# PERFORMANCE DURING FREQUENCY CERTAINTY AND FREQUENCY UNCERTAINTY CONDITIONS IN NORMAL-HEARING AND HEARING-IMPAIRED HUMAN SUBJECTS

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## ABSTRACT

The detection of sound is enhanced when the frequency of the sound is known (frequency certainty) as compared to when the frequency is not known (frequency uncertainty). The present study investigated the performance of normal-hearing and mild-to-moderate sensorineural hearing loss (SNHL) subjects in frequency certainty and frequency uncertainty conditions. Frequency certainty was induced by presenting preceding cue tones that matched the frequency of the to-be-detected signals, while frequency uncertainty involved the detection of randomly selected uncued tonal signals from a set of five different frequencies presented in background noise in a two-interval forced choice (2IFC) task. Results from the current study showed that performance in the frequency certainty in normal-hearing subjects were better compared to their performance in frequency uncertainty condition. The uncertainty effect (difference in detection rates in frequency certainty and uncertainty) was estimated to be between 2.7 to 3.7 dB throughout all centre frequencies (0.57, 1, 2.15 and 4 kHz). However, in SNHL subjects, the uncertainty effect was significantly lower (1.5 dB) than their age- and sex-matched controls (3.7 dB). In addition, the change in the uncertainty effect in all the subject showed significant negative correlation with a measure of cochlear frequency selectivity known as critical ratio (CR). It is suggested that the loss of uncertainty effect in SNHL subjects could have an adverse effect on their ability to detect speech signals in noise.

**ABSTRAK**

Pengesanan isyarat bunyi dapat dipertingkatkan apabila frekuensi isyarat bunyi tersebut dikenal pasti (frekuensi diketahui) berbanding apabila frekuensinya tidak dikenal pasti (frekuensi tidak diketahui). Kajian ini menyiasat prestasi dalam keadaan frekuensi diketahui dan frekuensi tidak diketahui antara subjek yang mempunyai tahap pendengaran yang normal dengan subjek yang mempunyai masalah pendengaran sensorineural yang ringan hingga sederhana. Keadaan frekuensi diketahui didorong dengan mengemukakan nada petunjuk yang mempunyai frekuensi yang sepadan dengan frekuensi isyarat yang akan dikesan, manakala keadaan frekuensi tidak diketahui pula melibatkan pengesanan isyarat yang dipilih secara rawak daripada set yang mengandungi lima frekuensi yang berlainan beserta bunyi latar belakang dalam tugas 'two-interval forced choice' (2IFC). Keputusan dari kajian semasa menunjukkan bahawa prestasi dalam keadaan frekuensi diketahui bagi subjek yang mempunyai tahap pendengaran yag normal adalah lebih baik berbanding prestasi dalam keadaan frekuensi tidak diketahui. Kesan ketidakpastian (perbezaan antara prestasi dalam keadaan frekuensi diketahui dan tidak diketahui dianggarkan antara 2.7 hingga 3.7 dB pada semua frekuensi pusat (0.57, 1, 2.15 dan 4 kHz). Walau bagaimanapun, kesan ketidakpastian bagi subjek yang mengalami masalah pendengaran sensorineural adalah jauh lebih rendah (1.5 dB) daripada daripada subjek yang mempunyai tahap pendengaran yang normal (3.7 dB) yang telah dipadankan umur dan jantina dengan subjek yang mengalami masalah pendengaran sensorineural. Kesan ketidakpastian ini mempunyai kaitan yang negatif dengan ukuran pemilihan frekuensi bunyi di koklea yang dikenali sebagai nisbah kritikal. Dicadangkan bahawa kehilangan kesan ketidakpastian ini memberi kesan yang negatif dalam prestasi pengesanan isyarat bunyi percakapan bagi individu yang mengalami masalah kehilangan pendengaran sensorineural.

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| % | : | percentage |
| μs | : | microsecond |
| 2IFC | : | two-interval forced choice |
| ANOVA | : | Analysis of variance |
| AP | : | action potential |
| BM | : | basilar membrane |
| $Ca^+$ | : | Calcium ion |
| CB | : | critical band |
| CF | : | centre frequency |
| cm | : | centimetre |
| CR | : | critical ratio |
| dB | : | decibel |
| dB A | : | decibel (A-weighted) |
| dB HL | : | decibel hearing level |
| dB SPL | : | decibel sound pressure level |
| ERB | : | equivalent rectangular bandwidth |
| ERP | : | event-related potential |
| fMRI | : | functional magnetic resonance imaging |
| Hz | : | hertz |
| IHCs | : | inner hair cells |
| IHS | : | Intelligent Hearing System |
| kHZ | : | kilohertz |
| $K^+$ | : | Potassium ion |
| KEMAR | : | Knowles Electronics Manikin for Acoustic Research |
| LabVIEW | : | Laboratory Virtual Instrument Engineering Workbench |
| log | : | logarithmic |
| mm | : | millimetre |
| ms | : | millisecond |
| M | : | mean |
| MOCS | : | medial olivocochlear system |
| N | : | number |

| | | |
|---|---|---|
| OAE | : | otoacoustic emission |
| OHCs | : | outer hair cells |
| PCI | : | peripheral component interconnect |
| PTA | : | pure tone audiometry |
| PTC | : | psychophysical tuning curve |
| TEOAE | : | transient evoked otoacoustic emission |
| s | : | second |
| $s^{-1}$ | : | per second |
| SEM | : | standard error mean |
| SMR | : | signal-to-masker ratio |
| SNR | : | signal-to-noise ratio |
| SNHL | : | sensorineural hearing loss |
| SOC | : | superior olivary complex |
| SPL | : | sound pressure level |
| USA | : | United States of America |

## LIST OF APPENDICES

# CHAPTER 1: GENERAL INTRODUCTION

During day-to-day listening, an individual is usually able to attend or focus on sounds of interest and ignore competing background sounds. The ability to focus on a specific auditory sound in the presence of other distracting signals is known as selective auditory attention. A real-world situation would be understanding speech sounds in a noisy environment.

Selective auditory attention can be aided by the presence of auditory cues which provide clues for the to-be-detected signals. Such cues may carry either the timing, direction or frequency components of the signals of interest (Greenberg and Larkin 1968; Spence and Driver, 1994; Wright and Dai, 1994). Of these attributes, the frequency of the signal is usually regarded as the most significant component (Scharf, 1988). The detection of an auditory signal is enhanced when the frequency of the signal is known or expected (frequency certainty) (Tanner and Norman, 1954; Greenberg and Larkin, 1968) as compared to when the frequency of the signal is not known or unexpected (frequency uncertainty) (Green, 1961; Johnson and Hafter, 1980; Buus, Schorer, Florentine and Zwicker, 1986; Schlauch and Hafter, 1991).

The enhancement of hearing sensitivity during frequency certainty is not just limited to the frequency of the expected signal, but extends to approximately one critical band (CB) around it (Greenberg and Larkin, 1968; Scharf, 1970; Dai, Scharf, and Buus, 1991). This attentional-mediated improvement in hearing sensitivity is also known as auditory attentional band. The width and shape of the attentional band closely corresponds to another physiological measure of the cochlear frequency selectivity known as the peripheral auditory filter (Moore, 1995). This filter represents the frequency resolving power of the cochlea and is generated by the fine tuning of the cochlear basilar membrane (BM) (Moore, 2007a).

Since the auditory attentional band is closely linked to the peripheral auditory filter (Dai et al., 1991.), any changes in the cochlear frequency selectivity (or auditory filters) would also alter the corresponding attentional bands. The auditory attentional band is generated as a result of a difference in hearing sensitivity of an individual during frequency certainty and uncertainty conditions (Tan, Robertson and Hammond, 2008). Hence, changes in the frequency selectivity could also have implications in the performance of an individual during frequency certainty and frequency uncertainty conditions. An example of this would be patients with sensorineural hearing loss (SNHL). With impaired cochlear frequency selectivity process (Gengel, 1972; Patterson, Nimmo-Smith, Weber and Milroy, 1982; Hall and Fernandes, 1983), their ability to detect signals during frequency certainty and frequency uncertainty tasks may be adversely affected.

The present study investigated the performance of normal-hearing and hearing-impaired subjects in frequency certainty and frequency uncertainty conditions. Frequency uncertainty condition involved detection of uncued tonal signals in background noise using a two-interval forced choice (2IFC) task. These signals were randomly selected from a set of five different signal frequencies. Frequency certainty condition was induced by adding preceding cue tones which matched the frequency of the to-be-detected signals in a similar task.

## 1.1 Specific objectives and hypothesis of the study

This dissertation consists of two separate studies.

1) Study 1 was conducted to validate the performance of normal-hearing subjects in frequency certainty and frequency uncertainty conditions and compare these results to the effects reported in the literature.
2) Study 2 was carried out to compare the performance of mild-to-moderate SNHL subjects in frequency certainty and frequency uncertainty conditions with their normal-hearing controls and to correlate the effects of frequency uncertainty in these subjects with a measure of cochlear frequency selectivity (critical ratio (CR)).

It is hypothesised that the loss of cochlear sensory cells and the subsequent deterioration of cochlear frequency selectivity in SNHL subjects would negatively impact their performance in frequency certainty and frequency uncertainty conditions.

## 1.2 Significance of the study

The commonest complaint of SNHL patients is difficulty in detecting speech in a noisy environment (Duquesnoy, 1983; Plomp, 1986). Despite using hearing assistive devices such as hearing aid or cochlea implant, the speech signal in noise usually remains unclear and distorted (Moore, 2007b). It is postulated that the impairment, at least in some of these patients may be related to their inability to utilize the frequency cues during their day-to-day listening in a noisy environment (Palva, 1955; Carhart and Tillman, 1970; Tan, 2008). Exploring the changes in their performance during frequency certainty and frequency uncertainty conditions in a frequency selective listening task could provide us a better understanding on how the underlying selective frequency listening mechanism in these individuals differ from the normal-hearing. This understanding can be used to improve the current technology of hearing assistive devices to enhance the ability of SNHL patients to detect speech signals in a noisy environment.

## CHAPTER 2: LITERATURE REVIEW

### 2.1 The human auditory system

Auditory system plays a crucial role in detecting and receiving sounds coming from the external environment. The sense of hearing is highly dependent on the physics of sound and normal functioning of the peripheral and central structures involved in sound processing.

#### 2.1.1 Peripheral auditory system

The peripheral portion of the auditory system is made up of three main components; the outer (external), middle and inner (internal) ear (Figure 2.1).

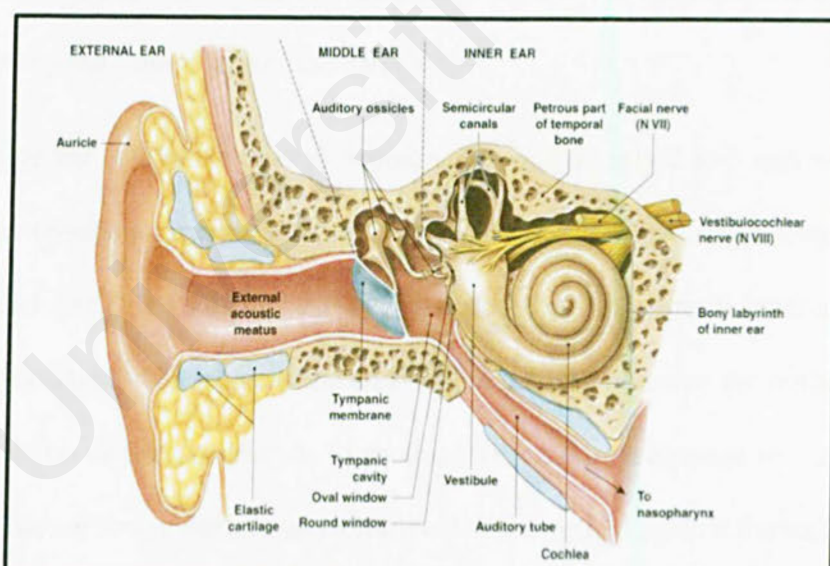



Figure 2.1: A cross-section of the peripheral portion of the auditory system with anatomic details of outer, middle and inner ear (Adapted from Pearson Benjamin Cummings, 2009).

The outer ear consists of the pinna (the auricle) and the ear canal (the external acoustic meatus). The pinna is made up of cartilage covered with skin, and it extends laterally from the side of the head, making it the most visible portion of the ear. It collects sound waves coming from different directions and directs it into the ear canal. The deep-like bowl portion of the pinna, which is adjacent to the ear canal is known as the concha. It marks the entrance of the ear canal. The concha plays a role as a natural amplifier, and has a resonant frequency at around 5000 Hz (Bess and Humes, 2008a).

The ear canal is made up of cartilaginous and bony portions. It is a long (≈2.5 cm) and narrow (≈5 to 7 mm) canal lined with skin, and leads to the eardrum (the tympanic membrane) (Bess and Humes, 2008a). It serves several important functions. Firstly, it directs the sound waves to the eardrum. Secondly, it provides protection for the auditory system. Its long and narrow structure together with the secretion of substances from ceruminous and sebaceous glands prevent any insect or foreign bodies from entering the canal (Bess and Humes, 2008a). Thirdly, the ear canal also acts as a natural amplifier. The resonant frequency of the ear canal is about 2500 Hz (Bess and Humes, 2008a). The pressure of the sound wave near this frequency region will be increased by at least 10 decibel (dB) by the time it strikes the eardrum.

The middle ear (tympanic cavity), which is a space of only 2 to 3 mm wide contains the ear drum (tympanic membrane) and the small middle ear bones (malleus, incus and stapes) called ossicles (Saladin, 2011). The ear drum is a multi-layered and semi-transparent structure, which forms the anatomic boundary between the outer and middle ear. The function of the ear drum is to produce vibration in response to sound pressure that hits it. The ear drum vibrates as air molecules are pushed against the membrane. The distance of movement of the ear drum is dependent on the force of air molecules that hit it. This force is related to the sound pressure level (SPL) or loudness of the incoming sound. The higher the SPL, the greater the force, and the longer the distance of movement of the ear drum.

The air filled middle ear cavity is supplied via a slight downward orientation tube called the Eustachian tube. This tube connects the middle ear to the nasopharynx, enabling air pressure equalization on both sides of the eardrum and drainage of excess fluid from the middle ear cavity into the nasopharynx. (Bess and Humes, 2008a).

The ossicles of the middle ear form a series of movable joints. Sound vibration from the tympanic membrane are transmitted through the middle ear by the mechanical movement of the ossicles. The manubrium of the malleus is attached directly to the large surface area of the eardrum (lateral side), whereas the footplate of the stapes is attached directly to the small surface area of the oval window (medial side). Incus, which is located in the middle between the malleus and the stapes allows the sound vibration to propel from the malleus to the stapes. The main role of the middle ear (ear drum and ossicles) is to act as an impedance-matching device. It enhances the sound pressure that would have been lost due to impedance mismatch created by the difference in impedance between air-filled ear canal and fluid-filled inner ear (DeBonis and Donohue, 2008).

When the sound vibration reaches the final part of the ossicles (the stapes), the footplate of the stapes at the oval window will move back and forth. This movement transmits the pressure of sound waves through the perilymph of scala vestibuli and scala tympani. Since liquid molecules are more difficult to move than air molecules, the SPL transmitted to the inner ear have to be amplified. The amplification is achieved by the anatomical structure of the oval window which is much smaller than the tympanic membrane, leading to an increase of sound waves pressure by about 15 to 20 times (Widmaier, Raff and Strang, 2011).

The inner ear, on the other hand, consists of three complex structures; the semicircular canals, the vestibule and the cochlea. The semicircular canals and the vestibule house the sensory organs for the vestibular system, which is important for the maintenance of balance and posture. The coiled and snail-shaped cochlea houses the sensory organ for hearing (organ of Corti). It consists of three primary chambers called scala vestibuli, scala media and scala tympani. Figure 2.2 shows the cross section of the cochlea, revealing its chambers and the organ of Corti.

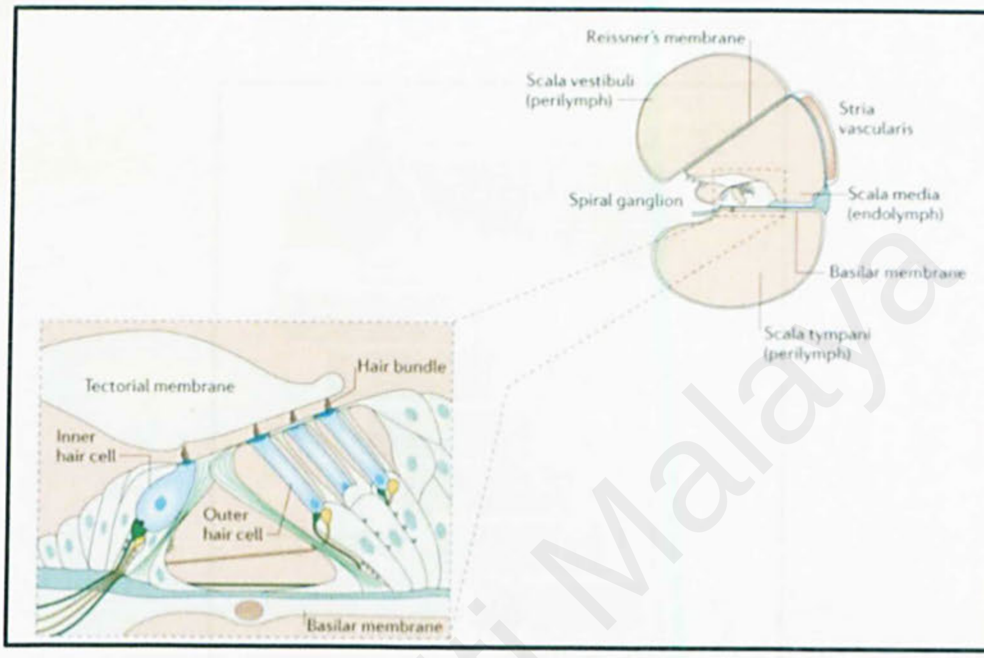



Figure 2.2: A cross section of the cochlea showing the scala vestibuli, scala media, and scala tympani, together with the organ of Corti which is situated on the basilar membrane. (Adapted from Hudspeth, 2014).

Scala media is separated from the scala vestibuli by Reissner's membrane, and from scala tympani by BM. Sound pressure waves are transmitted along the length of scala vestibuli and scala tympani, creating corresponding wave motion in the endolymph of scala media. This results in the vibration of the Reissner's membrane and displacement of BM, which produces travelling waves (Von Bekesy, 1960). These waves travel along the length of the cochlea from the basal end to the apical end.

The width of the BM is not uniform. It is narrower and stiffer at the basal end and wider and more flexible at the apical end. This structural characteristic enables it to differentiate frequencies of sound by producing separate points of maximal displacement of travelling waves along its length. A high-frequency sound causes greater displacement at the basal end of the BM, whereas the apical end of BM is more sensitive to low-frequency sounds. Figure 2.3 shows the patterns of sound wave displacement initiated by different sound frequencies. The systematic mapping in which high-frequency sounds are processed at the basal end and low-frequency sounds processed at the apical end is also referred to as tonotopic organization.

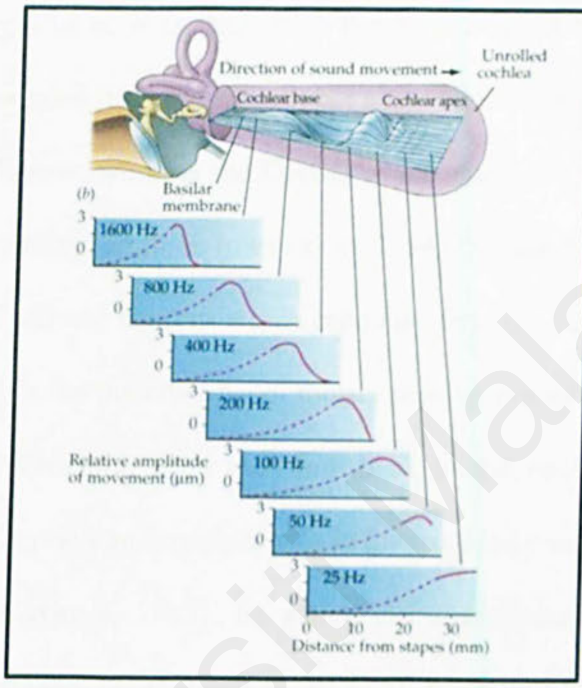



Figure 2.3: Patterns of travelling wave displacement on the basilar membrane based on the frequency of the sound stimulus (Adapted from Sinauer Associates, Inc., 2001).

The organ of Corti consists of thousands of sensory receptor cells known as hair cells. Each of these hair cell has tiny hairs known as stereocilia on its apical surface. Displacement of BM leads to the deflection of these stereocilia. As a result, receptor potentials are generated in the hair cells. Although stereocilia varies in length, it is mechanically connected to each other via fibrous connections known as tip links. The short stereocilia contains mechanically-gated potassium ion ($K^+$) channels, and the deflection of the stereocilia will open these channels. Since endolymph contains high concentration of $K^+$, these ions rush into the hair cells to depolarise its membrane. This results in the opening of voltage-gated calcium ion ($Ca^{2+}$) channels and influx of $Ca^{2+}$

into the hair cell which then triggers the release of the neurotransmitter glutamate (Oestreicher, Wolfgang and Felix, 2002). Bending of the hair cells in the opposite direction will slacken the tip links, close the channels and repolarise the cell. The released glutamate then binds to the receptors located on the dendrites of the afferent auditory neurons, leading to the generation of action potential (AP).

There are two types of cochlear hair cells; the inner hair cells (IHCs) and outer hair cells (OHCs). The rounded IHCs, which number approximately 3500 in each cochlea, are organized in a single row, whereas the OHCs, which number approximately 12000 in each cochlea, are organized in three rows (Yost, 1994) (Figure 2.2). The IHCs synapse with the dendrites of afferent neurons which send auditory information from the cochlea to the brain. The OHCs, on the other hand, mostly receive synaptic inputs from efferent neurons that send information from the brain back to the cochlea (Brownell, 1996; Venema, 2006). OHCs plays an important role in the frequency selectivity of the cochlea (Strelioff, Flock and Minser, 1985). Its active electromechanical feedback helps to amplify the sound stimulus by as much as 40 to 50 dB (Dallos, 1992; Fettiplace and Hackney, 2006; Moore, 2007a). This action also contributes to the high sensitivity of the BM to weak (near threshold) sounds as well as the sharp tuning on the BM (Dallos and Corey, 1991; Ulfendahl and Flock, 1998; Moore, 2007a). Hence, any damage to the OHCs results in the loss of hearing sensitivity and sharp tuning of the BM.

### 2.1.2 Central auditory system

Afferent auditory neurons leave the cochlea through a structure called modiolus. These afferents form the cochlear branch of the auditory nerve, which extends to the brainstem. Figure 2.4 shows the structures of the central auditory system. Cochlear nucleus in the brainstem marks the beginning of the central portion of the auditory system. From the cochlear nucleus, the nerve fibers project either to the ipsilateral or contralateral parts of the superior olivary complex (SOC). At this point, monaural sound (sound coming from one ear) is represented binaurally (both sides of the central auditory system). The ascending nerve fibers then projects to lateral lemniscus and inferior colliculus. Inferior colliculus is considered to be the largest auditory structure of the brainstem and it exhibits a high degree of tonotopicity. All ascending fibers then terminate at the medial geniculate body located in the thalamus before reaching the auditory cortex. Specific cortical areas capable of decoding information about the frequency, intensity and timing of sound is located in the Heschl's gyrus of temporal lobe (Bess and Humes, 2008a). Besides the ascending afferent system, there are also a set of descending efferent neurons from the cortex to the cochlea (not shown in the diagram). While the ascending (afferent) pathway carry auditory information from the cochlea to the cortex, the descending (efferent) pathways regulate and modify these incoming information (Bess and Humes, 2008a).

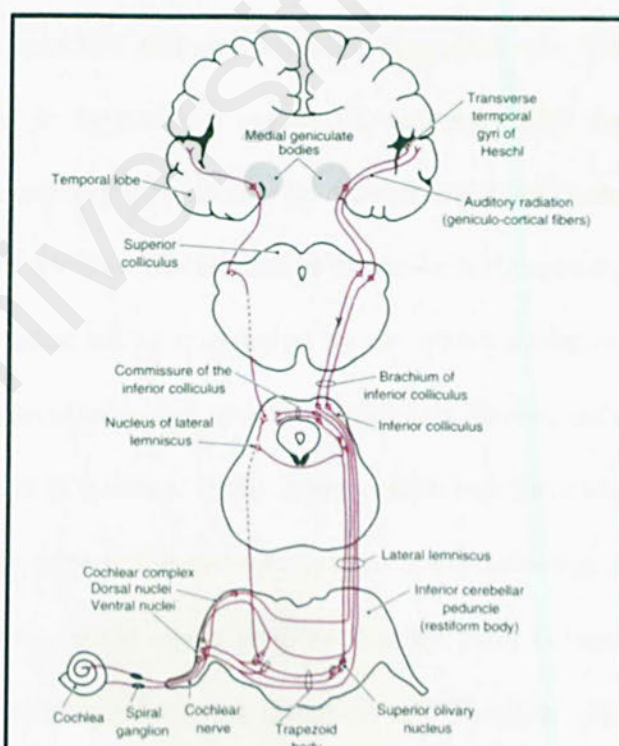



Figure 2.4: A diagram of central auditory system which consists of all neurons involved in the sound processing (Adapted from Lippincott Williams and Wilkins, 2013).

## 2.2 Selective attention

Our environment constantly provides our brain with a large amount of information. The process of selectively attending to salient information and filtering out other distracting stimuli is called selective attention. Selective attention enables us to quickly and effectively navigate in a busy world.

### 2.2.1 Selective auditory attention

Selective auditory attention refers specifically to the ability of an individual to attend or focus on sounds of interest in the presence of distracting background sound such as noise. The most frequently cited example of selective auditory attention is the *cocktail-party effect*. This effect describes the ability of an individual to listen to only one speaker in the presence of other distracting speakers (Cherry, 1953).

Early studies in selective auditory attention suggested that there would be a fixed location for a 'filter' in the auditory system (Broadbent, 1958) that marks the level of processing at which auditory input from relevant and irrelevant channels are differentially processed (Naatanen, 1992). The relevant information is thought to proceed through the filter to be further processed or interpreted by the higher auditory centres (Broadbent, 1958), while irrelevant information is either completely filtered out (Broadbent, 1958) or attenuated by the filter (Treisman, 1960). Some researchers have suggested that the filter is located at an early stage in the auditory system (early-selection theories) (Broadbent, 1958; Treisman, 1960), while others propose that the filter is located higher up in the cortical areas (late-selection theories) (Deutsch and Deutsch, 1963; Norman, 1968). However, the exact location of such a filter and its neural basis are still a subject of debate (Giard, Fort, Mouchetant-Rostaing and Pernier, 2000).

### 2.2.2 Acoustic features and auditory attentional selection

The relationship between acoustic features and selective auditory attention has been demonstrated in many psychoacoustical studies (Tanner and Norman, 1954; Greenberg and Larkin, 1968; Spence and Driver, 1994; Wright and Dai, 1994). The characteristics of the incoming sound stimuli which has been observed to play an important role in auditory attentional selection include the sound frequency (Tanner and Norman, 1954; Greenberg and Larkin, 1968), intensity (Green and Luce, 1974; Nosofsky, 1983), timing (Wright and Dai, 1994; Wright and Fitzgerald, 2004) and location (Rhodes, 1987; Spence and Driver, 1994).

As the topic of the current study focuses on the relationship between auditory attention and sound frequency, only this aspect of the stimuli is review here.

### 2.2.3 Frequency of sound stimuli and selective auditory attention

One of the earliest psychoacoustical study which demonstrated the ability of the auditory system to 'tune' to a particular frequency was carried out by Tanner and Norman in 1954. Tanner and Norman (1954) initially presented 1000 Hz signal in noise at a level such that his subjects could score about 65% correct detection. After several hundred trials, when the frequency of the signal was suddenly changed to 1300 Hz, the listeners' performance went down to 25% correct detection (chance level) indicating that they did not hear the signal. However, after the listeners were told about the change in the frequency, their performance for the new frequency again increase up to the expected 65% correct detection (Tanner and Norman, 1954). Based on the study, Tanner and Norman (1954) concluded that the listeners were more sensitive to the expected signal frequency compared to the unexpected frequency.

In 1961, Green performed signal detection experiments to measure the detection of tones in noise during frequency certainty and uncertainty condition. In the experiment, frequency certainty condition was induced by presenting a fixed signal frequency several times at a high level before the session, whereas frequency uncertainty condition was induced by presenting signals randomly selected from a broad range of frequencies. He observed that the uncertainty about signal frequency can decrease the subject's hearing sensitivity by as much as 3 to 4 dB (Green, 1961).

A more thorough study on the role of signal frequency in attentional selection was carried out by Greenberg and Larkin in 1968. Their method later came to be known as the probe-signal method. In Greenberg and Larkin's study, the listeners were led to expect a tone of a certain frequency (expected or target frequency), which was presented on 77% of the trials. Probe signals, whose frequencies differed from the target signal were presented on remaining 23% of the trials. Both the target and probe signals were presented at equally detectable levels in the presence of a continuous background noise. Greenberg and Larkin (1968) found that the target signals presented more frequently were detected at a higher rate compared to the infrequent probes. They also showed that target signals whose frequency matched a preceding cue tone were detected more successfully than probe signals whose frequency deviated from the cue. Greenberg and Larkin (1968) visualized their result by plotting the percentage of detection as a function of frequency to reveal the "attentional function" (Figure 2.5). The expected target signal (1100 Hz) was detected approximately 80% of the trials, whereas the detection rates of the probe signals decreased as their frequencies deviated from the target signal. Based on their results, Greenberg and Larkin (1968) proposed that subjects' attention (attentional band) was "tuned" or focused to a narrow band of frequencies around the target signal (about one critical band) and this resulted in changes of listener's sensitivity towards the signals (higher sensitivity to the target signal, less sensitivity to the probes). This differential effect of attention on listeners' sensitivity to varying signal frequencies is also sometimes referred to as auditory attentional filter. As can be seen in Figure 2.5, the width of the filter corresponds to about one CB around the target signal. Details regarding the CB will be discussed in subsequent sections.

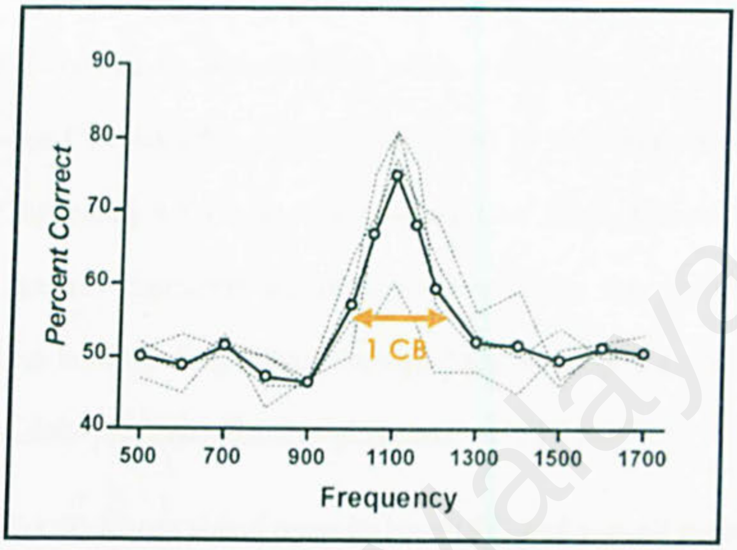



Figure 2.5: Performance detection level (percentage correct) at target (1100 Hz) and probe frequencies from 500 to 1700 Hz. Dotted lines represent result for each subject. Black line and open circle represent the average result of all subjects (N=4). (Figure adapted from Tan, 2008. Data taken from Greenberg and Larkin, 1968).

## 2.3 Auditory frequency selectivity

The ability of auditory system to separate or resolve two or more signals of different frequencies is known as auditory frequency selectivity. This ability largely depends on the normal functioning of the cochlea, particularly the OHCs (Moore, 1995). As described earlier, different frequency components of a sound will produce maximal vibration at different regions along the length of BM. Two components with different frequencies will be coded independently in the auditory nerve only if the separation of the maximal vibration caused by each component is sufficiently large (Moore, 1995). In other words, the resolved components will be processed at different location along the BM and will excite different group of hair cells before giving rise to APs in separate auditory nerve fibres before transmitting them to the central nervous system (Fettiplace and Hackney, 2006).

### 2.3.1 Measurement of frequency selectivity using the masking technique

Frequency selectivity can be demonstrated using the masking technique. In this technique, the threshold for detecting one signal is raised by the simultaneous presence of an interfering or distracting masker sound (Moss and Carr, 2003; Moore, 2007b). The more similar the spectral characteristics of the masker with the signal, the more effectively it interferes with the detection of the signal and the higher the threshold will be (Wegel and Lane, 1924: Jesteadt, Bacon and Lehman, 1982).

Masked threshold is the lowest sound pressure level (SPL) of a sound needed to make the sound audible to the listener in the presence of the masking stimulus. If the to-be-detected stimulus is a pure tone and the masking stimulus is broadband white noise, only a small portion of the noise band effectively contributes to the masking of the pure tone signal. This was originally demonstrated by Fletcher (1940), who measured the masked pure tone thresholds as a function of the bandwidth of a bandpass noise masker. In his experiment, Fletcher centred the background noise band at the tone frequency and the noise spectrum level was held constant. He showed that as the bandwidth of the noise increased (increase in total power density of the noise), the detection threshold for the masked pure tone also increased. However, the increase in the threshold was only up to a certain value, beyond which the threshold remained constant. Fletcher (1940) termed this value as the critical band (CB). In other words, CB refers to the frequency band of the background masker noise around the signal frequency which is effective in masking the signal. Figure 2.5 illustrates the concept of Fletcher's experiment.

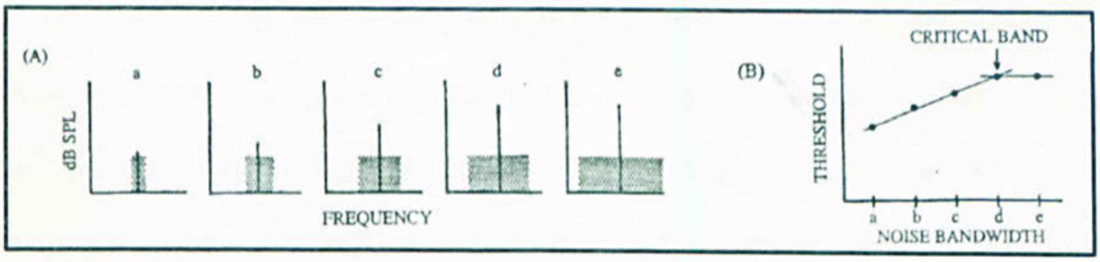



Figure 2.6: A) Shaded region represent the background noise and solid line represent masked pure tone (signal) threshold. The sequence from (a) to (d) depicts the increasing bandwidth of the noise resulting in an increase of the signal threshold (the height of the solid line). A further increase in noise bandwidth (e) however does not increase the signal threshold. B) Detection thresholds of the masked tones were plotted as a function of noise bandwidth. The detection threshold remained constant after reaching critical band. (Adapted from Moss and Carr, 2003).

### 2.3.2 Critical bands (CBs) and the concept of internal auditory filter

Based on his findings, Fletcher (1940) suggested that the peripheral auditory system contains an array of overlapping internal auditory filters (Figure 2.7). These filters were thought to be used by a listener when they are trying to detect signals in the presence of background noise (Fletcher, 1940). The width of the filter is suggested to be equal to the CBs that he measured from his experiments (Fletcher, 1940). Fletcher (1940) assumed that during a listening task, the listener only uses one filter with the centre frequency (CF) closest to the frequency of the to-be-detected signal. This filter will produce the highest signal-to-masker ratio (SMR) at its output. Only the components of the masking noise that pass though the filter contribute to the masking of the to-be-detected signal (Fletcher, 1940). The portion of the noise which does not contribute to the masking of the signal (outside the CBs) will be filtered out.

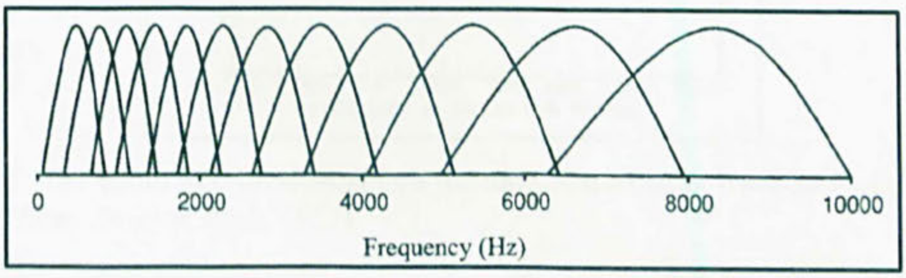



Figure 2.7: Auditory filters centred at the characteristic frequencies ranged from 500 to 8500 Hz. (Adapted from Zenke, 2014).

Although the assumptions made by Fletcher (1940) were not strictly correct (see Moore and Glasberg, 1987 and Patterson and Henning, 1977 for further review), his basic concepts of the auditory filter and CBs are widely accepted and were proven to be useful in many subsequent studies (Greenwood, 1961; Swets, Green and Tanner, 1962; Healy and Bacon, 2005; Buss, Hall and Grose, 2013). For example, the measurement of the CB was repeated by Zwicker and colleagues in 1957 using loudness summation method (Zwicker, Flottorp and Stevens, 1957) and they obtained similar results as Fletcher's. This method assumed that the loudness of a band of noise remains constant as the bandwidth increases up to the critical point (CB cut-off), after which its loudness will begin to increase. Zwicker et al., (1957) observed that the CB remained constant at a width of about 90 Hz over the low-frequency range, but grows rapidly to about 2000 Hz with increasing frequency values (Figure 2.8).

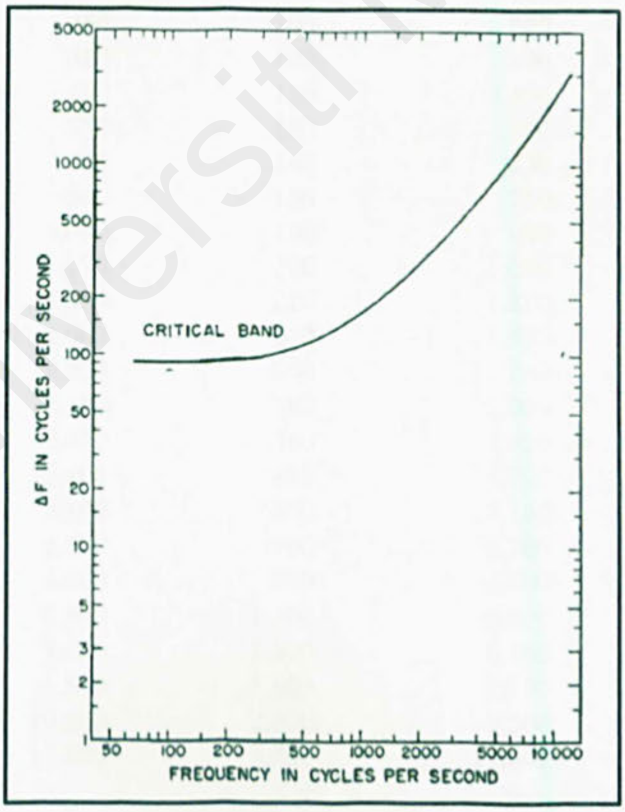



Figure 2.8: The width of critical band as a function of the centre frequency of the signal. (Adapted from Zwicker et al., 1957).

Greenwood (1961) and Scharf (1970) subsequently derived functions which relate CB to CF and the distance along the BM measured from the apex or helicotrema. The bandwidth and CF of these CBs are shown in the Table 2.1. The entire BM of the cochlea can be divided into about 24 CBs (Scharf, 1970). With the length of the BM of a human cochlea of about 32 mm, each CB would be about 1.3 mm (Scharf, 1970). This would correspond to approximately 1300 afferent neurons (cochlear IHCs) (Scharf, 1970).

Table 2.1: Values of critical bands as a function of centre frequency (CF). Also shown are the lower cut-off and upper cut-off for each centre frequency.

| Number | Center frequency (CF) (Hz) | Critical band (CB) (Hz) | Lower cutoff frequency (Hz) | Upper cutoff frequency (Hz) |
|---|---|---|---|---|
| 1 | 50 | – | – | 100 |
| 2 | 150 | 100 | 100 | 200 |
| 3 | 250 | 100 | 200 | 300 |
| 4 | 350 | 100 | 300 | 400 |
| 5 | 450 | 110 | 400 | 510 |
| 6 | 570 | 120 | 510 | 630 |
| 7 | 700 | 140 | 630 | 770 |
| 8 | 840 | 150 | 770 | 920 |
| 9 | 1,000 | 160 | 920 | 1,080 |
| 10 | 1,170 | 190 | 1,080 | 1,270 |
| 11 | 1,370 | 210 | 1,270 | 1,480 |
| 12 | 1,600 | 240 | 1,480 | 1,720 |
| 13 | 1,850 | 280 | 1,720 | 2,000 |
| 14 | 2,150 | 320 | 2,000 | 2,320 |
| 15 | 2,500 | 380 | 2,320 | 2,700 |
| 16 | 2,900 | 450 | 2,700 | 3,150 |
| 17 | 3,400 | 550 | 3,150 | 3,700 |
| 18 | 4,000 | 700 | 3,700 | 4,400 |
| 19 | 4,800 | 900 | 4,400 | 5,300 |
| 20 | 5,800 | 1,100 | 5,300 | 6,400 |
| 21 | 7,000 | 1,300 | 6,400 | 7,700 |
| 22 | 8,500 | 1,800 | 7,700 | 9,500 |
| 23 | 10,500 | 2,500 | 9,500 | 12,000 |
| 24 | 13,500 | 3,500 | 12,000 | 15,500 |

(Adapted from Scharf, 1970).

### 2.3.3 Estimation of auditory filter shape using the notched-noise method

The peripheral auditory filter shape can be more precisely estimated using the notched-noise method (Patterson, 1976). This can be done by determining the relative response of the filter as a function of the input signal frequency (Patterson, 1976). The input signal (tone) was presented with a masker that has a spectral notch centred at the signal frequency (notched-noise) (Patterson, 1976). This noise consists of two bands located on either side of the signal frequency (Patterson, 1976). The position of the noise edge is varied about the frequency of the tone and the signal threshold is measured as a function of the width of a spectral notch of the masker. The spectrum level of noise and the amplitude of the tone are held constant.

Using this method, Patterson (1976) noticed that the signal detection threshold decreased as the distance between the tone and the noise edge increased (increasing notch bandwidth). This is because as the width of the spectral notch is increased, the amount of noise that passed through the auditory filter became less, producing less masking of the tone (Moore, 2007b). The shape of an auditory filter centred at a CF obtained by Patterson is shown in Figure 2.9.

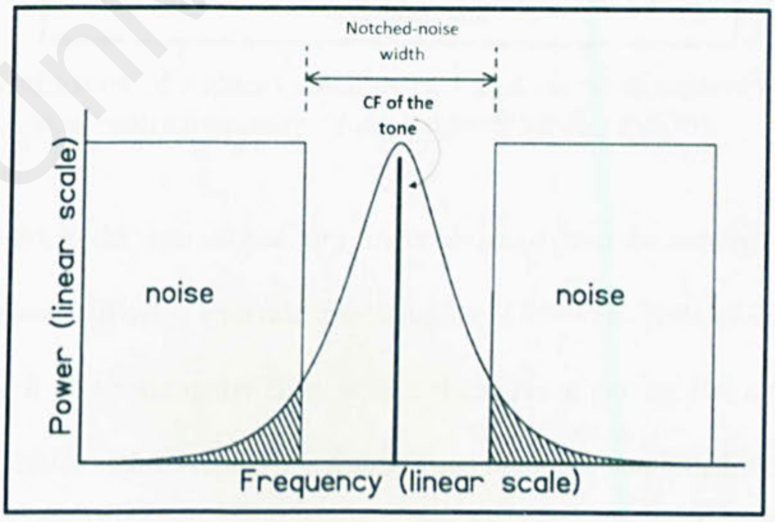



Figure 2.9: Auditory filter shape obtained using the notched-noise technique. Shaded region represents the amount of noise that is allowed to pass through the filter. The threshold of the tonal signal is measured as a function of the width of spectral notch from the central frequency (CF). (Adapted from Moore, 2007b).

The auditory filter shape in Figure 2.9 represents the frequency selectivity of the auditory system at a particular CF using a fixed level of background noise. However, the filter's shape (lower skirts and upper skirts) varies when the level of the background noise is varied (Moore, 2007b). The change in the auditory filter's shape (centred at 1 kHz) with an increase in background noise level is shown in Figure 2.10. The filter is approximately symmetric on the linear frequency scale at low and moderate noise levels. However, as the sound level increases, the filter becomes progressively less sharply tuned on the low-frequency side (Moore, 2007b).

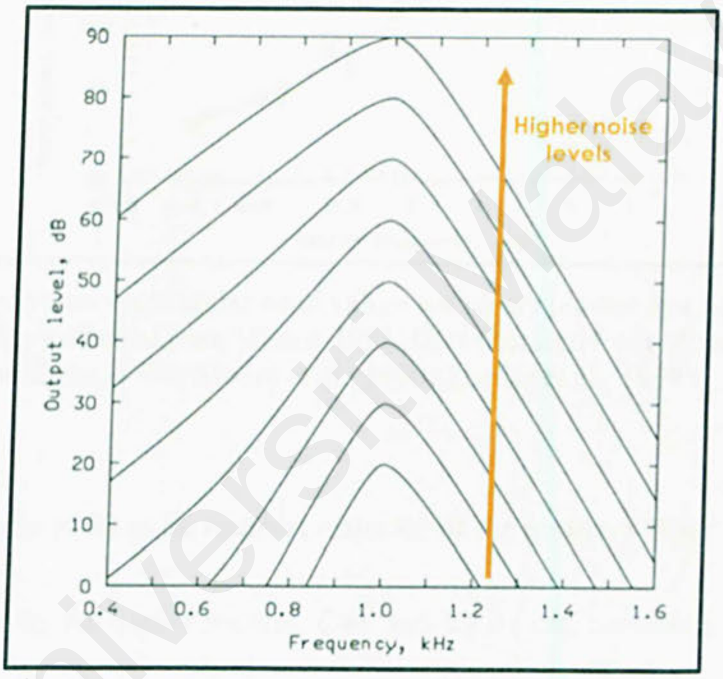



Figure 2.10: Estimation of auditory filter shape based on measurement of output level (dB) as a function of centre frequency. (Adapted from Moore, 2007b).

The bandwidth of the internal auditory filters obtained from the notched-noise method can also be represented using equivalent rectangular bandwidths (ERBs). ERB is defined as the bandwidth of a rectangular filter whose shape has a perfect flat top and vertical edges (Moore, 2007b) which represents a simplified model of auditory filters (see Moore and Glasberg, 1983; Dubno and Dirks, 1989; Moore, Peter and Glasberg, 1990 and Shailer, Moore, Glasberg, Watson and Harris, 1990 for further details). The measured

ERB values are shown in Figure 2.11. Although the ERBs values are approximately 11% larger than the CBs, ERBs dependence on frequency follows a similar course as the CBs, in which the values increase with an increase in CF (Moore and Glasberg, 1983; Dubno and Dirks, 1989; Moore et al., 1990; Shailer et al., 1990).

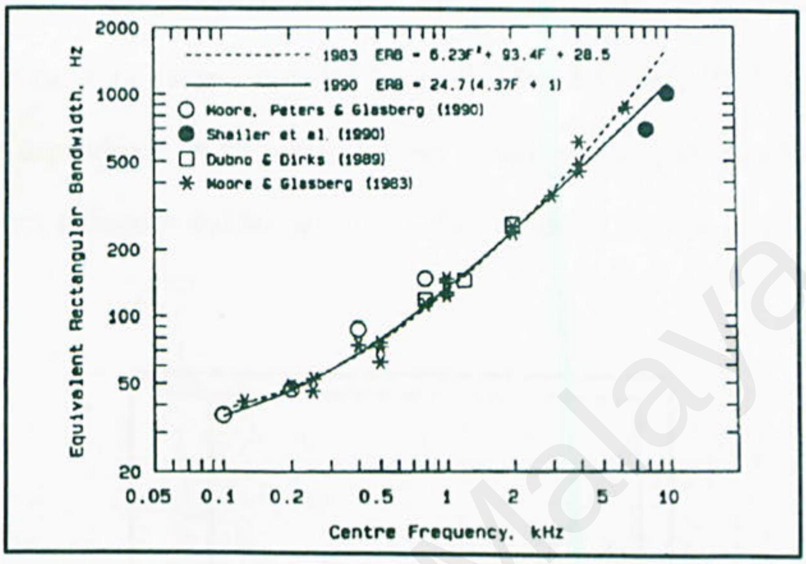



Figure 2.11: Equivalent rectangular band values which are plotted as a function of centre frequencies. (Figure adapted from Moore, 1995. Data obtained from Moore and Glasberg, 1983; Dubno and Dirks, 1989; Moore et al., 1990; Shailer et al., 1990).

### 2.3.4 Critical ratio (CR) as an indirect estimate of the auditory filter width

As mentioned in the earlier section, CBs and ERBs can be used to determine the auditory filter width. However, the task is tedious and time-consuming as the detection thresholds had to be measured against a variety of noise bandwidths. An alternative way to indirectly estimate the auditory filter bandwidth is by calculating the ratio of pure tone threshold to the noise spectrum level of the masker noise. This value is called the CR and is expressed in logarithmic unit (dB) (Zwicker et al., 1957). For example, if the pure tone threshold is 50 dB and the masker noise spectrum level is 30 dB, the CR will be 20 dB. This means the power of pure tone at threshold is 100 times greater ($10\log_{10}100 =$

20 dB) than the power in one cycle of noise[1] (Moss and Carr, 2003). With a wider auditory filter, more masking noise would pass through it, leading to more masking and a higher CR value. Figure 2.12 shows the comparison between the CBs measured directly (Zwicker et al., 1957) and the corresponding values estimated indirectly from the CRs using assumptions made by Fletcher (1940)[2]. The measured value of the CBs were about 2.5 times as wide as the values estimated from CRs (Zwicker et al., 1957; Scharf, 1970). However, its dependence on frequency follows almost similar patterns of change with signal frequency (Hawkins and Stevens, 1950; Zwicker et al., 1957; Saunders, Denny and Bock, 1978).

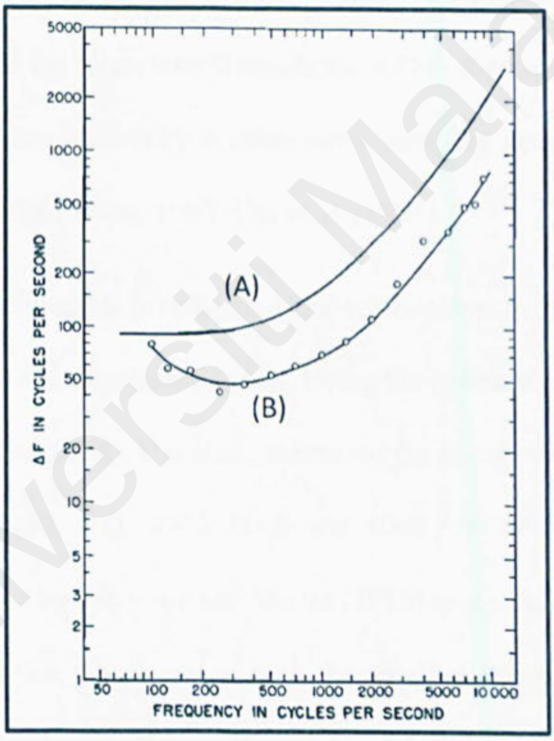



Figure 2.12: Comparison between (A) directly estimated critical bands from loudness summation method and (B) indirectly estimated critical band from critical ratio values. (Adapted from Zwicker et al., 1957).

The similarities of both of these curves for most of the frequency range (except frequencies below 200 Hz) suggest that they likely reflect the same underlying process

[1] Spectrum level of noise is power per 1 Hz
[2] Noise power integrated over the critical bands was equalled the power of the signal at threshold

(Zwicker et al., 1957). As such, it is reasonable to assume that CRs could provide an indirect one-point estimate of bandwidth of the internal auditory filters that are operative during the task of detecting pure tone signals in the presence of background noise (Patterson et al., 1982).

### 2.3.5 Relationship between auditory filter and attentional band

As discussed earlier in Section 2.2.3, when attending to a tone at a specific frequency, the listeners selectively attend to a narrow band of frequencies (about one CB) centred at the tone frequency. Although the tones were presented with equal level of energy, their sensitivity are enhanced for tones with frequencies within the range of the band (known as attentional band), while sensitivity to other tones with frequencies outside the band is decreased (Greenberg and Larkin, 1968; Dai et al., 1991).

In 1991, Dai and colleagues investigated the relationship between the peripheral or internal auditory filters and attentional bands. Using the probe-signal method introduced by Greenberg and Larkin (1968), Dai et al., measured the attentional bands in his subjects at five separate CFs (250, 500, 1000, 2000 and 4000 Hz) and compared it with the auditory filters measured by Patterson and Moore (1986) using the notched-noise method. Their results indicated that the shapes of both the attentional bands and auditory filters closely resembled each other at all five CFs (Figure 2.13).

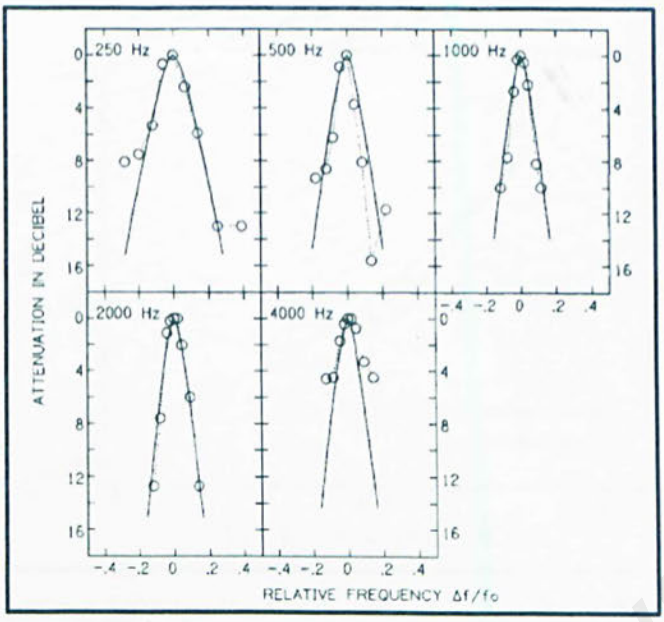



Figure 2.13: Shapes of attentional bands and auditory filters at 250, 500, 1000, 2000 and 4000 Hz. The curves represent the auditory filters measured by Patterson and Moore (1986). Open symbols represent the attentional bands measured by Dai et al., (1991). (Adapted from Dai et al., 1991).

Dai et al. (1991) also plotted the half-power bandwidth (3-dB down) of their attentional bands with the corresponding values from the auditory filters (Patterson and Moore, 1986) and CBs (Zwicker and Terhadt, 1980) (Figure 2.14). Their results revealed that the width of the attentional bands were close to the CBs (except for the lower frequencies: 0.25 to 0.5 kHz). The bandwidth of the attentional bands also corresponded with the width of the auditory filters. Based on the close relationship between the auditory filter and attentional bandwidth, Dai and colleagues' suggested that attention is most likely focused on the auditory filters centred at the target frequency during a selective frequency listening task.

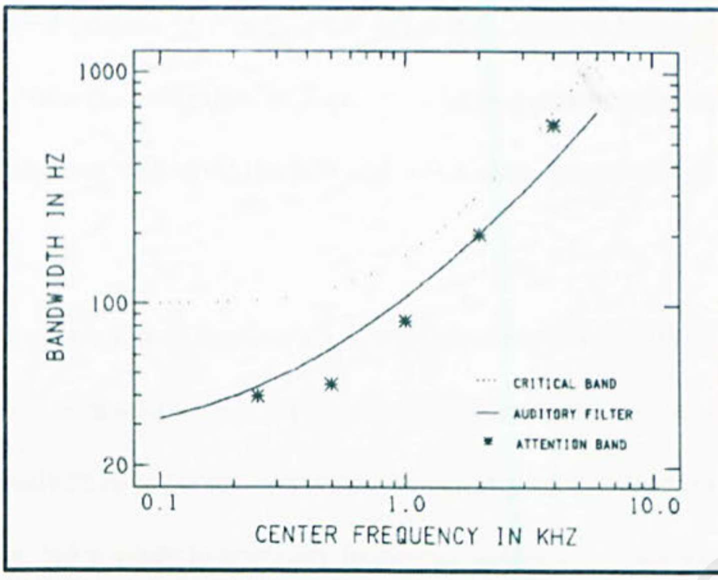



Figure 2.14: Comparison between the bandwidth of the auditory filter, attentional band and critical band. (Adapted from Dai et al., 1991; Data were taken from Zwicker and Terhadt, 1980; Patterson and Moore, 1986; Dai et al., 1991).

### 2.3.6 Changes in frequency selectivity in sensorineural hearing loss (SNHL) patients

SNHL is the most common form of hearing loss in developed countries. This condition can be caused by damage within the cochlea or nerve structures from the cochlea to the brain.

The most common case of SNHL is due to damaged or non-functional OHCs (Moore and Oxenham, 1998). OHCs are physiologically vulnerable and easily damaged compared to the IHCs (Moore, 2007a). Damage of OHCs can arise due to exposure to loud sounds (Moussavi-Najarkola, Khavanin, Mirzaei, Salehnia, Muhammadnejad and Akbari, 2012), consumption of exogenous toxins (ototoxic chemicals) (Campo, Morata and Hong, 2013), viral or bacterial infections (Perny, Roccio, Grandgirard, Solyga, Senn and Leib, 2016), autoimmune or hereditary diseases (genetic factor) (Akdag, Uçmak, Özkurt, Bozkurt, Akkurt, and Topçu, 2015) and metabolic disturbances (Xipeng, Ruiyu, Meng, Yanzhou, Kaosan and Liping, 2013). These agents can cause a variety of damages or disruptions to OHCs including an impairment of its stereocilia which can either be distorted, destroyed (reduce in number) or completely dead (Moore, 2007a). Impaired OHCs may result in the reduction or loss of its active mechanism that results in the broadening of frequency tuning on the BM and reduced the sensitivity of the BM (Moore, 2007a).

As mentioned previously in Section 2.1.1, the frequency selectivity of auditory system depends on the active mechanism of OHCs. Hence, SNHL patients, especially those with OHCs damage will have a poorer frequency selectivity of the cochlea. Florentine and colleagues conducted a study to compare frequency selectivity between normal-hearing and hearing-impaired subjects using various measures of frequency selectivity (Florentine, Buus, Scharf and Zwicker, 1980). Their results revealed that frequency selectivity for hearing-impaired subjects were reduced in the range of their cochlear hearing loss and correlated with the degree of hearing loss in SNHL (mild-to-moderate). In addition, the CBs of the SNHL subjects were four to five times as wide as normal subjects (Florentine et al., 1980). Their SNHL subjects included those with noise-induced hearing loss which are likely to be affected by the OHCs loss.

Patterson and colleagues studied subjects with age-related hearing loss and showed that the CRs and bandwidth of the auditory filters of these subjects broadened progressively with increasing age (Patterson et al., 1982). Since the OHCs are one of the predominant structures affected in this condition (Bredberg, 1968; Johnson and Hawkins, 1972; Schuknecht, 1974), the loss of frequency selectivity in older subjects may be also related to the loss of OHCs active mechanism and broadening of the BM tuning characteristics.

In another study, Glasberg and Moore (1986) directly measured and compared the auditory filter shapes between normal and impaired ears of unilateral SNHL subjects. Their results are shown in Figure 2.15. They found that the filter shapes for normal ears were narrower indicating a higher degree of frequency selectivity (Glasberg and Moore, 1986). In contrast, the auditory filter shapes for the impaired ears were much broader compared to the normal ears of the same subjects (Glasberg and Moore, 1986).

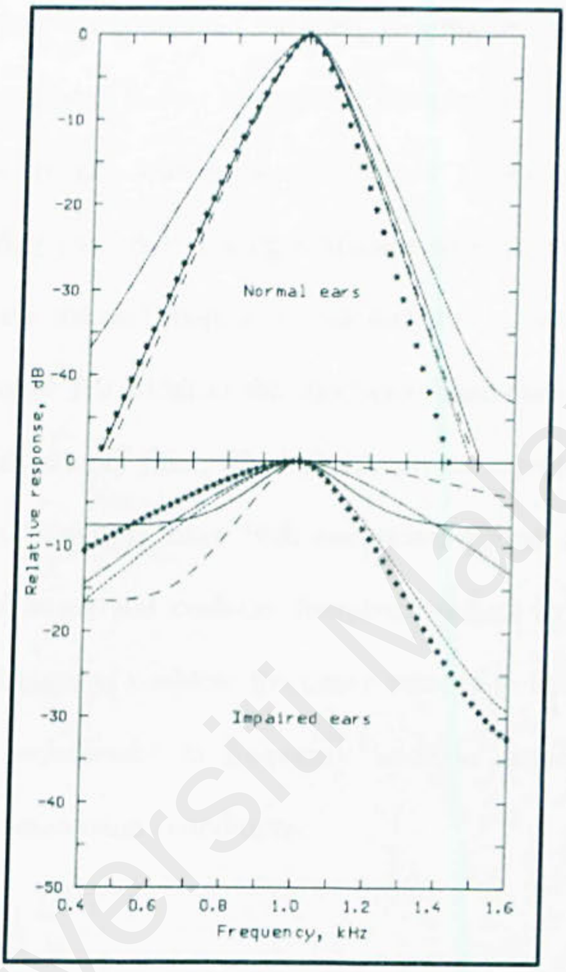



Figure 2.15: Auditory filter shapes at centre frequency of 1 kHz for normal (top) and impaired (bottom) ears. (Adapted from Glasberg and Moore, 1986)

The broadening of the peripheral auditory filters and subsequent deterioration of the frequency resolving power of the cochlea in SNHL patients, specifically those with OHCs loss (Pickles, 1988; Dobie and Van Hemel, 2005) could have implications on their ability to perform selective frequency listening. As the peripheral auditory filters are closely linked with the attentional bands involved in selective auditory attention, these bands could also be altered in these individuals. Such preliminary evidence has been recently reported (Bester, Robertson, Taljaard and Hammond, 2017).

## 2.4 Summary

Selective auditory attention refers to the ability of an individual to focus on specific auditory signal and ignore distracting background signals. Frequency of the signal plays an important role in auditory attentional selection. Hearing sensitivity is enhanced when the frequency of the signal is known or expected (frequency certainty) as compared to when the frequency is not known or unexpected (frequency uncertainty). The enhancement of hearing sensitivity during frequency-specific attention is observed at about 1 CB around the focused frequency area and this represents the width of the auditory attentional band. The width of the attentional band closely corresponds to the width of the peripheral auditory filter, which represents the tuning characteristic of BM (cochlear frequency selectivity). Since both attentional-mediated changes in hearing sensitivity (attentional band) and cochlear frequency selectivity (auditory filter) are closely related, any changes in cochlear frequency selectivity (such as in SNHL) will affect the detection performance in frequency selective listening tasks involving frequency certainty and uncertainty conditions.

# CHAPTER 3: GENERAL MATERIALS AND METHODS

## 3.1 Subjects

Participants were adult subjects aged 23–40 years. The purpose and procedures of the study and an informed consent were obtained. The study protocol was approved by the medical ethics committee of University of Malaya (UM) (ethical approval reference number: 1107.08). All experiments were performed at the Auditory Lab, Department of Physiology, Faculty of Medicine, UM.

## 3.2 Audiological assessments

### 3.2.1 Pure tone audiometry (PTA)

Pure tone audiometry (PTA) was done to evaluate the hearing sensitivity of each ear by measuring the hearing thresholds across the range of frequencies that are important for human communication. This was obtained using a calibrated high-frequency diagnostic audiometer (Siemens, SD28HF) coupled with a Sennheiser HDA-200 headphone. Test signals were pure tones with eight sinusoidal frequencies (250, 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz). Hearing thresholds (in dB HL) were determined for both ears using the modified Hughson-Westlake procedure[3]. Subjects were classified as having normal hearing if their hearing threshold were 20 dB HL or lower at the relevant test frequencies.

[3] Intensity level of the signals either increase or decrease in a 5-dB steps (ascending-descending method) according to the response given by the subject.

### 3.2.2 Transient evoked otoacoustic emissions (TEOAEs)

This test was carried out to determine the function of cochlear OHCs in the subjects. TEOAEs are low emission sounds produced by normally functioning OHCs as a response to brief clicks (Kemp, 1978). The TEOAEs amplitudes were measured using a diagnostic otoacoustic emission (OAE) analyser (Intelligent Hearing Systems, (IHS) SmartOAE) which was connected to a portable laptop running the SmartOAE software (version 3.69). An OAE probe (Etymotic Research, ER-10D) fitted with a soft and appropriate-sized ear tip was placed in the external ear canal of the subjects prior to the test. Subjects were seated comfortably in a sound-attenuated booth and were asked to limit their movements to reduce any background noise. The probe fit was confirmed using the in-the-ear calibration by the SmartOAE software.

Acoustic stimuli were 75 μs clicks (rectangular pulses) with peak equivalent level of 80 dB SPL presented to either the right or left ear. Clicks were generated using the non-linear protocol at the rate of 20 per second ($s^{-1}$). The responses were averaged 1024 times, filtered at 0.5 to 5 kHz within a time window of 25 ms, with the first 2.5 ms blanked out. The overall amplitude of the TEOAEs spectrum and the noise floor were recorded by the SmartOAE software. Any unwanted signal during the TEOAEs recordings were excluded using the software's artifact rejection setting.

## 3.3 Psychophysical testing

Subjects were seated in the ventilated sound-attenuated booth with ambient noise level of 29 dB A. They had to respond to instructions given on a computer screen while listening to signals delivered via a headphone and were aware that more than a single tone frequency will be presented during the testing.

### 3.3.1 Pure tone and noise stimuli

Tones and filtered background noise were generated digitally at a sampling rate of 44.1 kHz (16-bit precision), and were delivered via a Windows-based personal computer (PC), installed with a peripheral component interconnect (PCI) sound card (Creative Sound Blaster X-Fi) and Laboratory Virtual Instrument Engineering Workbench (LabVIEW) 13.0 software (National Instruments, Texas, United States of America (USA)).

All stimuli were delivered monaurally through a pair of Sennheiser HD 201 (Wedemark, Germany) headphones. Sound output levels were calibrated using Knowles Electronics Manikin for Acoustic Research (KEMAR) 43 AG ear simulator (G. R. A. S. Sound and Vibration, Holte, Denmark) connected to a data acquisition system (Spectra DAQ-200, Pioneer Hill Software, Poulsen, USA) and a spectrum analyser software (Spectra PLUS, Pioneer Hill Software, Poulsen, USA).

For the tone calibration, the sound output level of the headphone was measured as a function of the sound card output. The resulting best fit linear equation was obtained in the form of y = a$x$+b (y=sound output level (dB) and $x$= sound card output). This equation was used to calculate the equivalent dB SPL tone level for a given sound card output. An example of the calibration for 1 kHz tone is given in Figure 3.1

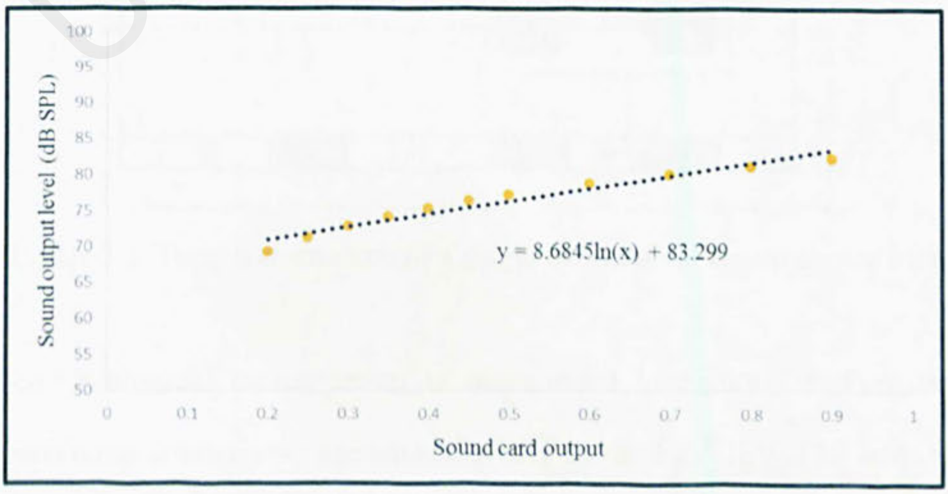



Figure 3.1: Sound output levels (dB SPL) of the headphone, calibrated for 1 kHz tone for a range of sound card outputs. The black dotted line represents the best fit linear line.

### 3.3.2 Two-interval forced choice (2IFC) trials

Two-interval forced choice (2IFC) trials were used to track the threshold as well as to measure the performance level of subjects for the detection of tonal stimuli in the presence of background noise during uncertainty and certainty conditions. Signals were presented only to the tested ear, which was chosen based on the audiogram of each subject.

Each 2IFC trial lasts for 2.25 seconds (s) and had two intervals which were clearly marked with numerals '1' and '2' on the computer screen (Figure 3.2). These intervals were separated by a 250 ms blank interval. A 250 ms 'respond now' message appeared on the screen after the second interval. Subjects were required to select one of the two interval containing the signal by clicking on the mouse button (left button for the first interval and right button for the second). Visual feedback was provided for their responses. A green light appeared to indicate a correct response, while a red light indicated an incorrect response. The responses given by the subject initiated the next trial sequence. A short practice session lasting about 15 trials using clearly audible tones were provided to each subject prior to the testing.

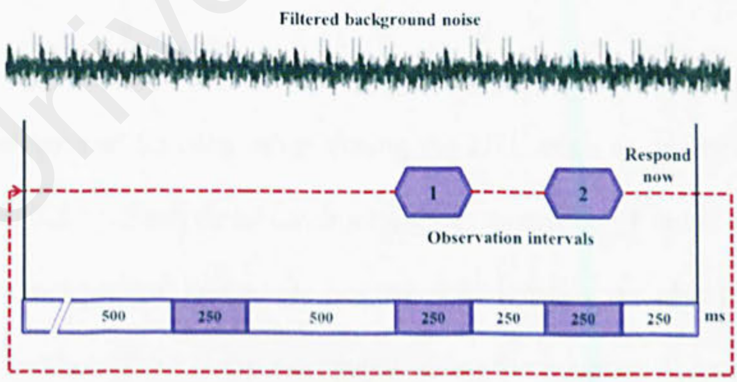



Figure 3.2: Temporal structure of a single two-interval forced choice trial

The psychophysical testing set-up is summarized in Figure 3.3. Pure tone and background noise stimuli were generated digitally by the LabVIEW 13.0 software. The background noise was presented throughout the trial and was filtered using the digital

Butterworth filter (order 10) available in LabVIEW. Sound stimuli from the PCI sound card was delivered to the subject via one of the channel of the headphone (monoaurally). Intervals '1' or '2' appeared on the computer screen located within the sound-attenuated booth to indicate the observation intervals. The subject responded by clicking the mouse button. All responses were recorded for further analysis.

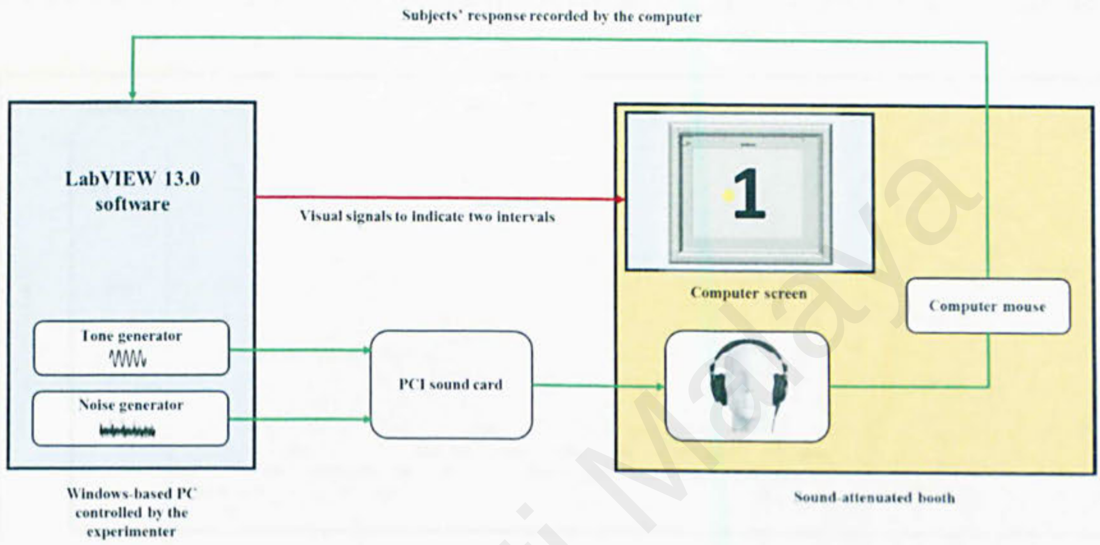



Figure 3.3: Psychophysical testing set-up

### 3.3.2.1 Threshold tracking method

Prior to the beginning of each experimental session, threshold level of the tonal signals in noise was determined for each subject using the 2IFC trials as described in the earlier section (Section 3.3.2). Each threshold tracking run consisted of either 80 or 100 trials. Cue tones were not present and the to-be-detected signals were always presented at a specific CF. Threshold level were calculated using the adaptive 'one-up, three-down' staircase procedure. This procedure calculates the signal threshold level required to produce 79.4 % correct detection on the psychometric function (Levitt, 1971).

The procedure had two phases, the 'rapid approximation' phase and the 'fine tracking' phase. During the first phase, the signal level was set at a clearly audible level. Following three consecutive correct responses, the signal level was decreased by 5 dB, and this continued until the first incorrect response was made by the subject. The first incorrect response marks the initiation of the second phase. Three consecutive correct responses in the second phase resulted in 1 dB decrease in signal level while a single incorrect response increase the signal level by 1 dB. An example of a threshold tracking run is provided in Figure 3.4. The average level of the last five reversals was taken as the subjects' threshold.

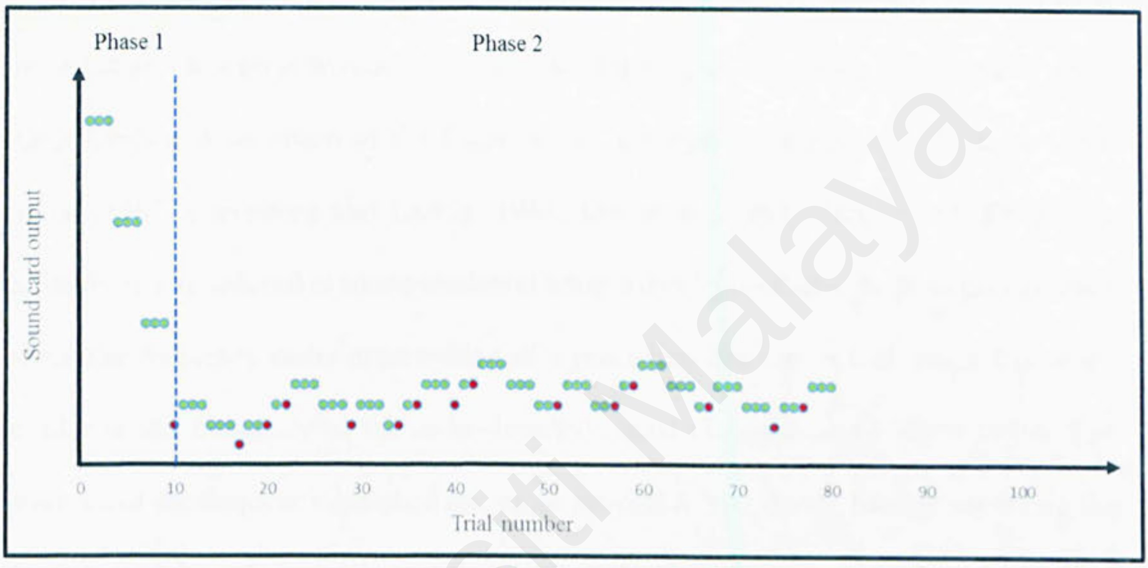



Figure 3.4: Example of a threshold tracking run from one subject. The run consists of 80 trials. Green circles represent correct responses while red circles symbol represent incorrect responses.

### 3.4 Statistical methods

Data obtained from the experiments were analysed using either the Statistical Package for the Social Sciences (SPSS Inc.) (version 23.0) or Microsoft Excel software (version 2013). Details regarding the statistical tests will be described in the relevant chapters. Significance level was set as $p < 0.05$.

# CHAPTER 4: PERFORMANCE DURING FREQUENCY CERTAINTY (CUED) AND UNCERTAINTY (UNCUED) CONDITIONS AT DIFFERENT CENTRE FREQUENCIES IN NORMAL-HEARING SUBJECTS

## 4.1 Introduction

Previous studies have shown that detection performance of near-threshold tones is much better when an individual is certain about the signal frequency compared to when the individual is uncertain of the frequency of the signal (Tanner and Norman, 1954, Green, 1961, Greenberg and Larkin, 1968; Dai et al., 1991, Tan, 2008). Frequency certainty can be induced in an experimental setup either by repetitive presentation of tones of similar frequency or by presentation of a preceding cue tone which has a frequency similar to the frequency of the to-be-detected signal (Johnson and Hafter, 1980). The presence of the frequency-matched cue tones provide a 'hint' to the listener regarding the frequency of the subsequent signal. In other words, the listener knows which location of the cochlea (either near to the basal or apical end of the BM) to focus on each trial. Frequency uncertainty condition, on the other hand, can be induced experimentally by varying the frequency of the signals randomly from trial to trial without the cue (Green, 1961; Greenberg and Larkin, 1968; Tan, 2008).

When the listener is uncertain of the frequency of the signal, their hearing sensitivity deteriorates (Green, 1961; Greenberg and Larkin, 1968, Tan, 2008; Tan et al., 2008). The difference in the performance of a subject between frequency certainty and frequency uncertainty conditions (referred to as uncertainty effect) can be as much as 3 dB in equivalent signal level (Green, 1961, Tan, 2008). The uncertainty effect can be produced even when as few as five signals are randomly chosen from a narrow range of frequencies (one CB away from CFs) (Tan, 2008).

In the current study, the uncertainty effect (difference between detection performance in frequency certainty and frequency uncertainty) was estimated at four different CFs in a group of normal-hearing subjects. In addition, the uncertainty effect was also measured at 1 kHz CF using two different background noise levels to determine if the change in the noise level affects the results. The performance of normal-hearing adults in the current task was validated by comparing the results with previously published data (Green, 1961; Scharf, Reeves and Suciu, 2007; Tan, 2008).

## 4.2 Materials and methods

Unless specified here, the experimental setup is based on the description provided in the general methods (Chapter 3).

### 4.2.1 Subjects

Six adults (1 male and 5 female) aged 24 to 39 years participated in this experiment. Four of them were postgraduate students from UM (including the author), while the other two subjects were staff working in UM. Each subject underwent audiometric assessment (PTA) and TEOAEs tests as described in Section 3.2.1 and Section 3.2.2 before completing the main experiment (psychophysical task).

### 4.2.2 Sound stimuli

All subjects underwent a total of four separate sessions of testing. Each session was conducted on separate days. As in the earlier study (Tan, 2008b), to-be-detected signals in each session were randomly chosen from a set of five different frequencies (0.2 probability for each signal) which ranged within one CB from the CF (Table 4.1). The bandwidth of background noise was adjusted accordingly for each CFs so that the upper and lower cut-off frequencies were three CBs away from the CFs (see the last column of Table 4.1). The spectrum level of the noise was set at 20 dB SPL for all the CFs.

Table 4.1: Five to-be-detected signal frequencies presented in each of the four sessions. Also shown are the critical band values and the bandwidths for the background masking noise for each of the CFs.

| Session | Centre frequencies, CF (Hz) | Critical band, CB (Hz)[4] | To-be-detected signals frequencies (Hz)[5] | | | | | Noise bandwidth (Hz) |
|---|---|---|---|---|---|---|---|---|
| 1 | 570 | 120 | 450 | 510 | 570 | 630 | 690 | 210–930 |
| 2 | 1000 | 160 | 840 | 920 | 1000 | 1080 | 1160 | 520–1480 |
| 3 | 2150 | 320 | 1850 | 2000 | 2150 | 2320 | 2490 | 1210–3130 |
| 4 | 4000 | 700 | 3400 | 3700 | 4000 | 4400 | 4800 | 2000–6200 |

To-be-detected signals at each CFs were presented at the threshold level determined by the threshold tracking procedure. However, according to Green, McKey and Licklider (1959), masked tones of lower frequencies are detected better than masked tones of higher frequencies in the presence of a flat (evenly-distributed spectral weighting) broadband masker. Accordingly, the amplitude of the remaining four signals were adjusted (+0.2 dB per 100 Hz for frequencies above the CF and –0.2 dB per 100 Hz for frequencies below the CF) so that all the five signals will be equally detectable (Green et al., 1959).

### 4.2.3 Frequency certainty and uncertainty tasks

At the beginning of each session, the threshold level at CF in noise for each subject was determined using the threshold tracking procedure mentioned in the general methods (Chapter 3).

Subsequently, subjects completed the psychophysical task which had a total of 6 blocks of trials (three uncued and three cued). Individual blocks had 100 trials each.



[4] Obtained from Table 2.1 (Scharf, 1970).
[5] Two nearest signal frequencies represent half CB away from CF, whereas the two most distant signal frequencies are approximately in one CB away from CF.

Uncued and cued blocks were presented in an alternate fashion (Table 4.2). Subjects completed all 600 trials in a single testing session which lasted about 1 hour. The uncued blocks (block 1, 3, 5) was designed to measure the performance level for the frequency uncertainty condition, while the cued blocks (block 2, 4, 6) were designed to measure the performance for the frequency certainty condition. Performance in all cued and uncued blocks were averaged across all the subjects.

Table 4.2: Six blocks with uncued and cued conditions

| Block | Conditions | Trials |
|---|---|---|
| 1 | Uncued | 100 |
| 2 | Cued | 100 |
| 3 | Uncued | 100 |
| 4 | Cued | 100 |
| 5 | Uncued | 100 |
| 6 | Cued | 100 |

For the cued trials, cue tone was set at 14 dB above the signal threshold level and was added 500 ms prior to the first observation interval (Figure 4.1). The cue tone had the same frequency and duration as the to-be-detected signal in that trial. The uncued trial was identical to the cued trial (provided in Figure 3.2) except for the presentation of a cue tone.

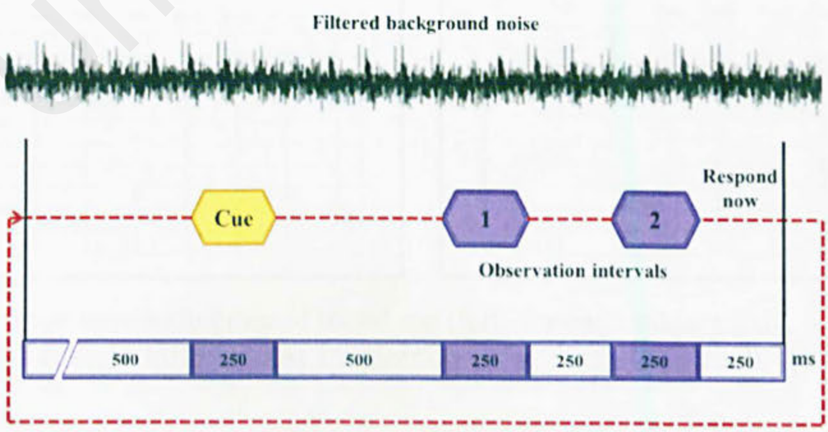



Figure 4.1: Temporal structure of a cued trial.

## 4.3 Results

### 4.3.1 Pure tone audiometry (PTA)

Audiometric results of the chosen ear (left) for the psychophysical experiments for the subjects (AN, KS, NM, NH, NI and WN) are shown in Figure 4.2. Results for their opposite ear (right) are shown in Appendix A. All of the subjects had normal hearing (threshold for both ears were ≤ 20 dB HL at all test frequencies).

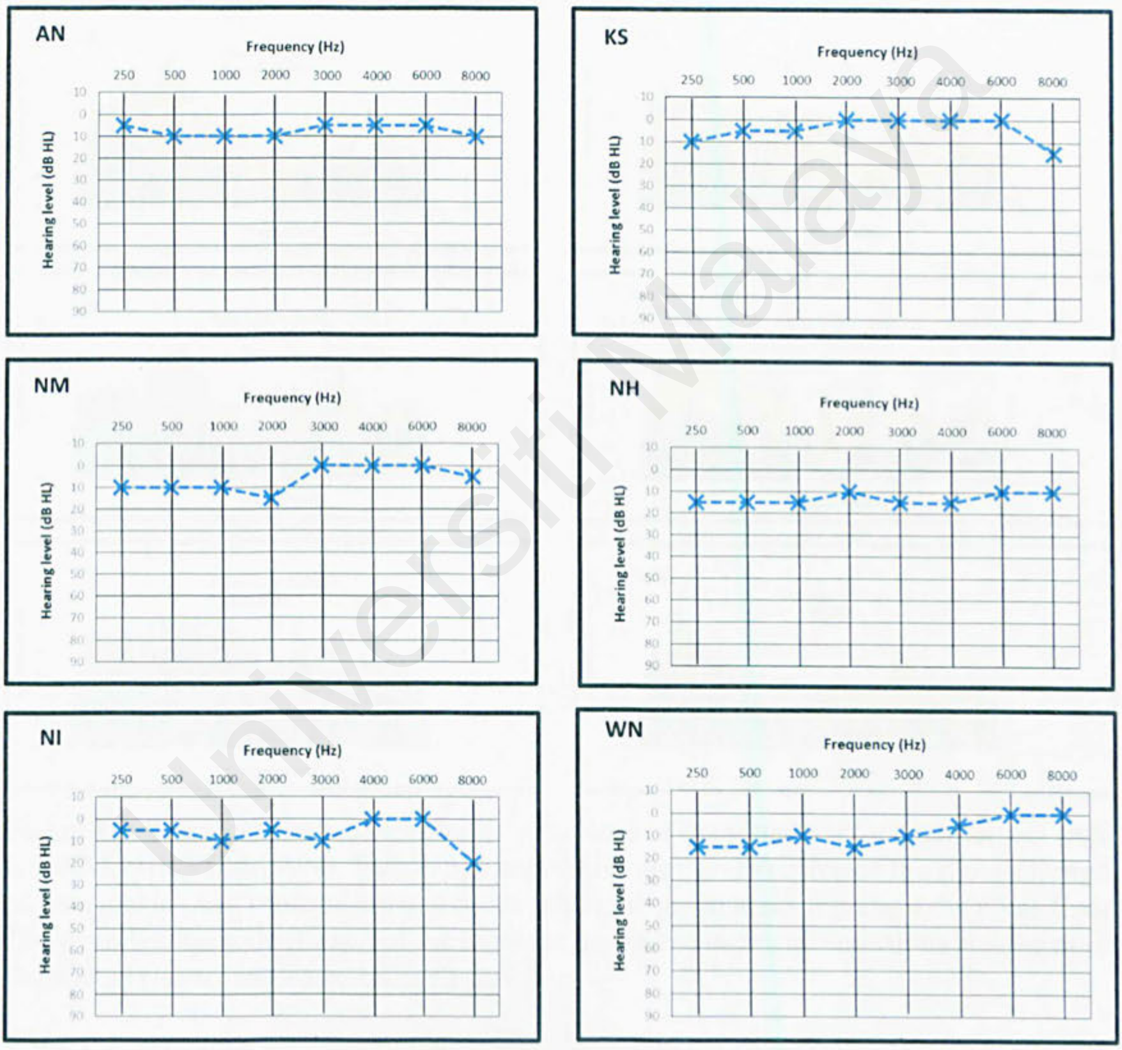



Figure 4.2: Pure tone audiogram of tested ear (left) for each subject (AN, KS, NM, NH, NI and WN) at eight different test frequencies (250, 500, 1000, 2000, 4000, 6000 and 8000 Hz).

### 4.3.2 Transient evoked otoacoustic emissions (TEOAEs)

Figure 4.3 shows the TEOAEs for the tested ear of all the six subjects. TEAOEs results of the opposite ears are shown in Appendix A. All six subjects had clear TEOAE responses exceeding the noise floor, indicating a normal cochlear OHC response (Kemp, 1978). These results are consistent with their normal audiometric results.

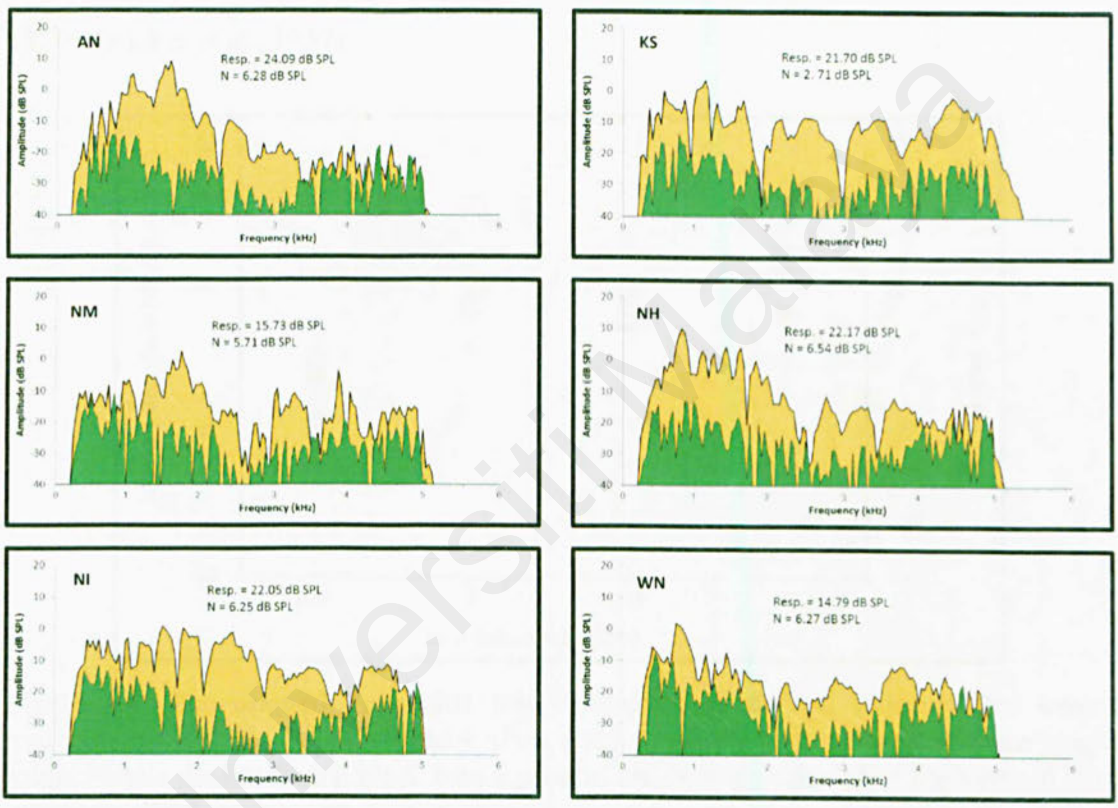



Figure 4.3: Transient evoked otoacoustic emissions of the tested ear for each subject (AN, KS, NM, NH, NI and WN). The orange area under the curves represent the signal strength of transient evoked otoacoustic emissions while the green areas represent the noise floor. The overall amplitude (Resp.) of the transient evoked otoacoustic emissions and the noise floor level (N) are indicated on each panel.

### 4.3.3 Masked thresholds and critical ratios (CRs)

The masked tone threshold level calculated from the threshold tracking procedure, as well as the CR for each subject at four CFs (0.57, 1, 2.15 and 4 kHz) are given in Figure 4.4. The CRs were calculated based on the difference between the masked tone threshold and the spectrum level of the noise at the CF (20 dB SPL). The CRs varied from 15.63 to 22.7 dB across the subjects and CFs. The mean ± SEM (Range) value of the CR for CF tones at 0.57, 1, 2.15 and 4 kHz were 17.3 ± 1.25 (15.63 – 18.64); 20.27 ± 1.48 (18.46 – 21.75); 20.82 ± 1.04 (19.6 – 22.69) and 21.41 ± 1.08 (19.99 – 22.18) dB, respectively. One-way Analysis of Variance (ANOVA) revealed a significant difference of these CR values ($F(3,20) = 13.3$, $p < 0.05$). The increasing value of CR with an increase in tone frequency are in agreement with results from previous studies (Hawkins and Stevens, 1950; Zwicker et al., 1957).

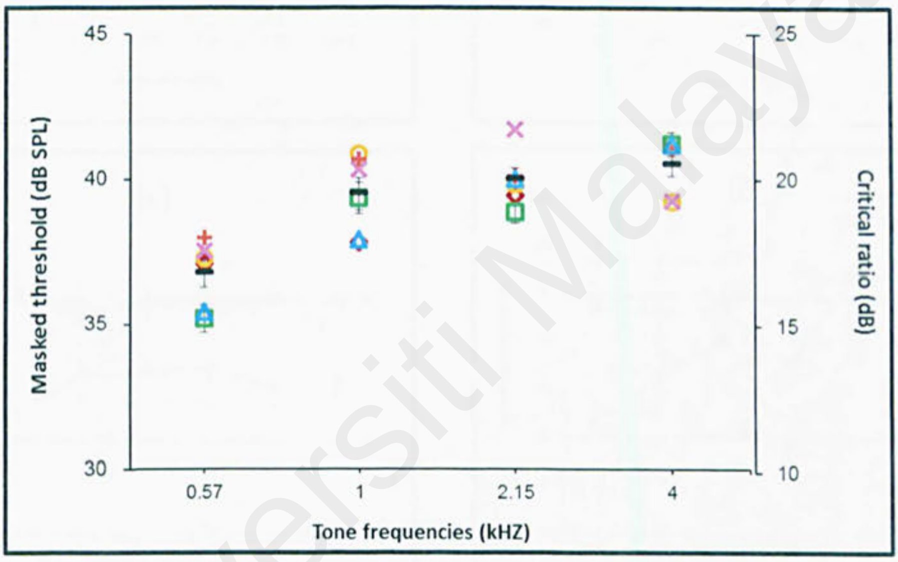



Figure 4.4: The masked thresholds and corresponding critical ratios of the centre frequencies tones (0.57, 1, 2.15 and 4 kHz). Each symbol represents value from a single subject while the horizontal black bars represent the average value (N = 6). Vertical bars indicate ± SEM.

### 4.3.4 Performance during frequency certainty and uncertainty conditions

Figure 4.5 shows the average detection rates in the cued and uncued conditions for each set of signal frequencies centred at 0.57, 1, 2.15 and 4 kHz. The performances of the subjects in the cued conditions (frequency certainty) were consistently better compared to the uncued conditions (frequency uncertainty). The overall detection rates in the cued conditions for all the CFs were close to the expected signal detection level based on the threshold tracking 'one-up, three-down' procedure (79.4%)[6]. However, when the subjects were unsure of the signal frequency (uncued), their overall detection rates deteriorated to about 60 to 65%.

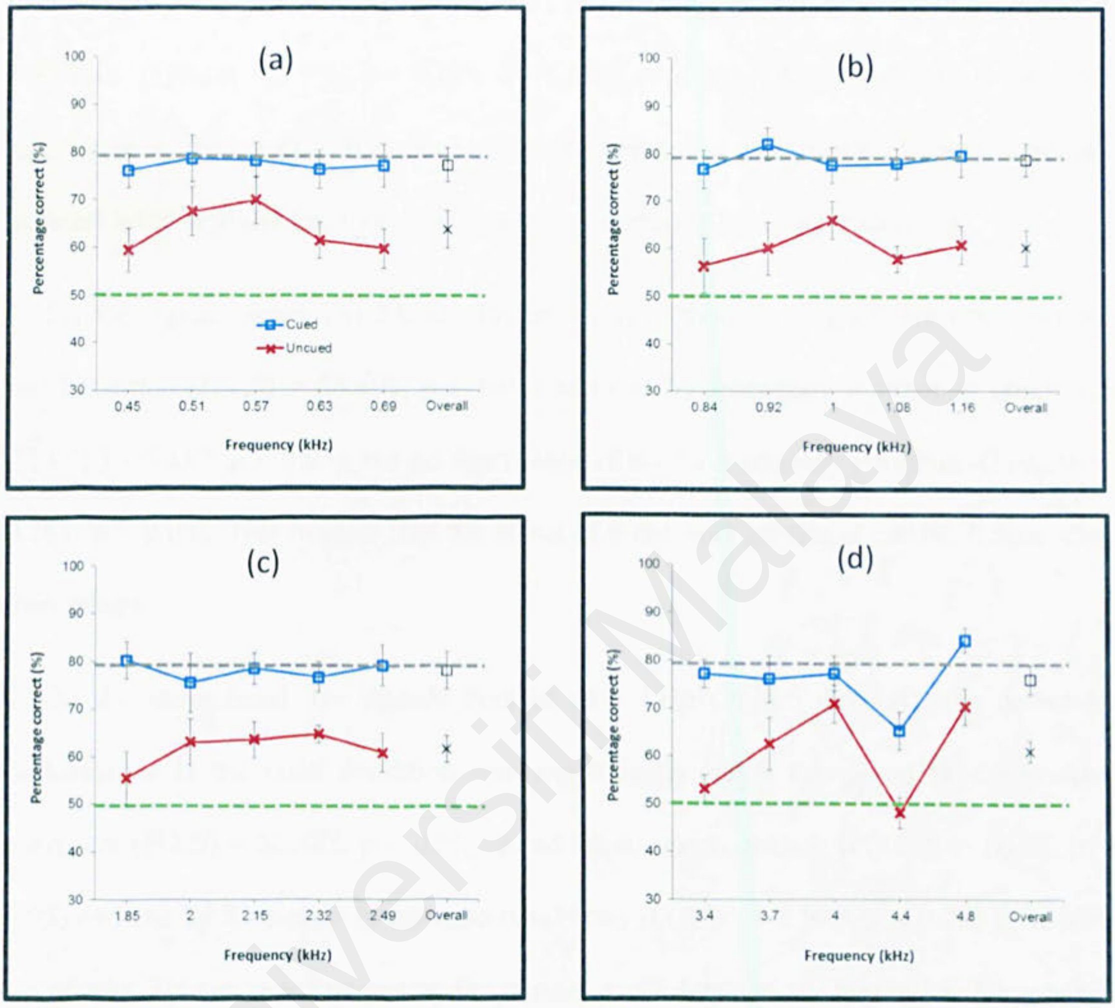



Figure 4.5: Mean percentage (%) correct detection (± SEM) of all subjects (N = 6) using four sets of signal frequencies centred at 0.57 kHz (a), 1 kHz (b), 2.15 kHz (c) and 4 kHz (d). Horizontal grey dotted lines represent the expected signal detection level in the frequency certainty condition based on the threshold tracking (one-up, three-down) procedure (79.4%), while green dotted lines represent the chance level (50 %). The overall columns represent the average detection rates for all five signal frequencies in each panel for cued (□) and uncued (x) conditions (these data points were based on 1800 trials (300 trials per subject).

Two-way repeated measures ANOVA for the data from Figure 4.5 (a) and (b) showed significant effects in cue condition [CF 0.57 kHz: ($F(1,5) = 48.108$, $p < 0.05$), CF 1 kHz:

[6] Since the procedure involved detection of signals in a two-interval forced choice (2IFC) trials at only one centre frequency (CF), the threshold value represents performance of the subject during frequency certainty condition (Levitt, 1971).

($F(1,5) = 37.248$, $p < 0.05$)]. This implies that the presence of preceding cue tones of similar frequencies as the to-be-detected signals during the trials improved the detection of the signals. However, the frequency [CF 0.57 kHz: ($F(4,20) = 2.185$, $p > 0.05$), CF 1 kHz: ($F(4,20) = 1.240$, $p > 0.05$)] and the cue by frequency interaction conditions [CF 0.57 kHz: ($F(4,20) = 1.739$, $p > 0.05$), CF 1 kHz: ($F(4,20) = 2.177$, $p > 0.05$)] were not significant indicating that all the five signal frequencies at each of the CFs were detected at equal levels and the cue tone produced equal effects at all five frequencies.

For the signals centred at 2 kHz, (Figure 4.5 (c)), there is a significant effect on the cue condition ($F(1,5) = 84.498$, $p < 0.05$) and cue by frequency interaction condition ($F(4,20) = 3.217$, $p < 0.05$), but no significant effect for frequency condition ($F(4,20) = 0.261$, $p > 0.05$). This implies that the effect of a cue was greater at certain frequencies than others.

On the other hand, for signals centred at 4 kHz (Figure 4.5 (d)), the detection performance in the cued condition was significantly better compared to the uncued condition ($F(1,5) = 30.387$, $p < 0.05$). In addition, the frequency ($F(4,20) = 10.53$, $p < 0.05$) and cue by frequency interaction conditions ($F(4,20) = 2.949$, $p < 0.05$) were also significant. This implies that certain frequencies were detected at a higher level compared to others, and the effect of the cue was greater at certain frequencies.

Although there are some variability in the statistical analysis of two-way ANOVA for each set of signal frequencies, the main finding for all four data sets indicates that the detection performance in cued conditions were significantly better than the uncued conditions. The analysis of the overall data (last column of each panel in Figure 4.5) for each data set also revealed a similar trend. The average detection rates across all five signal frequencies for the cued conditions were significantly higher than the corresponding average rates in the uncued conditions for all the four CFs (paired t-test, $p < 0.001$).

### 4.3.5 Uncertainty effect

The uncertainty effect at each CF was determined by calculating the difference between the overall detection performance in the cued conditions (frequency certainty) and the uncued conditions (frequency uncertainty) across all five signal frequencies for each subject. Thus, it provides the value of how much (in % signal detection terms) the performance of an individual dropped when he or she switched from listening in a frequency certainty condition to frequency uncertainty condition. Figure 4.6 shows the comparison of the uncertainty effect for each subject at the four sets of signal frequencies centred at 0.57, 1, 2.15 and 4 kHz.

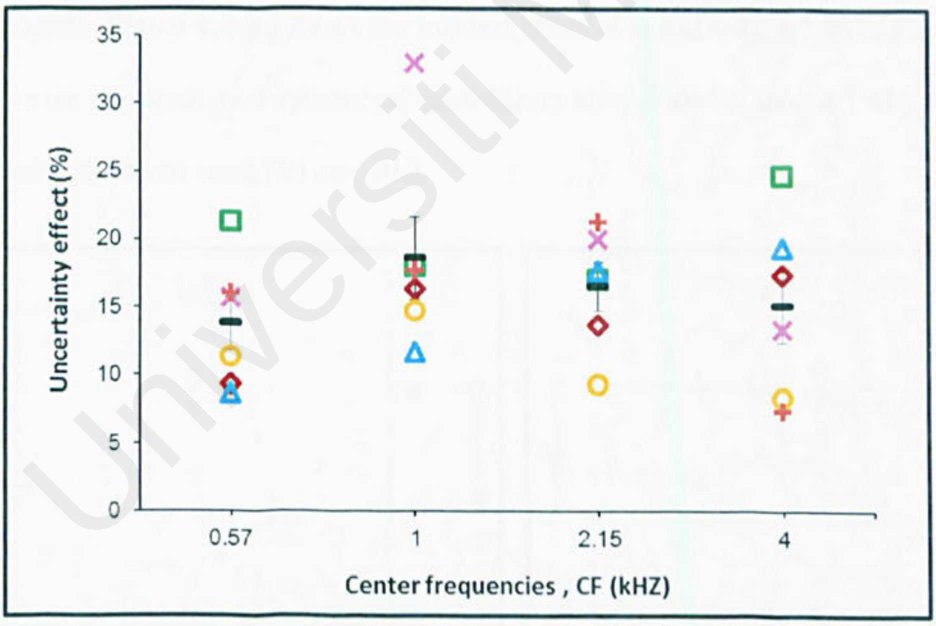



Figure 4.6: Uncertainty effect (%) calculated for signals centred at 0.57, 1, 2.15 and 4 kHz. Each symbol represents data for a single subject while the horizontal black bars represent the average value (N=6). Vertical bars indicate ± SEM.

The uncertainty effect varied from 8.33 to 33% across the subjects and CFs. The average uncertainty effect of all subjects for signal frequencies centred at 0.57 kHz was 13.72 ± 1.98 (8.66 – 21.33) [$M$ ± SEM (Range)] %. For signal frequencies centred at 1, 2.15 and 4 kHz, the average uncertainty effects were 18.55 ± 3.04 (11.66 – 33); 16.5 ± 1.79 (9.33 – 21.33) and 15.06 ± 2.73 (7.34 – 24.67) % respectively. One-way ANOVA revealed that there is no significant difference in the uncertainty effects computed across different CFs ($F(3,20) = 0.719$, $p > 0.05$).

### 4.3.6 Performance during frequency certainty and uncertainty conditions with a higher background noise level

In order to investigate whether the uncertainty effect (difference of performance between frequency certainty and uncertainty conditions) will be altered if a higher background noise level (spectrum level: 30 dB SPL) is used, an additional experiment was conducted using a similar set of signal frequencies centred at 1 kHz in the same set of six subjects. Figure 4.7 (a) shows the masked thresholds and CRs, whereas Figure 4.7 (b) shows the detection performance of the subjects for signals centred at 1 kHz when a higher noise level was used (30 dB SPL).

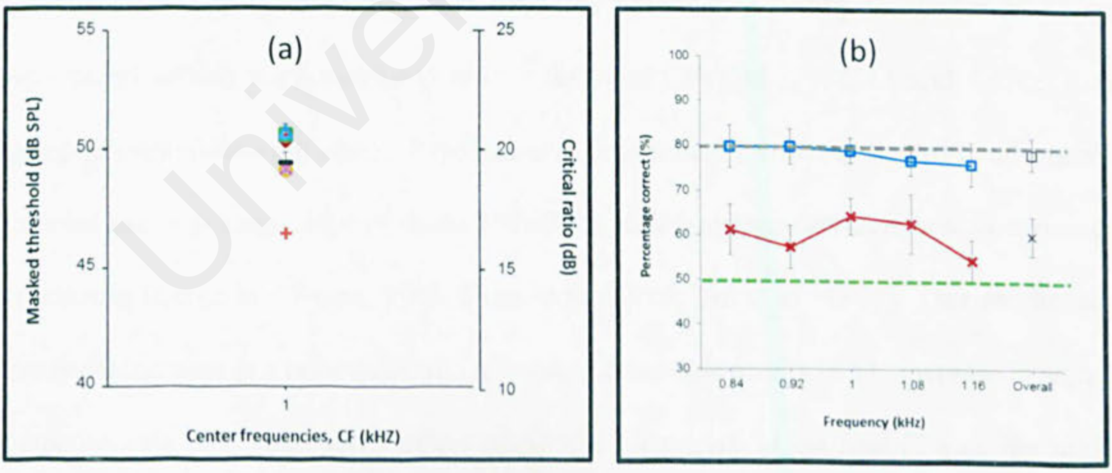



Figure 4.7: (a) The masked threshold and corresponding critical ratios of the tones centred at 1 kHz. Other details are similar to Figure 4.4. (b) Mean percentage correct detection (± SEM) of five signal frequencies centred at 1 kHz for the cued (□) and uncued (x) conditions in 30 dB SPL noise level. Other details are similar to Figure 4.5.

Two-way ANOVA revealed significant effects in the cue condition ($F(1,5) = 18.327$, $p < 0.05$), but not for the frequency ($F(4,20) = 1.732$, $p > 0.05$) and cue by frequency interaction conditions ($F(4,20) = 0.905$, $p > 0.05$). The average uncertainty effect was $20.44 \pm 0.73$ (17.16 – 21.9) [$M \pm$ SEM (Range)] %. Paired t-test revealed that this average uncertainty effect was not significantly different ($p > 0.05$) from the results obtained from the previous experiment involving a similar set of signal frequencies (Figure 4.5 (b)), which used a lower noise level (spectrum level: 20 dB SPL).

## 4.4 Discussion

Studies have shown that signal detection performance can be enhanced in frequency certainty conditions (Tanner and Norman, 1954; Greenberg and Larkin, 1968). When listeners become unaware of the frequency of the to-be-detected signal, their detection performance declines (Green, 1961; Johnson and Hafter, 1980; Buus et al., 1986; Schlauch and Hafter, 1991). In the current study, the difference in signal detection performances during frequency certainty and uncertainty conditions (referred to an uncertainty effect) were measured at four different CFs (0.57, 1, 2.15 and 4 kHz) in a group of normal-hearing adults. Psychometric functions for the detection of tonal signals in noise has an average slope of about 5%/dB for both frequency certainty and uncertainty conditions (Green and Swets, 1966; Buus et al., 1986; Dai et al., 1991). This means that every dB increase in a near-threshold tonal signal in noise results in 5% increase in signal detection rate. The uncertainty effect calculated for signals at the four CFs in this study were; 0.57 kHz: 13.72%, 1 kHz: 18.55%, 2.15 kHz: 16.5% and 4 kHz: 15.06%. Based on the 5%-correct/dB slope value of the psychometric function, the decline in performance detection (in effective stimulus intensity) when frequency uncertainty was introduced corresponds to 2.7 – 3.7 dB at all four CFs (0.57 kHz: 2.74 dB, 1 kHz: 3.71 dB, 2.15 kHz:

3.3 dB and 4 kHz: 3.01 dB). This finding agrees with previous published studies which reported that the maximum effect induced by frequency uncertainty was in the order of 3 – 4 dB (Green, 1961; Scharf et al., 2007; Tan, 2008).

The current study also revealed that the pattern of performance detection in both frequency certainty and uncertainty at all CFs were generally similar. Signals in frequency certainty condition were detected very close to the expected level based on threshold tracking procedure (79.4%), whereas detection levels for signals in frequency uncertainty conditions were reduced to approximately 60 – 65%. A notable exception to this trend is the data obtained for signals centred at 4 kHz. The detection of the 4.4 kHz signal was lower than the expected value in the cued condition, while the detection rates for this signal was close to 50% in the uncued condition (Figure 4.5(d)). Despite the signals being presented with levels that were supposedly equally detectable (Green et al., 1959), statistical test also showed that the signals centred at 4 kHz were the only set that were not detected at equal levels. This deviation is probably due to the signals being situated in the frequency region with large fluctuations in the noise spectrum. The external ear provides more amplification for frequency range between 3 to 5 kHz due to resonance. Such unequal amplification of both the noise and signals may have given rise to more complex results in this condition. Additionally, as the CB increases with the increase in CF, the separation of the signal frequencies used for signals centred at 4 kHz is also larger compared to the signals centred at the remaining three lower CFs (0.57, 1 and 2.15 kHz). Thus, the estimation used to make all the five signals in the 4 kHz CF set equally detectable (Green et al., 1959, see Section 4.3.2) may not be accurate.

Results from the current study also revealed that the uncertainty effect for signal frequencies centred at 1 kHz was the highest compared to the other CFs. An equivalent effect was also present even when a higher spectrum level of background noise was used

(20 dB SPL: 18.55%, 30 dB SPL: 18.33%). This finding is important because signal frequencies centred at 1 kHz presented at a higher level of background noise (30 dB SPL) was used in the next experiment.

# CHAPTER 5: COMPARISON OF PERFORMANCE DURING FREQUENCY CERTAINTY (CUED) AND UNCERTAINTY (UNCUED) CONDITIONS BETWEEN NORMAL-HEARING AND HEARING-IMPAIRED SUBJECTS

## 5.1 Introduction

As discussed in the review chapter, frequency certainty improves the hearing sensitivity of an individual about one CB around the CF via a selective attentional process (Greenberg and Larkin, 1968; Scharf, 1970; Dai et al., 1991). Although the underlying mechanism is unclear, the process is likely to be dependent on the normal functioning of the cochlea, particularly the active mechanism of the OHCs (Moore, 2007a; Tan, 2008). The integrity of the cochlear OHCs is crucial for the sharp tuning on the BM and high frequency selectivity, as well as normal hearing sensitivity to weak or near-threshold sounds (Moore, 2007a).

Individuals with SNHL usually have difficulty in understanding speech, especially in the presence of background noise. One possible reason for this is the deterioration of the cochlear frequency tuning in these patients (Liberman, Dodds and Learson, 1986). Patients with SNHL, particularly those with OHCs loss, have broader CBs and auditory filters (Florentine et al., 1980, Patterson et al., 1982; Glasberg and Moore, 1986). As the attention-mediated selective frequency listening process is likely to be dependent on the peripheral auditory filters (Dai et al., 1991; Moore, 1995), the broadening of the filter could have adverse effects on their performance during such tasks.

In the current study, the performance in frequency certainty and uncertainty conditions of a group of mild-to-moderate SNHL patients were compared with their age- and sex-matched normal-hearing controls. In order to relate the changes of subjects' performance with alteration of their auditory filter mechanism, the uncertainty effect obtained in these subjects were correlated with a measure of frequency selectivity; the CR. The CR is considered as an indirect estimate of the auditory filter bandwidth (see review chapter, Section 2.3.4 for further details) and thus is reflective of the underlying cochlear frequency selectivity.

## 5.2 Materials and methods

Except for the descriptions provided below, all other details are similar to those described in general methods (Chapter 3) and methods of Chapter 4.

### 5.2.1 Subjects

Eight hearing-impaired adults (2 males and 6 females) aged 23 to 40 years participated in this experiment. They were recruited from the Audiology Clinic, University Malaya Medical Centre (UMMC). Their hearing loss was classified as mild to moderate bilateral SNHL based on their clinical history, normal tympanogram results and their audiogram results including the absence of air-born gap[7]. The aetiology of the hearing loss included genetic factor (family history), exposure to loud noise and congenital with unknown cause. None of them reported long-term tinnitus or had been using any hearing aids.

Eight age- and sex-matched normal-hearing subjects were recruited as controls. Two of the normal-hearing subjects were the same subjects that participated in the first study (Chapter 4), while the remaining subjects were paid volunteers recruited from an email advertisement send via the UM student email group. None of the subjects had physical disabilities or chronic medical conditions.

[7] These were confirmed by the audiologists at the Audiology Clinic in UMMC.

### 5.2.2 Audiological and psychophysical testings

Both the hearing-impaired and normal-hearing groups underwent PTA and OAE tests. The testing procedures were similar to the methods described in Section 3.2.1. and Section 3.2.2. Subsequently, they underwent the psychophysical testing which includes the threshold tracking procedure and six blocks of 2IFC trials (three uncued and three cued blocks). These testing were identical to the procedures described in Section 3.2.2.1 and Section 4.2.3. However, only signals centred at 1 kHz (0.84, 0.92, 1, 1.08, 1.16 kHz) were used and the background noise level was set at spectrum level of 30 dB SPL at 1 kHz (bandwidth of the noise is 520 to 1480 Hz) (see Section 2.3.2, Table 2.1). All subjects including the hearing-impaired patients could clearly hear the background noise.

Since the background noise stimulus levels used in this study was higher, the opposite ear of the normal-hearing subjects were plugged with soft and appropriate-sized ear tip to prevent a possible 'leakage' of the sound to the untested ear. The ear chosen for the psychophysical testing in the hearing-impaired subjects was based on their audiogram results (PTA thresholds between 30 to 40 dB HL at 1 kHz). The test ear of normal-hearing subjects were then matched with those chosen for hearing-impaired subjects.

## 5.3 Results

### 5.3.1 Pure tone audiometry (PTA)

Audiometric results of the tested ears for the normal hearing (ET, FI, SG, AN, KX, NM, TN and YH) and hearing-impaired (FN, FR, KV, TL, SC, JY, SH and MB) subjects are shown in Figure 5.1 and Figure 5.2. Audiometric results of the opposite ears for the same subjects are shown in Appendix B (except for AN and NM as their audiograms were provided in Section 4.3.1). Hearing thresholds of the normal-hearing subjects were ≤20 dB HL at 1 kHz test frequency. All hearing-impaired subjects were classified as having mild-to-moderate hearing loss (although their PTA thresholds were worse at other test frequencies, the thresholds for all the subjects at 1000 Hz were between 30 to 35 dB HL).

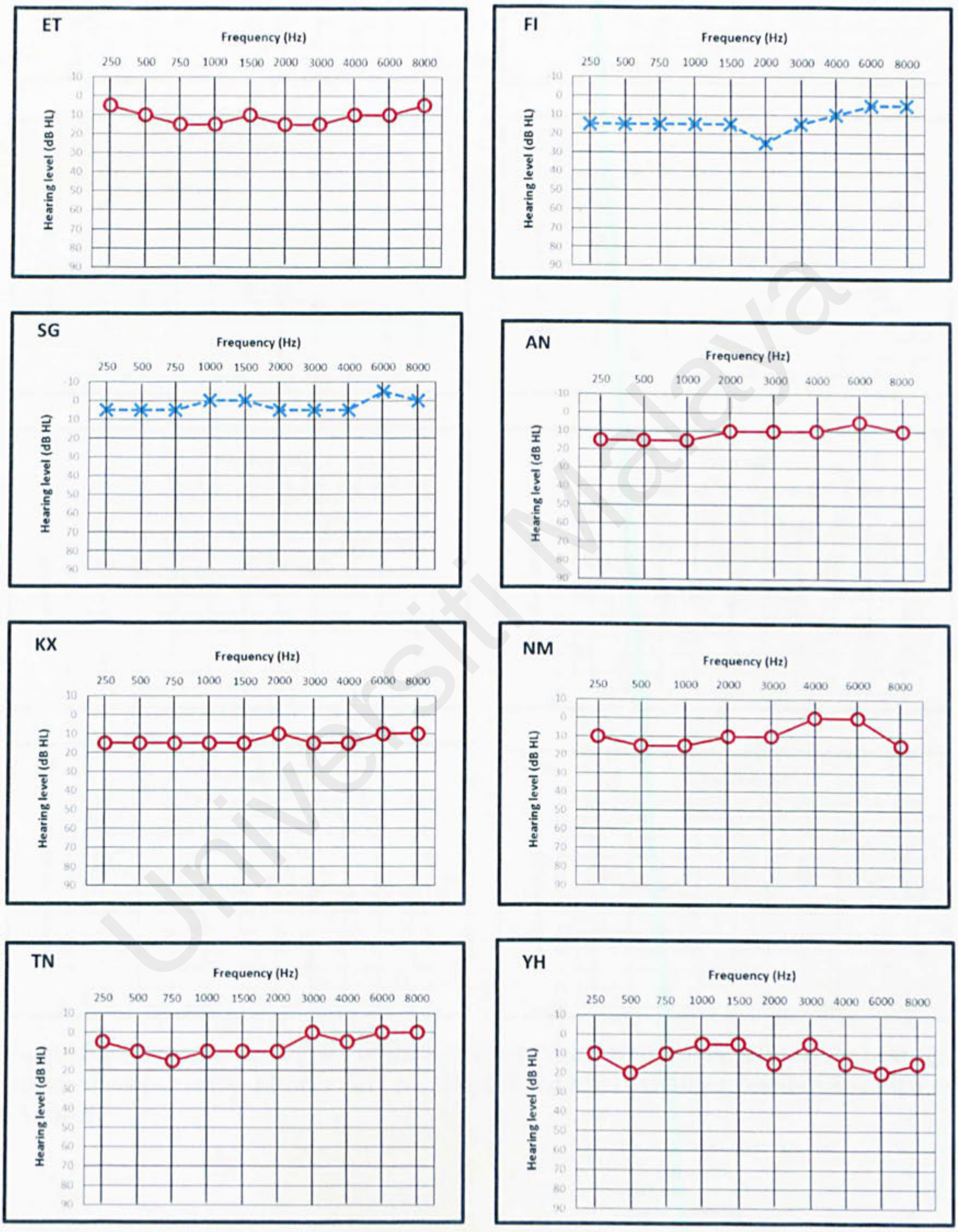



Figure 5.1: Pure tone audiogram of the tested ear [either right (o) or left (x)] for normal-hearing (ET, FI, SG, AN, KX, NM, TN and NH). The hearing threshold (dB HL) were measured at ten different test frequencies (250, 500, 750, 1000, 1500, 2000, 4000, 6000 and 8000 Hz) for all subjects except for AN and NM (their audiogram were taken from the previous experiment).

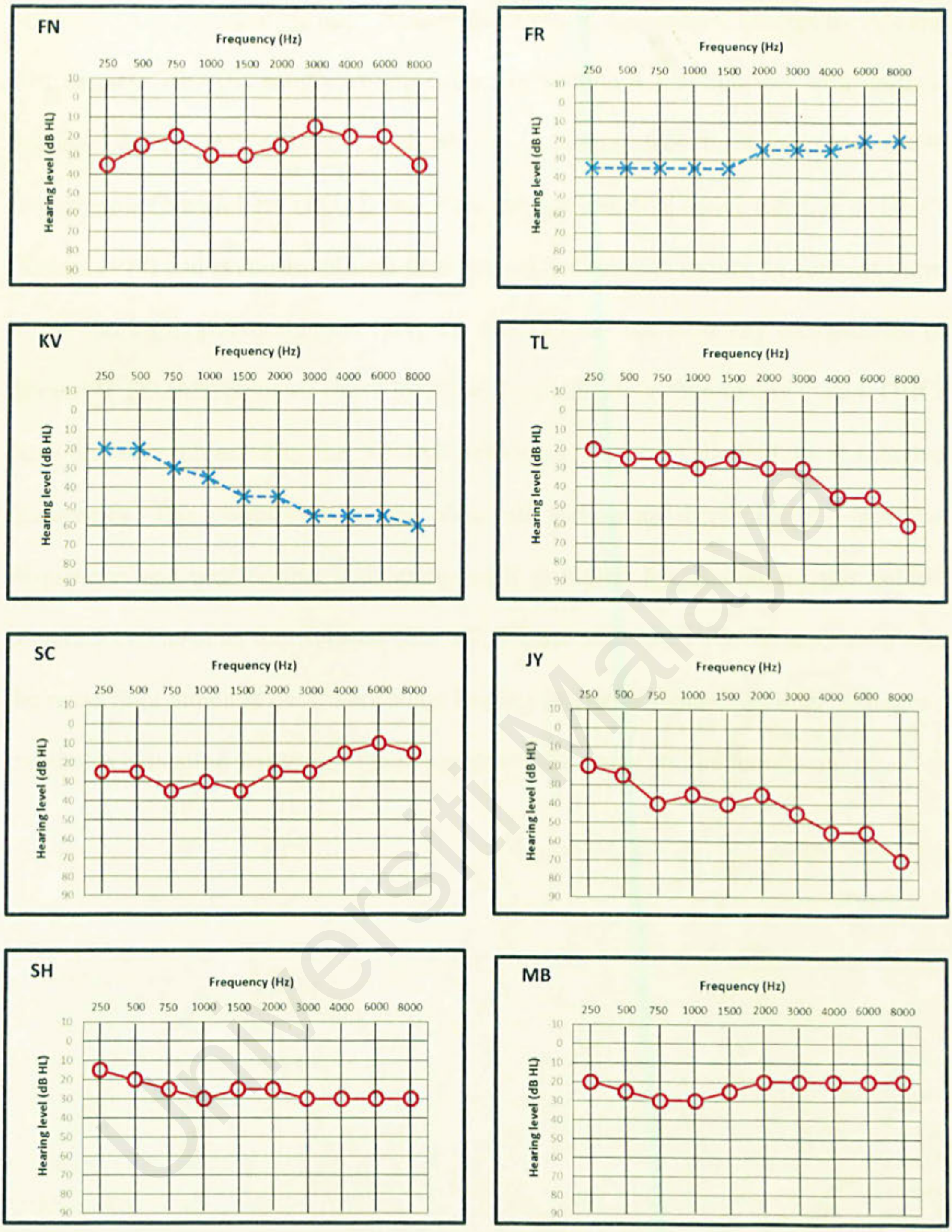



Figure 5.2: Pure tone audiogram of the tested ear [either right (o) or left (x)] for hearing-impaired subjects (FN, FR, KV, TL, SC, JY, SH and MB). All other details are similar to Figure 5.1.



### 5.3.2 Transient evoked otoacoustic emissions (TEOAEs)

Figure 5.3 and Figure 5.4 show the TEOAE recordings of normal-hearing (ET, FI, SG, AN, KX, NM, TN and YH) and hearing-impaired subjects (FN, FR, KV, TL, SC, JY, SH, MB). TEOAEs results of the opposite ears are shown in Appendix C (except for AN and NM as their TEOAEs results were provided in Section 4.3.2. Subjects with normal-hearing had TEOAE responses well above the noise floor throughout the tested frequencies. These robust TEOAE responses indicate a normal active function of OHCs (Kemp, 1978) and is consistent with their normal audiometric results. In contrast, three of the hearing-impaired subjects (KV, TL and JY) did not have any recognizable or detectable TEOAE responses above the noise floor indicating abnormality in their OHCs function. For subject FR, the TEOAE responses was only limited to the higher frequencies. This corresponds to the abnormal audiogram thresholds at lower test frequencies and near normal audiogram result at higher frequencies for this subject (Figure 5.2). The other four subjects (FN, SC, SH and MB) had TEOAE responses above the noise floor although there were some hearing impairment based on their audiogram thresholds indicating that some of their cochlear OHCs may still be functioning.

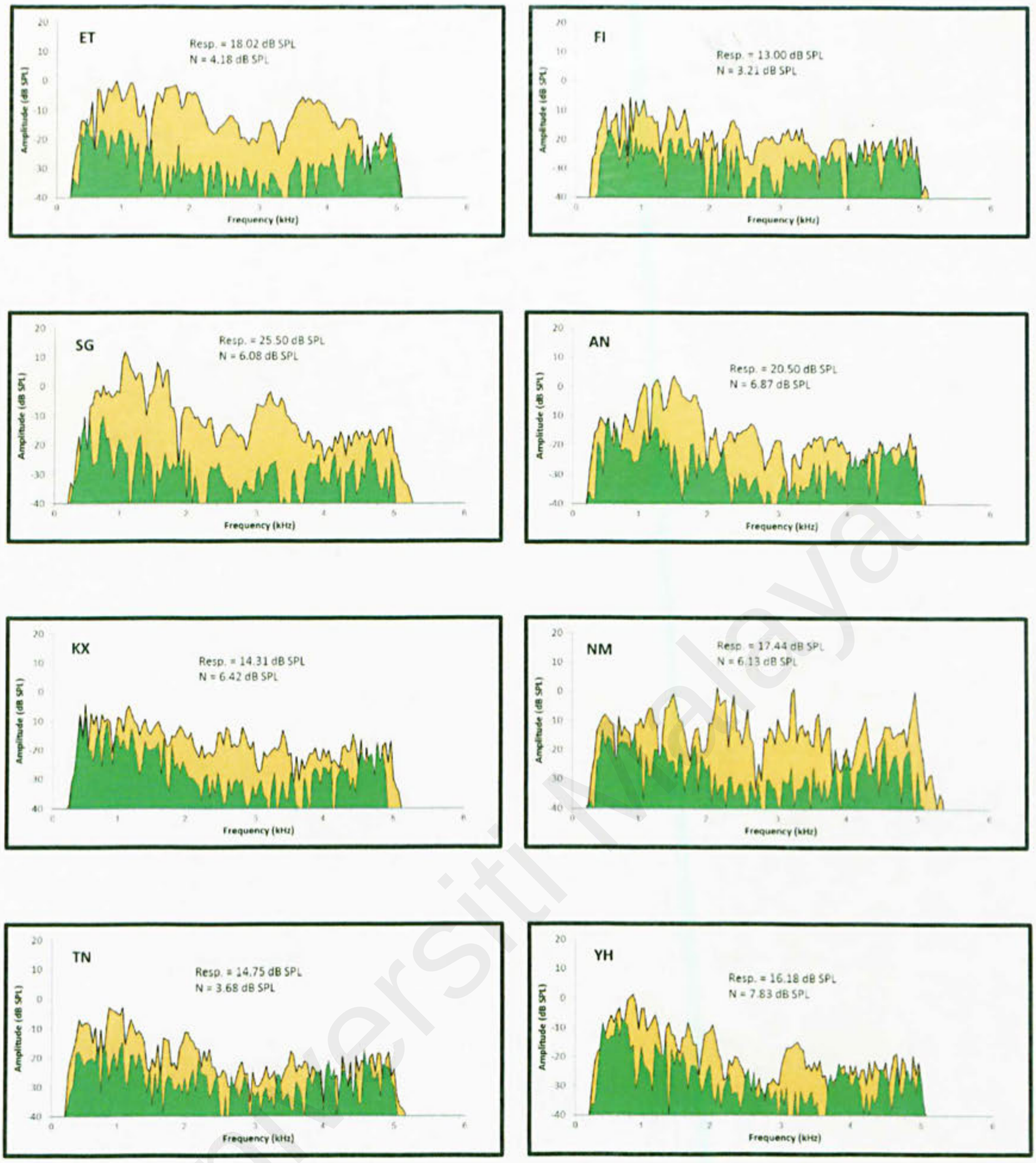



Figure 5.3: Transient evoked otoacoustic emissions of tested ear for normal hearing (ET, FI, SG, AN, KX, NM, TN and NH). The orange area under the curves represents the signal strength and the green area represents the noise floor. The overall amplitude (Resp.) of transient evoked otoacoustic emissions and the noise floor (N) are indicates on each panel.

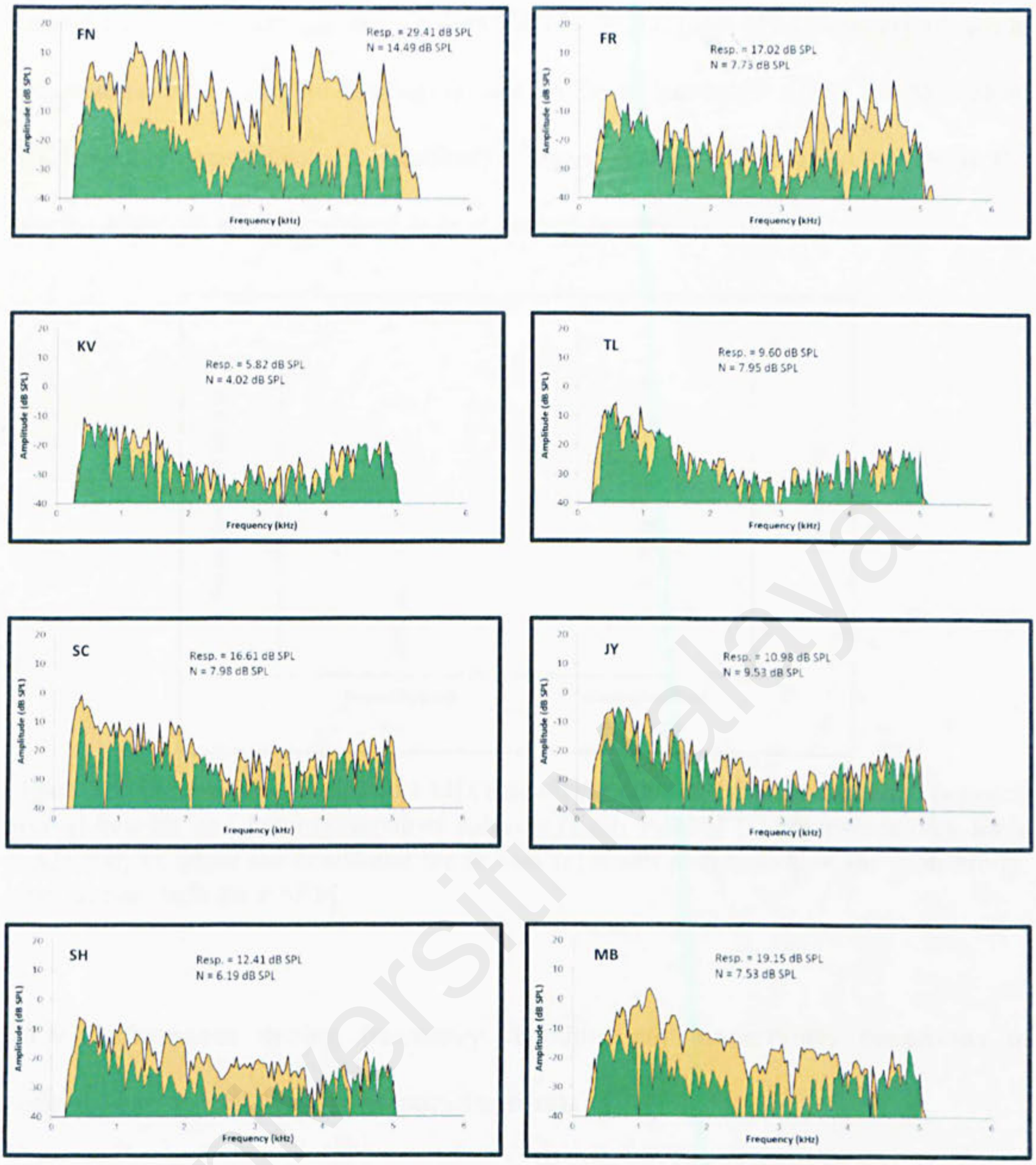



Figure 5.4: Transient evoked otoacoustic emissions of tested ear for hearing-impaired subject (FN, FR, KV, TL, SC, JY, SH and MB). All other details are similar to Figure 5.3

### 5.3.3 Masked thresholds and critical ratios (CRs) in normal-hearing and hearing-impaired subjects

The masked 1 kHz tone thresholds calculated from the threshold tracking procedure, as well as the CRs for each subject (both normal-hearing and hearing-impaired) are given in Figure 5.5. The CRs were calculated based on the difference between the masked threshold and the spectrum level of the noise at the CF (30 dB SPL). The average CR for normal-hearing subjects was 21.74 ± 0.33 (20.74 – 23.72) [$M$ ± SEM (Range)] dB, while the corresponding value for hearing-impaired subjects was 24.59 ± 0.65 (22.85 – 28.9) dB. Unpaired t-test revealed a significantly higher average CR value ($p < 0.05$) in the hearing-impaired group compared to their normal-hearing controls.

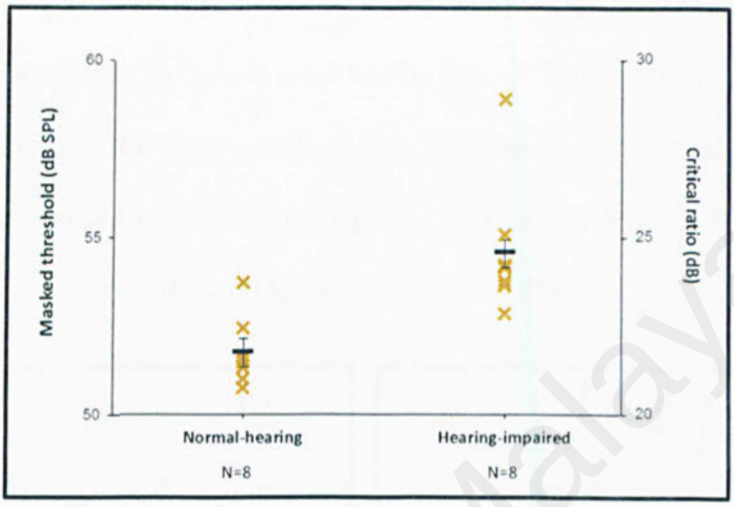



Figure 5.5: Comparison of masked 1 kHz tone thresholds and critical ratios (dB) between normal-hearing and hearing-impaired subjects. Each symbol (x) represents data for a single subject while the horizontal black bars represent average value for each group. Vertical bars indicate ± SEM.

### 5.3.4 Performance during frequency certainty and uncertainty conditions in normal-hearing and hearing-impaired subjects

Figure 5.6 shows the detection rates of the five tones (0.84, 0.92, 1, 1.08 and 1.16 kHz) centred at 1 kHz for cued and uncued conditions for both normal hearing (a) and hearing-impaired (b) subjects.

Although both groups showed better performances in the cued condition compared to the uncued condition, the differences were smaller in the hearing-impaired subjects compared to the normal-hearing controls. The overall % correct detection for normal-hearing subjects dropped from 81.38% in the cued condition to 62.92% in the uncued condition. In contrast, the overall % correct detection in cued and uncued conditions for hearing-impaired subjects were 78.42% and 71.12% respectively. For the normal-hearing group, analysis using two-way repeated measures ANOVA showed significant effects in cue ($F(1,7) = 63.705$, $p < 0.05$) and frequency conditions ($F(4,28) = 5.348$, $p < 0.05$). However, the effect of frequency conditions was small with positive value of Partial Eta Squred of 0.433. Analysis of cue by frequency interaction revealed no significant effect ($F(4,28) = 1.716$, $p > 0.05$). A similar analysis for hearing-impaired group also showed a slightly significant effect for the cue condition ($F(1,7) = 7.299$, $p < 0.05$), but the p-value was larger (0.03) than the corresponding value obtained for the normal-hearing group. There was no significant effects for the frequency ($F(4,28) = 0.439$, $p > 0.05$) and cue by frequency interaction conditions ($F(4,28) = 0.609$, $p > 0.05$).

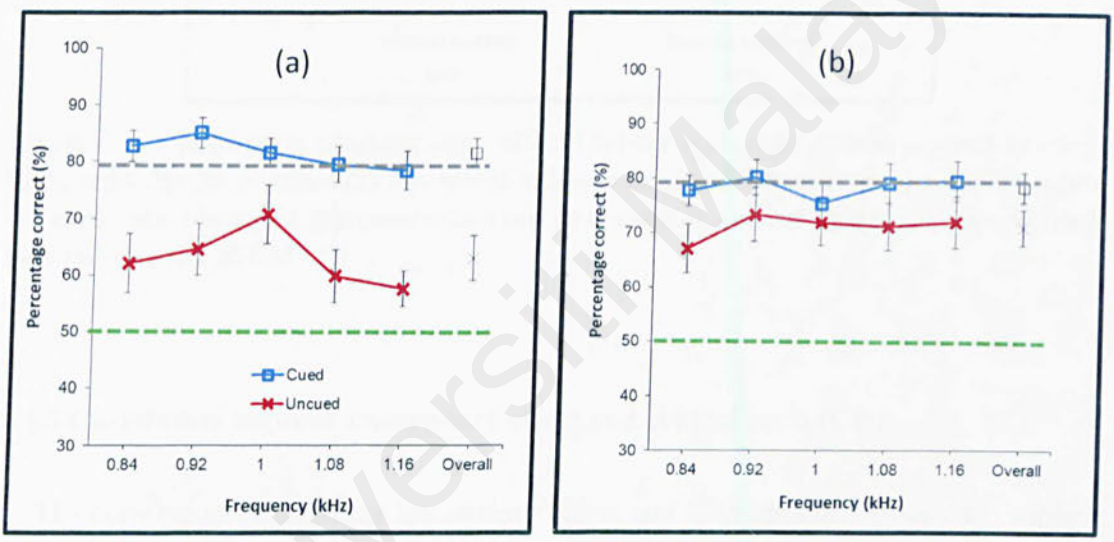



Figure 5.6: Mean % correct detection (± SEM) of signal frequencies centred at 1 kHz in (a) normal-hearing (N=8) and (b) hearing-impaired (N=8) subjects for cued (□) and uncued (x) conditions. Data points in the overall columns for cued and uncued conditions were based on 2400 trials (300 trials per subject). All other details are similar in Figure 4.5.



The uncertainty effects (performance in frequency certainty – performance in frequency uncertainty) for individual subjects in both groups are given in Figure 5.7. The uncertainty effect for normal-hearing subject (18.46%) is very close to the results obtained in the previous experiment (Chapter 4) for signals centred at 1 kHz (18.55%). The uncertainty effect for the hearing-impaired group was significantly smaller (unpaired t-test, $p < 0.05$) [7.29 ± 7.63 (-5 – 19.67)] % [$M \pm SD$ (Range)] %, compared to the effects seen in the normal-hearing group (18.46 ± 6.54 (10 – 30.33)). One subject in the hearing-impaired group had a slightly better detection (about 5%) of the uncued signals compared to the cued ones which resulted to a negative uncertainty effect value.

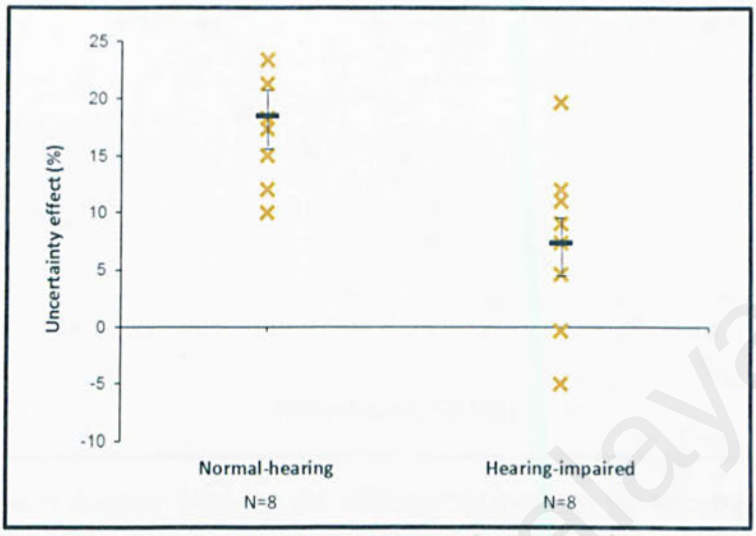



Figure 5.7: Comparison of uncertainty effect (%) between normal-hearing and hearing-impaired subjects. Symbol (x) represents values calculated for individual subjects, while the horizontal black line represents the average uncertainty effect for each group. Vertical bars indicate the ±SEM.

### 5.3.5 Correlation between uncertainty effect and critical ratio (CR)

The correlation between the uncertainty effect and CRs obtained from each subject (data of both normal-hearing and hearing-impaired groups were pooled together) is shown in Figure 5.8. The data points in the figure are scattered in two parts. The upper part constitutes data obtained mostly from the normal-hearing subjects, whereas the lower part represents data from mostly hearing-impaired subjects. There was a strong significant negative correlation between the uncertainty effect and CRs among the subjects (Pearson correlation test, $p < 0.0001$). This implies that an individual with a higher CR tends to have a smaller uncertainty effect during the task.

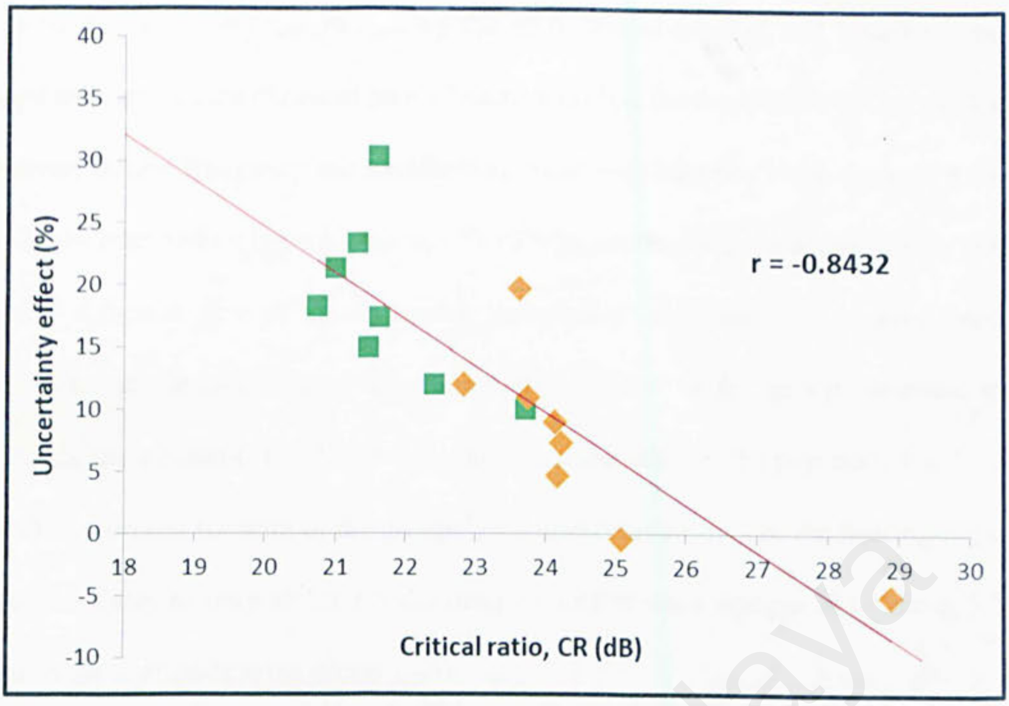



Figure 5.8: Scatter diagram showing the relationship between the uncertainty effect (%) and critical ratio (dB). Green symbol represents normal-hearing subjects while orange symbol represents hearing-impaired subjects (N=16). The red line represent the line of best fit for the linear regression.

**5.4 Discussion**

Results obtained from the current study revealed that CRs in SNHL subjects were significantly higher compared to the normal-hearing subjects. This finding agrees with previous published studies (Margolis and Goldberg, 1980; Phillips, Gordon-Salant, Fitzgibbons and Yeni-Komshian, 2000). An increase in the CR indicates broadening of their peripheral auditory filters (refer Section 2.3.4) (Florentine et al., 1980; Patterson et al., 1982; Hall and Fernandes, 1983; Glasberg and Moore, 1986; Horst, 1987). At least four of the SNHL subjects had abnormal TEOAE recordings, indicating that these subjects had impairment of their cochlear OHCs. A loss of OHCs active mechanism can lead to broadening of BM tuning curves which could subsequently reduce the resolving frequency power of the cochlea (Florentine et al., 1980; Pickles, 1988; Dobie and Van Hemel, 2005).

Performance in frequency certainty for both normal-hearing and hearing-impaired groups were around the expected level (79.4%) based on the threshold tracking procedure. However, during frequency uncertainty condition, the detection rates dropped to about 62.92% in normal-hearing subjects and 71.12% in hearing-impaired subjects. A smaller drop of detection rate in the frequency uncertainty conditions for hearing-impaired subjects led to a smaller overall uncertainty effect (7.3%) in this group compared to the normal-hearing controls (18.46%). Assuming that the slope of the psychometric function (5%/dB) is similar for both of the groups[8], the uncertainty effect in the hearing-impaired group translates to only about 1.5 dB drop in performance compared to about 3.7 dB effect in the normal-hearing group.

One previous study have investigated the difference in frequency certainty and frequency uncertainty effects in a group of SNHL subjects (Tan, 2008). Using a similar psychophysical testing paradigm and sound stimuli, Tan (2008) reported that five SNHL patients had < 5% difference between the average detection rates in frequency certainty and uncertainty conditions. Since many of his patients had severe hearing loss (> 60 dB HL) with hardly any OAE responses, he also attributed his findings to the impairment of their cochlear OHCs mechanism. However, comparison of his results with normal-hearing subjects were confounded by the usage of different levels of tones and background noise. The stimuli used for hearing-impaired were much higher than the normal-hearing controls as their hearing impairment was severe. As discussed in the review chapter (Section 2.3.3), a higher signal level would lead to a broader auditory filters and this could confound the results.

[8] Although large variations in the slope of psychometric function of hearing-impaired listeners were reported in the literature, the average slope values were usually not significantly different from those obtained from normal-hearing subjects (Marshall and Jesteadt, 1986; Arehart, Burns and Schlauch, 1990).

In the present study, we only selected subjects with mild-to-moderate SNHL. Although many of these subjects could have some degree of intact OHCs (evidence by presence of OAEs responses), the results appeared to mirror Tan's findings. The difference between the performance in frequency certainty and frequency uncertainty conditions were reduced compared to controls. This difference was found despite using similar stimuli levels for both groups. Tan did compare the uncertainty effects in his subjects against their audiometric thresholds and OAEs amplitudes, but did not find any significant correlations of the effect with these measures. However, he did not perform any further correlation with any measures of frequency selectivity. The current study is the first to show the relationship between CR and the change in uncertainty effect in normal-hearing and hearing-impaired human subjects.

Lyregaard (1982) suggested that the basic measure of hearing acuity should be a measure of frequency selectivity rather than a measure of absolute sensitivity. Accordingly, in the current study, the performance of the subjects were correlated with the measure of frequency selectivity, the CRs. It was observed that subjects with higher CRs had smaller differences in their detection performance between frequency certainty and frequency uncertainty conditions. This resulted from a higher detection rates in the frequency uncertainty condition compared to the control group. As the CR is an indirect estimate of the auditory filter bandwidth (see the review section), it is very likely that broadening of their peripheral auditory filters due to the impairment of frequency tuning of the cochlea contributed to this change. Further explanation about the reduction in uncertainty effect and its implications in real-world listening in SNHL patients are discussed in the next chapter.

# CHAPTER 6: GENERAL DISCUSSION AND CONCLUSION

## 6.1 Summary of findings

The results obtained from the two separate studies can be summarized as follows:

1) Performance in frequency certainty (cued condition) was better compared to the performance in frequency uncertainty (uncued condition) when the normal-hearing subjects were tested at four different CFs (0.57, 1, 2.15 and 4 kHz). Across the four sets of stimuli used, the differences in the detection rates between these two conditions (defined as uncertainty effect) was estimated to be 2.7 – 3.7 dB in equivalent sound level. This agrees with previously published data (Green, 1961; Scharf et al., 2007; Tan, 2008).
2) When a similar task was carried out by a group of SNHL patients, their average uncertainty effect was smaller (≈1.5 dB) compared to their age- and sex-matched controls (≈3.7 dB).
3) Furthermore, when the data from both normal-hearing and SNHL subjects were pooled together, the change in the detection rates from frequency certainty to frequency uncertainty conditions (uncertainty effect) was negatively correlated with the increase in CR in these subjects.
4) As a higher CR indicates poorer cochlear frequency selectivity, the loss of uncertainty effect in the hearing-impaired is likely to be related to the worsening of the peripheral frequency selectivity. At least in some of the SNHL subjects, this could be a result of cochlear OHCs impairment evidenced by a loss or decrease in their TEOAE responses.
5) The main outcome and novel finding of this study is the significant negative relationship between CR of normal-hearing and hearing-impaired subjects and

their corresponding uncertainty effect obtained from the psychophysical experiments.

## 6.2 Physiological mechanism for frequency selective listening

Frequency selectivity of an individual is dependent on the tuning on the BM which provides a physiological basis for the peripheral auditory filters (Moore, 2007a). Specifically, frequency selectivity is likely to be closely related to the width of these filters (Fletcher, 1940; Zwicker et al., 1957; Patterson, 1976). Narrow or sharply-tuned filters provide a better frequency selectivity, whereas broadly-tuned filters reduces it (Moore, 2007a). As the cochlear tonotopic arrangement is preserved up to the auditory cortical areas, it is expected that the peripheral filters are also represented at the higher order centres. As discussed earlier in the review section, it is assumed that during frequency certainty condition, an individual is able to focus on a single auditory filter centred at the frequency of the signal of interest (Greenberg and Larkin, 1968). This focusing is likely facilitated by the auditory areas of the cortex (Woldorff and Hillyard, 1991; Paltoglou, Sumner and Hall, 2009; Mikyska, 2012; Da Costa, van der Zwaag, Miller, Clarke and Melissa, 2013).

In 1973, Hillyard and colleagues reported that the N1 component in auditory event-related potential (ERP) was larger in amplitude for the attended sound stimuli compared to the ignored ones (Hillyard, Hink, Schwent and Picton, 1973). Since N1 component of the ERP is generated by the auditory cortex (Vaughan and Ritter, 1970), they suggested that there is enhanced activation of auditory cortical neurons due to the attentional effects (Hillyard et al., 1973). Since then, other electrophysiological studies have verified and extended their findings (Woldorff, Gallen, Hampson, Hillyard, Pantev, Sobel and Bloom, 1993; Yago, Escera, Alho and Giard, 2001; Mikyska, 2012).

More recently, several imaging studies have also showed that the neuronal responses to auditory signals with expected frequencies were enhanced. For example, in 2009, Paltoglou and colleagues carried out a study to measure human's brain activity when attending to specific sound frequency. They examined the response properties of neurons in the auditory cortex using functional magnetic resonance imaging (fMRI). Their results showed that the most consistent frequency-dependent responses during frequency-specific listening occurred in the area of primary auditory cortex (Paltoglou et al., 2009). A more thorough imaging study in frequency-specific modulation of auditory cortex was done by Da Costa and colleagues in 2013. Using high resolution and fine-scaled frequency mapping, they demonstrated that neural activity within the primary auditory cortex is strongly and dynamically modulated by attention (Da Costa et al., 2013). When their subjects attended to a particular sound frequency, the neuronal response within the related auditory cortex sensitive to that frequency is enhanced (Da Costa et al., 2013). They suggested that primary auditory cortex is able to tune into the attended frequency channel and rapidly switch to other channels to meet the task demands (Da Costa et al., 2013). This agrees with the findings from the current study which showed that a cue tone which was presented at the beginning of each trial could help the listener to focus on the subsequent signal although the cue and to-be-detected signals were varied from trial to trial.

The tuning of the auditory cortical neurons to the attended signal frequency could be related to the stimulus-specific reshaping of neuronal receptive fields (Kauramaki, Jaaskelainen and Sams, 2007; Jaaskelainen and Ahveninen, 2014). Using human subjects, Kauramaki and colleagues demonstrated that selective auditory attention not only increases the neuronal response in the auditory cortex, but also the tuning of its receptive fields (Kauramaki et al., 2007). Narrowing of their receptive fields (Fritz, Shamma, Elhilali and Klein, 2003; Kauramaki et al., 2007) have been argued to improve the hearing sensitivity of an individual to the expected signal frequency and enhance the detection of target sounds (Fritz et al., 2003). The transient and rapid changes in the neuronal receptive fields occurring in auditory cortical neurons due to a shift in attentional effect is likely related to short-term neuroplasticity as the effect only takes seconds to occur (Jaaskelainen and Ahveninen, 2014). However, it is important to remember that the observed neuronal modulation in the primary areas of auditory cortex does not necessarily mean that only this structure is involved. Inputs from other areas including non-primary auditory areas (Paltoglou et al., 2009) and even lower subcortical auditory centers (Slee and David, 2015) may also play a role in the process of auditory attention. Additionally, descending auditory efferent pathways, particularly the medial olivocochlear system (MOCS) has also been suggested to play an important role in selective frequency listening task (Tan, 2008; Smith, Aouad and Keil, 2012), including the generation of auditory attentional filters (Scharf, Magnan, Collet, Ulmer and Chays, 1994; Scharf, Magnan and Chays, 1997). However, the interplay of both the higher auditory centers and the efferent system and its underlying mechanism in aiding the detection of auditory signals in noise remains unclear (Giard et al., 2000).

### 6.3 Possible mechanism underlying frequency certainty and uncertainty effects

As discussed in Section 6.2., the neural mechanism for frequency-specific attentional effects reported in the current study is likely to be related to the short-term neural modulation at the auditory cortical areas (Fritz et al., 2003; Kauramaki et al., 2007). However, the basis for the frequency specific selection of auditory signals is likely produced by the filtering mechanism at the cochlear level. Hence, in order to understand the frequency certainty and uncertainty effects in the current study, it is important to consider the frequency characteristic of the peripheral auditory filters and its relationship with the range of signal frequencies used.

### 6.3.1 Normal-hearing listener

A set of five signals of different frequencies centred at a CF were used in the psychophysical experiments. Two of the closest signals were about half a CB away from the CF, while two most distant signals were 1 CB away from the CF. Since the bandwidth of auditory filters in a normal-hearing listener is about 1 CB (Dai et al., 1991), the two nearest signals to the CF mark the border of the auditory filter. This relationship for five signals centred at 1 kHz used in both Study 1 and Study 2 with the auditory filter centred at 1 kHz is depicted in Figure 6.1.

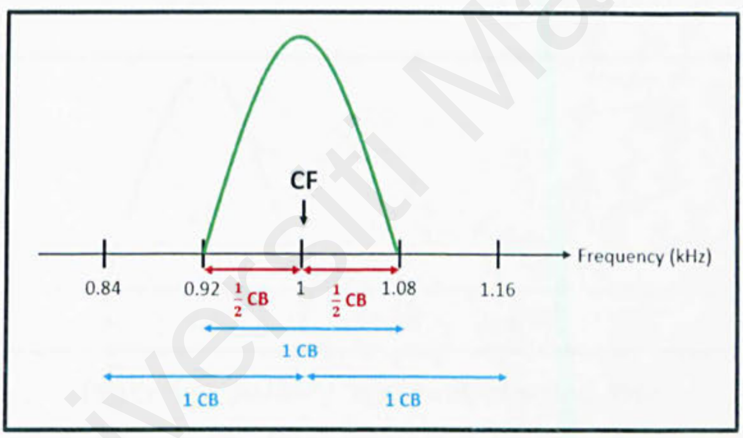



Figure 6.1: Relationship between signals frequencies used in the current study and auditory filter centred at centre frequency (1 kHz).

Peripheral auditory system contains many overlapping auditory filters (Fletcher, 1940) (see Figure 6.2). During the cued task (frequency certainty), the presence of cue tones help the normal-hearing listener to focus on the filter that has a CF that matches the frequency of the to-be-detected (expected) signal. This would produce the highest signal-to-noise ratio (SNR) at the filter output (Patterson, 1976; Patterson and Moore, 1986; Moore, 2007b) which would optimize the detection of the attended signal frequency. The remaining near-threshold signals with frequencies located outside or at the border of the filter range (more than half CB away from the CF) will be filtered out. For example, if the expected (cued) signal is 0.92 kHz, the chosen filter will be centred at 0.92 kHz. This allows for an increased hearing sensitivity of the listener for the expected 0.92 kHz signal. The remaining signals (0.84, 1, 1.08 and 1.16 kHz) will fall at the border or outside the frequency response range of the filter (see Figure 6.3) and the hearing sensitivity to these signals will be less compared to the attended signal.

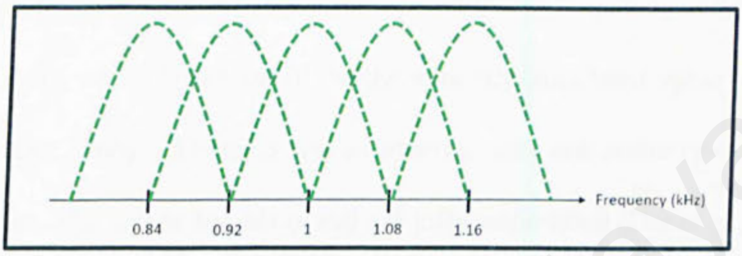



Figure 6.2: Overlapping auditory filters along the basilar membrane.

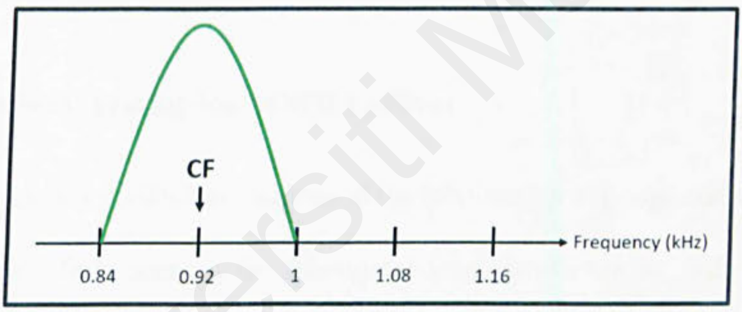



Figure 6.3: Auditory filters centred at 0.92 kHz.

During the uncued task (frequency uncertainty), as the signals were randomly selected from a set of five signal frequencies, the listener will not be able to focus on the correct filter. This is because, in the absence of cue tones, the listener do not know which frequency region he or she should attend to during the listening task. Even if the listener is expecting one of the signal frequency based on the previous trial, the to-be-detected signal in the subsequent trial will fall outside the filter centred at the frequency of the earlier signal (Figure 6.3). This will lead to a reduced hearing sensitivity and a reduction in their detection performance (uncertainty effect).

The idea of a listener focusing on a single auditory filter during the attentional task is not new. Previous researchers (Tanner and Norman, 1954; Green, 1961; Greenberg and Larkin, 1968; Dai et al., 1991; Tan, 2008) have also postulated that the uncertainty effect is induced by the inability of the listener to focus on a specific expected signal frequency. However, the uncertainty effect estimated from previous studies (Green, 1961; Scharf et al., 2007; Tan, 2008) and the current data showed that the decline of the detection performance in frequency uncertainty as compared to the frequency certainty condition is only about 3 dB, which falls short of the theoretically calculated value of about 20 dB (Green and Swets, 1966) if a listener was to attend to only one auditory filter and ignore the adjacent ones. The reason for this is still not fully understood (Dai et al., 1991; Scharf et al., 2007).

### 6.3.2 Sensorineural hearing loss (SNHL) patient

Although previous studies have addressed the relationship of peripheral auditory filters and uncertainty effects seen in the attentional frequency-listening task, very little is known about how these processes are altered in the hearing-impaired. SNHL patients are expected to have broader auditory filter as compared to normal-hearing listener (Florentine et al., 1980; Glasberg and Moore, 1986). An arbitrarily chosen broadened filter centred at 1 kHz is illustrated in Figure 6.4. Assuming that the filters are sufficiently broad, in addition to the CF (1 kHz) tone, the adjacent signal frequencies (0.92 and 1.08 kHz) used in the current study may also fall within the frequencies range of a particular filter. The increase in the bandwidth of the auditory filter is not expected to affect the signal detection in frequency certainty condition. However, during frequency uncertainty condition, where the listener does not know the exact signal to be presented in a particular trial, he or she may focus at a particular frequency based on the signal presented on the previous trial. Due to a broader filter, some of the subsequent signals may still fall within the frequency response range of this filter which will allow the listeners to detect them. Hence, the detection rates of SNHL subjects during the frequency uncertainty condition will be higher than the normal-hearing listener and this could reduce the uncertainty effect in SNHL patients compared to the normal-hearing listener.

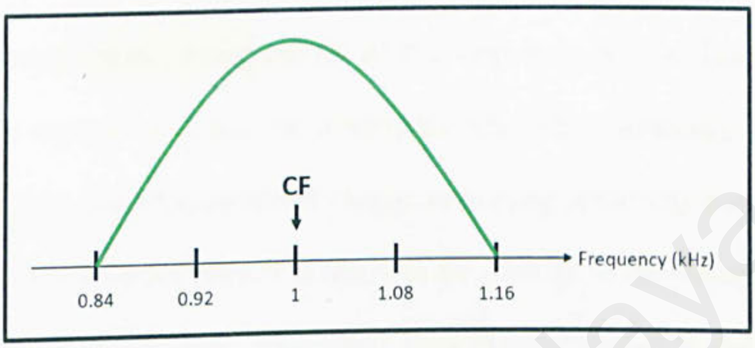



Figure 6.4: Illustration of broadening of auditory filter (centred at 1 kHz) in sensorineural hearing loss patient. The adjacent signals (0.92 and 1.08 kHz) fall within the frequencies range of the filter.

The current data which showed correlation between the CR (which represents the auditory filter bandwidth) and uncertainty effect also supports this argument. With a larger CR (broader auditory filter), the likelihood of adjacent signal frequencies falling within the attended filter range will be higher. Hence, the uncertainty effect will be smaller. Future studies involving similar experiments in the SNHL patients using a broader range of signal frequencies with larger frequency separation can be carried out to verify this mechanism. Their uncertainty effect should be restored to the equivalent level of normal-hearing subjects if the signal frequencies have larger separation and fall outside their attended filter range.

## 6.4 Implications for real-world listening

One of the factors attributed to the deficit of speech-in-noise intelligibility in SNHL patients is their poorer frequency selectivity (Liberman et al., 1986). However, the exact underlying mechanism is poorly understood. Can a loss of uncertainty effect as seen in the SNHL patients in the current study be used to explain their deficits?

As discussed earlier, being certain of the frequency of near-threshold signals will significantly improve its detection in noise (Green, 1961; Greenberg and Larkin, 1968; Tan, 2008). This attention-mediated change in hearing sensitivity based on the spectral information of the sound stimuli is likely to be relevant in day-to-day speech-in-noise communication. For example, individuals have distinct pitches in their speech sounds, indicating differences in frequency information (Moore, 2007b). If a listener focuses on the pitch (frequency) of another speaker's speech sounds, this may aid the detection of the speaker's voice (target) in the presence of other voices or noises (distractors). In contrast, by not paying attention to the distracting background sounds, the listener sensitivity to those signals will be less. Thus, the uncertainty effect (differential hearing sensitivity between frequency certainty and frequency uncertainty conditions) may provide a possible mechanism for separating the attended signals from the unattended background signals based on its spectral characteristics.

For normal-hearing listener (higher uncertainty effect), target signals can be well separated from the distractors. Although the uncertainty effect for detection of tones-in-noise is only about 3 dB, this effect should be sufficient to provide a significant advantage for detection of near-threshold speech sounds (Plomp, 1986; 1994). On the other hand, a reduced uncertainty effect such as those found in SNHL patients could affect their ability to separate near-threshold target sounds from the distracting background signals. Hence, a loss of uncertainty effect could affects their speech-in-noise intelligibility.

Sounds stimuli used in the current study were pure tones presented in narrowband noise. Speech sounds are invariably more complex compared to pure tones. Therefore, further studies should be carried out using actual speech sounds and distractors to determine how changes in frequency certainty and uncertainty conditions can impact the detection of speech signals in noise.

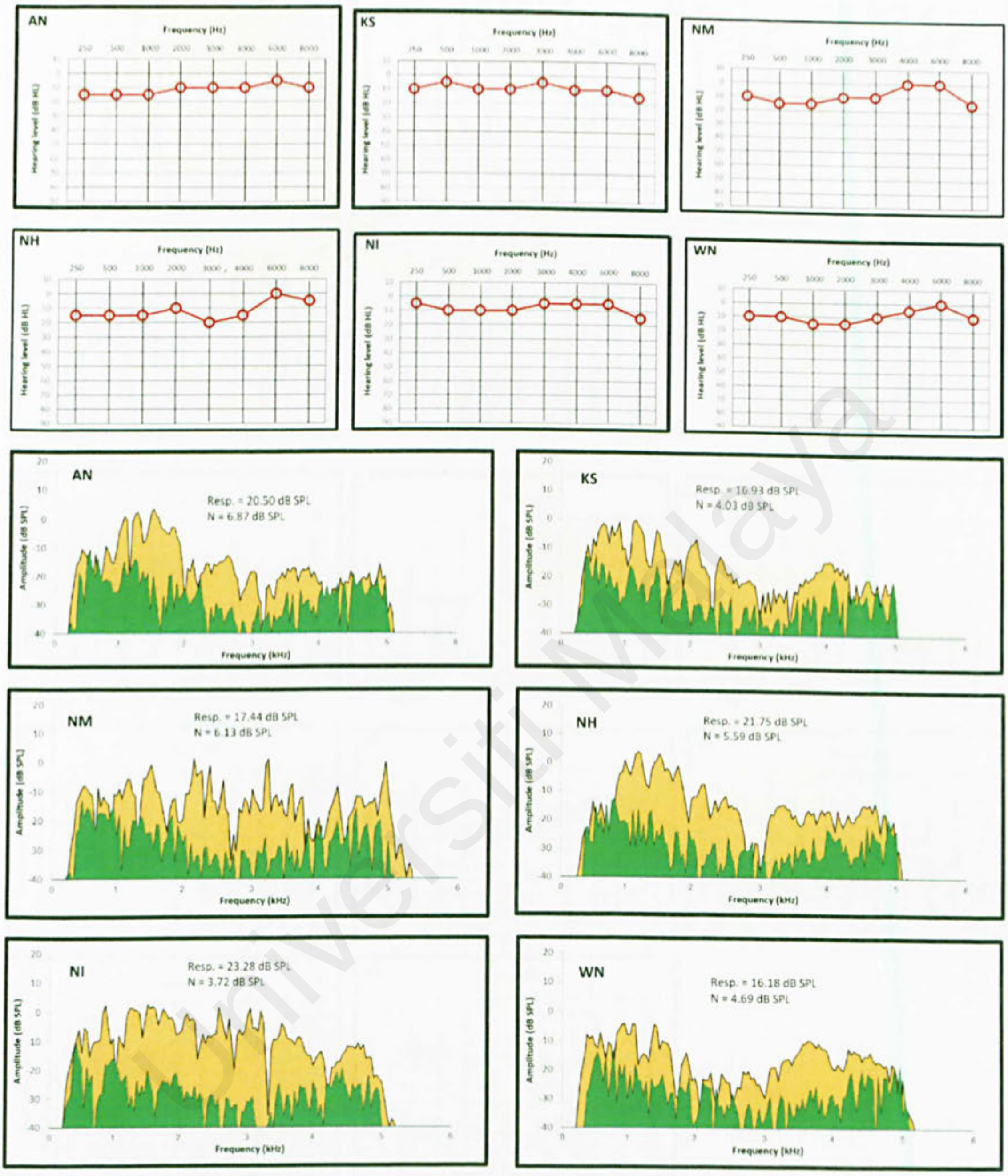
### 6.5 Implications for technology used in hearing-assistive devices

Usage of hearing assistive devices such as hearing aids can compensate for the loss of hearing sensitivity in quiet environment by amplifying the sound signals. However, in the presence of background sounds (noise), people with hearing loss usually report unclear and distorted signals despite using these devices as both the signal and the background noise are amplified (Duquesnoy, 1983; Plomp, 1986). One of the reasons for this may be related to the inability of these hearing assistive devices to address the attention-mediated changes in hearing sensitivity.

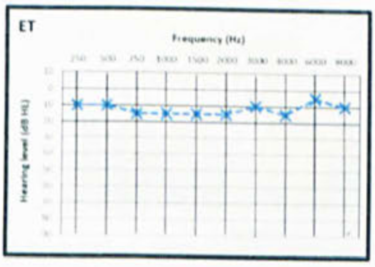
In the current study, SNHL subjects not only had poorer hearing thresholds, but also suffered from a loss of frequency uncertainty effect compared to normal-hearing individuals. As discussed earlier, the presence of the uncertainty effect may provide the ability to separate the target signal from the distracting background signals (see section 6.3). However, current hearing assistive devices do not have the ability to compensate for this loss. Hence, it may be useful if the consequence of loss of uncertainty effect in SNHL patients is taken into consideration when devising any new device for their use.

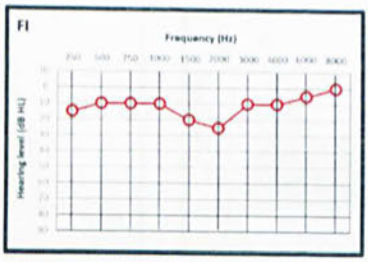
# APPENDICES

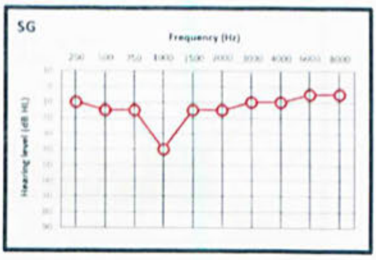
## Appendix A: PTA and TEOAE of opposite ear for experiment in Chapter 4

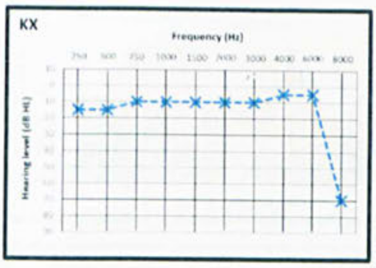


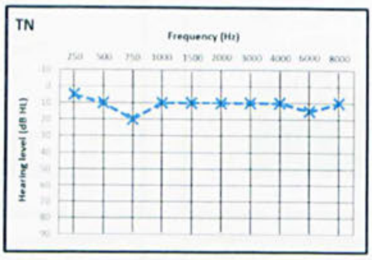
## Appendix B: PTA of opposite ear of normal-hearing and hearing-impaired subjects for experiment in Chapter 5

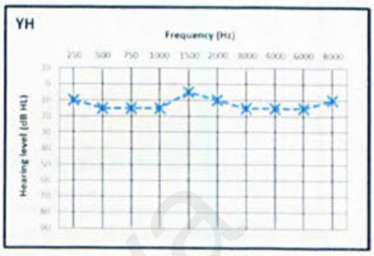


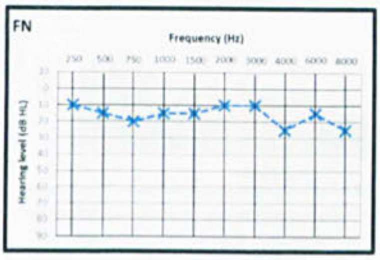



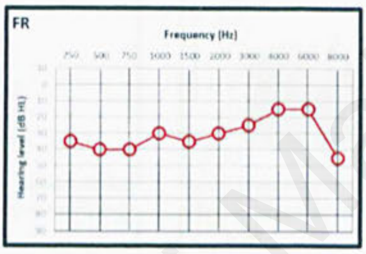



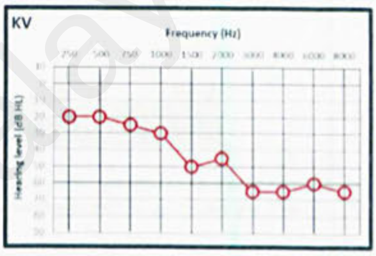



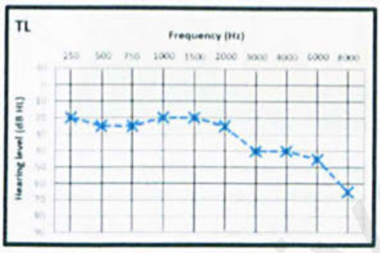



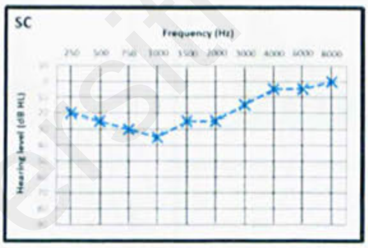



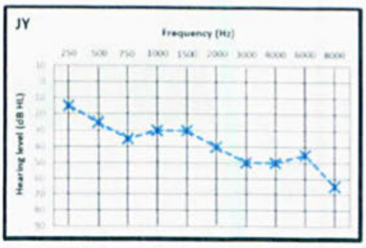



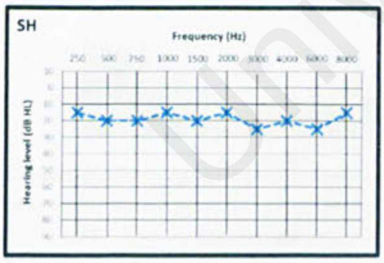



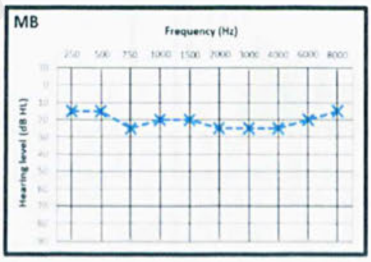



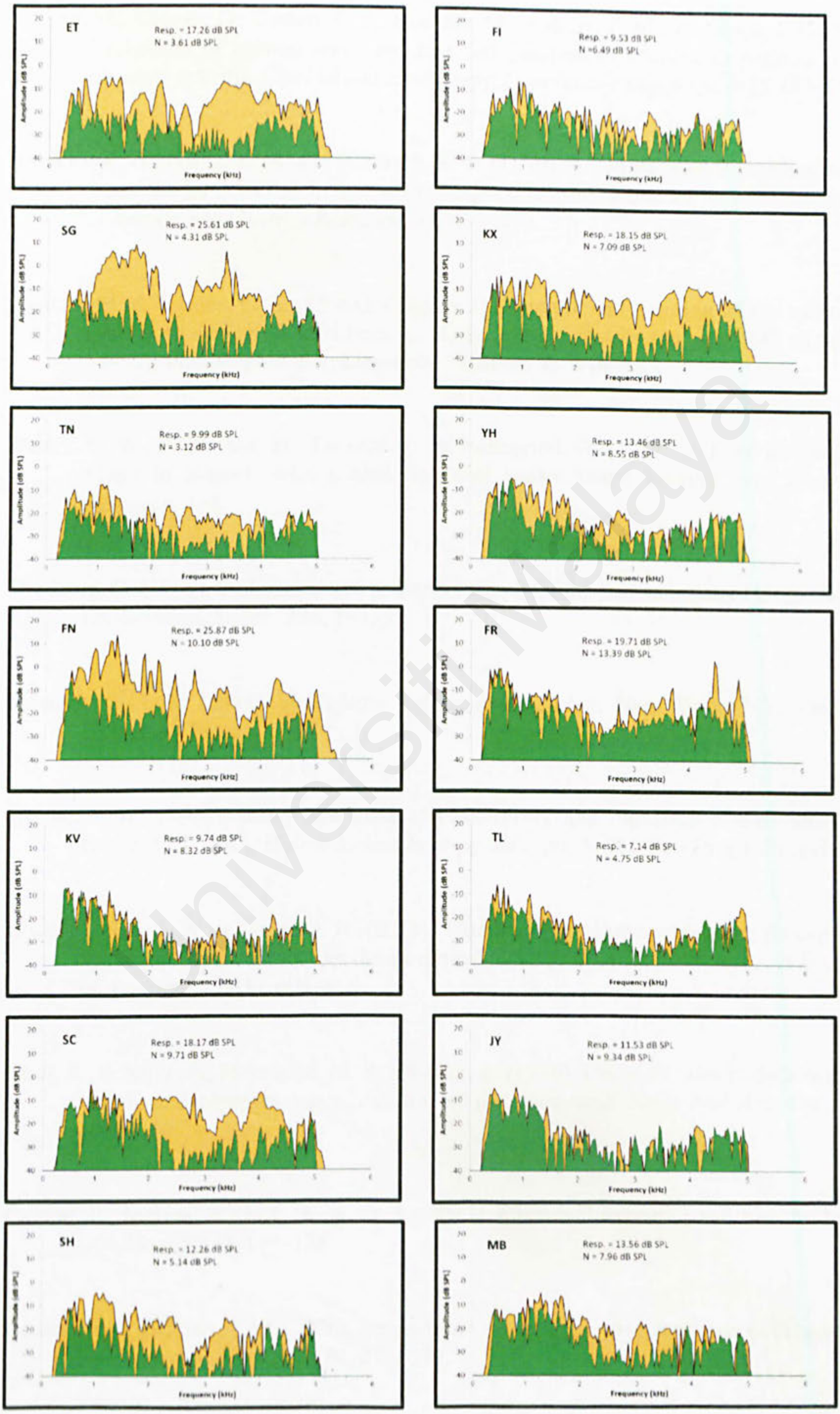



## Appendix C: TEOAE of opposite ear of normal-hearing and hearing-impaired subjects for experiment in Chapter 5



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