTA)
NLo = 287 NHi = 2 Test time = 102s
RejLev = 49.5dBspl Repro = 99% Stim stab = 100%
Hardware = USBOAE Probe = Probe 1

Test Environment (USIO6C85.DTA)
NLo = 201 NHi = 0 Test time = 102s
RejLev = 49.5dBspl Repro = 99% Stim stab = 100%
Hardware = USBOAE Probe = Probe 1

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Appendix 6.1 Results of Shapiro-Wilk Normality Test – Tone-In-Noise Detection Thresholds – Normal Hearing Subjects

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the statistic and the second number is the p-value of the Shapiro-Wilk normality test (IBM SPSS Statistics 21).

Tone-In-Noise Detection Thresholds - Shapiro-Wilk Normality Test			
Spatial Information Configuration			
DT1	DT2	FF1	FF2
0.962	0.788	0.934	0.961
0.534	0.000	0.150	0.513

Appendix 6.2 Results of Wilcoxon Signed Rank Test – Effects of spatial information on Tone-In-Noise detection thresholds – Normal Hearing Subjects

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the Z value and the second number is the p-value of the Wilcoxon test (IBM SPSS Statistics 21).

Tone-In-Noise Detection Thresholds – Results of Wilcoxon Signed Rank Test		
DT1	DT2	-2.634
		0.008
FF1	FF2	-0.522
		0.602
DT1	FF1	-4.016
		0.000
DT2	FF2	-3.984
		0.000

Appendix 6.3 Results of Mann Whitney U Test – Comparison of AIN and TIN detection thresholds

Note: Tuples which are shaded indicate statistical significance. The first number in each tuple is the U value and the second number is the p-value of the Friedman test (IBM SPSS Statistics 21).

TIN and AIN Detection Thresholds – Results of Mann-Whitney U Test		
DT1 (Exp 4)	DT (Exp 2 Part 2)	50.5
		0.003
DT2 (Exp 4)	DT (Exp 2 Part 2)	111.0
		0.517
FF1 (Exp 4)	FF100$_4$ (Exp 2 Part 1)	74.0
		0.043
FF2 (Exp 4)	FF100$_4$ (Exp 2 Part 1)	108.5
		0.462

Appendix 7.1 Experiment 1 Calibration Data

Calibration with human subject

Condition	Left Ear (Back)	Right Ear (Back)
Train Noise (80dBA)	80.2	80.2
Train Alarm (62dBA)	62.2	61.5
Train Alarm (59dBA)	59.3	58.4
Train Alarm (56dBA)	55.9	55.1

Calibration with mannequin

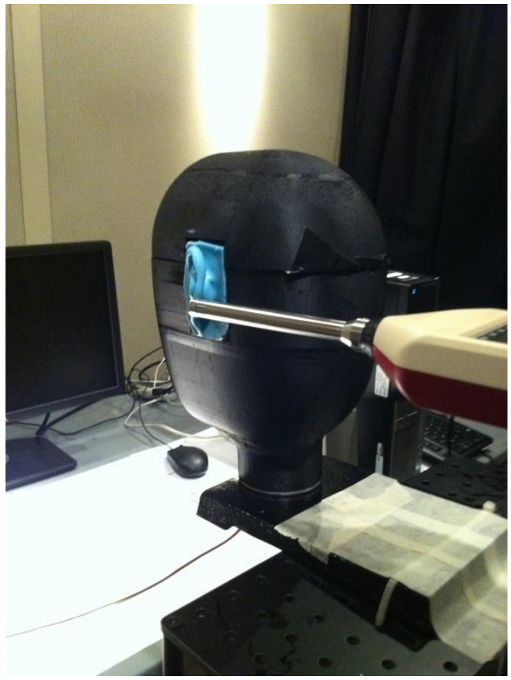
Condition	Left Ear (dBA)		Right Ear (dBA)	
	Back	Down	Back	Down
Train Noise (80dBA)	80.2	80.3	80.3	80.2
Train Alarm (62dBA)	62.3	62.4	61.0	61.1
Train Alarm (59dBA)	59.5	59.3	58.5	58.8
Train Alarm (56dBA)	56.5	56.4	55.3	55.0

Back: Sound Level Meter pointed from back of the ear

Down: Sound Level Meter pointed in a downward direction

Calibration with human subject ('Back' pointing angle)

Calibration with mannequin ('Back' pointing angle)



Calibration with mannequin ('Down' pointing angle)

Appendix 7.2 Experiment 2 Calibration Data: Free-Field Conditions

Part 1: Free-Field – Train Alarm played by the speaker at front-left, Train Noise played by the speakers at left and right

Calibration with human subject

Condition	Left Ear (dBA)	Right Ear (dBA)
Train Noise (80dBA)	80.6	80.4
Train Alarm (80dBA)	80.2	79.1
Train Alarm (75dBA)	74.7	73.6
Train Alarm (70dBA)	70.8	69.3
Train Alarm (65dBA)	65.8	64.1
Train Alarm (60dBA)	60.6	58.5
Train Alarm (55dBA)	55.9	53.9
Train Alarm (50dBA)	50.4	48.7

Calibration with mannequin

Condition	Left Ear (dBA)	Right Ear (dBA)
Train Noise (80dBA)	80.2	80.1
Train Alarm (80dBA)	80.4	78.5
Train Alarm (75dBA)	75.4	74.6
Train Alarm (70dBA)	70.5	68.5
Train Alarm (65dBA)	65.7	63.7
Train Alarm (60dBA)	60.7	58.3
Train Alarm (55dBA)	55.3	53.8
Train Alarm (50dBA)	49.8	48.1

Part 2: Free-Field – Both Train Alarm and Train Noise played by the speaker at front

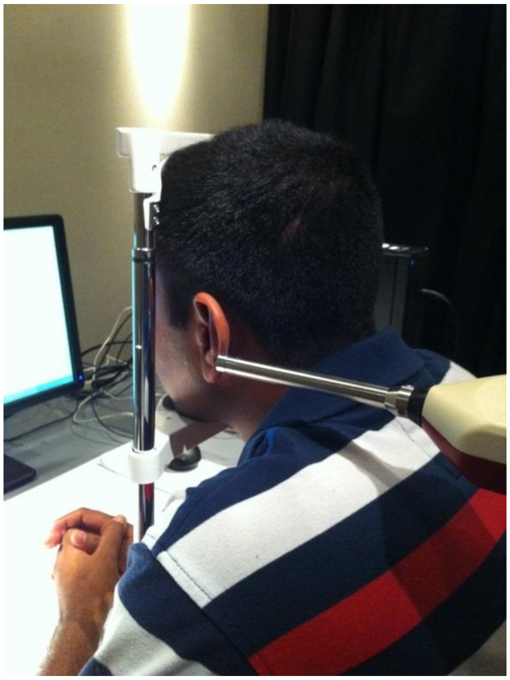
Calibration with human subject

Condition	Left Ear (dBA)	Right Ear (dBA)
Train Noise (80dBA)	79.9	80.0
Train Alarm (80dBA)	80.6	80.1
Train Alarm (75dBA)	75.3	75.5
Train Alarm (70dBA)	70.8	70.7
Train Alarm (65dBA)	65.9	65.2
Train Alarm (60dBA)	58.8	58.3
Train Alarm (55dBA)	55.4	55.5
Train Alarm (50dBA)	50.5	50.1

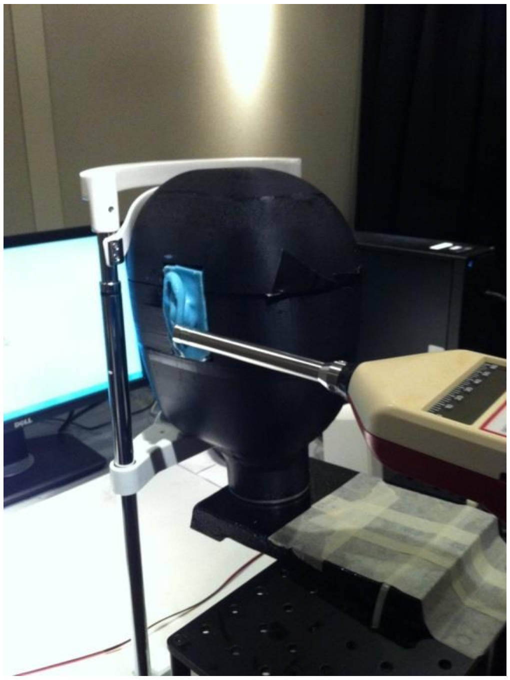
Calibration with mannequin

Condition	Left Ear (dBA)	Right Ear (dBA)
Train Noise (80dBA)	79.9	80.5
Train Alarm (80dBA)	80.1	80.4
Train Alarm (75dBA)	75.2	75.5
Train Alarm (70dBA)	70.0	70.2
Train Alarm (65dBA)	65.2	65.3
Train Alarm (60dBA)	60.3	60.7
Train Alarm (55dBA)	55.3	55.2
Train Alarm (50dBA)	50.5	50.4

Calibration with human subject



Calibration with mannequin



For all calibrations, Sound Level Meter was pointed from the back of the ear

Appendix 7.3 Experiment 4 Calibration Data: Free-Field Condition

1 kHz Pure Tone played by the speaker at front left

Calibration with human subject

Condition	Left Ear (dBA)	Right Ear (dBA)
Pink Noise (80dBA)	80.6	80.6
1kHz Tone (80dBA)	79.9	78.2
1kHz Tone (75dBA)	74.6	74.0
1kHz Tone (70dBA)	69.8	68.7
1kHz Tone (65dBA)	65.1	63.8
1kHz Tone (60dBA)	59.6	59.1
1kHz Tone (55dBA)	55.1	53.9
1kHz Tone (50dBA)	49.4	48.5

Calibration with mannequin

Condition	Left Ear (dBA)	Right Ear (dBA)
Pink Noise (80dBA)	80.2	80.3
1kHz Tone (80dBA)	80.1	79.1
1kHz Tone (75dBA)	75.6	74.1
1kHz Tone (70dBA)	70.4	69.1
1kHz Tone (65dBA)	65.3	64.3
1kHz Tone (60dBA)	60.3	58.9
1kHz Tone (55dBA)	55.0	54.0
1kHz Tone (50dBA)	50.0	49.1

2 kHz Pure Tone in played by the speaker at front-left

Calibration with human subject

Condition	Left Ear (dBA)	Right Ear (dBA)
Pink Noise (80dBA)	80.6	80.6
2kHz Tone (80dBA)	80.1	79.2
2kHz Tone (75dBA)	74.6	73.8
2kHz Tone (70dBA)	70.1	69.3
2kHz Tone (65dBA)	65.2	63.7
2kHz Tone (60dBA)	60.8	59.1
2kHz Tone (55dBA)	54.3	53.9
2kHz Tone (50dBA)	49.5	48.2

Calibration with mannequin

Condition	Left Ear (dBA)	Right Ear (dBA)
Pink Noise (80dBA)	80.2	80.3
2kHz Tone (80dBA)	80.2	78.9
2kHz Tone (75dBA)	75.5	74.2
2kHz Tone (70dBA)	70.5	69.0
2kHz Tone (65dBA)	65.8	64.2
2kHz Tone (60dBA)	60.4	59.1
2kHz Tone (55dBA)	55.4	53.9
2kHz Tone (50dBA)	50.1	48.8

For all calibrations, Sound Level Meter was pointed from back of the ear.