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Institute of Sound and Vibration Research

Binaural hearing with bone conduction stimulation

by

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONEMENT

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BINAURAL HEARING WITH BONE CONDUCTION STIMULATION

By Hala Mousa AlOmari

It has been argued that apparent masking-level differences (MLDs) in users of bilateral bone-anchored hearing aids (BAHAs) provide evidence of binaural hearing. However, there is considerably less acoustical isolation between the two ears with bone conduction (BC) compared to air conduction (AC). The apparent MLDs may have arisen, at least in part, from inter-cranial interference between signals arising from the two BAHAs (i.e. monaural effect). That might also explain some of the inter-individual variation in both the magnitude and the *direction* of the MLDs reported in BAHA users. The present study was composed of three experimental stages with the main aim to investigate the influence of interference in normal hearing participants by measuring masking level difference in AC and BC to explore the conditions contributing to the reported variation. An additional aim was to investigate the performance of a newly designed BC transducer; the balanced electromagnetic separation transducer (BEST), for bone conduction research as well as more general clinical use.

Stage 1 evaluated the performance of the BEST in comparison to the clinically used RadioEar B71 in a series of acoustical (sensitivity and harmonic distortion) and psychoacoustical (hearing thresholds and vibrotactile thresholds) measurements. The results from these studies led to the use of the BEST in the second and third stages because they produced significantly lower harmonic distortion at low frequencies (mainly 250 Hz). The psychoacoustic measurements alluded to the need to use different calibration values with the BESTs.

Stage 2 was a preliminary investigation comparing the MLDs with standard bilateral configurations between the AC and BC in nine normal-hearing participants. Signals were pure tones at one of three frequencies (250, 500, 1000 Hz), presented via AC or BC. Broadband noise (100- 5000 Hz) was always presented via AC at 70 dB SPL. Thresholds were estimated using a three-alternative forced choice procedure combined with an adaptive staircase. Transducers used were insert earphones and the BESTs for BC testing. The results from this stage showed a statistical significant difference between AC and BC MLDs at 250, 500 and 1000 Hz (mean difference is 9.4, 6.6 and 3.5 dB respectively). Evidence of the change in the MLDs direction is observed at 250 Hz in three participants.

Stage 3 consisted of the investigation of inter-cranial interference in eighteen normal hearing participants. This stage was composed of three main measurements. The first measurement compared the AC and BC MLDs at three test frequencies. The second measurement evaluated the transcranial attenuation (TA). The third measurement was the novel feature of the study it evaluated the monaural interference effect through the measurement of the diotic and dichotic conditions in one test ear. A significant discrepancy was found between the AC and BC MLDs of approximately 6, 1.5 and 2.5 dB at 500, 1000 and 2000 Hz, respectively. The TA was found to be lower than 10 dB at the three test frequencies. Measurable MTLDs were reported in some of the participants, high inter-subject variability was observed in the direction of the MTLDs.

The BEST can reliably replace the B71 in clinical setup. Formal adjustment of the reference equivalent threshold force levels is advised. Binaural hearing was achieved through bilateral BC stimulation to a lesser magnitude compared to AC MLDs in normal hearing participants. The discrepancy between the AC and BC MLDs was reduced with the increase in the frequency. The discrepancy can partially be explained by the cross-talk of the signal in one ear. The results showed that in some participants the magnitude of the monaural tone level difference was similar to the magnitude of the BC MLD. Further investigation is recommended to investigate the association of the transcranial delay with the discrepancy between the AC and BC MLDs. This investigation also recommends the investigation of the AC and BC MLDs in patients fitted with bilateral BAHAs.

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Declaration of authorship

I, Hala Mousa AlOmari declare that the thesis entitled “Binaural hearing with bone conduction stimulation” and the work presented in it are my own work, and have been generated by me as the result of my own original research.

I confirm that:

This work was done wholly or mainly while in candidature for a research degree at this University;

Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;

Where I have consulted the published work of others, this is always clearly attributed;

Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;

I have acknowledged all main sources of help;

Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;

Parts of this work have been published as:

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AlOmari H., Semeraro H., McMahon M., and Rowan D. 2011. Furthers studies comparing two bone conduction transducers for clinical practice and auditory research: the BEST vs. B71 (abstract). International Journal of Audiology, 50(10), 736.

AlOmari H., Vaughan A. & Rowan D. 2010. Evaluation of two types of transducer for auditory research (abstract). International Journal of Audiology, 49, 701.

Signed: …………………………………………………………………………………

Date: ………………………………………………………………………......................

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I dedicate this PhD thesis to Mom and Dad, thank you ever so much.

List of abbreviations

ABR	Auditory brainstem response
AC	Air conduction
B&K	Brüel and Kjær
BAHA	Bone anchored hearing aid
BC	Bone conduction
BCI	Bone conduction implantable hearing aids
BEST	Balanced electromagnetic separation transducer
$BEST_{LFR}$	Low frequency reinforced BEST
MLDs	Masking level differences
MTLD	Monaural tone level difference
CEA	Congenital ear atresia
CHL	Conductive hearing loss
EML	Effective masking level
HL	Hearing level
HRTF	Head-related transfer function
ILD	Interaural level difference
IPD	Interaural phase difference
ISO	International organisation for standardisation
ITD	Interaural time difference
MHL	Mixed hearing loss
MLDs	Masking level differences
NBN	Narrow band noise
RETFL	Reference equivalent threshold force level
SL	Sensation level
SNHL	Sensorineural hearing loss
TA	Transcranial attenuation
TD	Transcranial delay
THD	Total harmonic distortion
IA	Interaural attenuation

Definitions

Air conduction (AC): sound energy causes vibration of the air particles to pass to the ear canal vibrating the eardrum and connected middle ear ossicles creating a sound pressure in the cochlear fluids leading to hearing sensation.

Bilateral: Having or formed of two sides; two sided. In audiology, it is used when talking about the right and left ears. When referencing to one ear the term used is **Unilateral.**

Binaural hearing: " denotes our faculty for taking advantage from comparisons of the acoustic signals at the two ears" (Akeroyd, 2006). The benefits of binaural hearing include the "ability to perceive the direction and location of the sound source, the ability to segregate and selectively attend to different sound sources and partial release from both energetic and informational masking"(Boothroyd, 2006).

Bone conduction (BC): ISO 389-3 (1994) defines bone conduction as "transmission of sound to the inner ear primarily by means of mechanical vibration of the cranial bones". The vibration occurs if the sound is loud enough to cause the bones to vibrate, or the stimulus has to be delivered by a vibrating device (transducer) applied to the skull (Gelfand, 1998).

Bone conduction transducers: "electromechanical transducer intended to produce the sensation of hearing by vibrating the cranial bones" (ISO 398-3, 1994). BC transducers are used in clinical evaluation of hearing to differentiate between the types of hearing loss. Furthermore, the BC hearing aids are similar to the bone transducer with a difference that it has a microphone that picks the signal and transforms it to vibratory signal on the skull. Commercial uses of BC transducers include military communication, mobile phones, and incorporated into music players.

Cross-talk: when the sound is bilaterally received by a BC device the signals can interfere due to the small interaural differences

Dichotic: the presentation of one signal to the right ear and a different signal to the left ear (Gelfand, 1998).

Diotic: presentation of an identical signal to both ears.

Interaural attenuation (IA): “the reduction in the intensity of the test signal as it crosses the skull”, it is also called transcranial transmission loss (Smith & Markides, 1981). IA varies from person to person and is dependent on the type of earphone.

Interaural differences: binaural benefits occur due to differences between the signals reaching the two ears arising from the spatial separation of the ears. In addition, to the effects of the head movements on these differences (Boothroyd, 2006). The interaural differences include the interaural time (ITD) and level differences (ILD), and the spectral cues. For more elaboration on these terms refer to Section 2.3.2.

Masking level differences (MLDs): “the difference (advantage) in masked threshold between dichoically presented stimuli and signals that are presented monotically (or diotically)” (Gelfand, 1998). Monotically (monaural) is when the signal and noise are presented to one ear, the monaural advantage occurs when an identical noise is presented to the unstimulated ear. Binaural advantage occurs when the stimuli is different at the two ears (Gelfand, 1998).

Occlusion effect: “the change (usually an increase) in level of a bone-conducted signal reaching the inner ear when an earphone or an earplug is placed over or at the entrance of the ear canal, thereby forming an enclosed air volume in the external ear. The effect is greatest at low frequencies” (ISO 8253-1, 1998).

Transcranial attenuation (TA): “the difference in sensitivity between the ipsilaterally transmitted and contralaterally transmitted BC sound when the stimulation is at similar position at the two sides of the cranium” (Stenfelt, 2012).

Transcranial delay: the time it takes for the sound to arrive from the mastoid to the cochlea on the same side of the head, a delay may occur due to the mechanical properties of the head at the point of stimulation.

Types of hearing loss: hearing loss is categorised according to the damaged part of the auditory system. The types of hearing loss include: conductive hearing loss which occurs when the outer or middle ear are affected, sensorineural hearing loss results from inner ear or nerve damage. Finally, mixed hearing loss is a combination of conductive and sensorineural hearing loss

Chapter one. Introduction

Bilateral fitting of hearing aids lead to a number of advantages including sound source localisation and improved speech discrimination in social events (Libby, 1980; Noble, 2006). Bilateral fitting of bone conduction (BC) hearing aids has traditionally been dismissed because of the lack of isolation between the cochlea due to the high transcranial transmission (Priwin et al, 2007). Therefore, fitting of BC hearing aids was exclusive to one ear even if the hearing loss was bilateral. Patients fitted with a BC hearing aid include (all of which cannot be fitted with a regular hearing aid due a number of reasons): patients with conductive hearing loss (CHL), patients with mixed hearing loss (MHL) and patients with profound single sided deafness (SSD). Recent studies have explored bilateral fitting of BC hearing aids by testing different aspects of the binaural hearing and recommended bilateral fitting (Snik et al, 1998; Bosman et al, 2001; Priwin et al, 2004), despite wide variation in the results between the studies and the lack of clear evidence of binaural benefit.

The complexity of bone conduction hearing is attributed to a number of factors that include: different modes of skull vibration (Bekesy, 1948), several pathways leading to the cochlea (Stenfelt & Goode, 2005) as well as the method of coupling the hearing aid which influences the benefit and use. For example, soft bands are used for children, and steel bands are used for trials in adults. On the other hand, implantable BC (BCI) hearing aids produce optimal results because the fixture is surgically implanted to the bone removing any influence of skin and tissue (Tjellstrom et al, 2001; Mcdermott et al, 2002; Snik et al, 2004; Snik et al, 2008). Moreover, coupling the vibrator to the teeth is currently possible through SoundBite system which is mainly advocated for the use in patients with SSD (Popelka, 2010).

Binaural hearing with BC stimulation have been explored by reporting self-report benefit (Dutt et al, 2002a; Dutt et al, 2002b) and through audiological testing (Van Der Pouw et al, 1998; Bosman et al, 2001; Dutt et al, 2002a; Priwin et al, 2004). Three audiological tests in particular have been used to measure binaural hearing: sound-source localisation in the horizontal plane, speech intelligibility in noise and the detection of a tone in noise under different bilateral conditions. The latter involves measuring the improved audibility of the tone when either the tone or the noise is presented with an interaural difference (e.g. in phase) compared to when both are presented identically to both ears. These three tests have been shown to be dependent on binaural hearing in normal-hearing listeners with AC hearing. For example, the principle outcome measure of the tone in noise test is referred to as the binaural 'masking-level differences' (MLDs), and is reported to provide the clearest evidence for binaural hearing with BCIs (Bosman et al, 2001). However, there is a theoretical reason to doubt the assumption that the three tests, including the binaural MLDs, are dependent on binaural hearing with BC hearing, even in normal-hearing listeners. Monaural cues might arise from the interference between the sounds presented to the two devices during BC transmission, i.e. cross-talk, allowing individuals with poor binaural hearing to achieve better scores than might be expected (i.e. mimicking the results with binaural hearing).

The presumption that tests of binaural hearing with air conduction (AC) also test binaural hearing with BC might be invalid, and thus the evidence of binaural hearing with BCIs could have a different interpretation. For example, the auditory system interprets the interaural time difference (ITD) differently from the interaural level difference in patients with CHL (ITD is disrupted while the ILD is normal) (Hausler et al, 1983; Noble et al, 1994). Rowan and Grey (2008) argue that the interaural phase difference can be converted to ILD with bilateral BC stimulation in normal hearing participants performing lateralisation task. Inter-subject variation in BC transmission properties might also explain some of the high inter-subject variability, in particular, some of the curious findings with the binaural MLDs (e.g. of large values in the opposite direction than expected for binaural hearing). At the time of starting this project, very little was known about the binaural MLDs with BC and how it should be interpreted even in normal-hearing listeners.

The literature lacks comprehensive studies regarding bilateral bone conduction fitting. To date there are no clear criteria regarding fitting patients with two BCI hearing aids prompting more research in this field. Furthermore, the studies conducted on patients with bilateral BCI hearing aids relied on their recommendations for bilateral fitting on one particular test (MLDs).

1.1 Research aims and questions

The overall aim of this PhD was to explore the binaural hearing with BC stimulation in normal hearing participants using MLDs. MLD test is one of many laboratory tests that investigate binaural hearing by measuring the release from masking when the signal is presented with different interaural configuration than the masker (Yost, 1988). The aim of the present study was to reduce the variables that may interfere with the interpretation of the results by using pure tones rather than complex tones. These variables include the type of the signal used, the performance of the BC transducer, the frequency response of the BC transducer, and the test environment. A secondary aim is to identify a suitable BC transducer for conducting the experiments. A new BC transducer has recently been introduced (Håkansson, 2003) that claims to address the limitations associated with the current clinical BC transducer (RadioEar B71). Consequently, this thesis considers the following questions:

1. Is the balanced electromagnetic separation transducer (BEST) more suitable for investigation of binaural tests than the clinically used B71? Specifically, does it have lower total harmonic distortion? Does it have wider dynamic range? Is it suitable to be used under the current calibration standard (ISO 389-3, 1999)?

2. How does the binaural MLDs compare between the AC and BC under otherwise identical conditions? This was important as it aids in understanding the cues normal hearing participants use with bilateral BC stimulation. It also addresses the question whether generalisation from the AC studies can be extended to BC.

3. How does the frequency of the tone affect the binaural MLDs with BC compared to AC? This is relevant because AC binaural MLDs is known to decrease as the frequency is increased from low to high. Would an increase in the frequency result in a decrease in the overall BC binaural MLDs?

4. Is there a relation between the transcranial attenuation and the binaural MLDs? The significance of this is to address the hypothesis that the magnitude of the transcranial attenuation is related to the magnitude of the discrepancy between the AC and BC binaural MLDs.

5. Is it possible to measure binaural MLDs with monaural BC hearing and can this account for the discrepancy between the AC and BC binaural MLDs? The significance of this is to allow the understanding of the effect of cross-talk of the signal and its contribution to the overall binaural MLDs.

1.2 Outline of the thesis

The review of literature presented in Chapter two reports the background theory of binaural hearing with AC stimulation, Chapter two introduces the basic concepts associated with binaural hearing. It is followed by an introduction to bone conduction hearing in general. The background research in binaural hearing with BC stimulation is outlined and discussed. The factors associated with MLDs are outlined and explained because the manipulation of the test setup can have a great influence on the resultant MLDs. Chapter two also introduces the model of cross-talk proposed by Zurek (1986). The literature review points out the need for basic research in binaural hearing with bone conduction stimulation to understand whether the benefit reported with bilateral BCI hearing aids is an actual benefit?

This thesis is composed of three main experimental stages, summarised in Figure 1.1. The first stage evaluates the performance of the newly designed bone transducer (Chapter three), the balanced electromagnetic separation transducer (BEST), in comparison to the clinically used transducer RadioEar B71. This evaluation aimed to encompass the full range of testing including acoustical (sensitivity and harmonic distortion) and psychoacoustical (hearing thresholds and vibrotactile thresholds) measurements to ensure that future testing with the BESTs would not be influenced by transducer artefacts. The results from this evaluation led to the use of the newly designed BEST in the binaural studies as it proved to be superior in the production of lower harmonic distortion at low frequencies when compared with the B71.

The second stage consisted of preliminary investigation of the masking level difference with AC and BC using the new transducers (Chapter four). The main aim was to develop a methodology that is suitable for investigation of MLDs with AC vs. BC with the intention of understanding effects of cross-talk during BC. A second aim was to compare the AC and BC MLD’s at several frequencies and across different individuals with

Outline of the thesis

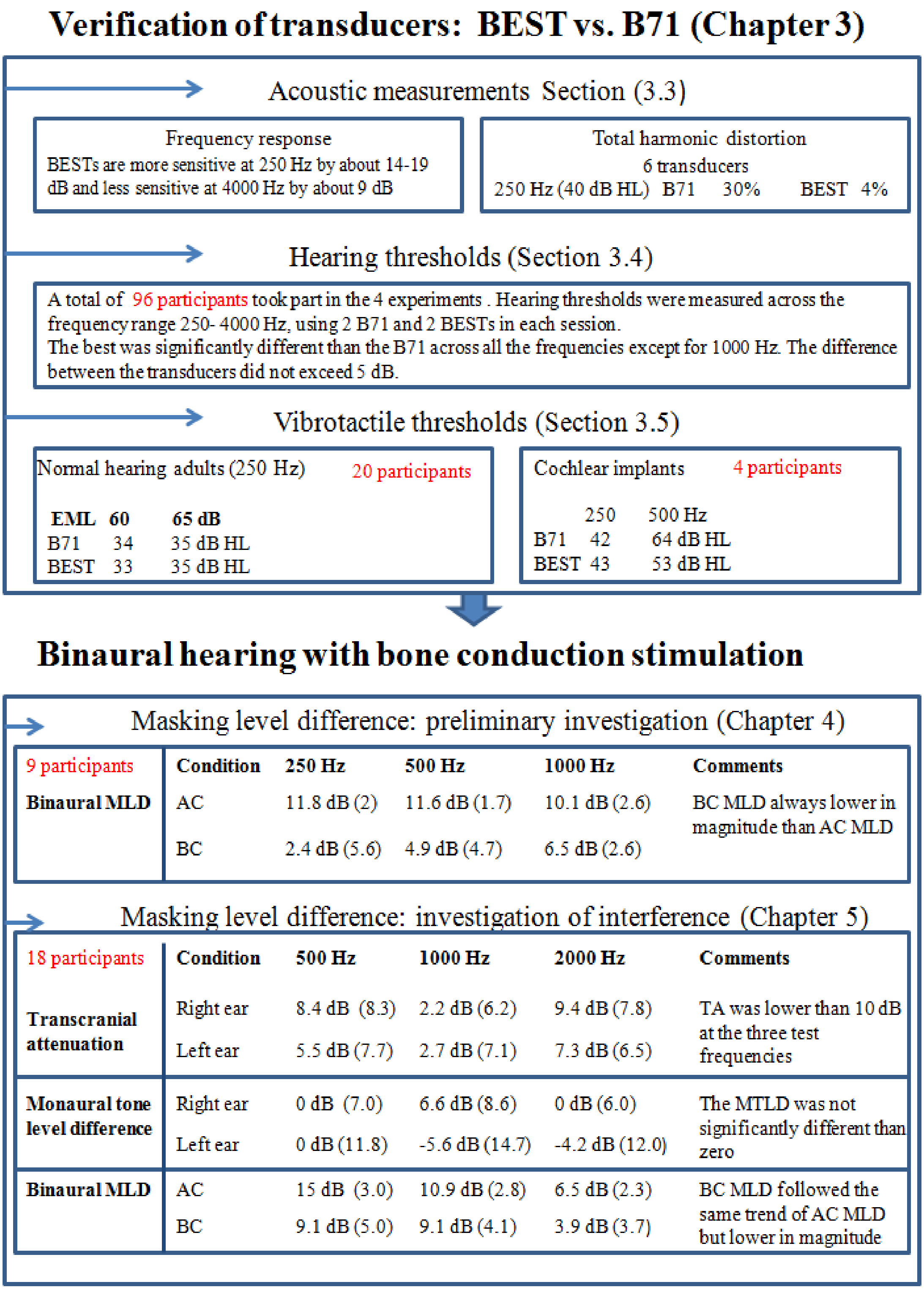

Figure 1.1 Outline of the thesis, with summary of results for the overall results, values in brackets represent the standard deviations.

probably different transcranial characteristics. The AC MLDs were always measured because the results can be cross checked with background studies.

The BC MLDs were measured in the same conditions as the AC to investigate the performance of the participants in the two tasks and to identify any discrepancy between the results. The preliminary investigation also aimed to investigate the variability of the participants by measuring the MLDs in three test sessions.

The third experimental stage was an extension of preliminary investigation with the inclusion of the investigation of the interference of the signal by evaluating the monaural bilateral BC MLDs and evaluating the TA (Chapter five). The test frequencies were extended to include 2000 Hz with slight methodological changes aimed at improving the quality of the testing. The results of the 18 participants taking part in the study were explored. Similar to the preliminary investigation the AC MLDs were part of the main evaluation. This stage aimed to investigate the monaural effect as a possible contributor to the lower magnitude associated with the BC MLDs reported in the preliminary investigation.

Chapter six provides an overall summary of the results reported in the three experimental stages. Finally, Chapter Seven concludes the results obtained and paves the way for the future studies. The main clinical implications of the first experimental stage indicate that caution should be taken when calibrating different types of BC transducers under the current calibration standard. The main evaluation of binaural hearing with BC stimulation was conducted on normal hearing participants to evaluate the cues used without the influence of pathologies. In general, the bilateral BC hearing aids are fitted for patients with conductive hearing loss. Thus, the current results may not fully reflect BC MLDs expected in patients with hearing losses due to a number of reasons that include: patients have been deprived of binaural cues due to the nature of hearing loss and the placement of the transducer differs between normal hearing participants (mastoid) and patients (further back). The change in placement can influence the phase of the signal and the possibility of the TA (Stenfelt, 2012). However, the current study provides provisional guidance for future research with patients as the methodology proved to be consistent and stable over time.

1.3 Original contribution to knowledge

A number of contributions to bone conduction have been made in the current thesis:

- The first experimental stage resulted in:
  - The sensitivity of the BEST was better than the B71 by 14-19 dB at 250 Hz. Furthermore, the BESTs produced significantly lower total harmonic distortion compared to the B71s at 250 Hz (Chapter Three). The results indicate that the BESTs can substitute the B71s for clinical purposes.
  - The hearing thresholds with normal hearing individuals indicated that the current calibration standard should be adjusted with the B71 and the BESTs at some of the test frequencies mainly at and above 2000 Hz. The difference between the reference and the BEST was > 5 dB at 2000 and 3000 Hz (Chapter Three).
  - Comparison between the BEST and B71 by measuring the vibrotactile thresholds demonstrated that the two transducers produced similar vibrotactile thresholds at 250 Hz with normal hearing participants. However, the BESTs were more tactile by about 11 dB at 500 Hz compared to the B71 when the thresholds were measured in deaf participants (small sample size).
- The second experimental stage resulted in the following contributions:
  - The preliminary investigation of MLDs documented a measurable BC MLDs at the three test frequencies. The BC MLDs was always lower in magnitude compared to the AC MLDs. Furthermore, the magnitude of the difference between the AC and BC MLDs decreased with increase in frequency.
- The third experimental stage resulted in the following contributions:
  - The documented discrepancy between the AC and BC MLDs observed in the preliminary investigation was retained. The BC MLDs followed the AC MLDs in trend. Increase in the frequency resulted in a decrease in the MLD.
  - The monaural tone level difference (MTLD) tested with bilateral BC showed wide variation between the individual. It was observed that the results could be grouped based on the direction as some participants had negative MLDs. Due to the different direction the averaged MTLDs were not significantly

different than 0 dB. However, significant MTLDs were observed once the individual results were grouped based on the direction of the MTLDs.

- The change in the direction of the MTLDs between the participants supports the cross-talk model results in that the TD does affect the results.
- It was documented that the measurement of the transcranial attenuation resulted in a TA magnitude that was lower than 10 dB at the three test frequencies, with the lowest TA measured at 1000 Hz. These results indicate that due to the relatively small magnitude of TA, the cross-talk possibly had an impact on the magnitude of the BC MLDs.
- The discrepancy between the AC and BC MLDs can be partially explained by the MTLDs. The results of the study indicated a relation between the TA and MTLDs. However, binaural benefit cannot be determined without the measurement of the TD.

1.4 Papers and conferences

Aspects of this study have been reported at a number of abstracts presented in peer reviewed journal:

- AlOmari H. & Rowan D. 2013. “Masking-level difference with bone-conduction stimulation in normal-hearing listeners” (abstract). International Journal of Audiology, 52, 285.
- AlOmari H., Semeraro H., McMahon M., and Rowan D. 2011 “Furthers studies comparing two bone conduction transducers for clinical practice and auditory research: the BEST vs. B71” (abstract). International Journal of Audiology, 50 (10), 736
- AlOmari H., Vaughan A. & Rowan D. 2010. “Evaluation of two types of transducer for auditory research” (abstract). International Journal of Audiology, 49,701.

Chapter two. Background

The literature involving binaural hearing with bone conduction stimulation is limited to a few investigations involving patients bilaterally fitted with bone anchored hearing aids (BAHA's). Studies on patients fitted with BCI hearing aids are ideal provided that there are normative results to compare the outcome to because the effect of cross-talk is unknown. These studies have compared the resultant outcome to the normative literature with AC stimulation. In the case of BC stimulation this cannot be assumed because of the inherent nature of the sound transmission characteristics of the AC and BC. Therefore, this study aimed to investigate and report the normative results of the binaural test by measuring the masking level differences. This would provide a comparative base for studies on patients as well as investigate the difference between the AC and BC binaural hearing.

This Chapter introduces the two main sound pathways and highlights the differences between them. This leads to the introduction of the binaural hearing with AC because it is thoroughly investigated and reported in the literature. The terminology frequently used with AC is described and explained. The binaural hearing with BC is introduced including the model of cross-talk.

2.1 Sound pathways

2.1.1 Air conduction

The air conduction (AC) is the first route of hearing. The auditory system consists of the outer, middle and inner ears; the auditory nerve, and the central auditory pathways (Figure 2.1). The outer ear is composed of the pinna and the external auditory meatus. It is separated from the middle ear by the tympanic membrane. The middle ear is an air filled chamber containing the ossicles: malleus, incus, and stapes. The ossicles are connected to the bony walls of the middle ear cavity by ligaments and tendons of the stapedius and tensor tympani muscles, and the annular ligament that holds the stapes foot plate in the oval window. The inner ear includes the sensory organ for hearing (cochlea) and the balance system (semicircular canals, utricle and saccule).

Sound waves travelling through air particles are collected and directed by the troughs and ridges of the pinna to the “S” shaped tube like external auditory meatus ending with the transparent tympanic membrane (TM). The acoustic energy from the sound wave causes the TM to move which leads to the movement of the attached ossicles. The way the ossicles are formed and the size of the TM in comparison to the oval window leads to boosting the sound signal.

The fluid filled cochlea receives the mechanical energy in the form of hydraulic energy. The cochlea, which is shaped like a snail, contains the tonotopically organised basilar membrane (BM). The base of the BM interprets the high frequency components of sound, whereas its apex is responsible for interpreting the low frequency sound components. The organ of Corti resting on the BM contains the inner and outer hair cells creating yet another form of energy transformation by transforming the hydraulic energy to chemical energy through the ion channels that exchange ions in response to the sound. It then transmits the signal to the acoustic nerve, which in turn leads to a final electrical energy transformation travelling up to the brain.

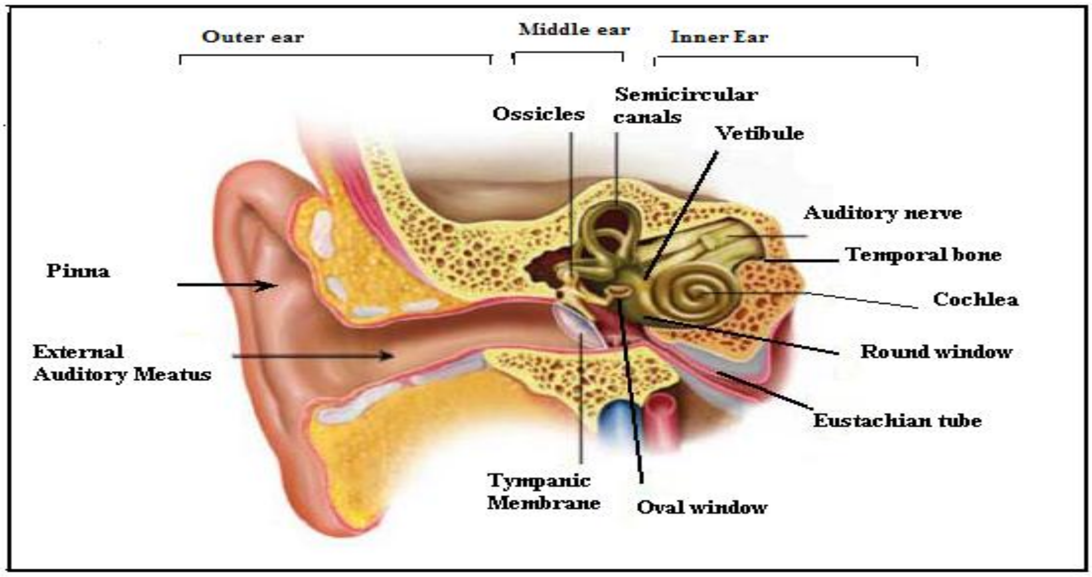

Figure 2.1 Structures of the ear adapted from http://www.boystownhospital.org/knowledgeCenter/articles/HearingLoss/Pages/TheNormalEar.aspx with permission of Boys town national research hospital.

2.1.2 Bone conduction

Bone conduction (BC) is the second route of hearing. The vibration of the cranial bones of the skull leads to hearing sensation. For the acoustic signal to create vibration of the skull bones it has to be 60 dB more intense than the AC stimulation (Reinfeldt et al, 2007). Furthermore, the vibration of the cranial bones can be induced by bone conduction transducers, tuning forks and bone conduction hearing aids.

The human skull is composed of 22 bones, eight of which contribute to the cranium; the bony case around the brain and one of the major parts of the skull. The second major part is the facial bone providing support to the face and mouth that is formed of the remaining 14 bones. All these bones take the form of curved plates with thicknesses of about 0.5 cm (Gelfand, 1998).

The temporal bone is the inferior part of the side of the skull, it houses the cochlea and has five main divisions one of which is the mastoid bone where the BC transducer is placed for hearing testing. Sound can be transmitted through the vibrations of the skull in addition to the cartilage, tissue and cerebrospinal fluid that is transmitted and interpreted in the inner ear. The speed of sound in the bones of the skull is about seven times faster than the air, and four times greater in tissue, blood and brain matter (Henry & Letowski, 2007).

The skull vibrates in different modes according to the frequency of the stimulating signal (Figure 2.2 a, b and c) this was observed by Bekesy (1948): at frequencies lower than 200 Hz the skull vibrates as a rigid body (a). Between 800- 1500 Hz the nodal compression line between the forehead and occipit causes the two extremities to vibrate in opposite phase (b), and at frequencies higher than 1500 Hz the skull vibrates in four segments separated by nodal lines. The skull vibration modes contribute to the theories of BC hearing that will be described in the following Section 2.1.2.1.

Békésy (1932) demonstrated that BC sound is perceived the same way as the AC sound. He performed tone cancelling experiment by presenting two 400 Hz tones one by AC and the other by BC, the signals were of the same amplitude, differing in phase with one being out of phase of the other, he found that the tones cancelled each other indicating that the basilar membrane is stimulated in the same way as when the signal is presented through AC (Gelfand, 1998; Stenfelt & Goode, 2005).

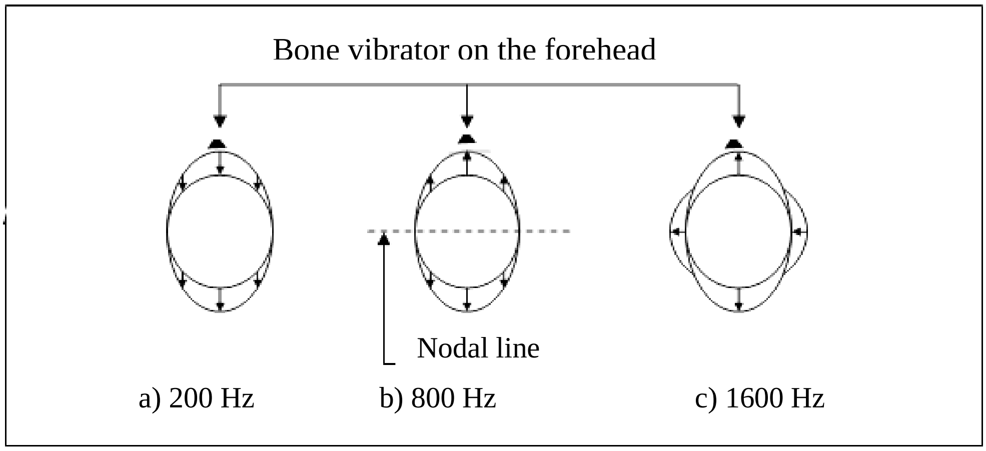

Figure 2.2 Skull vibration modes with different stimulation frequencies with the bone vibrator placed on the forehead.

Several studies were performed afterwards to verify Békésy's (1932) results. Psychophysical measurements were performed by Khanna et al (1976) over different sensation levels to examine the cancellation of AC by BC signals on one participant, cancellation was observed and repeatable confirming the results reported by Békésy (1932), they have noted that the cancellation task was sensitive to head and jaw movement. Furthermore, Khanna et al (1976) results showed linearity of sound transmission through the skull by the cancellation task, they increased the level of the BC signals in 10 dB steps over a 40 dB range (40- 70 dB), the AC level required for cancellation was also increased by 10 dB.

Loudness balance tests in normal hearing participants were conducted to explore the loudness growth through AC and BC stimulation. The participant's task was to match the output level of the bone transducer to the fixed level of the headphones. The magnitude of the difference between the AC and BC sound level at the low frequencies (250-750 Hz) was about 6-10 dB with the BC being perceived louder, on the other hand the difference was reduced to about 4-5 dB at higher frequencies (Stenfelt & Håkansson 2002). The results indicate different sound transmission properties between AC and BC at levels tested between 30-80 dB HL and not differences in the excitation of the basilar membrane. The difference in the loudness was attributed to changes of the level of the

AC sound path possibly due to the contraction of the stapedius muscle, factors related to the distortion of the BC transducer and tactile stimulation may have contributed to the results (Stenfelt & Håkansson 2002).

Auditory brainstem responses (ABR) were conducted to evaluate the AC versus BC stimuli. Stimuli included clicks and tone bursts at octave frequencies from 250 to 4000 Hz. It was found that the latency of wave V was longer in BC compared to AC stimulation but the overall hearing thresholds were comparable between the AC and BC, this has been thought to be due to the low pass filter characteristics of the bone transducer. However, their findings were consistent for the clicks and tone burst stimuli indicating that the latency difference was independent from the stimulus spectrum suggesting that it was not related to the frequency responses of both the AC and BC transducers. They concluded that there was an inherent differences in transmission between the AC and BC affecting the response latency but not related to the amplitude spectrum in the signal that might be due to the filter effect f transmission of the evoking BC stimulus through the skull (Gorga et al, 1993).

2.1.2.1 Bone conduction stimulation and transmission

Sound transmission through BC is explained by two theories based on the anatomical division of the ear and the skull vibration modes: the inertial and compressional theories (Tonndorf, 1966). The inertial BC component is caused by the vibration of the whole skull as a unit, making oscillatory movements in the direction of an acting force (Figure 2.2 -a). This force leads to a relative motion between the stapes and the oval window, i.e. inertia of the ossicular chain leading to cochlear stimulation in the same manner as that produced by AC signal.

On the other hand, compressional BC occurs due to the response of the skull to an alternating vibration producing segmental compression and expansion, it is greatest at high frequencies. In other words, the vibratory energy on the skull would cause compression and expansion of the cochlear shell. This is facilitated by the compliance of the round window as the fluid component of the cochlea is incompressible, in addition to the presence of the semicircular canals the fluid is displaced from the scala vestibule to the scala tympani.

The components contributing to hearing through BC can be due to either radiation of sound in the air or fluid, or from inertial force on a mass. Stenfelt & Goode (2005) identified five main elements contributing to sound transmission through BC hearing by studying cadaver heads and temporal bone specimens. Vital structures of the cochlea and the middle ear were preserved despite the removal of the skull structure in the temporal bone specimens. Their findings were compared to results with whole cadaver head or live human experiments where possible. The skin and soft tissue can be affected by the post-mortem effects when the whole cadaver head is used.

The five elements are summarised from Stenfelt & Goode (2005) :

1. Sound radiated in the ear canal

Vibration applied to the skull creates a motion of the surrounding air due to the deformation of the ear canal. This results in sound pressure in the ear canal. This pressure leads to the movement of the tympanic membrane and the attached ossicles. In turn, this stimulates the cochlea in the same manner as the AC sound. The bony part of the external ear canal does not contribute to the sound radiation in the ear canal because the skull vibrates as a whole unit below its resonant frequency (0.8- 1 kHz) this leads to no sound radiation. However, this component works best at low frequencies because the cartilage part of the ear canal is responsible for most of the sound radiation. Stenfelt & Goode (2005) found that the removal of the cartilaginous part of the ear canal results in a 10 to 15 dB lower sound pressure in the ear canal with BC stimulation.

The contribution is mainly seen in the form of the occlusion effect. Occlusion effect occurs when the external ear canal is obstructed and the signal perception is enhanced mainly due to the contribution of the bone conduction route. The ear canal becomes a dominant component with BC over the AC stimulation when it is occluded. This effect is characterised by low frequency emphasis of the sound. In patients using hearing aids with a full ear mould a frequent complaint is the different perception of their own voice. It is mainly due to the occlusion of the ear creating more amplification of low frequencies, it is usually resolved by placing a small vent (if possible) in the ear mould to allow air to enter the ear canal. The occlusion effect is used in the clinical test as the Bing test.

Two explanations have been proposed to explain the occlusion effect. Huising (1960) relate the change in the resonance properties of the ear canal because the resonance of an open tube differs from the closed tube. This is correct at high frequencies as the resonance and the anti-resonance determine the acoustic properties of the ear canal above 2 kHz.

The second explanation proposed by Tonndorf (1966) is related to the overall effect of the mass of the air column in the ear canal coupled with the compliance of the ear canal and the tympanic membrane produces a high pass filter effect on the sound. Occluding the canal removes the high pass filter so that the low frequencies are enhanced. This theory is correct for low frequencies as the mass and compliance of the ear canal air determines the acoustic properties. The exact perceived level of sound enhancement and frequency range is determined by the type and place of the occlusion (Stenfelt & Goode, 2005).

2. Middle ear ossicle inertia

The inertia of the middle ear ossicles contributes to BC pathway at the low and middle frequencies. The middle ear ossicles are connected to ligaments and tendons of the middle ear muscles. The TM and the annular tendon connect the stapes footplate to the oval window. The middle ear ossicles inertia is dominant at the resonant frequency of the ossicles (1.5-3.5 kHz) at frequencies below 1.5 kHz. The inertia of the middle ear is not an important contribution to the perception of BC (Stenfelt, 2006). Removal of the ossicles only minimally affects BC threshold, therefore, the ossicular inertia cannot be considered the main factor in BC hearing for the low and mid frequencies.

3. Inertia of the cochlea fluids

BC stimulation results in vibration of the temporal bone creating inertial forces on the fluids of the cochlea. As the fluid is incompressible, displacement will only occur to the membranes of the oval and round windows due to the presence of a pressure gradient. The pressure gradient produces a fluid flow between the scala vestibuli and scala tympani setting a travelling wave on the basilar membrane.

The fluid inertia is likely to be the most important contributor to BC in normal ears at low frequencies but of less importance at higher frequencies. Patients with otoscelerotic ears have the footplate of the stapes fixated in the oval window with normal bone conduction thresholds at low frequencies and a maximum loss at 2 kHz. This leads to minimal contribution of the middle ear that the response should be from within the cochlea. As the skull vibrates as a unit it follows that the compression and expansion of the skull could not be the reason for the normal thresholds.

4. Compression of the cochlear walls

This phenomenon is often referred to as inner ear compression or the distortional component (Tonndorf, 1966). When the skull is stimulated with bone conduction stimulus a transverse wave is formed causing compression and expansion of the bone. If the otic capsule is involved, a change in the cochlear fluid spaces would occur. Due to the incompressible nature of the cochlear fluids, the fluid must move causing the round and the oval windows to bulge outwards.

This component is not a major contributor to bone conduction hearing for the frequency range up to and including 4 kHz (Stenfelt & Goode, 2005). For example, with fixation of the stapes footplate, the fluid wave produced by compression cannot be displaced at the oval window which will lead to an increase in the fluid flow toward the scala tympani and increase stimulation of the basilar membrane (i.e. better hearing thresholds). On the other hand, in otoscelerosis the hearing thresholds are worse by up to 20 dB at 2 kHz and 5-10 dB lower at 1and 4 kHz. This component could apply at frequencies above 4 kHz because BC sensitivity is not lowered in otoscelerosis.

5. Pressure transmission from the cerebrospinal fluids

Sound transmission through the cerebrospinal fluids is transmitted to the cochlear fluids, primarily, through the cochlear aqueduct (Watanabe et al, 2008). This pathway fails to explain several BC findings, thus cannot be accounted as a main component.

Sohmer et al (2000) measured BC hearing thresholds at various places on the skull including the eye, they found that the thresholds obtained with the transducer on the eyes were similar to the thresholds obtained from various parts of the skull. This indicates that the cerebrospinal fluids carry the frequency pressure signal and communicates with the inner ear fluids. Furthermore, they stated that with this result “there is no need to vibrate bone in order to obtain 'bone conduction' responses”. The results can be used to confirm that the cerebrospinal fluid can be used to carry the vibrational information. However, it does not help in explaining the limitations associated with bone conduction pathways for example, the sound lateralisation, transcranial attenuation and certain lesions of the middle ear ossicles (Stenfelt & Goode, 2005).

The above contributors collectively explain hearing by bone conduction stimulation. The inertia of the cochlear fluids is considered the main contributor at low frequencies The inertia of the middle ear is the contributor at mid frequencies and with the compression of the cochlear walls contributing to the hearing at higher frequencies. Sound radiating in the external ear does not contribute to the normal BC hearing with the ear canals un-occluded. However, this contributor becomes a dominant influence on the BC hearing at frequencies below 1 kHz when the ear canal is occluded.

2.2 Application of bone conduction

2.2.1 Clinical evaluation

Clinical bone conduction evaluation is regularly performed in audiology clinics to differentiate between the conductive (CHL) and sensorineural hearing loss (SNHL). Historically, the tuning forks were the first clinical application used to compare hearing abilities by performing either Weber or Renne tests. Tuning fork tests are still used till this day as a preliminary or screening test tool. However, tuning forks are widely replaced by the electrically driven bone transducers from audiometers for clinical diagnostic testing.

A bone conduction transducer is defined by the International Organisation for Standardisation (ISO) 389-3 (1999) as an “electromechanical transducer intended to produce sensation of hearing by vibrations of the cranial bones”. The transducer converts the electrical audio signal to mechanical energy. ISO 389-3 (1999) specifies the characteristics required of the bone transducers based on previous studies examining each specific area. For example, the contact area with the skull and the tension of the headband coupled to the bone transducer and most importantly the calibration instructions.

There are several types of bone conduction transducers available for use in the clinics. RadioEar B70 series were used before the development of B71 and B72. The B71, which is currently the most widely used transducer in audiology clinics, has the advantage of smaller size and lighter weight (19 g) compared to the B72 (48 g). The B71 produces lower airborne radiation compared to the B72 (Bell et al, 1980).

Recently, a new bone vibrator, the balanced electromagnetic separation transducer (BEST) has been introduced. The BEST is reported to address the limitations associated with the clinically used B71 (Håkansson, 2003). Currently there are two main versions of the BEST. The first is the BEST-original introduced by Håkansson (2003). The second version is a low frequency reinforced BEST ($BEST_{LFR}$) which is designed to have better frequency response at low frequencies to be used for clinical and vibrotactile measurements (Håkansson personal communication, 2009). Refer to Section 3.2 for a comprehensive comparison between the B71 and BESTs.

A commercial bone vibrator TEAC HP-F100 has also been introduced as possible clinical replacement to the B71 due it its wider frequency range especially at high frequencies up to 16 kHz compared to 4 kHz with the B71 (Popelka et al, 2010). However, the TEAC HP-F100 has a contact area of 4.15 cm^2 that does not conform to the ISO 389-3 (1999) recommended contact area of 1.75 cm^2. Furthermore, it is heavier and bulkier compared to B71. A transducer with larger contact area would be difficult to place on the forehead or the mastoid. It can also be associated with heavier mass which would make it difficult to place on the same place (Queller & Khanna, 1982). Additionally, smaller tip sizes can lead to patient discomfort (Goodhill & Holcomb, 1955).

2.2.1.1 Issues associated with bone conduction evaluation

Procedural variables associated with bone conduction testing include the international specification of reference zero for pure tone audiometric testing. The reference equivalent threshold force levels (RETFLs) is defined as “the vibratory force levels produced by bone vibrator on a specified mechanical coupler when the vibrator is excited electrically at a level corresponding to the threshold of hearing of a young otologically normal persons” (ISO 389-3, 1999).

The current ISO 389-3 (1999) originated from studies in three countries using different transducers (KH70 and B71) that has been specified according to the IEC 60645-1 (Dirks et al, 1979; Richter & Brinkmann, 1981; Robinson & Shipton, 1982). Prior to the formation of the current standard (ISO 389-4, 1999), subjective calibration of the bone vibrators was performed by measuring equal AC and BC thresholds among population with normal hearing thresholds or pure SNHL in each centre. This method proved to be inconsistent and time consuming (Dirks et al, 1979) . Dirks et al (1979) evaluated several types of the same model of the mechanical coupler Brüel and Kjaer 4930 using the same bone vibrator and found differences in the output levels which was as great as 10 dB when the same electrical input was used. The results suggested that the tolerances of the artificial mastoids needed control. The lack of consistency in their results was reported to be due to a change in the original design of the B&K artificial mastoid. The manufacturers changed the material used to obtain the impedance and the method for connecting the two layers of the synthetic rubber was changed from cementing to bonding together with vulcanizing process. This finding showed that studies measuring the hearing thresholds with new design required adjustment as the addition of the new pad showed uniformity between the centres used in their study but had greater impedance compared to the previous model.

Table 2.1 illustrates the results of the three main investigations that led the formation of the current RETFLs. Two investigations used the B71 (Dirks et al, 1979; Robinson & Shipton, 1982) and one investigation used the KH70 (Richter & Brinkmann, 1981). Two main differences can be observed (Table 2.1) between the studies. The first is the use of a different number of participants in each study. The second difference was the masking noise used. Furthermore, the results reported by Dirks et al (1979) were taken from three test centres in the United States of America. To adjust for the difference in the masking noise the results were normalised to an arbitrary masking noise of 35 dB effective masking level (EML) (Robinson & Shipton, 1982).

The thresholds of the three investigations were reported unadjusted and adjusted to AC thresholds. Adjusting the BC thresholds to match the AC thresholds was to eliminate airborne gap due to difference in the reference 0 dB HL between the AC and BC results which can lead vague diagnostic significance (Hood, 1979). Hood (1979) argues that from a clinical point the RETFLs should be aligned to the RETSPLs and not reported independently because there is convincing evidence that the hearing thresholds are attributed to cochlear sensitivity and not a function of the conductive mechanism.

Conversely, ISO 389-3 (1999) RETFLs used the unadjusted data based on the concept that the AC and BC have two different pathways and thus the results should not be adjusted. Furthermore, the unadjusted results were more stable than the adjusted threshold (Frank et al, 1988). The RETFLs recommendation was based on the average thresholds of the two types of transducers. It can be observed from Table 2.1 that there was considerable difference in the hearing thresholds between the frequencies especially with the results of KH70 compared to the B71. Differences were mainly observed at 250, 2000 and 4000 Hz. However, the ISO 389-3 (1999) did not take these differences into account and reported that the RETFLs can be used with any type of vibrator.

Table 2.1 Investigations leading to the formation of ISO standard (ISO 389-4, 1999).

	Study	**Dirks et al., 1979**		**Robinson& Shipton 1982**		**Richter & Brinkman 1981***		**RETFL Recommendation**
	Type BC	B71		B71		KH70		
	N ears	60		136		50		
	N subject	60		68		25		
	Masking noise	30 dB adjusted EML		40 dB adjusted SL		30 dB adjusted EML		35 dB
	Hearing thresholds (equivalent force levels dB re 1μN)							
Frequency (Hz)	**250 (SD) ****	61.1	62.7	67.1 (7.4)	63	68.7 (6.1)	70.3	67.0
	500 (SD)	59.4	58.9	59.2 (8.0)	59.2	54.5 (5.8)	58.1	58.0
	1000 (SD)	38.7	39.4	41.9 (8.8)	42	41.9 (7.6)	44.5	42.0
	2000 (SD)	32.5	32.6	33.7 (9.2)	34.3	28.0 (8.0)	28.6	31.0
	3000 (SD)	28	28.1	30.6 (6.9)	30.5	29.8 (6.1)	31.4	30.0
	4000 (SD)	31.2	31.4	32.9 (7.1)	33.2	38.1 (8.3)	37.3	35.5

* Wider frequency range was included 125, 750, 1500, 5000. 6000, 6300 and 8000 Hz, masking noise at and below 250 Hz was presented at 40 dB EML.
**SD in dB

Frank et al (1988) proposed that the RETFLs for BC audiometry should be specified by the type of bone vibrator. Their study evaluated the BC hearing thresholds of 100 participants using three different types of bone vibrators (B71, B72 and KH70). Masking noise was presented at 30 dB EML to the non-test ear similar to the type and level of the masking noise used in the studies formulating the standard. The test ear was not occluded during the testing except at 3000 Hz and 4000 Hz by an ear plug placed in the ear canal to prevent airborne radiation. The finding of this study showed that the B72 and KH70 produced significantly higher thresholds (10.5 dB) when compared to the B71 at 250 Hz. At 500 Hz the thresholds were significantly lower (5.5 dB) than B71. Similar thresholds were obtained at the rest of the test frequencies.

A second variable is associated with the masking to the non-test ear. Masking noise should be one third of an octave centred at the frequency tested and delivered through either supra-aural or insert earphones at a hearing level sufficient to prevent the signal from crossing to the non-test ear. The limitation occurs with the possibility of occlusion where the threshold is lowered due to the insert or the headphone covering the ear. This effect is greatest at lower frequencies, in addition to the risk of over masking or under masking which occurs when the amount of masking noise is lower than the signal required to mask the signal. Therefore, the estimated threshold would be lower than the actual threshold. On the other hand, over masking leads to the masking noise travelling to the better ear leading to inaccurate estimation of the threshold. The studies that led to the specification of the RETFLs have used different masking levels which may have contributed to differences between the studies (ISO 389-3, 1999). However, they have used a correction factor to correct for this difference (Dirks et al, 1979; Richter & Brinkmann, 1981; Robinson & Shipton, 1982).

A third identified variable is the transducer itself. It is affected by sound radiating to the ear canal and perceived through air conduction at high frequencies (> 2000 Hz). Haughton (1982) suggested that the vibrators should be enclosed in a more rigid casing. A solution currently used in the clinics to prevent airborne radiation is to place a soft ear plug in the ear canal when testing high frequencies (Lightfoot, 1979; Lightfoot & Hughes, 1993). On the other hand, low frequencies are affected by distortion due to the non-linear frequency response leading to the production of harmonics that could be as loud as the fundamental frequency. The final issue associated with the psychoacoustic measurements is vibrotactile thresholds. It is when the vibration of the transducer becomes felt rather than heard thus affecting the accuracy of the measurements (Boothroyd .A & Cawkwell, 1970; Lamore, 1984). This is mainly apparent at low frequencies at high presentation levels which limit testing to frequencies at and above 500 Hz.

Placement of the bone transducer on the skull is the fourth variable. The effective output of the bone transducers is sensitive to variation of placement (Weatherton & Goetzinger, 1971). The two common sites of placing the transducers are on the forehead and on the mastoid bone. The threshold of hearing is approximately 10 dB higher at the forehead placement. The British Society of Audiology (2004) recommends the placement on the mastoid bone and the international standards provide RETFLs for both sites of placement (ISO 8253-1, 1998).

The worsening of thresholds at the forehead could be related to thickness of the bone in that area of the skull. Stimulation in the region of the thinnest skull bone (a restricted part of the temporal area) were significantly better by 5-12 dB (depending on frequency) than those obtained to stimulation at the forehead at all frequencies (Sohmer et al 2000). Skin thickness and bone structure varies between locations and between subjects (Studebaker, 1962).

The integrity of the current RETFLs has been questioned in a number of studies. Lightfoot & Hughes (1993) pointed out that the large air-bone gaps in their study could have resulted from discrepancies between the air and bone conduction standards, and recommended that frequencies above 4000 Hz should be avoided. Furthermore, O'Neill et al (2000) have reported a systematic error in bone conduction thresholds characterised by a notch at 2000 Hz in normal hearing subjects. However, a number of methodological limitations have been associated with this study, for example, the small sample number.

2.2.2 Hearing aids

The second application is for hearing aid fitting. The BC hearing aids are similar to the bone transducer with the difference that they have a microphone that picks the signal and transforms it to a vibratory signal on the skull. There are two main types of bone conduction hearing aids: the non-implantable hearing aids and BC implantable (BCI) hearing aids.

Non-implantable hearing aids include the conventional hearing aids and the SoundBite system. The conventional hearing aids are placed transcutaneously on the skin through a steel band or a soft headband that has been advocated recently for use in paediatric population (Aazh et al, 2005; Hol et al, 2005; Verhagen et al, 2008). The limitation of this coupling method is that it causes headaches and skin irritation thus affecting the proper use of the hearing aid. More importantly, the soft tissue of the skin causes attenuation of the signal (Mylanus et al, 1994). Furthermore, the limitations include the variability of the transducer placement on the bone and flaccidity of the headband with constant use.

SoundBite is a non-surgical hearing instrument that uses BC hearing through a device fitted on the teeth. (Popelka, 2010; Håkansson, 2011). The sound waves are captured through a microphone unit fitted behind the ear. The sound waves are then converted into vibrations transmitted through the custom made, in-the-mouth hearing device. It is mainly used for single-sided deafness and CHL.

The second fitting method is percutaneous BCI. The bone anchored hearing aids (BAHA) developed by Håkansson et al (1985) are widely used. The Oticon Ponto is another commercial BCI. The fitting procedure is performed by surgically implanting a titanium fixture to the temporal bone allowing for it to osseointergrate with the bone-a process that takes up to two months (Tjellstrom et al, 2001). A percutaneous abutment is then attached to the fixture. An external sound processor “snaps” into the abutment, which transmits sound directly via the bone to the inner ear. This can be connected and disconnected at the user’s will.

2.2.3 Communication and leisure

A third application is in communication and leisure. It is argued that bone conduction can be used for the military communication as it will keep the ears free to make use of the surrounding environment (Walker et al, 2005). Other commercial applications include mobile phones ear piece and BC headphones incorporated through music device to be used underwater that keeps the ears free.

There are some bone-phones marketed to keep the ears free and preserve awareness of the surrounding environment. Bone-phones are mainly used when playing sports. The concept of these phones is great but the customer reviews are mixed between the products fulfilling the purpose provided that the volume was low. The increase in the volume of the signal results in poor sound quality that was reported by most reviewers of the product (Consumer-Review, 2013).

2.3 Binaural hearing

The ability to use information coming to both ears develops naturally without being taught. An example of the binaural ability is seen in the animal's capability of locating sound sources in the jungle. The same applies in the human's ability to locate sound sources and interpret them. Binaural is related to having two functioning ears. There are advantages associated with binaural listening opposed to listening monaurally (i.e. with one ear). Locating a sound source in auditory space is related to having two functioning ears as well as the ability to tune in to a conversation when there is background noise.

The benefit of binaural hearing has been well established for normal hearing subjects and for patients with hearing loss where bilateral fitting is advocated and systematically used when the hearing loss is bilateral (Hickson, 2006; Kiessling et al, 2006). Recent research shows that adults and children benefit from bilateral cochlear implants (Verschuur & Lutman, 2003; Verschuur et al, 2005; Van Deun et al, 2009) .

The cues that are used to judge the presence of binaural benefit, in addition to the methods for measuring binaural hearing will be discussed in the following sections.

2.3.1 Terminology

The auditory space is defined relative to the head and consists of three planes (Figure 2.3). The horizontal plane passes through the interaural axis which is an imaginary line that passes between the two ears at the upper margins of the ear canals and lower margins of the eyes. The frontal plane lies at right angles to the horizontal plane and intersects the upper margins of the entrances to the ear canals. The median plane lies at right angles to the horizontal and frontal planes passing over the centre of the head and dividing the auditory space into left and right. Sound presented away from this plane is called lateral. Sound angle direction is specified by its azimuth (horizontal plane) and its elevation (median plane). A sound with 0^{o} azimuth and elevation is right in front of the head, whereas sound with 90° azimuth and 0° elevation lies directly opposite of the right ear.

Localisation is the ability to determine the direction of sound source and indicates the appropriate direction to direct visual attention. Most of the cues used in localisation depend on comparison of signals reaching the two ears. The performance in localisation depends on how well the perceived signal corresponds to the actual location, in addition to the subject's detection of small shifts in the direction of the sound source.

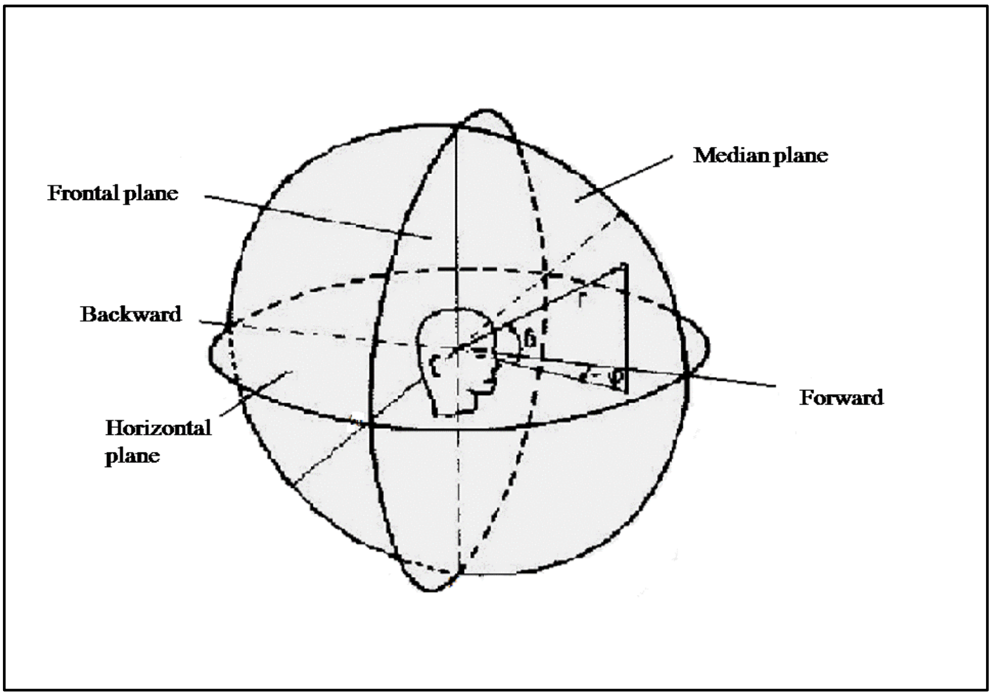

Figure 2.3 Representation of the auditory planes reproduced from Moore (1997).

Sounds presented from an external source are perceived to be externalised (i.e. reported to be heard outside of the head). Lateralisation is perceived when headphones are used it is described by the apparent location of the sound source within the head.

Bilateral listening involves the use of both ears, whereas unilateral listening involves one ear. Diotic is the presentation of identical signals to both ears where dichotic is the presentation of one signal to the right ear and a different signal to the left ear (Gelfand, 1998).

Head shadow occurs when the head is between the sound source and the ear being investigated causing the signal to be attenuated, this effect is significant for frequencies above 1500 Hz because their wavelength are small compared to the size of the head (Blauert, 1997).

2.3.2 Acoustics of auditory space perception

The fact that the head is round and the ears are on the sides of the head creates a set of acoustical cues when sounds reach the ears from a particular location. A signal presented from a source on one side of the head will reach the ear on the same side of the source before it reaches the ear on the other side, i.e. there is a time difference between the first and the second ear, this time difference is the interaural time difference (ITD). The signal will be lower in level at the second ear (far ear) compared to the first (more intense), this is termed as the interaural level difference (ILD), illustrated in Figure 2.4.

The ITD and ILD are the main auditory cues used in binaural hearing in the horizontal plane, the difference in time and/or level depends on the location of the sound source and on the type of signal presented. Furthermore, the cue used for discrimination of the location of the sound source is highly related with the type of signal which differs between low and high frequencies. For certain complex signals those cues work together which is the basis of the duplex theory discussed in Section 2.2.2.3.

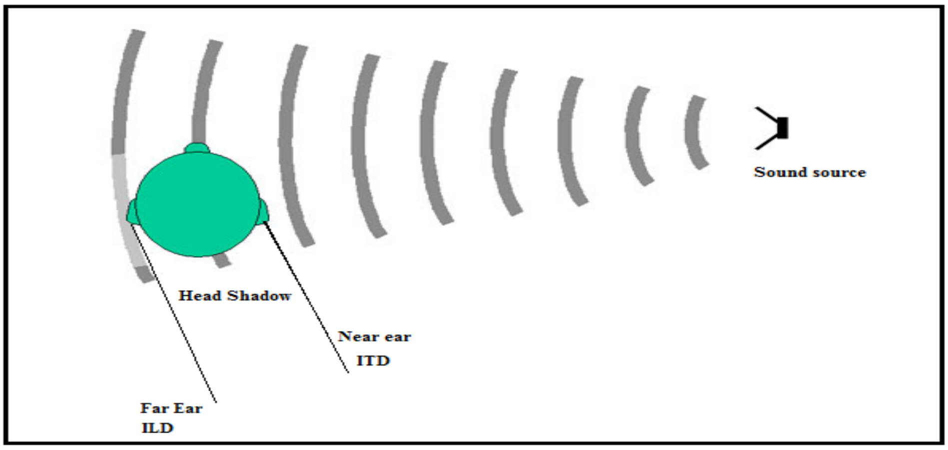

Figure 2.4 Representation of the spatial cues used when the sound source is on the right side.

Other cues are used to determine if the signal is presented from heights. For example the unique shape of the pinna causes spectral changes in the signal, as well as the reflection of the signal of the body and shoulders.

The following sections will deal with the cues humans use in the horizontal plane as those are the main cues used in binaural hearing experiments. Cues used in the median plane will be briefly mentioned.

2.3.2.1 Interaural time differences

The difference in time between the two ears is the ITD (Figure 2.5). The difference is largest when the signal is presented at 90^{o} azimuth measured to be 660μs. The difference decreases as the sound source moves in the horizontal plane until it reaches 0° in this case the ITD would be 0 μs because of the equal difference between the two ears (Feddersen et al, 1957).

In low frequencies pure tones (<1500 Hz) the wavelength of the signal is larger than the distance the signal has to travel from the near ear to the far ear, the time difference could be expressed as phase difference. With low frequencies the hair cells in the inner ear fire regularly with the phase of the signal.

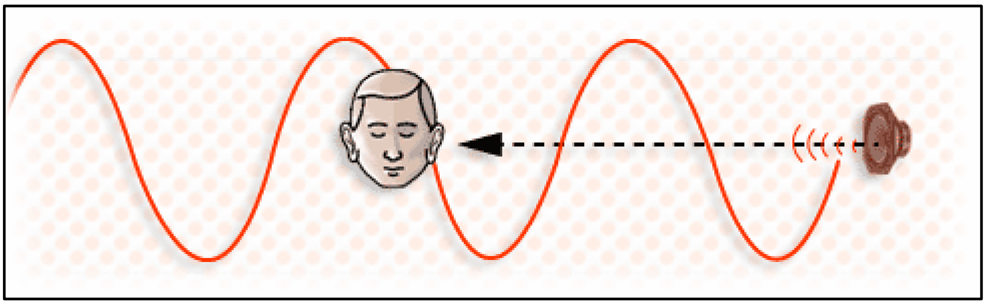

Figure 2.5 The ITD with a low frequency pure tone. (http://www.neuroreille.com/promenade/english/ear/exear/exear.htm)

Phase differences depend on the frequency and the location of the sound source, because the distance between the ears is constant. On the other hand, high frequencies have smaller wavelengths and the difference in time cannot be calculated between the two ears as the head casts and “acoustical shadow” preventing the signals to pass.

Interaural phase differences (IPD) becomes ambiguous with frequencies above 750 Hz because the distance between the two ears is equal to half a wavelength of the sound, so it becomes impossible to tell whether the phase of the signal is leading or lagging at a certain ear.

The onset and offset of the signal are important cues for the binaural hearing and are primarily based at low frequency content of the signal. At higher frequencies monitoring the differences in the overall envelope of sound signals is aided by the onsets and the offsets. With a sound onset, the delay between the two ears is used to determine the input direction of the corresponding sound source. This is particularly useful in reverberant environments. After the onset of the signal, there is a short time frame leading to the sound reaching the ear but not the reflected sound. The auditory system uses this time frame to evaluate the sound source direction.

The poor discrimination of ITDs at high pure tone frequencies may be the result of progressive loss of accuracy with which inner hair cells can phase lock to the fine structure of the pure tone (Akeroyd, 2006). However, with complex tones, the phase difference at high frequencies may not be perceived by the listener but the time difference may still be used. The binaural system is completely insensitive to the ITDs for narrowband stimuli above about 1.5 kHz although it does respond to low-frequency envelopes of high-frequency stimuli (Wang & Brown, 2005).

2.3.2.2 Interaural level differences

The interaural level difference (ILD) is the difference in the perceived level between the right and left ear and similar to the ITD, it is greatest when the sound is 90° to one side of the head. It is produced because the 'shadowing' effect of the head prevents some of the incoming sound energy from reaching the ear that is turned away from the direction of the source.

Measurements of ILD conducted by Freddesen (1957) found that there was no ILD between the ears when the sound source was directly in front 0^{o} or behind 180^{o} the head as it is equidistant between the two ears. Their study also found that for 200 Hz, the ILD was negligible at all azimuth angles and increased with frequency reaching 20 dB at 6000 Hz.

ILD is most pronounced at frequencies above approximately 1.5 kHz because the head is large compared to the wavelength of the incoming sound, producing substantial reflection of the incoming signal. ILDs measured at the eardrum exhibit much more subject-to-subject variability, and for a given subject the ILD is a much more complicated function of frequency, even for a given source position

2.3.2.3 Duplex theory

The duplex theory dates back to Lord Rayleigh (1907). The basis of this theory is that there are two separate mechanisms for sinusoids. The physical cue of ILD should be most useful at high frequencies, while the cue of ITD should be most useful at low frequencies. As mentioned in the previous sections, each of these cues is useful for some frequencies more than the others, therefore, the duplex theory proposes that the auditory system uses both of these cues according to the situation.

The duplex theory overcomes the problems associated with the use of each of the basic interaural cue for localisation. With an on-going narrowband signal, the ITD with low frequencies is used in localisation tasks. Whereas at high frequencies, the ILD is the cue used as the ITD can exceed the signal period leading to ambiguities in localisation.

The duplex theory has limitations when the signals have wider bandwidths. This could be associated with the binaural system placing special significance on the timing of the signal onset that it precludes the use of ITD in the on-going portion of the waveform. Another limitation is that the duplex theory only accounts for sounds in the horizontal plane and it does not take account of the pinna influence in localisation (Gelfand, 2004).

2.3.2.4 Spectral cues

The shape of the pinna gives rise to reflections and resonances that change the spectrum of the sound at the ear drum depending on the angle of incidence of the sound wave. To some extent, reflections off the shoulders and body also modify the spectrum. Sound source to the rear give rise to a reduced high frequency response compared to those at the front due to the forward facing shape of the pinna (Rumsey, 2001).

The major contribution of the pinna is in localising sound sources in the median plane in monaural listening. Gardner & Gardner (1973) examined the effect of pinna cavity occlusion on the median plane using random noise band signals. The results obtained from this experiment showed that the localisation ability decreases with increasing occlusion. Participants in this experiment also showed better results in the anterior sector of the median plan compared to the posterior sector. Overall localisation results with all degrees of occlusion were better for broadband noise compared to narrow band signals.

At high frequencies the head and shoulders and the external ears act as subtle comb filters that vary depending on source elevation and azimuth. The sound arriving at the ear canal is influenced by sound reflected off the body. The identification of the sound is also aided by head movement.

Middlebrooks & Green (1991) showed a significant role of the spectral shape i.e. monaural listening (frequencies around 1 kHz and at 5 to 6 kHz and higher) in discrimination of frontward from rearward horizontal plane source.

2.3.3 Plasticity of binaural system

Binaural plasticity refers to the capacity of the auditory system to make changes to its functions over a life time. It is dependent on critical periods of development. The patterns of sensory activation or lack of it influence the maturation of the neural activity (Schmerber et al, 2005).

The superior olivary complex is where the developmental and adaptive tuning in the binaural processing takes place. A large proportion of neurons are thought to be sensitive to ITD in the medial superior olive, whereas the neurons in the lateral superior olivary complex are thought to be sensitive to ILD.

The auditory pathways are adaptive to binaural inputs even after childhood. The capacity of the brain to recalibrate auditory localisation cues extend into adulthood (Schmerber et al, 2005). This finding was based on testing time-intensity trading experiment, i.e. testing the relative strength of the binaural cues. In other words, the relative value of the ITD required to compensate for the ILD in order to produce a sound image within the midline of the head. Eleven participants with bilateral congenital atresia (born with occluded ear canals) showed significant individual differences in the values of the lateralisation cues suggesting that that the capacity for behavioural adaptation and auditory plasticity is dependent on multiple individual factors. Their study indicated that the auditory pathways are adaptive to binaural inputs even after childhood when the children were deprived of binaural stimulation.

Patients with unilateral congenital atresia were able to make use of the interaural differences after one year of the reconstructive surgery. The binaural benefit was attributed to the stimulation of the cochlea through one's own voice in bone conduction (Snik et al, 1995).

In congenital unilateral hearing loss the auditory brainstem rearranges the binaural connections according to the signal input received from the normal hearing ear. Whereas, acquiring unilateral hearing loss in adulthood does not show such neural rearrangement. This shows the sensitivity of the binaural mechanism to hearing loss during the developmental period (Moore, 1991).

The results presented in this section indicate that the auditory system is adaptive to some extent and could benefit from the rehabilitation with binaural hearing aids even if there was a period of deprivation. This finding could be useful for children or adults with bilateral CHL who have been fitted with only one hearing aid. This could mean that there is a possibility of benefitting from a second BAHA.

2.4 Clinical evaluation of binaural hearing: masking level differences

Masking level differences (MLDs) test is one of many binaural tests used to evaluate binaural hearing. The basic principle of the MLDs test is the change in the interaural listening conditions causing an alteration in the performance of the listener. It is characterised by an improvement in a person's detection threshold of a signal within noise as a consequence of changing the phase in one ear relative to the second ear. In other words, MLD is the level (dB) difference that is necessary to maintain the listener's performance constant when changes in the interaural listening conditions are introduced. Different terms are used to describe this test: binaural release from masking, binaural unmasking, binaural analysis, and binaural masking level differences (Libby, 1980).

The MLDs conditions are expressed in shortened letters to express the relationship among the stimuli and the ears. The signal is represented with an “S” , “N” is the noise condition, and the sub-letter “m” added to either conditions would mean that it is monaurally presented (for example condition (a) in Figure 2.6 indicates that the signal and the noise are presented to one ear). SoNo means that the same signal and the same noise are presented simultaneously to both ears (condition (b). “π" indicates inverting the phase of either the signal or the noise in one of the ears (180° out of phase).

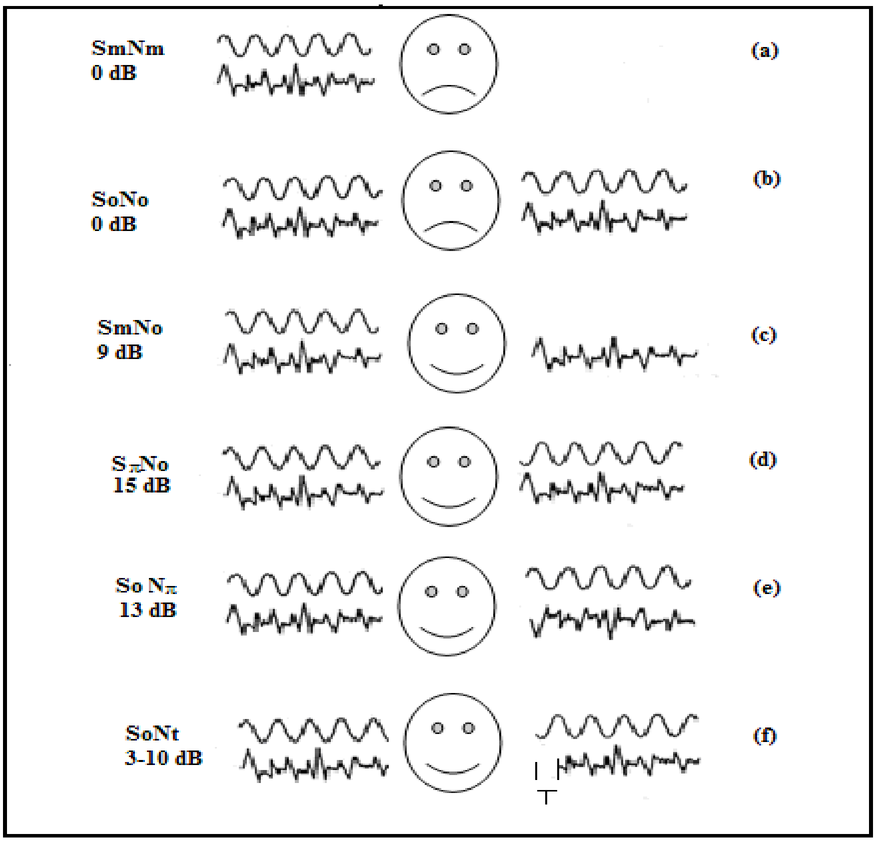

Figure 2.6 Illustration of conditions that create binaural MLDs, for different combination of signal and maskers levels (redrawn from Gelfand (1998).

MLDs measurements are influenced by signal and noise variables. Table 2.2 shows some examples of studies with different MLD parameters. Signal variables include the frequency presented where lower frequencies produce the largest MLD. For example, a signal presented at a frequency of 250 Hz produces 15 dB MLD which decreases to a uniform 3 dB for frequencies above 2000 Hz (Levitt & Voroba, 1980). The signal phase

Table 2.2 Studies of binaural MLD with normal hearing participants

Study	Participants	Masker band	Masker level	Frequency	MLD (dB)	Results and conclusion
Hall & Harvey, 1985	10 Normal hearing	BBN (2000 Hz wide)	50 dB (spectrum level)	500 Hz	14.2	Type of headphone was not mentioned
				2000 Hz	3	
Hall &Grose, 1994	8 Normal hearing	NBN (100 Hz wide)	Fixed pressure spectrum 60 dB	500 Hz	17.9 (SD 1.4)	This result with insert earphone (Etymotic 3A)
			Equal sensation level 35 dB		15.2 (SD 1.9)	
Beijonon (1995) reported by Bosman et al ., 2001	Normal hearing	Not reported	Not reported	500 Hz	11.5	These results were reported by Bosman (2001) of a Masters thesis
				1000 Hz	9.3	
				2000 Hz	6.2	
Bernstien et al., 1998	19 Normal hearing	NBN (50 Hz wide)	Spectrum equal to 50 dB SPL	500 Hz	15.8 (SD4.7)	The MLD was greater in the NBN condition but should more variation between subjects with SD of 4.7 dB compared to 2.3 dB with the BBN
				4000 Hz	5.8 (SD 3.1)	
		BBN (100-8500 Hz)		500 Hz	13.6 (SD 2.3)	
				4000 Hz	1.4 (SD 1.6)	
Van Deun, 2009	10 Normal hearing	NBN 1/3 octave	75 dB SPL	500 Hz	Median 18.8	These results were obtained using Sennheiser HD250 Linear II headphones
		BBN (200-1000 Hz)			Median 13.0	

has a profound influence on the MLDs. The MLD is largest when the signals phase is inverted by 180˚. Another variable is duration of the signal which has a minimal influence on the MLDs. An MLD increase of 1-2 dB has been noted when the duration of the signal was less than 50 ms (Green & Yost, 1975). The largest MLDs are seen when the signals have the same intensity at the two ears where a 3 dB difference between the two ears causes a change to the MLDs. The signal bandwidth also plays a role in MLDs measurement, the largest MLDs occur when the signal contains energy in the frequency region below 1000 Hz (Green & Yost, 1975).

Variables related to the masker also influence the magnitude of the MLD. The masker presented to both ears should be correlated (i.e. presented from the same noise generator), otherwise, the MLDs could be influenced by 3-4 dB. The masker level is another variable influencing the size of the MLD, an increase in the MLD is observed as the noise level increases up to an effective level of 40-50 dB after which it becomes stable (Levitt & Voroba, 1980).

The masker bandwidth also influences the MLDs, the narrower the bandwidth the larger is the MLD. Nevertheless, Bernstein et al(1998) showed that the greatest amount of inter-subject variability occurred with narrow band noise (NBN) masker. Similar to the signal, inverting the phase of the masker produces the largest MLD. Whereas varying the interaural level difference of the masker level between the eras lowers the MLD.

The test-retest reliability has been measured with AC MLD for both 500 Hz tone and speech stimuli and was found to be reliable and consistent. (Stubblefield & Goldstein, 1977).

2.5 Influence of hearing loss on binaural hearing

Hearing loss has a diverse effect on binaural hearing. The type and degree of hearing loss influence localisation. It has been reported that impaired localisation is considered to be one of the major difficulties experienced by people with hearing loss, in addition to the difficulty encountered with listening to speech in noise (Noble et al, 1994).

The symmetry of hearing loss also influences localisation ability. Mild symmetrical hearing loss has no noticeable influence on localisation ability. Asymmetrical hearing losses, however, severely disrupt localisation in the horizontal plane showing larger than normal thresholds for detecting ITDs and ILDs (Hausler et al, 1983).

Subjects with symmetrical losses show normal or near-normal localisation for broadband noise stimuli. Conversely, they often show impaired performance for narrowband stimuli. Hearing loss of cochlear origin affect the ability of the auditory system to preserve the temporal cues inherent in the signal. CHL also distorts the acoustic temporal cues (Hausler et al, 1983).

Noble et al (1994) designed a study to explore the degree and type of hearing loss in different frequency regions on various aspects of auditory localisation. The investigation included three main groups; participants with normal hearing, participants with conductive hearing loss (CHL) or mixed hearing losses (MHL), and participants with sensorineural hearing loss (SNHL). The sound stimuli used was bursts of pink noise. Test conditions included the horizontal and vertical planes tested in an anechoic chamber. They found that the localisation performance significantly differed between the SNHL and CHL/ MHL. The low frequency ITD cues were more disrupted in this group compared to the SNHL, leading them to score less.

Binaural hearing ability was also severely disrupted with hearing protection devices. The greater the attenuation provided by the devices the greater the influence in the localisation (Brungart et al, 2003).

SNHL disrupts the ability to use spectral cues which can be attributed to either the lack of audibility associated with the hearing loss or the irresolvable patterns of the spectral peaks(Moore, 1997).

The effect of conductive hearing loss on binaural hearing has been evaluated in a number of studies. Hausler et al (1983) showed that participants with CHL had normal just noticeable differences in ILDs but abnormal ITDs. Their results also showed abnormally large horizontal minimum audible angles on the horizontal plane mainly to the sides.

On the other hand, Kaga et al (2001) measured lateralisation with bilateral BC stimulation in twenty children and a young adult with bilateral congenital microtia or atresia. They reported that half of the participants (10 out of 20) had approximately normal ITDs, and 10% of the patients showed ILD threshold elevation. This study concluded that bone conduction lateralisation was maintained in many of the patients.

2.6 Binaural hearing with bone conduction stimulation: background studies

2.6.1 Factors associated with binaural bone conduction

Factors that influence bone conduction measurement are related to the transducer itself such as the frequency response, the production of distortion at lower frequencies, and the airborne radiation at high frequencies. In addition to the influence of bone condition transmission routes inside the head that add up to our perception of a bone conduction hearing (Section 2.1.2).

This section describes the factors associated with two signals transmitting inside the head that can influence the perception of binaural hearing. Two main factors are identified that may influence the signal transmission: the transcranial attenuation and transcranial delay. This section will also discuss a mathematical model that shows how these factors have a significant impact in the human perception of hearing when stimulated with two bone conduction transducers.

2.6.1.1 Transcranial attenuation

Transcranial attenuation (TA) reflects the cranial rather than the aural stimulation. It replaces the interaural attenuation (IA) when stimulated by an AC signal. IA is the reduction in the intensity of the signal as it crosses the skull (Smith & Markides, 1981). In other words, TA is the difference in bone conduction hearing thresholds between the contralateral and ipsilateral cochlea. Since the bone is a good sound transmitter, it is assumed that when placing the bone vibrator on the forehead, the sound will reach both cochlea at the same time, provided that the pathway to each cochlea is symmetrical.

TA is reported to vary with frequency and is associated with inter-subject variation (Nolan & Lyon, 1981; Stenfelt, 2012). There is also reported discrepancy between the objective measures in-vitro and the psychoacoustic measures in-vivo. Archer (1952) reported that the application of a bone vibrator on the skull stimulates both cochlea with very little difference in the level over the frequency range 250 to 2000 Hz. This notion has been supported by Dirks (1985), who believes that the TA across the skull is negligible regardless of the side of the vibrator.

Conversely, Vanniasegaram et al (1994) found a significant attenuation at 4 kHz. Additionally, it was reported that the transmission loss from the ipsilateral mastoid process to the contralateral cochlea varies between -5 and +15 dB (Studebaker, 1962). Moreover, objective measures directly quantifying the TA performed by Stenfelt et al (2000) on a dry male skull with added damping material reported values of TA ranging from -5 to 10 dB for the energy transmission with a tendency toward higher attenuation at the higher frequencies indicating dependency on the frequency. Studies with dry skulls can give insight to sound transmission in the human head. The results obtained should be viewed with consideration because a dry skull would be different than a live skull due to the internal properties. In addition to the multiple pathways associated with bone conduction that might not be reflected by a dry skull. Another drawback associated with this study is that it only used one dry skull.

In a more recent investigation Stenfelt (2012) conducted measurements of TA in unilaterally deaf patients in two head positions, the mastoid and the parietal bone (where a BAHA is usually fitted) at 31 frequencies. The results were highly variable between the participants (up to 40 dB). The median TA results for the mastoid position ranged from 3-5 dB at frequencies up to 0.5 kHz and around 0 dB at frequencies ranging from 0.5 to 1.8 kHz, increasing to about 10 dB at 3-5 kHz as well as showing a slight reduction at higher frequencies. The TA for the BAHA position was 2-3 dB lower compared to the mastoid position. These results indicate that the positioning of the vibrator has an impact on the results of the testing. Therefore, results from the mastoid position should be used with caution when referring to the BAHA position. Furthermore, this study used a B71 transducer which is associated with a number of limitations and generally not used at higher frequencies because of its frequency response and production of high distortion levels at low frequencies. There was no mention of whether the patients involved were fitted with a unilateral BAHA or even a conventional hearing aid. This could influence the reported results due to the influence of the surgery on the skin properties.

Stenfelt & Zeitooni (2013) reported measuring TA in 20 normal hearing adults as part of an investigation of the binaural cues using BC stimulation. The signal was presented through a BEST transducer placed on the mastoid bone where the non-test ear was masked with modified ER2 insert earphones. The insert foam tip was cut into small wings to avoid the occlusion effect. The masking noise was a third-octave band-pass filtered noise with the centre frequency equal to the test frequency. The results indicated a tendency of the median data to be around 5 dB at low frequencies, close to 0 dB at mid-frequencies (1-2 kHz) and around 10 dB at higher frequencies. However, the range of the participant responses was wide around 21 dB at each frequency. The standard error of the mean ranged between 0.7-1.6 dB.

The implications of small reported TA in clinical testing is important. In pure tone audiometry, masking should always be applied to the non-test ear when there is asymmetry in pure tone thresholds between the two ears. It has another implication in the rehabilitation with bone conduction hearing aids, as the small TA would mean that the signal stimulates both cochlea almost equally thus two bone conduction hearing aids would not be useful. On the other hand, it could mean that stimulating patients suffering from unilateral hearing loss who also have small TA benefit from rehabilitation with one BAHA placed on the worse hearing ear. The sound would be transmitted to the better hearing ear without any attenuation thus the patients would benefit from the hearing aid especially in the cases of single sided deafness (Stenfelt, 2005).

2.6.1.2 Transcranial delay

Transcranial delay (TD) is the speed of sound through the structures of the head. TD depends on the mechanical properties of the head at the point of stimulation. This definition is used when the sound transmitted in the space is excluded from AC perception. It corresponds to ITD with air conduction stimulation which may be as large as 600 to 800 µs depending on the head size when the ear is stimulated at 90º to either side in the free field (Henry & Letowski, 2007).

Bekesy (1948) was the first to measure TD through placing the vibratory source on his teeth and measuring the speed of sound through the head by comparing the times of the signal arrival at the two pickup points placed on the forehead and the back of the head. He produced click stimuli from his teeth which yielded TD of 570 ms^{-1}.

The propagation velocity of the bone conducted sound was calculated through cancellation experiments. It was found to be 260 ms^{-1} at frequencies below 500 Hz and 330 ms^{-1} at frequencies below 2000 Hz (Tonndorf & Jahn, 1981). Stenfelt & Goode (2005) measurements conducted on cadavers skulls showed that the phase velocity of the waves changed with frequency, especially when the estimation was performed on the cranial bone, at lower frequencies. The reported phase velocity of 100 ms^{-1} increased to 250 ms^{-1} at frequencies up to 2000 Hz and 300 ms^{-1} at 10 kHz.

The influence of the TD in binaural hearing could be translated to the change of phase of the signal between the two ears that could result in an apparent benefit in certain types of tests. It can also influence the signal relation between the two ears (Rowan & Gray, 2008).

2.6.1.3 Model of sound interaction in bone conduction

Binaural hearing with air conduction stimulation depends on the difference in the level of the sound arriving to both ears which is dominant at high frequencies. Furthermore, the difference in time (phase) of the signal arrival also contributes to binaural hearing which is dominant at lower frequencies (Section 2.3.2). Figure 2.7 shows the contribution of the AC and BC pathways in binaural hearing.

Sound arriving through AC is influenced by different external pathways which in addition to the influence of the head and pinna, leads to phase and level differences of the sound reaching the two cochlea. These differences will be transmitted to the cochlear nucleus (CN) and the superior olivary complex (SO) where it will be processed and compared aiding in locating the sound source. The SO is the lowest level capable of receiving binaural information. The neurons code the interaction resulting from level and phase differences in the stimuli at the two ears as excitory (ipsilateral stimuli) and inhibitory (contralateral stimuli) inputs. The high frequencies and ILDs are received in the lateral SO, whereas the lower frequencies and ITDs are received in the medial SO (Gelfand, 1998).

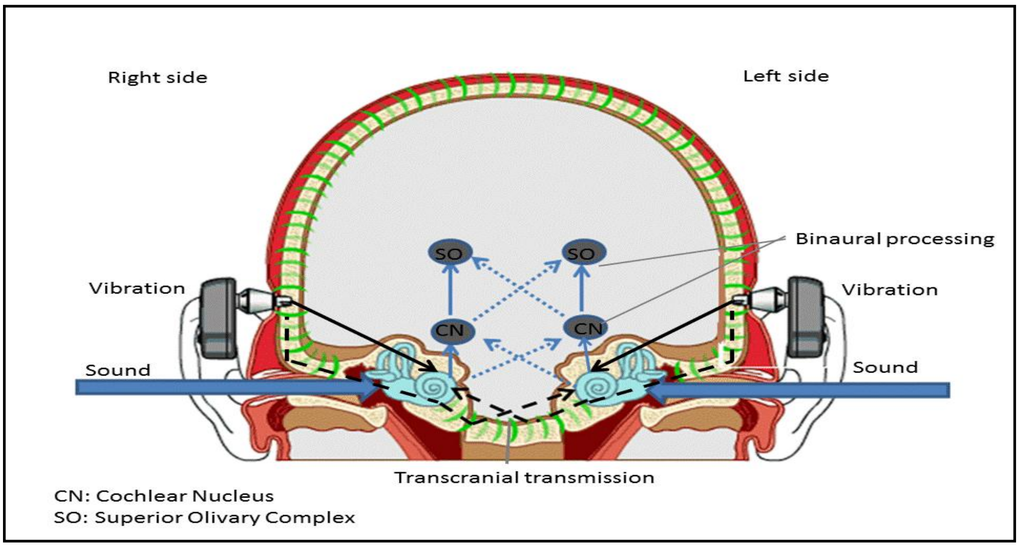

Figure 2.7 Representation of the auditory system. The Sound (AC) is transmitted to each cochlea separately and the binaural processing is conducted centrally by comparing the two signals (Thick blue lines). The vibrational sound (BC) is summed at the cochlear level due to transcranial transmission (Adaptation from Stenfelt, 2005).

The vibratory signal caused by the bilateral stimulation with bone conduction will be affected by similar external influences as the AC signal. However, due to transcranial transmission the sound arriving from the ipsilateral and contralateral ear will interact at the cochlear level as shown in Figure 2.7. This means that if the transfer function from the BCI to the cochlea is equal in the two ears it will lead to equal stimulation to both cochlea and the interaural differences will be lost leading to the loss of binaural processing (Stenfelt, 2005).

A mathematical model was proposed in an attempt to explain binaural hearing in patients with conductive hearing losses (Zurek, 1986). Several assumptions were made in order to simplify the model. It assumes symmetric pathways to each cochlea which might be different in reality. It also assumes negligible air conduction pathway which is expected with patients with conductive hearing loss. The model illustrated in Figure 2.8 addresses the influence of bilateral symmetric conductive hearing loss. The sound which is produced from a source on the right side will be influenced by external components represented by the ITD (τ) and ILD (α) and the internal interference components represented by the TA (β) and TD (δ) which influences the contralateral signal at both the right and left cochlea. Therefore, the resultant stimulation at the cochlea will add together either positively or negatively. Since two hearing aids will be fitted bilaterally, the transducer gain (TG) of the BAHAs will be assumed to be equal and thus will not be included in the calculation. TG is the vibration force of the BAHA converted from the sound pressure at the microphone.

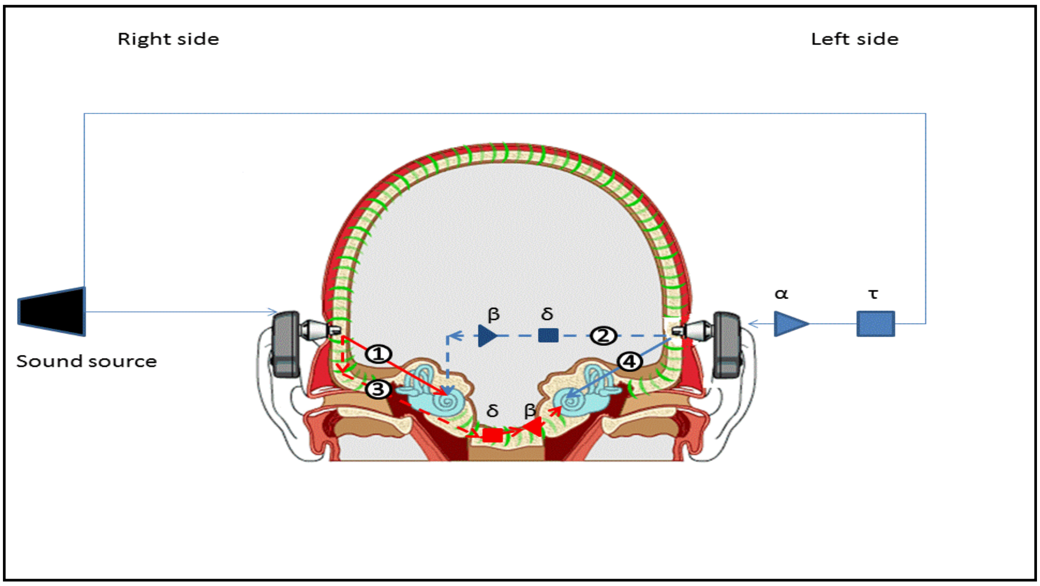

Figure 2.8 Stimulation pathways involved in bilateral bone conduction, for the right cochlea and left cochlea (assuming negligible AC stimulation) adapted from Zurek (1986) and Rowan &Gray (2008).

A closer look at sound transmission at each cochlea would show that the right cochlea gets the direct signal marked in Figure 2.8 by number 1, and the contralateral signal marked by number 2 that comes from the contralateral BAHA and is influenced by the combination of ITD, ILD and TA and TD. The left cochlea will receive signal 4 which is influenced by the external path ITD and ILD in addition to the signal number 3 that arrives from the right BAHA and is influenced by the internal factors TD and TA. This clearly indicates that if there is any binaural benefit, it will rely greatly on the internal parameters TA and TD. The TA and TD have been shown to vary with frequency and among individuals (Nolan & Lyon, 1981; Tonndorf & Jahn, 1981; Stenfelt, 2012).

This model can be used as a predictor for measuring masking level differences with pure tones while the masking is constant stimulation. The following equations were formulated based on Zurek (1986) model using the numbered pathways in Figure 2.8 for a sine wave signal.

Stimulation at the right cochlea = Pathway 1+ Pathway 2

Stimulation at the left cochlea = Pathway 4 + Pathway 3

Right ipsilateral Pathway 1 $=Sin(2\pi ft)$

Right contralateral Pathway 2= 10^$(\frac{-(\alpha+\beta_R)}{20}) * Sin(2\pi ft-(\tau+\delta_R)$

Left contralateral pathway 3= 10^$(\frac{-(\beta_L)}{20}) * Sin(2\pi ft-\delta_L)$

Left ipsilateral pathway 4= 10^$(\frac{-(\alpha)}{20}) * Sin(2\pi ft-\tau)$

Applying the current model to a 500 Hz pure tone stimulating the right ear is shown in Figure 2.9 A. It is assumed that the sine wave is not influenced by external factors. Furthermore, it assumes that the TA and the TD are zero so the sound is summed leading to an increase in amplitude at the right cochlea (Figure 2.9 B). This shows that the patient may report enhancement in sound level at a cochlear level which is not due to binaural hearing but due to the crossing of the sound.

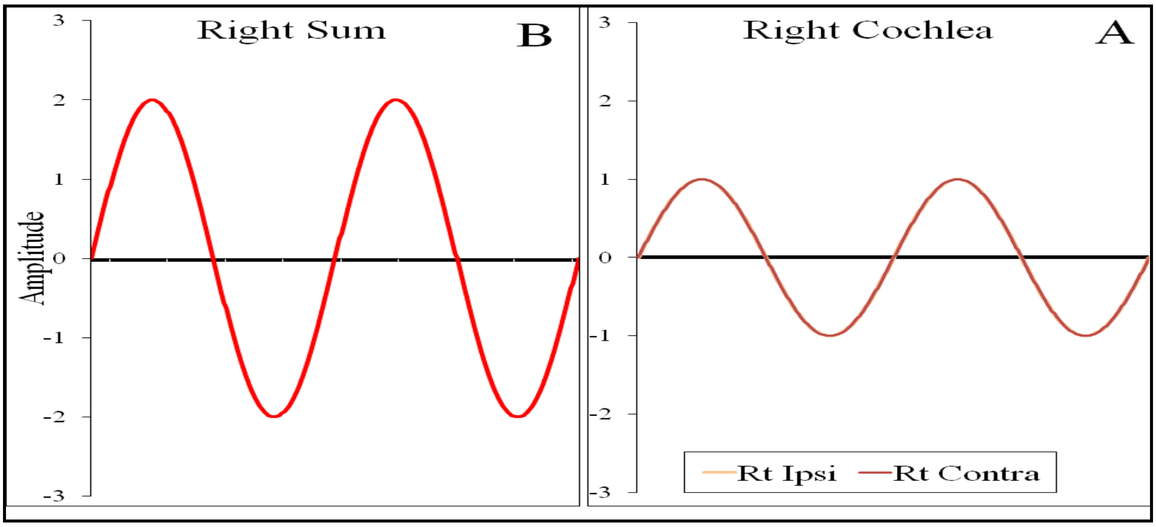

Figure 2.9 A 500 Hz sine wave at the right cochlea (A) increases in amplitude when the TA and TD are zero (B).

Figure 2.10 plots the prediction of the So and Sπ using a TA range of 5-15 dB (Section 2.6.1.1) and a TD range of 0-360º. It shows that a person with small TA, for example, 5 dB and a 0 TD will demonstrate a greater gain level compared to a person with a higher TA and a higher TD.

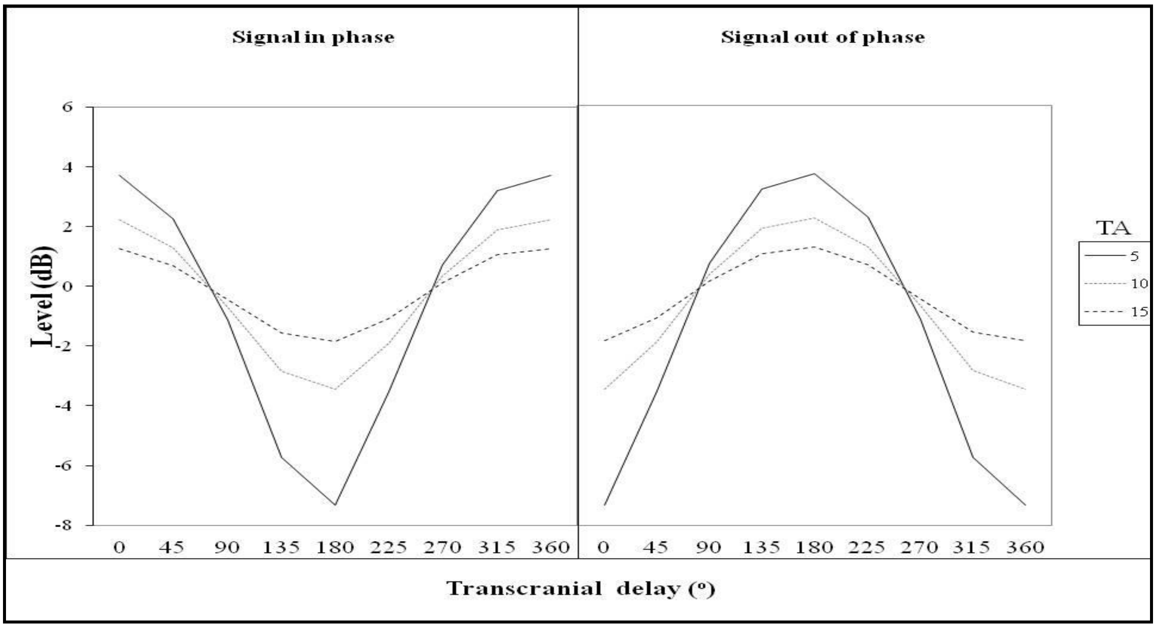

Figure 2.10 Application of a range of TD and TA to the model, the left panel show the signal in phase while the right panel shows the signal 180° out of phase.

For patients with bilateral conductive hearing loss, this model predicts that the phase would be disrupted due to all the transformations that occur to the signal resulting in poorer than normal results. However, the level is enhanced leading to better than normal results (Zurek, 1986). These predictions were confirmed in a study on normal hearing participants and patients with conductive hearing loss by Hausler et al (1983). Their results showed that the interaural level differences were the same for both groups while the interaural just noticeable time differences were considerably worse for the hearing impaired group compared to the normal hearing participants.

2.6.2 Bone conduction for single sided deafness

Patients with single sided deafness (SSD) were believed not to require any form of hearing aids because they have one functioning ear and they can make adjustments in their environment to accommodate their hearing, such as communication skills (e.g. preferential seating). However, patient complaints about reduced quality of life led to fitting of either a contralateral routing of signal (CROS) hearing aid or BAHA hearing aid (Hol et al, 2004). A CROS hearing aid comprises what looks like two wire connected hearing aids with only a microphone fitted to the deaf ear. The signal received at the deaf side will be routed through the wire to the hearing aid fitted on the good hearing ear. If the better hearing ear has any degree of hearing loss, a BiCROS will be fitted which will amplify the signals received to that side.

Recent studies advocating the fitting of BAHA in unilateral hearing loss on the deaf ear as a transcranial CROS application state that patients showed favourable results (Bosman et al, 2002; Hol et al, 2004; Stenfelt, 2005). The assumption for this fitting is that the patients have low TA therefore the fitting would be feasible as the signal will be transmitted to the better hearing ear without delay reducing the head shadow effect which would be encountered when fitting the CROS hearing aid. Furthermore, the BAHA would address the limitations associated with the CROS hearing aids. It allows the sound to pass naturally to the better hearing ear without an earmould obstructing the ear thereby producing better sound quality and better perception of own voice. Patients using CROS hearing aids report poor quality of own voice which is mainly due to the occlusion effect (Bosman et al, 2002).

Patients with acquired hearing losses fitted with a BAHA showed improvement in speech understanding when the primary signal was spatially separated from background noise. They reported that the BAHA was effective in reducing psychosocial consequences of unilateral SNHL. However, the localisation performance did not improve with BAHA use (Newman et al, 2008). Similar results on localisation were reported by Hol et al (2004). Their participants with unilateral BAHA and a normal hearing ear were unable to localise the sound source. On the other hand, benefit has been reported with the speech in noise measurements.

Stenfelt (2005) devised a theoretical model that predicts the benefit of fitting a BAHA to patients with unilateral hearing loss. Those patients mainly have one functioning cochlea and a dead ear. Therefore, if the sound arriving by air conduction is stronger, than the bone conduction stimulation then no benefit would be expected from the BC stimulation. On the other hand, if the stimulation was stronger from the BC stimulation then a benefit would be expected. This greatly relies on the TA which is variable between individuals and between studies. It also relies on the functional gain of the BAHA which is the amplified signal at the cochlea relative to the same sound transmitted by normal AC.

In line with Zurek's (1986) model, Stenfelt (2005) concluded that the TA is the main factor that may predict the benefit of a BAHA for unilateral deaf patients. Patients with low or medium TA could benefit to a greater extent compared to patients with higher TA. The outcome also depends on the BAHA setting and on the environment where the benefit is associated with better signal to noise environments. Speech perception in noise is only expected to improve when the speech and noise are spatially separated with the speech source on the impaired side and noise source either on the good side or diffused.

Patients appreciate the BAHA for unilateral hearing loss as shown in the aforementioned studies (Bosman et al, 2002; Hol et al, 2004; Stenfelt, 2005). The benefit with the BAHA has been similar to the CROS hearing aid. The patients preferred the BAHA over the CROS due to the un-occluded good hearing ear. Their results with speech perception in noise were better in the BAHA compared to the CROS hearing aid. In questionnaire responses, the patients reported advantages of the aided over the unaided condition and with most favourable results with the BAHA.

One of the limitations associated with the previous studies is that the BAHA was always fitted last and this could have influenced the patient's response giving them more practice time as they had used the CROS hearing aid prior to the BAHA. Furthermore, there was no mention of the selection method of the patients which could mean that patients who were selected are the ones who sought help. The motivation of the patients could have influenced the results (Baguley et al, 2006).

2.6.3 Bilateral bone conduction stimulation

This section will review the background studies evaluating the stimulation with bilateral hearing aids in order to understand the mechanism involved in interpreting the signal. The background studies will be divided in two sections, the first will look at studies that have used normal hearing participants as it provides the baseline for understanding of the mechanisms without influence of pathologies. The second section will look at the research with bilateral stimulation with pathological ears.

2.6.3.1 Normal hearing

Studies of bilateral bone conduction stimulation with normal hearing participant's sets the bench mark of normative data so that results with pathological ears would be meaningful. It increases our understanding of complex BC hearing. The literature reports are limited in this field especially with binaural hearing studies involving bone conduction stimulation. Reports with normal ears have shown greater variability between individuals compared to results with air conduction. The results should be interpreted with caution because measurements of the hearing thresholds with one transducers resulted in greater inter-subject variation for BC compared to AC results (Alomari et al, 2010). The variability is also influenced by: the placement of the transducer (Mcbride et al, 2008), the occlusion effect(Aazh et al, 2005; Stenfelt & Reinfeldt, 2007), and the airborne radiation (Bell et al, 1980). Therefore, there are a number of manipulations performed to maintain the accuracy of testing. Guarding against airborne radiation is done by placing a foam tip. Occlusion effect is avoided by testing the ears with clear ear canals. Furthermore, normal hearing participants would have the previous exposure to binaural cues which could bias the results.

Measurements of ITD and ILD were conducted on control group of 31 normal hearing participants to investigate the time-intensity trading in comparison to patients with unilateral atresia. Two bone vibrators were placed on the zygomatic bone in front of their ears, the ITD mean was 360 µs (SD 188 µs) and the ILD mean was 6.8 dB (SD 3 dB). The control group reported perceiving their head has shrunk which is an indication that the sound image was affected when stimulated through BC. However, patients with congenital atresia did not report the same sensation (Schmerber et al, 2005). This discrepancy in the participants' results could be an indication of the sound image changing and it could also be due to the patients with bilateral atresia not knowing how it should sound like because of their congenital hearing loss for years (average age of participants was 14 years). The interpretation of the results of the normal group could be un-representative of the clinical situations with patients because the placement was not the typical place (mastoid) that has been recommended in the international standards (ISO 389-3, 1999). The influence of changing the place could influence the phase of the signal as well as influence the bone pathway.

Modified bone conduction transducers were used to evaluate spatial hearing by testing the localisation performance of the participants (Macdonald et al, 2006). The transducers were modified to produce stereo sounds and were placed on the condyle. The authors used broadband Gaussian noise bursts. The results showed that the participants were able to locate the sound source in a similar manner to the AC localisation. The head related transfer functions for individuals for each transducer were accounted for. The study concluded that the stereo BC apparatus can be effective in spatial interface. Limitations that could arise from the small number of participants as only four participants took part. There was no mention of previous experience with acoustic testing. They have produced occlusion effect by placing the headphones and bone vibrators simultaneously which could have influenced the bone conduction results. The participants' results with spatial hearing should have worsened with the occlusion as the ITD is supposed to enhance hearing because of the amplification that occurs with the occlusion effect at low frequencies. The ILD, however, is expected to be reduced because of the amplification of the low frequencies leading to increased masking of the high frequency components.

In a similar study investigating virtual localisation in normal hearing participants Romeo (2010) applied bone conduction simulation from the cross-talk model to insert earphones. The author applied several TA and two TD values. Her results showed that when the TA was larger than 10 dB the participants were able to localise compared to normal hearing participants, while with TA values lower than 10 dB the localisation ability was less accurate. On the other hand, TD manipulations were associated with the stimulus type where delays > 0.2 ms allowed more accurate localisation. These results clearly show that better localisation ability is dependent on the TA results. Participants performed better with increased TA simulations (refer to Table 2.3 for more details).

Speech testing was also conducted on eight normal hearing participants by Walker et al (2005). The testing was conducted using a stereo nonclinical bone transducer (Temco bone conduction headset) and AC (Sennheiser HD-520) transducer. The aim of the study was to establish the effect of occluding the ear canal with BC and separation of interaural cues. Their study used coordinate response measure (CRM) task which is a non-standardised communication performance task used to measure the speech intelligibility in environments relevant to the military environment. The test includes a call sign and colour- number combination (Bolia et al, 2000).

CRM was used to assess the efficacy of using spatial audio to enhance speech intelligibility in multi-talker environments. The task was measured with AC and BC stimulation with the ear canal open and plugged. The results showed that subjects performance when stimulated by AC were always better than BC stimulation. The performance also improved with the increase in the interaural time delay in the three test conditions. The plugged condition made little or no difference in the performance with BC stimulation. Their results also suggested that for BC, the ILDs were more effective at producing spatial separation than the ITDs. They concluded that BC headphones could be a promising alternative to headphones.

Studies of binaural interaction are used to evaluate the sound interaction in the brain by measuring the binaural auditory brainstem responses (ABR) and subtracting the combined monaural responses for both ears. Setou et al (2001) examined the binaural interaction in seven normal hearing adults while plugging their ears with silicone rubber and measuring ABR with click stimuli. They found that the bilateral interaction wave was a sharp negative wave, similar to the shape of the air binaural interaction for the same stimulation level indicating that the binaural interaction exists with bone conduction ABRs. Based on these results, they inferred that bilateral lateralisation could occur with children with bilateral microtia or atresia.

Lateralisation studies were performed to investigate the influence of bilateral BC stimulation. Jahn and Tonndorf (1982) showed lateralisation was accomplished by variation of phase and intensity of the signal in normal hearing participants. They reported that the type of the stimulus always influenced the task, for example, clicks and tone pips with short rise times were easier to lateralise compared to pure tones. Pure tones required more training. The results support the possibility that listeners with substantial CHL, cross-talk might extract usable localisation information from air conducted transients before the arrival of bone conduction interference.

Rowan & Gray (2008) examined the lateralisation of seven normal hearing participants using two BC transducers (B71). Two high frequency pure tones were used (3000 and 6000 Hz).13 IPDs were evaluated between 180º and -180º. The test was conducted in 30º steps. Although humans are not capable of using IPD cues in high frequencies with AC stimulation, this study found that when sound is presented though BC stimulation binaural signals are interpreted in a different manner. The IPDs were converted into ILDs. However, no evidence of lateralisation was found in two of the 7 participants. Despite the reported inter-subject variability and the small sample size, this study managed to prove that the cues in binaural hearing are interpreted differently with BC which could be due to the interference of signals due to cross-talk.

Masking level differences was evaluated by Tompkins (2008) in eight normal hearing participants using two matched BC transducers (B71). One test frequency (1000 Hz) was evaluated in three phase conditions (SoNo, SπNo and SoNπ). Broad-band Gaussian noise (500- 2500 Hz) presented at 55 dB HL was used to mask the signals. The noise and tone were presented either through two inserts or through two BC transducers. Tompkins' (2008) main findings include a statistical significant difference between the AC and BC MLDs. Only three out of the eight participants had positive BC MLDs while the other five had negative or negligible BC MLDs. The overall BC MLDs were not statistically significant when the signal was inverted by 180º. Whereas, inverting the phase of the masking noise resulted in a statistical significant BC MLDs (the direction of the MLDs was always positive). The change in the MLDs direction between the AC and BC MLDs when the signal was inverted supports the notion that the interference of the signals at one cochlea is a stronger contributor to the BC MLDs.

A recent investigation by Stenfelt & Zeitooni (2013) looked at the ability to use binaural cues in 20 normal hearing participants in a series of binaural tasks, the tasks were always compared to AC results. The study included the investigation of the spatial release from masking using the Swedish sentence matrix, binaural intelligibility difference (BILD), binaural (MLD), and finally the precedence effect[1]. The results of this study are tabulated in Table 2.3 S. [It should be noted that the Stenfelt & Zeitooni (2013) study was not available when the present study was designed].

The main findings of Stenfelt& Zeitooni (2013) show that the results of the BC without any signal manipulation were similar to the results obtained with AC stimulation. However, the manipulation of the signal or noise direction or phase, produced more

[1] The precedence effect "the ability of the auditory system to fuse the sound image from two approximately equally loud sounds at the two ears with short interaural time delay" (Stenfelt & Zeitooni, 2013)

variable results and wider spread of data with the BC compared to AC despite all the participants having normal hearing thresholds (Table 2.3). In spatial release from masking, BILD and binaural MLD, the binaural benefit for the AC was numerically double of that of the BC results.

Stenfelt & Zeitooni (2013) argue that the use of non-stationary chirp signal would be more efficient for the measurement of the binaural MLD compared to stationary tonal signals. However, the trend of their results is similar to the trend reported by Tompkins (2008). Inverting the phase of the signal resulted in a binaural release of masking that was higher in the AC compared to the BC. Conversely, converting the phase of the masking noise resulted in a binaural benefit that was higher for the BC compared to the AC. Tompkins (2008) reported that inverting the phase of the signal resulted in change in the direction of binaural MLD with BC stimulation and some of the participants had negative MLD, this trend was not reported by Stenfelt & Zeitooni (2013).

2.6.3.2 Pathological ears

Bilateral bone conduction testing was evaluated with pathological ears to investigate the physiology of BC signal transmission (Kaga et al, 2001; Sheykholeslami et al, 2003). Furthermore, examination of pathological ears were conducted in patients fitted with bilateral BAHAs to investigate the benefit of binaural hearing (Snik et al, 1998; Van Der Pouw et al, 1998; Bosman et al, 2001; Dutt et al, 2002a; Dutt et al, 2002b; Priwin et al, 2004). These studies have investigated binaural hearing characterised by localisation tests, speech perception in quiet and noise, masking level differences, and finally through self-report questionnaires assessing patient’s reactions and attitudes towards their hearing aids.

The knowledge, attitude, and practice towards prescription of binaural hearing aids by audiologists have been evaluated by Dutt et al (2002c) by sending questionnaires to the practitioners. Some questions were specific to the application of BAHAs. The response rate was 59% (total 950 sent questionnaires), 37% were aware of the studies that showed benefit with bilateral BAHAs, 25% of the respondents did not believe there was sufficient evidence to demonstrate benefit, 4% did not believe it worked, 34% had no opinion. These responses show the scarce information available to audiologists and the need for further studies in the field of bilateral BC amplification. It also points out that the bilateral BAHA fitting was not acknowledged by most practitioners who responded to the questionnaire. One respondent answered the question of the attitude towards a bilateral BAHA that common sense suggests that bilateral aiding is better than unilateral, and blamed the lack of funding on the fitting one aid. This clearly indicates the lack of awareness of the complexity of bone conduction and hence the bilateral fitting.

Patients born with congenital ear defects such as microtia and atresia present challenges in fitting hearing aids because fitting of AC hearing aids would not be possible. Hence they are usually fitted with BC hearing aids either implanted devices (example BAHA) or conventional hearing aids coupled with a softband or steal band depending on the age. The second challenge encountered is the difficulty in quantifying the exact degree of CHL due to the masking dilemma, and the lack of ability to determine whether both cochlea are functioning so scans are used to check that the cochlea is present.

Studies have shown that in such patients the auditory pathways are adaptive to binaural input even after childhood. These positive indicators have led to the recommendation that patients with bilateral atresia should systematically be fitted with BAHAs bilaterally. However, the results also pointed out that the variation in the responses were high in time and intensity trading task (Schmerber et al, 2005). Binaural interaction through click ABR was evaluated in 10 children with bilateral congenital external auditory canal atresia, it was found that binaural interaction existed but with higher variation compared to the normal hearing control group in that study (Sheykholeslami et al, 2003). Both of these studies were not able to use masking because it was difficult to administer. Children with aural atresia could sufficiently retain binaural hearing ability in terms of both intensity and time differences (Kaga et al, 2001)

Four studies were identified that measured binaural hearing in terms of localisation testing, speech perception and binaural release from masking with bilateral BAHAs (Snik et al, 1998; Van Der Pouw et al, 1998; Bosman et al, 2001; Priwin et al, 2004). These studies show some similarities and it should be noted that Bosman et al (2001) recruited the same participants of Snik et al(1998) and van der Pouw et al (1998) with similar test setup so the reported results will mention the main study from Bosman et al (2001) and the results of Priwin et al (2004) with 12 participants.

The bilateral localisation scores for patients with bilateral BAHAs are shown in Table 3.2. The bilateral stimulation was always better when compared to the unilateral condition and was reported to be well above the chance level. However, a correct score at 30º was around 45% (Bosman et al, 2001) and 25% (Priwin et al, 2004). The slightly better score in Bosman et al (2001) could be due to having a larger sample or due to the setup of the speakers at half a circle compared to complete circle in Priwin et al (2004). The setup could have made the task more difficult in the latter study. Both of these studies did not use a control group to compare the results with. The scores reported for the correct speaker was low compared to the scores within ±30° which is a wide range. Most studies of localisation with normal hearing subjects and with the hearing impaired have used 9-11 speaker array with an interval of 18° and more presentations per speaker (Noble et al, 1994; Verschuur et al, 2005; Van Deun et al, 2009). However, in studies of Bosman et al (2001) and Priwin et al (2004) have used 7 loudspeakers and intervals of 30° and 12 loudspeakers at 30° respectively. The methodology was not consistent for all of the subjects and the repeat per speaker was small.

Speech reception threshold in quiet showed a 4 dB improvement in the bilateral fitting compared to the unilateral fitting by Bosman et al (2001) compared to 5.4 dB improvements in the 12 participant in Priwin et al (2004). Bosman et al (2001) reported a lack of correlation between the speech thresholds and the bone conduction thresholds, i.e. the pure tone BC hearing thresholds could not predict the speech perception thresholds. This was attributed to the confounding effects of the individual volume control setting. It should be mentioned that no adjustments were made to the volume control of the BAHAs and was left as used by the patient (Bosman et al, 2001). Whereas, Priwin et al (2004) have used two matched transducers with the volume control set to the maximum and they claimed that with that setup the BAHAs did not produce any distortion.

Speech intelligibility in quiet was also evaluated by Dutt et al (2002a) in sound field through Arthur- Boothroyd word lists and using BKB sentences. Testing in the sound field has shown that the bilateral condition was slightly better than the unilateral condition in the levels tested, it also showed that as the level was increased, the average overall score was better (for both the bilateral and unilateral conditions. There was no advantage in the bilateral condition when the BKB sentences were used and speech recognition of 100% was achieved in both conditions. This indicates that the added amplification from the second BAHA was useful but does not mean that the better result was due to binaural benefit.

Speech in noise tests which could indicate binaural hearing due to the use of interaural cues showed marginal improvement and more flexibility in day to day situations (Dutt et al, 2002a). Results from Bosman et al (2001) and Priwin et al (2004) were similar in that having a second BAHA has helped in lowering the signal to noise ratio especially when the noise was presented to the ear that was first aided with a BAHA. Whereas when the masking was coming from the shadow side (unaided), the signal to noise ratio was slightly improved in the bilateral condition compared to the unilateral condition.

MLDs were evaluated by Bosman et al (2001) and Priwin et al (2004). Bosman et al (2001) used the direct input of the two matched BAHA's for the evaluation. These were checked for the phase and amplitude on a subgroup of nine participants where the signals were pure tones at 125, 250, 500 and 1000 Hz.

The results of the binaural MLDs were reported to be 6.1, 6, 6.6 and 4.1 dB for 125, 250, 500 and 1000 Hz respectively. This shows that changing the frequency did not influence the release of masking -except for a minimal reduction at 1000 Hz- as would be expected in AC testing, for example. They have reported a lack of correlation between their measurement of MLD and the localisation and speech in noise results attributing this to the small number of the participants. According to Bosman et al (2001), the strongest argument for confirming that binaural hearing is achievable by bone conduction stimulation was due to the results of the MLD and the directional hearing. This argument is criticized for the lack of description of their individual results, in addition to the MLD results proving to be small and not influenced by changing the frequency.

Furthermore, Priwin et al (2004) measured the MLD at 250, 500 and 1000 Hz for patients with bilateral BAHA's, as with Bosman et al (2001), this study concluded that the benefits with bilateral BAHAs are greater than the drawbacks. The same study has reported high inter-subject variability in MLD testing and an average difference in conditions of –2 to 3 dB for the three frequencies which is still lower than what is expected. Also reported were small changes with changing the frequency. Moreover, there was no mention of whether the BAHA's were matched or they were the subjects own hearing aids.

Dutt et al, (2002) reported the Birmingham group experience with 11 of their 15 bilateral BAHA users using the Glasgow benefit inventory (GBI). Modification of the questionnaire was conducted by adding four questions relating to the success of the BAHA and a 10 cm analogue scale reflecting state of health before and after first BAHA and the second BAHA. They have also used the Chung and Stephens's questionnaire to assess the benefit of binaural hearing aid fitting which was used to determine how certain audiological, physical and social factors influence the use of bilateral hearing aids. The participants included have used the second BAHA for a minimum of 12 months to be included in the study (this allowed for acclimatisation with the bilateral aids and to eliminate any bias due to initial enthusiasm). All the included participants have asked to be fitted with a second BAHA.

Most of the patients believed that the second BAHA made their overall life much better; they felt more optimistic about their future. This study reported that patients who were fitted with a second BAHA for less than two years have reported no difference compared to the first BAHA. However, a gradual period of acclimatisation was reported by some patients who used their BAHA's for longer periods. High degree of patient satisfaction was reported with bilateral BAHAs. Limitations of this study include the patients asking for a second BAHA fitting which could mean that their judgment was influenced by their motivation to have the second BAHA. The questionnaire compared the second BAHA to the unilateral condition and there was no mention if the patients were given questionnaires in the unilateral condition prior to fitting, so this also could have influenced the patient's judgment.

Table 2.3 Studies reporting bilateral bone conduction with normal hearing participants and pathological ears

Study	Measurement	Participants	Transducer	Stimulus	Test method	Results & comments
Setou et al 2001	Binaural interaction with ABR	7 normal hearing adults	Not specified	Clicks level 45 dBHL	Binaural, right and left monaural.	Binaural interaction exists with BC.
Sheykholeslami et al 2003	Binaural interaction with ABR in children	10 children (2-13 yrs)	BR-41 Rion	Clicks level 45 dBHL	Monaural Rt & Lt binaural testing	Binaural interaction exists with BC in children. The gross response properties was similar in children (bilateral atresia) and adults (NH)
Schmerber et al 2005	Time- intensity trading	11 male children (12-18 years) CEA ,CG	Modified Rion PV60 bone transducers.	500 Hz Continuous NBN at 65-70 dB HL	Self recording apparatus. BC placed in front of the ear (zygomatic bone)	-Time-intensity trading was present. -Significant individual differences. -ITD mean 716 µs SD 469 µs -IID mean 12.5 dB SD 5.3 dB
		31 normal hearing adults				-ITD mean 360 µs SD 188 µs -IID mean 6.8 dB SD 3 dB
Walker et al 2005	Dichotic speech presentation task	8 trained adult listeners	Temco bone conduction headset	Phrases of CRM corpus	Manipulation of ITD and ILD	Limited amount of interaural isolation in dichotic speech perception task with stereo BC phones. Results indicate that reliable spatial separation is possible
MacDonald et al 2006	Virtual localisation	4 Normal hearing adults	Temco HG-17 placed on the condyle	Gaussian noise bursts (0.3-5 kHz) at 75 dBA (4 loudspeakers)	8 virtual locations on the horizontal plane separated by 45̊	The transducer was placed on the condyle. The performance with the bone conduction was similar to AC

Romeo (2010)	Virtual localisation	15 Normal hearing adults	Insert earphones ER-2	Three noise conditions at 55 dBA : -BBN -NBN 500 Hz -NBN 2kHz	4 virtual locations on the horizontal plane separated by 40̊, TD and TA manipulation	The error increased as the TA decreased with the three stimuli types. TD was highly influenced with the stimulus type, least errors occurred with the BBN and with the higher TD. Most errors occurred with the 500 Hz with the higher TD
Jahn & Tonndorf (1982)	Lateralisation	2 Adults (authors)	B72 (matched) mastoid	Clicks, tone pips and pure tones presented at most comfortable level	Clicks duration was 0.1 ms. Tone pips of 1000 Hz, 60 ms in duration	Lateralisation was accomplished by varying the time and intensity differences between the signals. The task was easier with clicks and tone pips compared to continuous pure tones.
Kaga et al (2001)	Lateralisation of ITD and ILD, with AC and BC stimulation	21 Children CEA, CG of 12 Normal hearing adults	BC on mastoid, CG ear plugged	500 Hz NBN at a level of 30 dB SL	Self recording apparatus	CG showed no statistical significant difference between AC and BC ITD or ILD. For the CEA: ILD showed elevation by 10%. Recommendation of bilateral BAHA fitting for children.
Rowan & Gray (2008)	Lateralisation of high frequency pure tone with bilateral BC	7 Normal hearing adults	B71 on the mastoid	3 kHz pure tone at 32 dB HL 6 kHz Pure tone at 26 dB HL	13 IPDs were used ranging from -180̊ to 180̊ in 30̊ intervals	Evidence for lateralisation with half of the participants at 3000 Hz.
Dutt et al (2002a)	1-Soundfield speech 2- Speech in quiet 3- Speech in noise 4- Speech in simulated party noise	11 Patients	Bilateral BAHAs, type not specified	1- Arthur-Boothroyd (AB) lists 2- BKB sentence 3- BKB sentences with 4- open set speech recognition	1- Presented at 30, 40 and 50 dB 2- Thresholds for Rt, Lt and bilateral 3- SNR of 10,0,-10 dB 4- speech presented at 70 dBA	1- Bilateral better than the best unilateral. 2- Speech in quiet was similar for unilateral and bilateral conditions 3- Speech in noise 11 patients scored marginally better with bilateral BAHA 4-Bilateral BAHAs provided maximum flexibility when noise was controlled to day-to-day situation

Bosman et al (2001)	Sound localisation	25 Patient: – 10 chronic otitis media - 8 Cholesteatoma -6 CEA -1 Schisis	Bilateral BAHAs. Either BAHA HC 200 or Classic 300.	1s NBN bursts centre frequency of 500 and 2000 Hz at 65 dBA	7 (15 pts) or 9 (10 pts) loudspeakers arc	Unilateral responses were at chance level. The bilateral scores were significantly better than the unilateral scores.
	SR in quiet			- Plomp and Mimpen (Female speaker) Smoorenburg (Male speaker)	Speech presented to the front of the listener	A significant 4dB improvement with the bilateral condition.
	SR in noise				Speech to the front speaker. Masking noise side. 65 dB	Bilateral condition was significantly better than the unilateral condition
	binaural MLD	9 of the 25 patients	Two matched BAHA 300 were used	Pure tones of 125, 250, 500 and 1000 Hz. 1/3 octave WN at test frequency, at the patients most comfortable level	Three conditions were tested SoNo, SπNo, S_oN_π. The most comfortable level was determined in 1 dB steps	MLD for SπNo condition was 6.2, 6.0, 6.6 and 4.1 at the stimulus frequencies of 125, 250, 500 and 1000 Hz respectively. The S_oN_π results were fairly similar to the SπNo.
Dutt et al (2002b)	Patient satisfaction with BAHAs	11 Patents	Bilateral BAHAs, type not specified	-Glasgow benefit inventory - Chung and Stephens binaural HA questionnaire	Two postal questionnaires	Patients reported a high degree of satisfaction with the bilateral aids. They reported an improvement in the state of health and hence the quality of life compared with the unilateral hearing aid.
Tompkins (2008)	binaural MLD, Monaural MLD	8 participants	-3A insert earphones -Bilateral matched B71	1000 Hz pure tone. Broadband noise (500- 2500 Hz) at 55 dB HL	Three conditions were tested SoNo, SπNo, SoNπ	The AC benefit was 8.4 and 6.7 dB for the signal and noise inversion, respectively. Whereas, it was 2.2 and 9.2 dB for the signal and noise inversion, respectively.

Priwin et al (2004)	Free field tone thresholds	12 participants: - 8 with chronic otitis media - One with external otitis - Three CEA	Two BAHAs calibrated with equal characteristics controlled by the research panel.	Warble tones frequency range 250-8000 Hz	12 loudspeakers spaced by 30° intervals, placed in a circle with 1m radius	The average improvement with the bilateral fitting ranged between 2 and 7 dB.
	Directional hearing			NBN centred at 500 or 2000 Hz at 65dBHL		Correct at 30° score of 25% for both stimuli. Correct at 45° score of 55% for both stimuli. Bilateral fitted BAHA's were significant
	SRT quiet			Phonetically balanced three word sentences	50% correct score, speech presented from front 0°	The average improvement in the speech perception in quiet was 5.4
	SRT noise			Same lists as in quiet, speech presented at the comfortable level Speech weighted noise	Speech presented from the front. Noise was presented ±90° or from the 11 remaining speakers	When the masking noise was presented from the 11 speakers speech perception was improved by lowering the SNR threshold by 2.8 dB in the bilateral condition
	binaural MLD			Pure tones of 250, 500 and 1000 Hz. NBN centred at the frequency at 65 dB HL	Three conditions were tested SoNo, SπNo, SoNπ. Two repeats	SoNo was normalised to zero. SπNo the 250 Hz showed minimal change with an average of 3 dB when inverting the tone and -5 dB when inverting the noise. Similar results were obtained for 500 and 1000 Hz with an average threshold for inverting the tone of 2 dB and 3 dB and inverting the noise of – 4 dB and -3 dB for the two frequencies respectively.

Stenfelt & Zeitooni (2013)	Spatial release from masking	20 participants	AC bilateral HDA 200 Sennheiser earphones BC bilateral BESTs All tests were computerised and programmed by MATLAB	Matrix sentence test (Swedish) in speech weighted noise presented at 40 dB HL	SoNo SoN_{45} SoN_{90}	AC BC SoNo –8 –8.1 SoN_{45} –16.7 –12.6 Benefit of changing the noise source from 45º to 90º was 8.6 and 7.6 dB for AC for the BC it was 4.5 and 4 dB.
	Binaural intelligibility difference			Same speech matrix as in spatial release form masking	SoNo SπNo SoNπ	The sentence benefit for the AC was 6.8 and 7.6 dB for the noise and signal inversion, respectively. The BC benefit was 3.7 and 3.8 dB for the noise and signal inversion, respectively.
	Masking level difference			1 s chirp tone (400 and 600 Hz) rate of 10 Hz. Band limited WN 100-2000 Hz at 60 dB SPL	2 dB step-size SoNo SπNo SoNπ	The AC benefit was 11.7 and 8.8 dB. Whereas, the BC benefit was 4.9 and 10.5 dB for the signal and noise inversion, respectively.
	The precedence effect			1s noise burst with a low frequency (LF) content (400-600 Hz), high frequency (HF) content (3000-5000 Hz), or broad band (BB) content (200-6000 Hz)	Sound location between –90º and 90º for 13 presentations with interaural time delay between 0-20ms	- No interaural sound delay produced midline sound position for AC and BC for the three noise stimulus. - AC: 0.5-0.8 ms lateralisation was towards 90º for the three stimulus types. BC LF: delay up to 0.8ms the sound image at the midline, at 1.2 ms the LF noise was lateralised to 45º, full lateralisation was observed at 20 ms. BC HF:0.8 ms the apparent sound image towards 45º, full lateralisation was observed at interaural delay of 3.5 ms.

CG: control Group. NBN: narrow band noise. CEA: congenital ear canal atresia CRM: coordinate response measure
SR: speech recognition SRT: speech reception threshold MLD: masking level difference WN: white noise

2.7 Contributors to BC MLD: Summery

Table 2.4 Summary of the BC MLDs contributors

Factor related to:	Contributor	The anticipated influence on the binaural BC MLD
Sound transmission in the head	**The occlusion effect**	The signal at low frequencies would be perceived louder that at the high frequencies. However, it is anticipated that the MLD would not be affected because the occlusion would be symmetrical.
	Modes of skull vibration	The modes of the skull vibration are influenced by the frequency of the signal (Figure 2.2). - At low frequencies (< 800 Hz) the skull vibrates as a whole unit. - At mid frequencies (<1600 Hz) the skull vibrates in two sections in opposite phase. - At high frequencies (> 1600 Hz) the skull vibrates in four segments.
	Transcranial attenuation	Low TA would be associated with low BC MLD Mid TA would be associated with a present BC MLD High TA would be associated with BC MLD comparable to the AC MLD
	Transcranial delay	The TD is anticipated to influence the phase of the signal. Based on Zurek (1986) model the influence is expected to vary with frequency and among individuals.
	Sound transmission in the head	Five main sound transmission pathways influence hearing through BC stimulation. These pathways collectively contribute to the perception of BC signal. Therefore, the influence on the BC MLD would be unknown.
BC transducer/ BCI device	**Distortion of the BC vibrator**	The distortion is highest with higher presentation levels and at low frequencies. It is anticipated to influence the perception and quality of the signal.
	Frequency response of the bone transducer	The frequency response of the BC transducer is limited to frequencies between 250 and 4000 Hz. It is associated with peaks at different frequencies. Careful calibration is required prior to testing.
	Dynamic range	The dynamic range for BC transducers is limited to 70 dB. Therefore, the level of the signal may be low when testing patients with CHL. The use of an amplifier may lead to signal distortion.
Type of stimulus	**Pure tones**	BC MLDs have been measured in patients with CHL using pure tone signals (Table 2.3). The advantage of using pure tones that the cues used can be identified at specific frequencies. BC MLDs were significantly lower than AC MLDs in the reported literature (Table 2.3)
	Speech	Speech signals were used to evaluate the BILD (Stenfelt & Zeitooni, 2013). The AC BILD was numerically double the BC BILD.

2.8 Summary and aims

Bilateral BC hearing aids have recently been recommended for patients with bilateral conductive hearing loss replacing unilateral fitting which had been traditionally recommended based on the small transcranial attenuation with BC. This recommendation was based on a series of clinical studies either from self-report questionnaires (Dutt et al, 2002b) or from psychoacoustical measures (Snik et al, 1998; Van Der Pouw et al, 1998; Bosman et al, 2001; Dutt et al, 2002a; Dutt et al, 2002b; Priwin et al, 2004). Similarly, several papers have also recommended unilateral BC hearing aid fitting for unilateral conductive hearing loss (Hol et al, 2005) . Part of the benefit that has been observed in both situations can be explained without specific consideration to binaural hearing *per se*; overcoming the head-shadow effect is an important but not binaural benefit, for example. However, part of the benefit has also been attributed to binaural hearing, particularly the findings of an MLD (Bosman et al, 2001; Priwin et al, 2004). A recent systematic review concluded that the evidence for bilateral fitting using BC was inconclusive (Colquitt et al, 2011). A more fundamental problem is that it is not even clear whether the MLD with BC can be interpreted in the same way as for AC and whether it can be used specifically for binaural hearing testing in users of BC devices. This arises because of the limited acoustic isolation between the cochleae and the effects of acoustical interference between the sounds originating from the two sides of the head en route to both cochleae.

The comparison of the interaural cues between the normal hearing participants and participants with conductive hearing loss was compared by Hausler et al (1983). The ILDs were the same for the two groups while the ITDs were considerably worse for the hearing impaired group. It is curious why one cue would be present while the other is impaired. Zurek (1986) cross-talk model attempted to show that the apparent binaural benefit could be due to the monaural benefit rather than an actual binaural hearing. Apart from the external manipulation of the signal time or level, the signal goes through an internal manipulation. The internal manipulation would influence the time and level of the signal due to the contribution of the TA and TD. The external and internal signal manipulation would result in an enhancement or destruction of the coming signal at one cochlea. Thus, the results of the MLD test in particular would be too complex to explain because the TA and TD varies from one individual to the other (refer to Section 2.6.1).

Normal hearing participants have also been reported to be tested with bilateral BC tasks (Hausler et al, 1983; Macdonald et al, 2006; Rowan & Gray, 2008). The findings of these studies are interesting in that normal hearing participants stimulated with bilateral BC transducers performed similar to participants with CHL in ILD and ITD tasks (Hausler et al, 1983). MacDonald et al (2006) reported that with the preserving of the head transfer function, participants with bilateral BC stimulation performed in a similar manner to the AC stimulation in localisation tasks. An evidence of lateralisation of high frequency tonal signals was reported by Rowan & Gray (2008) in normal hearing participants. Their results indicated that the external IPDs were converted to internal ILD. Even though humans are insensitive to IPDs at high frequencies, this clearly indicates that with BC stimulation, localisation mechanism differs from the AC mechanism. Uncertainties are associated with bilateral BC stimulation that includes the cues used. The influence of cross-talk on the signal presented via the two BC transducers can influence the phase of the signal.

The gap of knowledge is evident with the limited number of investigations into binaural hearing with bone conduction stimulation. The review of literature found two studies that investigated binaural MLDs with normal hearing participants using bone conduction transducers (Stenfelt & Zeitooni, 2013; Tompkins, 2008). These two studies reported a similar trend for the MLDs despite using two different types of stimuli: tonal (Tompkins, 2008) and chirp signals (Stenfelt & Zeitooni, 2013). Stenfelt (2011) mentioned that due to the nature of the bone conduction, sinusoids from two sources add either constructively or destructively depending on the signals phase. Therefore, the results are influenced by the summation of the two signals as well as the binaural. Thus, it was recommended that binaural MLDs are not suited for testing binaural hearing with BC stimulation using stationary sinusoids. However, this notion has not been supported by research that could quantify what occurs with bilateral BC stimulation. Furthermore, similar trends were reported by Tompkins (2008) and Stenfelt & Zeitooni (2013), which indicate that the signal was not the major contributor to the binaural MLD.

Stenfelt & Zeitooni (2013) reported that the cross-talk of the signal may have contributed to the BC benefit reported. This conclusion supports the notion that given the low TA and the presence of the TD, the acoustic interference can produce spurious changes in the level at one ear depending on the relative level and phase of the two input sounds. This can interfere with the measurement of the MLDs and can, in principle, produce MLDs on the basis of monaural hearing alone. It is important to better understand BC measurements of MLDs in normal hearing participants in order to help in interpreting the results of bilateral fitting of BCI and the associated binaural benefit (if present).

The aims of this study were:

1. Evaluate the performance of the newly designed BEST for clinical use by evaluating the acoustical and psychoacoustical aspects of the device (Chapter 3). Investigate the use of the current RETFLS with the BESTs. Would the BESTs require an adjustment for them to be used clinically? (Chapter 3)

2. Develop methodology to test MLD in normal hearing participants with bone conduction stimulation in such a way as to relate their performance on the MLD test to their AC results and their transcranial parameters (Chapters 4 and 5). Part of this involves ensuring the test-retest repeatability is sufficiently high.

3. Compare the AC and BC MLD at a range of test frequencies (Chapters 4 and 5).

4. Develop a methodology for investigating the TA in the same sample. The TA measured will investigate the associated discrepancy between the AC and BC MLD (Chapter 5).

5. Estimate the monaural tone level difference arising with BC and investigate the hypothesis that the discrepancy between the AC and BC MLD can be explained by the monaural interference effect (Chapter 5).

6. Compare the results obtained in this study with that of BAHA MLD, to address the relationship between the BC MLDs in normal hearing participants and participants with hearing losses. This association is currently unknown.

Chapter three. Verification of transducers

3.1 Overview and aims

The main aim of this chapter was to compare the performance of the BEST in relation to the B71 for experimental and clinical practice. The planned investigation of the MLD with bilateral BC stimulation requires the use of two matched BC transducers with the capability of producing sufficiently loud stimuli at low frequencies. Therefore, it was of value to evaluate the $BEST_{LFR}$ transducers for consistency and stability. Furthermore, the BEST can be a clinical replacement of the B71 provided that it produces favourable results and conforms to the international standards. An additional aim was to account for the procedural variables associated with BC stimulation (Section 2.2.1.1). The variables include proper placement of the transducers on the prominent part of the mastoid bone, taking account of the tension of the headband, and measuring threshold on a sufficient number of normal hearing participants.

The B71 is widely used in audiology clinics where numerous background studies are in place to evaluate the acoustical or psychoacoustical characteristics of the B71 (Boothroyd & Cawkwell, 1970; Lightfoot, 1979; Bell et al, 1980; Haughton & Pardoe, 1981; Frank et al, 1988; O'neill et al, 2000; Stenfelt & Håkansson 2002). However, little is known about the performance of the BEST (Håkansson, 2003). The planned investigation will address the gap of knowledge associated with the applicability of the current RETFLs with the new BEST. It is assumed that the current RETFLs would be applicable with the BESTs because it is not transducer specific and the BEST has been designed to follow the recommendations stated in the standards (IEC 373) in terms of the contact area. Nevertheless, Frank et al (1988) reported that the RETFLs should be transducer specific.

Furthermore, reports of a systematic error at 2000 Hz suggest that the RETFL should be adjusted even with the B71 (O'neill et al, 2000). The current RETFLs were also criticised for not accounting for the air conduction thresholds leading to exaggerated air-bone gaps at high frequencies (Lightfoot & Hughes, 1993). Margolis et al (2010) evaluated a new automated technique for measuring the hearing thresholds and their results indicated that the variability in the results obtained with the bone conduction thresholds are likely to be due to inconsistencies with the current RETFL.

Figure 3.1 illustrates the general setup of the current study. The study is made up of two main parts, an acoustical and psychoacoustical evaluation. Each part would provide a different aspect for the applicability of the BEST in clinical practice.

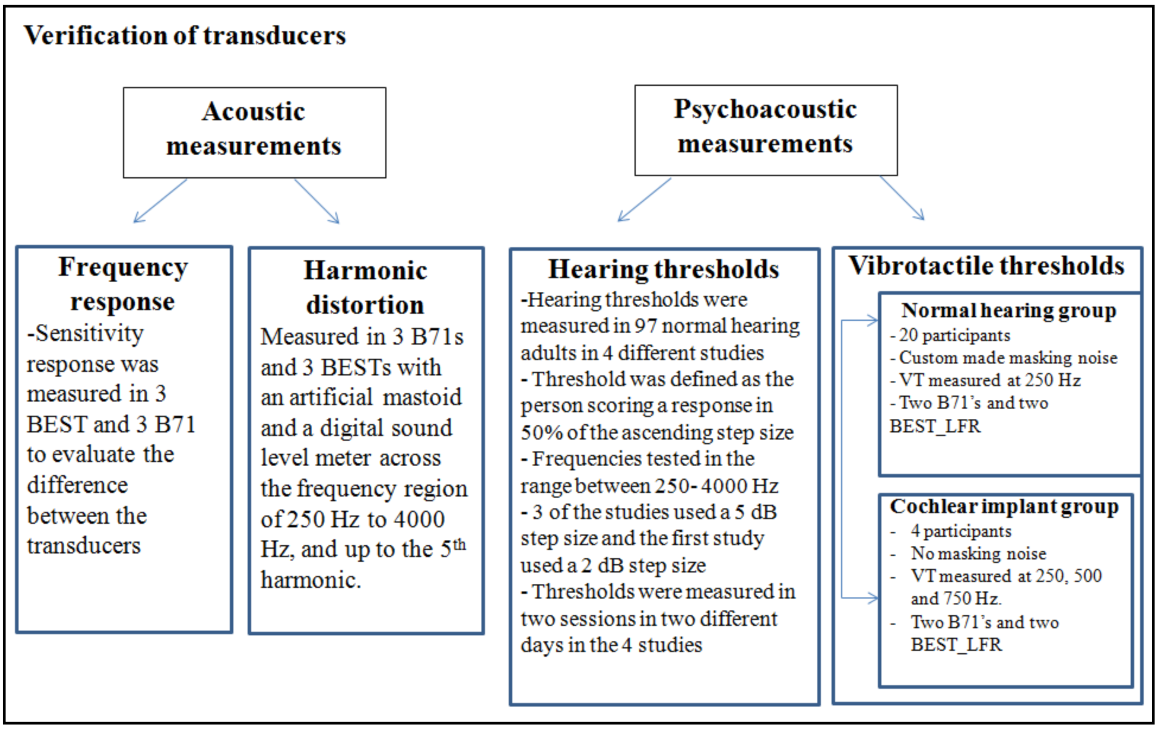

Figure 3.1 verification of transducers study plan.

The present study aimed to answer the following questions:

- Does the BEST perform better than the B71?
- Are the current RETFLs applicable with the BEST?
- Are the BESTs consistent enough to be used in planned future research?

To address these questions the following objectives were set:

- Report the acoustic characteristics of the BEST and the B71 measured using the Brüel and Kjaer 4930 artificial mastoid (ISO 389-3, 1999) in order to evaluate the differences between the two different versions of transducers-if any. The measurement also aimed to investigate the stability of the BEST when tested in different sessions. Furthermore, the production of the THD was evaluated for the different types of BC transducers to address the claim that the BEST produces lower harmonic distortion compared to the B71.

- Determine if the current RETFLs are applicable with the BESTs. It is assumed that the current RETFLs are applicable with the BESTs because the international standard (ISO 389-3, 1999) is not transducer specific. However, no normative data have been measured using the BESTs. Normative data would confirm that the transducers follow the current RETFLs.
- Determine whether the BESTs are less vibrotactile compared to the B71, the BESTs are claimed to be less tactile in the low frequency reinforced versions, if true this will result in the extension of clinical testing to include low frequencies.

The design of this study aimed to investigate the performance of the experimental BEST in comparison to the clinically used B71. Therefore, it was hypothesised that the two transducers are similar, thus the use of the RETFLs would be applicable with the BESTs. Addressing these aims will provide better understanding of bone conduction testing, in addition to provide basic information about the BESTs which is not reported in the literature (Table 3.1).

Approval of the Institute of Sound & Vibration Research Human Experimentation Safety and Ethics Committee was granted prior to initiation of the study (Appendix A).

3.2 Detailed comparison between B71 and BEST

The B71 is an electromagnetic transducer that works by creating a magnetic field from the electrical current that moves the magnetic rod back and forth. Due to the inherent mass of the rod, the high frequency output is limited to 4000 Hz (Popelka et al, 2010). Whereas the BEST is an improved electromagnetic transducer which uses a balanced suspension principle to avoid strong requirement of a stiff spring suspension in addition to a high mass in order to get low distortion and a good low frequency response (Håkansson, 2003). The internal design of the BEST makes it lighter (15 mg) in comparison with the B71 (20 mg).

The tension of the headband is recommended to be 5.4 ± 0.5 N (Bs-4009, 1991) with bone transducers. The high coupling force > 7.5 N influences the test-retest reliability increasing the sense of discomfort to the patient. On the other hand, low coupling force is difficult to remain in position on the mastoid process in clinical practice (Lau, 1986) and erratic responses were reported when the force was less than 2 N (Goodhill & Holcomb, 1955). A recent study investigated the static force of the headband using a leather headband and compared it to the clinically used P-3333. It found that the tension affected the hearing thresholds minimally with a difference of less than 2 dB across the static force levels used of 5.4, 4.4, 3.4 and finally 2.4 N (Toll et al, 2011). The BEST is lighter in weight compared to the B71. Therefore, the same coupling force could influence the threshold of hearing and should be investigated for clinical measurements. There are no current reports of the coupling force with the BESTs. Toll et al (2011) reported that the coupling force would not influence the results by more than 2 dB.

Table 3.1 Summary of the main characteristics of B71 and the BEST (Original and low frequency reinforced LFR).

	B71	**BEST**	
		Original	**LFR**
Contact tip area	1.75 cm2	1.75 cm2	1.75 cm2
Weight	19.9 g	15 g	15 g
Internal design	Variable reluctance principle	Separated static and dynamic fluxes	Separated static and dynamic fluxes
Recommended tension of headband	5.4 N per ISO	Unknown	Unknown
Frequency response, resonant frequency at low frequencies	≈ 500 Hz (Dirks & Kamm, 1975) 450 Hz (Richards & Frank, 1982) 420 Hz (Håkansson , 2003)	300 Hz (Håkansson ,2003)	200 Hz, frequency response sheet
Harmonic distortion at 250 Hz (40 dB HL)	61% (Håkansson , 2003) 17% at 50 dB HL (Stenfelt & Håkansson 2002)	3.3 % (Håkansson , 2003)	Unknown
RETFLs	ISO 389-3 (1999)	Unknown	Unknown
Air-borne radiation at high frequencies	4.3 dB at 4000 Hz (Frank & Crandell, 1986). 5-10 dB at and above 2000 Hz above the vibratory output (Bell et al, 1980)	The BEST produced less air-borne radiation compared to the B71 at 2000 and 3000 Hz but more at 4000 Hz (Vaughan, 2008)	Unknown
Vibrotactile thresholds at low frequencies	25 dB at 250 Hz, 55 dB at 500 Hz and 70 dB at 1000 Hz (Boothroyd & Cawkwell, 1970)	Unknown	Unknown

Acoustic characteristics include harmonic distortion, frequency response characteristics, placement, and airborne radiation. Undesirable harmonics when testing at low frequencies have been noted with the B71. It has also been noted that the output voltage of the second and third harmonics grow disproportionately to the input (Sanders & Olsen, 1964). This finding led to the recommendation that frequencies under 500 Hz should not be evaluated in clinical practice. The manufacturers of the BEST report that it produces low distortion at low frequencies (Håkansson, 2003). Håkansson (2003) reported that the BEST produced 3.3% total harmonic distortion compared to 61% with the B71 when 250 Hz tone is presented at 40 dB HL on an artificial mastoid. Furthermore, Håkansson (2003) reported the appearance of additional non-harmonic peaks at 250 Hz with only the B71. These non-harmonic peaks were not observed at the other frequencies with BEST or the B71. It should also be noted that Håkansson (2003) used only one B71 for the measurement where the transducer was chosen randomly from one of the audiology test rooms.

The resonant peak of the frequency response is set by the manufacturers slightly above the lowest frequency of interest (Håkansson, 2003). The B71 is characterised by three main resonant peaks observed at 500 Hz, 1500 and 3800 Hz that decrease in amplitude as the frequency increases. Therefore, the threshold of hearing is not usually measured at 250 Hz in clinical setup because it is associated with large distortion levels. The $\text{BEST}_{\text{original}}$ on the other hand, has lower frequency response with the three main peaks observed at 300, 1000 and 3800 Hz. This indicates that the 250 Hz could be measured clinically (Håkansson, 2003). The BEST_{LFR} has an even lower resonant peak at 200 Hz with similar response to the BEST at higher frequencies (manufacturer frequency response sheets).

Håkansson (2003) introductory report of the BEST is promising because the internal design of the BEST differs from the B71 which might make it less vibrotactile giving it more dynamic range of testing especially at low frequencies. Furthermore, the production of lower harmonic distortion compared to the B71 at low frequencies will provide confidence in measuring low frequencies. The smaller mass and smaller size could add more comfort to its placement. On the other hand, the issue with wider frequency range for high frequencies (>4000 Hz) and a flatter frequency response has not been addressed.

3.3 Acoustical evaluation

The acoustical evaluation of the transducers consisted of evaluating the sensitivity in addition to measuring the harmonic distortion. Several B71s were used for this part of the study in order to evaluate the consistency and stability of their performance. The two main types of the BEST were used: BEST original and two low frequency reinforced $BEST_{LFR}$.

All testing was performed in a sound treated booth. Care was taken to ensure that the placement of the transducers on the artificial mastoid was consistent.

3.3.1 Sensitivity

Sensitivity of a BC transducer refers to the minimum magnitude of an input signal required to produce a specified output signal (specified signal to noise ratio). Each of the transducers was provided with a frequency response sheet from the manufacturer. The frequency response of the BEST has a greater output at low frequencies which can be as great as 20 dB (refer to Håkansson (2003). Measurements of the voltage of each transducer were performed using B&K artificial mastoid (type 4930, SN 331282) and B&K digital sound level meter (2260). The digital sound level meter was set to read 94 dB SPL for the reference voltage signal. K-factor equalled 0 dB and the sensitivity was set at –26 dB re 1 V/Pa. Care was taken to keep the temperature of the two artificial mastoids at 23±1ºC by placing them overnight in a cool room and taking measurements of the temperature prior to testing.

The sensitivity of the transducers was checked by recording the output results at different frequencies using the same input level 20 dB at 250 and 40 dB at the rest of the frequencies. The results were cross-checked using a second artificial mastoid type 4930 (SN 728278) with two versions of each type of transducer. The transducer was placed on the centre of the artificial mastoid and a weight of 550 gm provided with each calibration kit was placed on the loading arm that contains rubber retaining-bands to keep the transducer in place and to ensure virtually mass-less rear support for the device under calibration.

Table 3.2 Observed SPL on the sound level meter (dB re 1μV) using B&K 4930 (SN 331282) filtered to third-octave band. Three B71 and three BESTs were used. The equivalent dB HL is calculated.

Dial (dB)	Frequency (Hz)	Booth1		B71-31920	9			BEST		$BEST_{LFR1}$		$BEST_{LFR2}$	
		dB re 1μV	dB HL	dB re 1μV	dB HL	dB re 1μV	dB HL	dB re 1μV	dB HL	dB re 1μV	dB HL	dB re 1μV	dB HL
20	250	66.3	18.5	67.2	19.4	68.7	20.9	81.2	33.4	85.5	37.7	86.8	39.0
40	500	82.9	44.1	84.8	46.0	83.2	44.4	76.4	37.6	78.5	39.7	78.5	39.7
40	1000	65.9	42.6	66.4	43.1	66.0	42.7	64.9	41.6	66.4	43.1	66.2	42.9
40	2000	55.9	42.9	57.6	44.6	55.0	42.0	54.2	41.2	55.0	42.0	55.0	42.0
40	3000	54.2	42.4	54.4	42.6	52.5	40.7	52.1	40.3	51.4	39.6	51.2	39.4
40	4000	55.0	39.7	56.9	41.6	55.3	40.0	45.0	29.7	45.5	30.2	43.3	28.0

Table 3.3 Observed SPL on the sound level meter (dB re 1μV), using B&K 4930 (SN 728278) filtered to third-octave band. Two B71 and two BESTs were used. The equivalent dB HL is calculated.

Dial (dB)	Frequency (Hz)	B71-Booth1		B71-5037		$BEST_{LFR1}$		$BEST_{LFR2}$	
		dB re 1μV	dB HL	dB re 1μV	dB HL	dB re 1μV	dB HL	dB re 1μV	dB HL
20	250	66.8	16.8	70.3	20.3	89.2	39.2	84.5	34.5
40	500	77.8	37.1	77.4	36.7	78.7	38.0	76.7	36.0
40	1000	64.6	38.9	66.3	40.6	68.3	42.6	67.3	41.6
40	2000	54.6	38.9	55.0	39.3	56.4	40.7	56.8	41.1
40	3000	52.4	37.7	52.4	37.7	52.7	38.0	53.0	38.3
40	4000	52.1	36.4	51.1	35.4	45.9	30.2	46.5	30.8

Table 3.2 and Table 3.3 tabulate the results of the investigation of the sensitivity of the transducers using two different artificial mastoids, five B71s and the three BESTs. The results are tabulated in dB re 1 1μV and dB HL. The conversion to dB HL used the sensitivity for each specific mastoid (Appendix C). The force sensitivity taken from the calibration chart is usually reported in mV/N converted to μV/N. Then 20 log (sensitivity force in μV/N) is calculated which is the sensitivity of the artificial mastoid. This resultant number is added to the sensitivity of each specific artificial mastoid taken from the frequency response graph.

The B71s were within the tolerance levels recommended by IEC 60645-1 (2001) which is ±4 dB at 125 to 4000 Hz. One B71 (Booth1) was used with the second artificial mastoid. The second B71 transducer was a new version planned to be used with the psychoacoustical study. The vibratory force levels in dB re 1 μV were similar. However, sensitivity correction of the artificial mastoid showed that at 500 Hz, the difference between the artificial mastoids was 7 dB with the first artificial mastoid (SN 331282) producing higher levels. The rest of the differences between the two artificial mastoids were less than 4 dB. This discrepancy could be due to a number of reasons including the placement of the vibrator on the artificial mastoid. It could also be due to the bone vibrator itself having reduced stability over time as the measurements with the second artificial mastoid (SN 728278) was conducted after a period of time for the purpose of verification. The second artificial mastoid was professionally calibrated by the national physical laboratory (NPL) and calibration documents were provided. The pressure and humidity could affect the results (IEC 60645-1, 2001).

The results with the BESTs were within the ±4 dB for the frequencies between 500 and 3000 Hz. At 250 Hz the three BESTs showed more sensitivity (–14 to –19 dB) compared to the B71. A higher sensitivity means that a dial level of 20 dB would be heard as 34 to 39 dB depending on the transducer used. This confirms the results of the frequency response curve reported by Håkansson (2003) showing that the BESTs are more sensitive than the B71s at low frequencies. On the other hand, at 4000 Hz the BESTs were less sensitive than the B71s by about 9 dB. The two versions of the BEST (LFR) were further investigated with a second artificial mastoid. Two observations can be made from Figure 3.2. The first was that the results of the BESTs were similar using the two artificial mastoids. The second observation was the two B71s produced different results when calibrated with the second artificial mastoid. These results indicated that the BESTs were more stable compared to the B71. The results also indicated that the differences between the same type of transducer is more likely to be due to differences in the performance of the transducer rather than differences due to the artificial mastoid. It should be noted that the measurements reported in Table 3.2 were all performed in the same setting in one test session. Whereas, the results reported in Table 3.3 were tested later in the study after the initial results of the study of the hearing thresholds indicated that the discrepancy between the transducers could be due to an influence of the artificial mastoid (Section 3.4).

The BESTs showed improved sensitivity at 250 Hz by about 20 dB (i.e. allowing for intensities up to 60 dB to be tested opposed to the current maximum limit of 45 dB achieved with the B71 at 250 Hz). The better sensitivity means that the dynamic test range at low frequencies (250 Hz) is enhanced. However, the improved dynamic range should not be associated with high distortion levels similar to the B71. Better sensitivity at low frequencies will also aid in the development and improvement of the bone conduction hearing aids by giving more amplification if needed at this frequency.

On the other hand, no remarkable improvements were observed at higher frequencies which would be desirable as they would extend the testing beyond 4000 Hz.

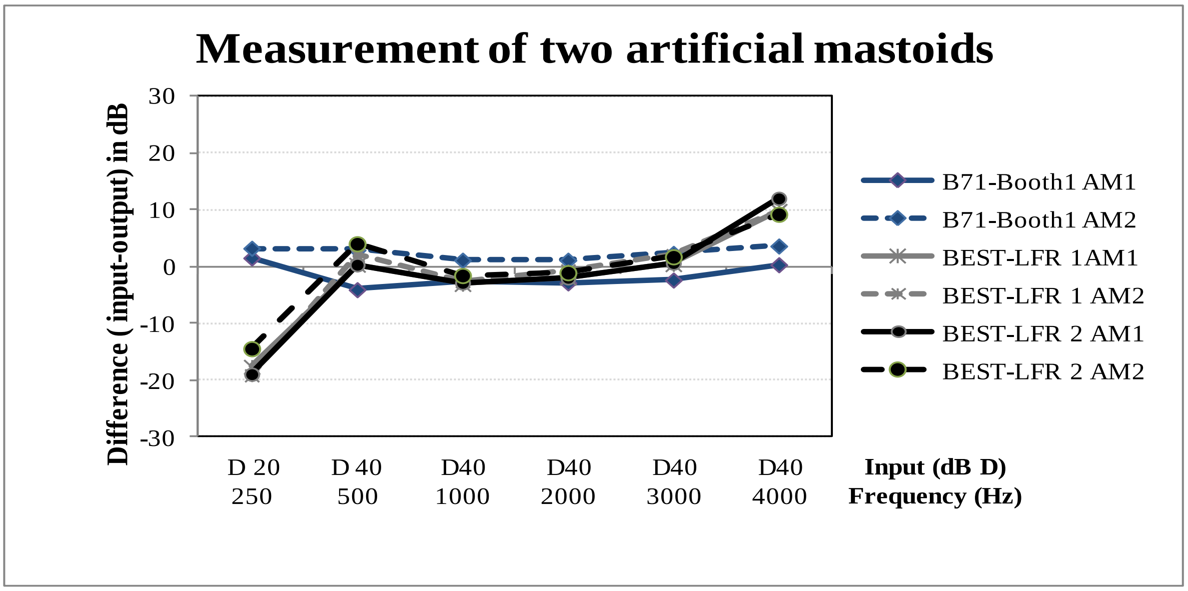

Figure 3.2 The results of one B71 and two BESTs using two artificial mastoids (AM): AM1 (SN 331282) and AM2 (SN 728278).

3.3.2 Harmonic distortion

Clinical evaluation of hearing thresholds with bone conduction transducers is limited to the frequencies above 500 Hz. This is mainly because of the production of large levels of THD at low frequencies, which leads to ambiguous test outcomes. The hearing threshold would probably be a result of the second harmonic rather than the main test frequency ISO 8253-1 (1998) . The BSA (2011) excluded 250 Hz from the main test battery for evaluating the hearing thresholds mainly due to the above mentioned reason. Håkansson (2003) reported that the BESTs produce significantly lower THD at 250 Hz compared to the B71. This finding would make the BEST a better clinical choice because it would give a wider dynamic range of testing as seen with the sensitivity and it would extend the clinical testing to include 250 Hz which may impact the diagnosis of the type of hearing loss.

The total harmonic distortion (THD) was measured to evaluate the performance of the BEST in comparison to the B71 using three versions of the B71 and the three available BESTs. ISO 389-3 (1999) recommends that the THD should not exceed 1% for fundamental frequencies for 500 and 1000 Hz, 2% for 250 to 400 Hz inclusive and 1250 Hz upwards at levels equivalent to 0 dB re 1 μV. At higher presentation levels IEC 60645-1 (2001) reported that the maximum permissible acoustic THD expressed in percentage for a vibratory source to be 5.5% at a presentation level of 20 dB HL for frequencies between 200 and 400 Hz. For frequencies between 500 to 800 Hz with a presentation level of 50 dB HL the permissible THD should not exceed 5.5%. Finally, THD should not exceed 5.5% when the presentation level is 60 dB HL for frequencies between 1000 and 4000 Hz.

3.3.2.1 Specific methods

The instruments used to evaluate the total harmonic distortion included a KC 50 audiometer to produce the pure tone signals (All the audiometers at the department are annually calibrated). The audiometer used was within the calibration period and within the electrical safety check. Artificial mastoid B&K 4930 (SN 331282) was mainly used for measurement of the harmonics. The results with a limited number of frequencies were later cross checked with a second artificial mastoid (SN 728278). Two sound level meters were used to evaluate the resultant harmonics. A digital B&K sound level meter type 2260 which has a display screen that shows the frequency spectrum and allows a visual inspection of the harmonics. The second sound level meter was B&K 2230 with a third octave filter attached. The sensitivity of the two sound level meters was set according to the manufacturer instructions for testing the BC transducers.

The calibration of the artificial mastoid took two aspects into account. The first aspect was sensitivity for each artificial mastoid which is calculated from the manufacturer sheet for each artificial mastoid (Appendix C). The second aspect was the temperature of the artificial mastoid which influences the test results. Therefore, testing was performed with the artificial mastoid temperature of 23±1ºC as specified by IEC 60645-1 (2001).

Care was taken to place the vibrators at the same place at the artificial mastoid. Pure tones were set at frequencies: 250, 500, 750, 1000, 1500, 2000, 3000, and 4000 Hz. These pure tone signals were chosen to evaluate the harmonics at the frequencies used in the clinical testing while adding the half octave frequencies. The THD was calculated for three B71 and three BEST transducers using the levels reported by Håkansson (2003) to evaluate the main trends for the harmonic production at different frequencies and for comparison with the present results. Different levels were used at each frequency which was presented at a high level and near the maximum level of the audiometer (different for each frequency). This would lead to the largest production of harmonics as the harmonic distortion is reported to grow disproportionally with the increase in the level (Stenfelt & Håkansson 2002).

The growth of the harmonics at 250 Hz was evaluated at 20, 40 and 60 dB HL which means that the vibratory alternating force levels in dB re 1µV was the same for all the transducers resulting in different dial levels. It was mentioned in the previous section that the BESTs had different sensitivity at 250 and 4000 Hz. Therefore, if the dial level was used, it would mean that the output would be higher at 250 Hz and the comparison between the transducers would not be at the same level. The frequency 250 Hz was chosen for further comparison because it is the frequency associated with the production of large harmonics with the B71.

The harmonics were noted up to the 12 kHz. Lightfoot (2000) recommends that correction for the sensitivity of the artificial mastoid should be added to the harmonics before the calculation is performed as each artificial mastoid has a unique frequency response curve. For the artificial mastoid used, the correction levels started at frequencies >1500 Hz. At 1500 Hz, 4 dB was added to the difference between the second and the first harmonic and 10 dB was added to the difference between the third and the first harmonic.

The harmonic distortion nonlinearity and overall distortion percentage was calculated according to the following formula.

$$\text{THD} = \frac{\text{Total harmonic power}}{\text{Fundamental power}} \times 100\ \%.$$

The distortion can be specified in terms of the spectrum of the output. The distortion was calculated as the difference between all the harmonic levels with respect to the fundamental. The calculation of the total harmonic distortion combines the distortion products and reports them in percentage of the total RMS value of the output (Hartmann, 1997). With an input level of 40 dB HL at 250 Hz, for example, the vibratory force level was 87.8 dB re 1 µV, the second harmonic was 79.1 dB re 1 µV. This means that the second harmonic was –8.7 dB lower than the fundamental. The third harmonic was measured at 41.6 dB re 1 µV, the difference relative to the fundamental was –46.2 dB. For the second harmonic the distortion was calculated by the following formula $79.1 - 87.8 = 20\log\frac{P2}{Pt}$ where Pt represents the root mean square sound pressure in the unfiltered signal. The outcome was 36.7% indicating that the involvement of the second harmonic was large. The same was applied to the third and fourth harmonics. The total harmonic distortion is $100 * \sqrt{(\frac{P2^2}{Pt^2} + \frac{P3^2}{Pt^2} + \cdots)}$ which in this example was equivalent to 36.7%.

3.3.2.2 Results and discussion

The comparison between the harmonic distortion produced by B71 and the BESTs showed that the BEST produced a markedly lower THD compared to the B71 at 250 Hz. Figure 3.3 displays the results of the three B71s and the three BESTs at the frequency range evaluated. The THD at 250 Hz was higher in the B71's transducers compared to the BESTs for the levels reported by Håkansson as an output. It was noted that the amount of distortion had ranged from 17-36% for the same type of transducer (B71) and at the same presentation level 40 dB HL, indicating variability in the transducers with the same output voltage. It should be noted that the presentation level was high which resulted in unfavourable results with the B71s. The permissible THD used in the IEC 60645-1 (2001) have cited using a level of 20 dB for frequencies between 200 and 400 Hz.

On the other hand, the three BESTs seemed to be more consistent with harmonic distortion ranging from 0.3- 0.7% at 250 Hz at 40 dB HL (Figure 3.3). It is observed that the BESTs produced lower harmonic distortion (maximum of 0.8% at 750 Hz for the

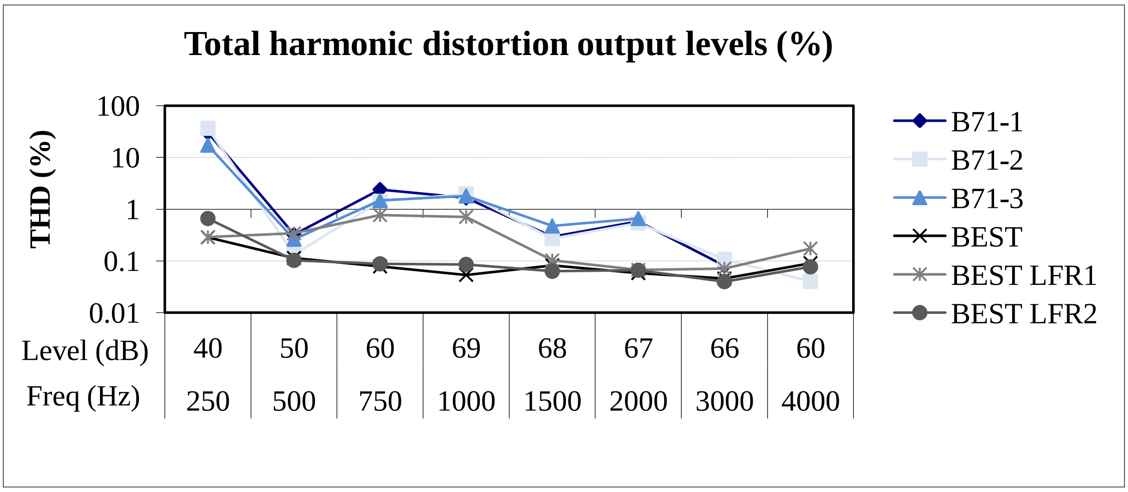

Figure 3.3 THD (%) plotted for all the transducer with levels (dB) indicated as an output in the evaluated frequency range (Hz).

$BEST_{LFR1}$) which is within the permissible tolerance levels of 5.5% (IEC 60645-1, 2001). The B71s produced harmonic distortion that was lower than 2% at 750 Hz and 1000 Hz which was within the recommended permissible THD of 5.5% at this presentation level (IEC 60645-1, 2001). The $BEST_{LFR1}$ appeared to perform differently compared to the other BEST transducers at 750 and 1000 Hz by producing higher THD. However, the results were still within the acceptable tolerance levels. At 500 Hz, the B71 and BEST transducers performed in the same manner.

Figure 3.4 and Figure 3.5 represent the harmonics for a fundamental frequency of 250 Hz for 6 transducers. Due to the different frequency response of the BEST compared to the B71, the level on the audiometer dial would not be equal. Therefore, a distinction was made between dB HL which was corrected to have the same output for all the transducers (Figure 3.4). Figure 3.5 displays the harmonics in dB Dial indicating that the output levels differed between the transducers, the BESTs would be driven up to higher levels at 250 compared to the B71s.

Table 3.4 shows the growth of the THD in (%) using the same output level for all the transducers measured up to the 5^{th} harmonic at 250 Hz. Three presentation levels were used and the THD was measured accordingly. At low presentation level of 20 dB HL, the THD for the B71s was below the recommended distortion of 5.5%. However the increase of the presentation level resulted in a large increase of the THD. An increase in 5 dB HL level resulted in an increase of 14% in the THD. These results confirmed that the growth of harmonics was not proportional with the increase in the presentation level.

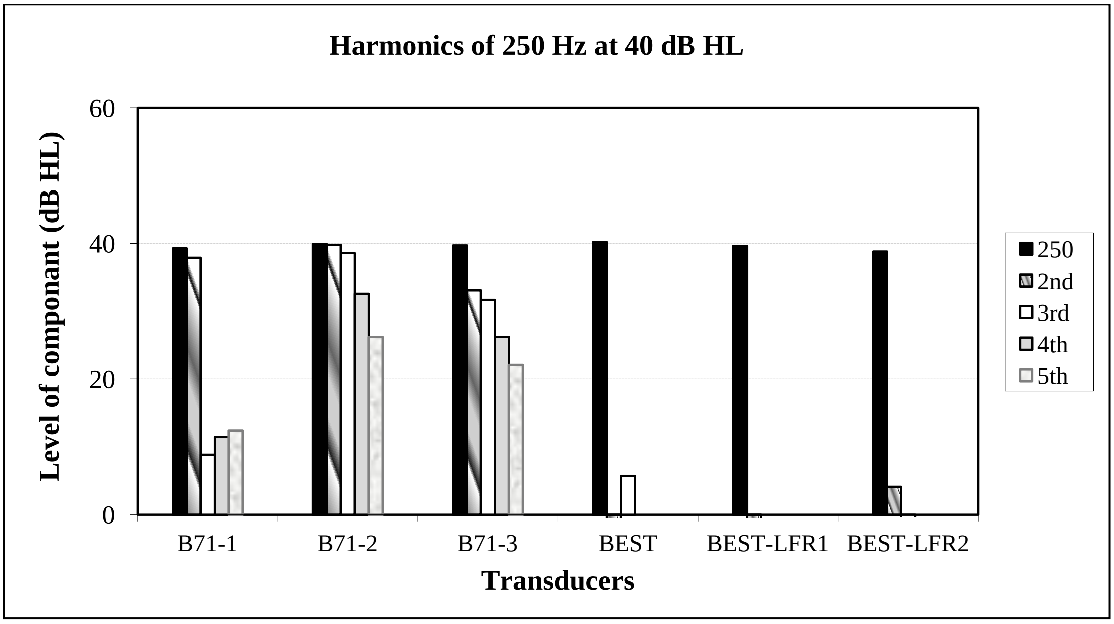

Figure 3.4 Representation of the harmonics at 250 Hz at a level of 40 dB HL.

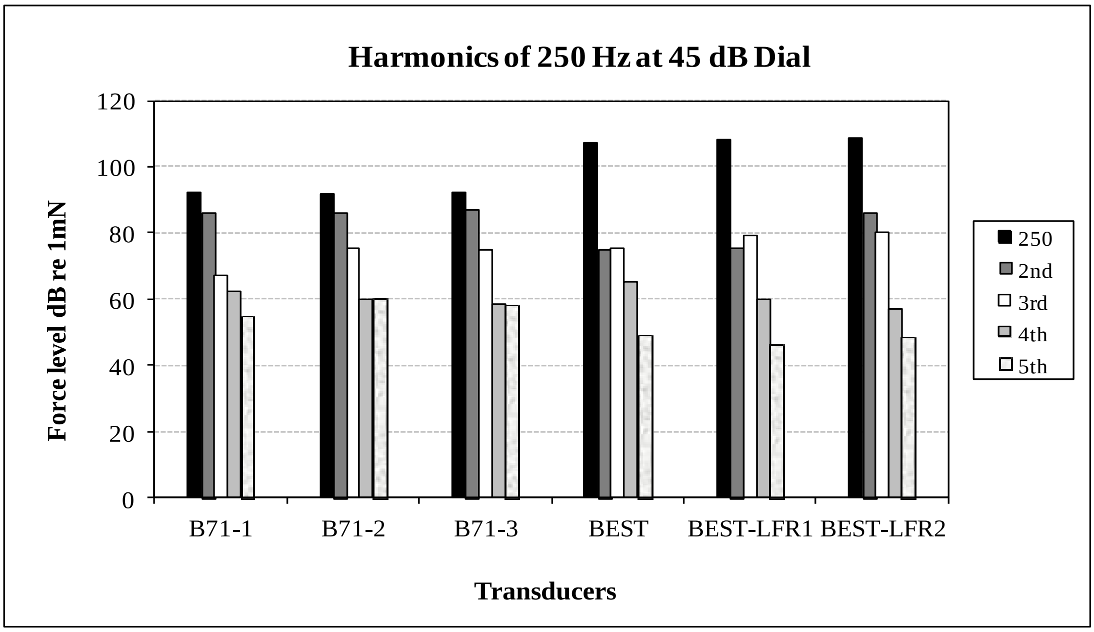

Figure 3.5 Representation of the harmonics at an equal input level at 250 Hz at a level of 45 dB dial.

The BESTs, on the other hand, showed much lower THD compared to the B71s at the three presentation levels, confirming the results reported by Håkansson (2003) that the

BESTs were better than the B71 at 250 Hz. The resultant THD did increase with the presentation level from non-measurable at 20 dB HL to less than 1% at presentation level of 40 dB HL, and finally it reached 6.7 % at 60 dB HL presentation level.

The Max level indicated in the table is different for B71 and the BEST because the BEST can be driven at a higher level. With a maximum level of 60 dB HL for the BESTs, the THD was still lower than the B71s at the maximum presentation level of 45 dB HL. This indicates that the BESTs were better than the B71s at 250 Hz by producing lower levels of THD.

Table 3.4 The growth of the THD (%) at 250 Hz using different output levels

Level	Transducer					
	B71-1	B71-2	B71-3	BEST	$BEST_{LFR1}$	$BEST_{LFR2}$
20 dB HL	4.2	3.0	2.2	0.1	NM	NM
40 dB HL	36.7	33.6	17.5	0.3	0.2	0.6
Max level*	50.5	53.6	56.6	5.9	4.5	6.7
NM: not measurable						
*Max level was 45 dB HL for the B71 and 60 dB HL for the BEST's						

Cross-check of the results obtained with the digital sound level meter was performed by re-testing with B&K 2203 sound level meter with a third harmonic filter attached. Two test frequencies were used 250 and 500 Hz, with the levels used input levels (i.e. level on the dial) because the distortion is more noticeable at lower frequencies. The levels used were 40 dB dial at 250 Hz and 50 dB dial at 500 Hz.

Figure 3.6 shows a lack of consistency between the two sound level meters for B71-2 at 250 Hz. Later in the study this transducer, was removed because it showed variability in its performance with time (indicated by Experiment 2 measuring the hearing thresholds) with the degree of discrepancy large at around 19%. At 500 Hz the apparent differences between the transducers was small reaching a maximum of 0.5% for the B71-1 which is within the permissible limits at this presentation level (IEC 60645-1, 2001).

Furthermore, the results were evaluated with a second artificial mastoid (SN 728278) and with a second audiometer (SN 0435) because of issues related to the sensitivity of the artificial mastoids and issues related to the placement of the vibrator on the artificial mastoid. The results are displayed in Table 3.5. The use of two artificial mastoids with the same audiometer resulted in approximately the same results. This indicates that the change in artificial mastoid at these two frequencies did not influence the resultant outcome at the two test frequencies. The results using the same artificial mastoid with two audiometers of the same type were also similar with a discrepancy of 0.8% for the B71. But the results with the BESTs were similar. This may have been due to the internal distortion of the audiometer.

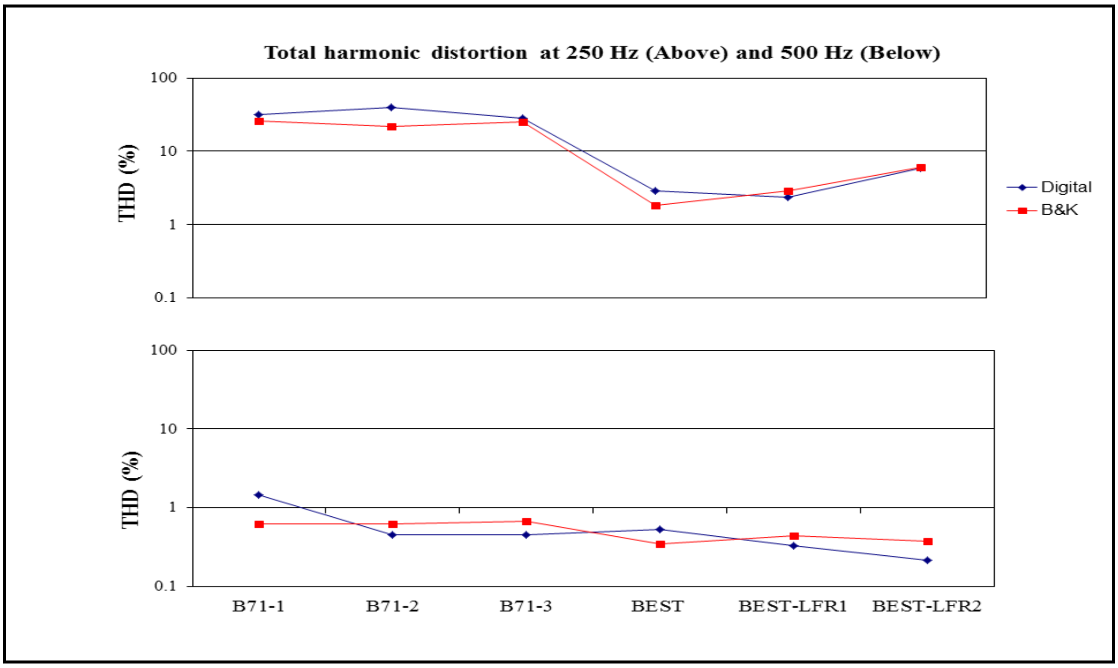

Figure 3.6 Repeatability of the THD (%) measured with two sound level meters. Measurement was performed at 250 Hz with 40 dB input level (upper panel) and 500 Hz at 50 dB input level (lower panel).

Table 3.5 THD (%) measured by two artificial mastoids using two different audiometers for signal presentation at 250 and 500 Hz.

		250 Hz at 20 dB D			500 Hz at 40 dB D		
Artificial mastoid	**Audiometer**	**B71 (B1)**	**BEST LFR1**	**BEST LFR2**	**B71 (B1)**	**BEST LFR1**	**BEST LFR2**
728278	**KC50 (0119)**	3.7	0.2	0.2	0.4	0.1	0.1
728278	**KC50 (0435)**	4.5	0.2	0.2	0.4	0.1	0.0
331282	**KC50 (0119)**	3.7	0.2	0.7	0.2	0.2	0.1

The current results are lower than the levels reported by Håkansson (2003). Håkansson (2003) reported that the B71 produced 61% THD compared to 3.3% for the BEST at 40 dB HL. Figure 3.7 shows the THD (%) as reported by Håkansson (2003) in comparison to the results obtained in this study. The blue line represents the B71 reported by

Håkansson (2003) while the red connected lines represent the B71s used in the current study. The intermittent blue line is the BEST original used by Håkansson (2003), while red represents the current study. Finally, the red dotted line represents the $BEST_{LFR}$. The graph clearly shows discrepancy between the two studies although the same levels reported by Håkansson (2003) were used in the present study.

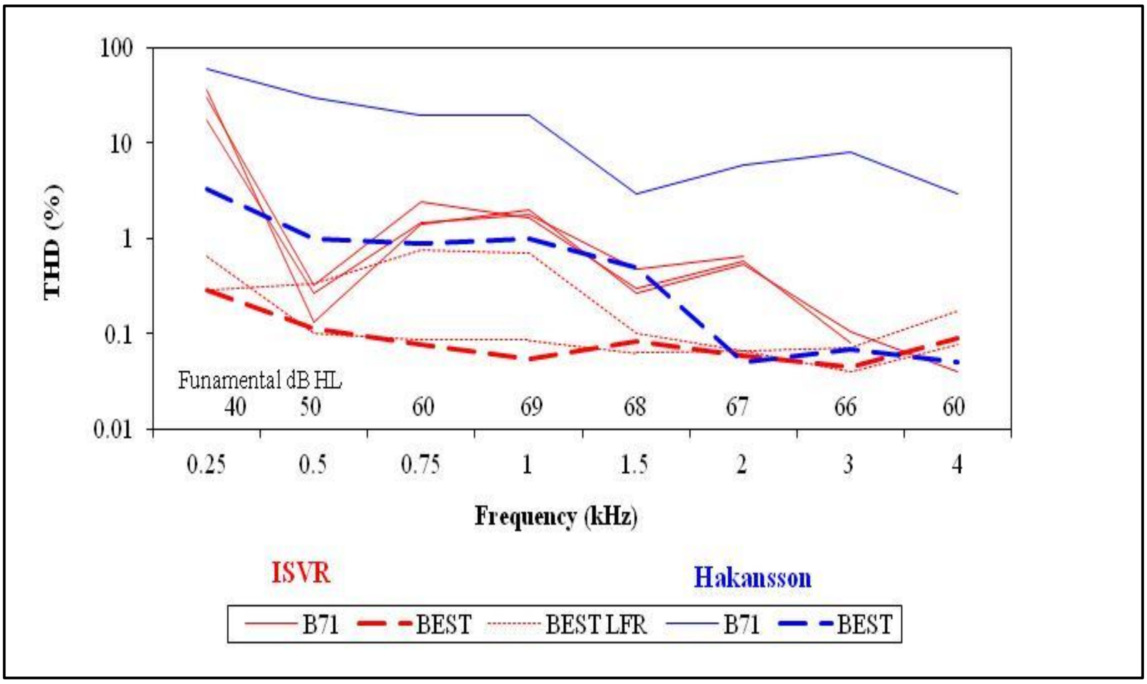

Figure 3.7 THD (%) is plotted for the BESTs and B71 from this study (red) compared to the results obtained by Håkansson (2003) in blue for the same output levels.

The reasons for the discrepancy could be due to the fact that the BEST was not in its original case, or due to the selection of only one B71 in Håkansson (2003) study. The B71 was selected randomly from one of the hospital clinics. Bone transducers are sensitive to external elements such as being dropped or having an internal problem. However, clinics have frequent calibration and testing of the instruments thus it is more probable that the discrepancy could be due to variability of the B71 transducers.

Håkansson (2003) reported an intermediate peaks for the B71 at 250 Hz between the harmonics that could not be explained. No intermediate levels were observed at the spectrogram of the digital SLM. An amplifier connected to the artificial mastoid was used in the Håkansson (2003) study which could have led to the higher harmonic levels as well as to the presence of the intermediate peaks. If the harmonics obtained for the

B71 were amplified, this could explain why the intermediate peaks that are showing appeared. Or, it might be due to the distortion added from the amplifier itself.

Stenfelt & Håkansson (2002) reported measuring the harmonic distortion for the B71 at different presentation levels at 250 Hz with the use of an external amplifier. They reported a THD of 17% at 50 dB HL and 64% at 60 dB HL. They did not measure the THD at 40 dB HL. However, it is assumed that the THD would be lower than the reported. The THD measured by Stenfelt & Håkansson (2002) is smaller than that reported by Håkansson (2003) and the present study. These results show variability between the B71 in the three studies which could be an indication of the variability of the performance of B71 specifically at 250 Hz.

3.3.3 Summary of results

The acoustical evaluation of the BEST in comparison to the B71 measured the sensitivity and the total harmonic distortion of a number of different versions of the BESTs in comparison to the B71. All of the measurements were conducted with an artificial mastoid (B&K type 4930) and B&K digital sound level meter (2260). Different versions of the AM and SLM were used to eliminate the sources of variability and to ensure the measurements were stable, even if the calibration device was changed. Furthermore, the results were evaluated using different versions of the same audiometer to ensure that the internal distortion of the audiometer did not influence the results.

The measurement of the sensitivity confirmed the results reported by Håkansson (2003) that the BESTs had wider dynamic range compared to the B71 specifically at 250 Hz. The present investigation showed that the BESTs were –14 to –19 dB more sensitive than the B71 when the same calibration standard was used. Moreover, the BESTs were less sensitive than the B71 by 9 dB at 4000 Hz. The current findings indicate that correction factors should be used with the BESTs. This also indicates that while the low frequency sensitivity was improved with the BEST, the variability with the high frequencies was not addressed indicating that the airborne radiation problem remained unresolved.

The results of the THD indicate superiority in the performance of the three BESTs in comparison to the B71 mainly at 250 Hz. This means that the BESTs can be used with the future studies involving measuring the hearing thresholds and vibrotactile thresholds with the certainty that the response would be due to the fundamental frequency rather than the harmonics.

At the frequencies from 500 to 4000 Hz, both transducers were within the permissible limits of THD production. This means that the BESTs can be used in the upcoming studies based on the lower harmonic. However, further investigation should be carried out to investigate the psychoacoustical performance. The measurements were conducted over a period of time and using different sound level meters, artificial mastoids and audiometers. All of the results were consistent for the two main types of transducers evaluated.

3.4 Hearing thresholds

The evaluation of hearing thresholds was investigated in four experiments with a total of 96 participants (18-30 years). The participants were recruited from the student population through advertisements and emails sent to different faculties at the University of Southampton. Their participation was on voluntary basis with no payment.

Four main experiments were conducted over a period of two years (Experiment 1 to 4). Experiment 2 was conducted by a proficient undergraduate student closely monitored by the main investigator. The third experiment was conducted by another undergraduate student who was also monitored by the main investigator. The two students were competent audiology students in their third year of study. In principle, the thresholds were measured in almost the same way in the four studies, with the exception that experiment 1&2 collected the thresholds manually following the guidelines of the BSA recommended procedures (2004). Whereas for Experiment 3&4, the thresholds were collected through an automated method utilising MATLAB computer programme.

The main aim of this study was to evaluate the performance of the BESTs in comparison to the B71 in order to investigate their suitability for use in the future clinical research evaluating binaural hearing with bone conduction stimulation.

Additional aims of this study included:

- Investigating the stability of the hearing thresholds in two different sessions using the BESTs and B71s.
- Evaluating the results of the hearing thresholds measured with the BESTs in relation to the current RETFLs.
- Comparing the results from the different studies, with the different B71s and BESTs as different participants took part in each study.

3.4.1 Specific methods

BSA (2004) recommended procedures for pure tone audiometry were followed in all of the experiments. To keep the participant motivated and to reduce the testing time, it was decided to use larger step sizes, 5 dB steps, compared to the 2 dB steps used in experiment 1. The pure tones were presented at 30 dB (the manual method) for the automated method this level was roved by 5 dB. A 10 down-5 up steps were used in the final three studies.

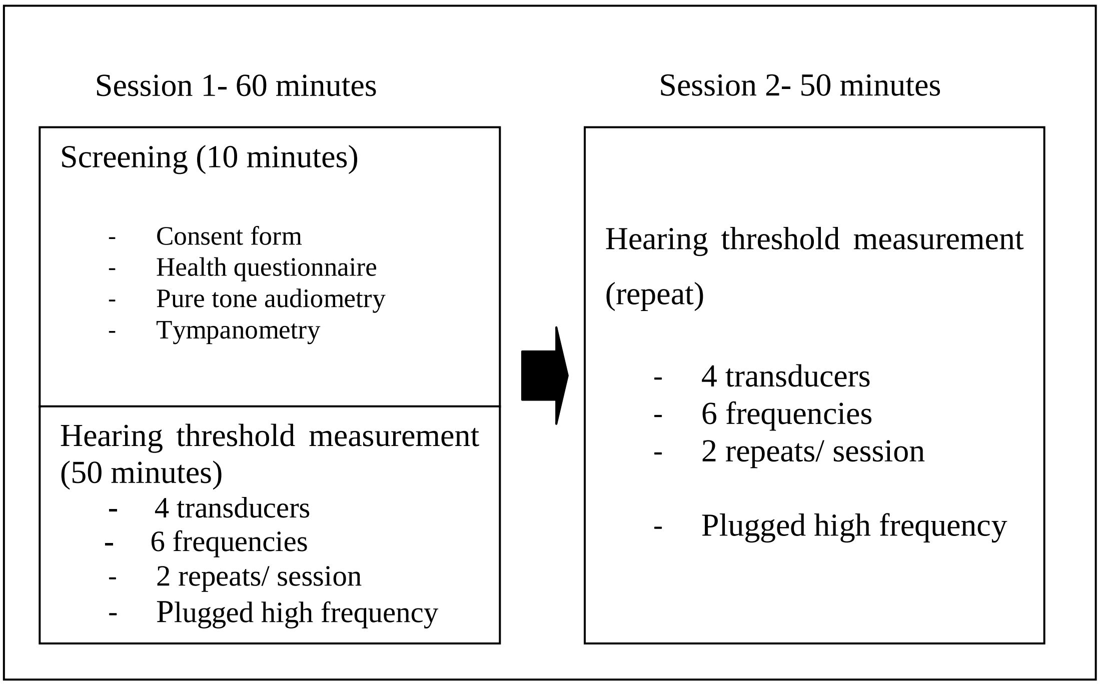

Figure 3.8 Experimental structure for a given subject.

Figure 3.8 is an example of the structure of the session for a given participant. It shows that each participant taking part in this study had to attend two test sessions lasting approximately 90 minutes each. The first session always included hearing screening to certify that participants taking part in this study had normal hearing and no recent history of middle ear disease. This was evaluated through hearing questionnaire and measuring the middle ear pressure and hearing thresholds. The screening was followed by the main testing.

The transducer was placed on the most prominent part of the mastoid process. The participants were instructed to indicate if the transducer slipped off their head at any point in the testing by raising their hand. The transducer was not removed between testing frequencies for any specific transducer type. However, it was removed to change the type of the transducer and to give the participants a break from the tension of the headband which can cause discomfort if placed for a long duration.

It should be noted that these are the broad aims of the study and there have been slight changes in the methodology of the studies performed chronologically during the period of 2009 to 2011, the procedural differences are outlined in Table 3.6. The BEST original was used in the three studies, and the $BEST_{LFR1}$ was used in Experiment 1, 3 and 4 while $BEST_{LFR2}$ was used in Experiment 1 and 4.

Table 3.6 The main differences between the hearing threshold experiments

Hearing thresholds	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Participants	20	22	30	24
B71	1	2 (one	2	2
BEST	3	1	2	2
AC part of test	No	Yes	Yes	Yes
AC Transducer	None	ER 3A	ER 5A	ER 5A
Frequencies (kHz)	0.25, 0.5,1,2,3,4	0.5,1,2,3,4	0.25, 0.5,1,2,3,4	0.25, 0.5,1,2,3,4
Masking Level (dB	None	35 dB HL	35 dB HL	35 dB HL
Step size	2 dB	5 dB	5 dB	5 dB
Method	Manual	Manual	Automated	Automated
Repeats within session	2 Repeats	2 Repeats	2 Repeat	1 Repeat
Repeats of sessions	2 Sessions	2 Sessions	2 Sessions	2 Sessions
Use of ear plugs	Yes at 2,3,4	Yes 3,4 kHz	Yes 3,4 kHz	Yes 3,4 kHz
Randomisation	Yes	Yes	Yes	Yes
Use of attenuator	At 250 Hz for BESTs	20 dB for all transducers	Not used	Not used

It was decided after the end of the first experiment to evaluate the AC hearing thresholds as main part of the study because of the reports that indicated that the errors that appear in the studies could be due to the discrepancy between the AC and BC standards (Hood, 1979; Frank et al, 1988; Lightfoot & Hughes, 1993) because the current RETFL standard (ISO 389-3, 1999) did not account for the AC thresholds. The AC thresholds were always measured first because their setup was different and to familiarise the participants with the test procedure.

3.4.1.1 Pilot study

A pilot study was performed on eight volunteers prior to the first study measuring the thresholds. Initially it was decided to have two test sessions measuring two transducers in each session. Six test frequencies were tested with three repeats for each frequency in each session. Furthermore a step size of 1 dB was chosen for threshold measurement.

Variations in the participant's responses were seen, clearly indicating that three repeats for each frequency would cause the participants to lose interest. The test had to be interrupted frequently in order to motivate the participants to focus on the signal as a clear drift was seen in their responses. Using 1 dB step size, increased testing time for approximately 7 minutes per frequency compared to 5 minutes per frequency with 2 dB steps.

The hearing thresholds were decided to be tested with all the transducers in the same test session in order to get consistent and comparable results. Furthermore, the number of repeats per threshold measurement was reduced to two instead of three. The step size was increased to reduce the test time. This method allowed for obtaining a repeat on a different session for each of the transducers, which in turn allowed for testing the repeatability of the results on different test days. This method reduced the influence of day to day test variation on a specific transducer.

3.4.1.2 Screening guidelines

All the participants had normal-hearing thresholds. The age limit of the participants was between 18 to 30 years. Participants were mostly from the University of Southampton student population. Participants were recruited through an invitation email or invitation letters. To ensure normal hearing status and healthy middle ears, all the participants were screened using a health questionnaire (Appendix B-1). The questionnaire included questions about the general health, pervious ear infections, ear surgeries, head trauma, as well as persistent tinnitus and noise exposure within 48 hours (only one participant was told to come on a different session because she has been exposed to loud music the previous night).

The questionnaire was followed by tympanometry (GSI tympanometer) to ensure that middle ear status was within normal limits. The results were based on the recommended British Society of Audiology (BSA) procedures for testing and calibration (British Society of Audiology, 1992), type 'A' tympanogram was required. Screening pure tone audiometry (KC 50 audiometer) was performed to assess the hearing thresholds for both the air conduction (0.5, 1, 2, 3, 4, 8 kHz) and bone conduction (0.5, 1, 2, 3, 4 kHz), all participants had thresholds ≤ 20 dB HL and symmetry between the ears < 10 dB.

Participants were excluded if they had excessive wax, middle ear problems, head injury, tinnitus or hearing loss.

3.4.1.3 Participants

Hearing thresholds were collected from 96 participants in total. The number of participants in each experiment is indicated in Table 3.6. All participants were briefed about the experiment and were given written instructions about the tasks required from them. Their understanding of the procedure was checked; they provided a signed consent before commencing the study. Participants were required to follow the screening guideline of the study (Section 3.4.1.2).

A total of 26 participants were included in the fourth experiment. The results for two participants were excluded because one did not attend the second session, consequently, the results for the first session were taken out of the analysis. Participant number 16 results were later removed due to the wide variability in the responses that had a big influence on the averaged results. Despite passing the screening, this participant showed thresholds exceeding 25 dB HL in both AC and BC measurements which were outside the inclusion criteria.

3.4.1.4 Setup

Equipment

The evaluation of the hearing thresholds was conducted through a manual method in the first two experiments using a KC50 audiometer. The third and fourth experiments used an automated method. The signals were generated through the math works program MATLAB downloaded on a portable laptop. The digital signal was played through a soundcard (Creative extigy) then amplified through a KC 50 audiometer. A second audiometer (KC 50) was used to generate the narrowband masking noise (NBN) to mask the non-test ear.

Stimulus

Pure tone frequencies between 250 and 4000 Hz were generated directly from the audiometer in the first two studies (manual presentation). The method of signal presentation was later adjusted to be automatically presented through a MATLAB code that was installed on a laptop and connected to a sound card. The level was further controlled by the audiometer KC 50. Calibration of the signals ensured that the signal was not distorted. Using the automated method ensured that the tester bias was smaller as there was no involvement in determining the thresholds. The tester involvement was to monitor the participants and to change the NBN centre frequency presented from the second channel of the audiometer (Manual method) or from a second audiometer (automated method).

The duration of the signal presentation was 1-3s, it was intended to comply with the BSA (2004) recommended procedures. The pause between the presentations was random to avoid the participant guessing when the next signal would be presented.

Masking noise was presented to the non-test ear in the last three of the experiments. The type of the masking noise was NBN centred at the test frequency. The level of the signal presentation was 35 dB HL following the guidelines of ISO 389-3 (1999). This level was considered to be sufficiently loud to prevent cross hearing from the non-test ear.

Transducers

Insert earphones were used to deliver the pure tone signals when AC was measured as part of the main investigation. The type of insert ear phone used in each study is indicated in Table 3.6. The BC transducers used were B71 and the BEST transducers to compare the performance of the participants in the same session. Experiment three replicated the use of the B71A and B71B which were used in the first and second experiments respectively. This was done to evaluate the repeatability of the results with a different group of participants and to evaluate the automated procedure compared to the manual presentation used in the first two studies. The fourth Experiment used two different versions of B71 that were not used in any of the previous testing (B71C, B71D). The BEST (BEST) in its original form was used in the three first Experiments. $BEST_{LFR1}$ was used in the four experiments, while $BEST_{LFR2}$ was used in the first and last experiment. An E.A.R plug was used at 3 and 4 kHz in the four experiments and at 2 kHz in the first experiment.

The masking noise was presented via Etymotic Research ER-3A (Experiment 2) or through ER 5A (Experiment 3 and 4).

The transducer (AC and BC) was placed on the left ear for all of the participants. One steel-band was used for all of the BC transducers with a measured tension of 5.4 N. The investigator placed the BC vibrator on the most prominent part of the mastoid bone.

Response system

The participants responded to the signal by pressing the regular response button in the first two experiments. The participant was instructed to press the button for the duration of the signal presentation to ensure that the participant does not respond positively when the signal is not presented, which occurs when the signal level is faint. Therefore, pressing for the duration of the signal presentation would give confidence that the response was accurate. Tester bias could occur in this situation, so as a precaution measure, the presentation was 1-3s long. For the final two studies, the signals were controlled by the MATLAB program, a computer mouse was used as a response button and the participants had to press the left click button every time they heard the signals. The automated method had the facility to count the false positive and visual monitoring of random pressing of the button was carried out by the investigator to ensure that the participant was alert throughout the testing. The test was stopped by the tester if the participant kept pressing the button. In which case, the participant would be reinstructed and that frequency would be repeated. The threshold is determined as 3 out of 4 hits in an ascending manner.

3.4.1.5 Calibration

The inserts were calibrated following the guidelines of ISO 389-4 (1999). As the sensitivity of the BESTs is lower than the b71 an attenuator was used in manual testing to decrease the level of the signal directly presented from the audiometer. The attenuator was used in the first study only at 250 Hz. It was later decided to use the same attenuator for all of the frequencies in Experiment two to eliminate tester bias and to provide some sort of blinding to the tester in terms of the results. Two B71s were used in Experiment two and one of the BESTs. Furthermore, the audiometer was KC 50 (0435) different from the audiometer used in experiment 1 (0119).

Calibration of all the transducers was performed by following ISO 389-3 (1999) calibration protocol with the B&K artificial mastoid type 4930 and digital sound level meter B&K 2260 Investigator Sound Level Meter. The Calibration of the insert earphones used a B&K occluded ear simulator 4175 following ISO 389-2 (1997). Calibration of the narrow band noise followed the recommended procedure described in ISO 398-4 (1999).

The RETFLs used were reported in ISO 389-3 specifications and the sensitivity levels used for the artificial mastoid. Later in the study, two other artificial mastoids were used. Each artificial mastoid was corrected according to its own specification sheet to calculate the sensitivity specific to each artificial mastoid. The RETFL values were used for both the B71s and the BESTs because there are no RETFL values specific for the BEST.

The digital sound level meter performance was checked for linearity and internal distortion by using the same voltage from the audiometer fed into an oscilloscope and comparing it to the output coming out of the artificial mastoid. The wave was observed on the oscilloscope and checked according to the divisions. The digital sound level meter performed linearly with minimal internal distortion and the audiometer was checked in the same manner.

The results of the sensitivity check indicated that the BESTs required correction factors either added to the manual results or to the automated program presented through MATLAB. These correction factors were added to ensure that the levels for the BESTs and B71s were equal according to the RETFL values.

Due to the sensitivity of the measurements in the various studies and after the realisation that the volume control unit on the audiometer could cause large variation if moved slightly, the knobs were taped to fix their position. The calibration was checked on a weekly basis and whenever the audiometer was used for clinical testing by other colleagues.

3.4.1.6 Artificial mastoid check

Psychoacoustic measurements of the hearing thresholds in the first three studies revealed a dip at 2000 Hz that ranged in magnitude between 7-9 dB for the different transducers used regardless of the type. The reoccurrence of the dip indicated two possible interpretations. The first is that there is a systematic error with the current RETFLs leading to inaccurate results when measuring the thresholds similar to the O'Neill et al (2000) report. The second possible interpretation could have been due to the artificial mastoid (SN 331282) used in the first three studies measuring the hearing thresholds (Mark Lutman, personal communication).

Therefore, the check of the artificial mastoid was conducted with the following aims:

- Investigating the discrepancy in the hearing thresholds observed at 2000 Hz with two different artificial mastoids of the same model.
- Investigating the performance of the basic artificial mastoid to two different artificial mastoids with different frequencies.

These aims were addressed by repeating the calibration with an additional two artificial mastoids, one that is present at ISVR and used for the annual calibration (SN 2404338). The second artificial mastoid was lent to this study by the Royal South Hants Hospital (SN 728278). This artificial mastoid was professionally calibrated by NPL. It is hypothesised that these two artificial mastoids would produce similar results.

A preliminary investigation of the transducers indicated a discrepancy between the AM borrowed from the RSH hospital and the AM used in the previous studies. Therefore, measurements were conducted using six transducers while taking 10 measurements per transducer. The transducer was completely removed from the artificial mastoid and replaced in each trial. Consistent placement, as possible, was ensured through the use of a custom made device (Figure 3.9). The BC transducer was left in place using the device, after the removal of the device the results were recorded. All the measurements were conducted in the same test session.

Two main frequencies were chosen to be tested. Firstly, 2 kHz as it showed worsening in threshold in the first three studies. Secondly, 0.25 kHz was as this frequency was one of the main frequencies used for the harmonic distortion measurement so it was important to check whether there was variation between the artificial mastoids at this frequency.

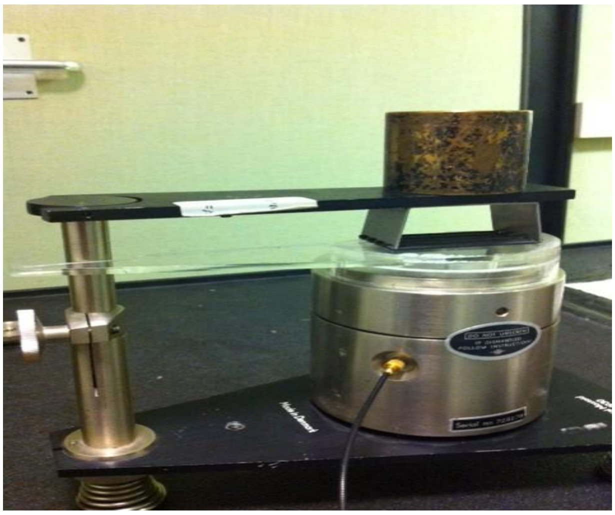

Figure 3.9 Artificial mastoid with the custom made device to ensure the transducers remain in place.

Figure 3.10 illustrates the results measured in seven transducers that were used in the hearing thresholds studies. The measurements were conducted at 250 Hz, the y axis shows the correction required to achieve the current RETFL. This graph indicates that there was no noticeable difference between the three artificial mastoids.

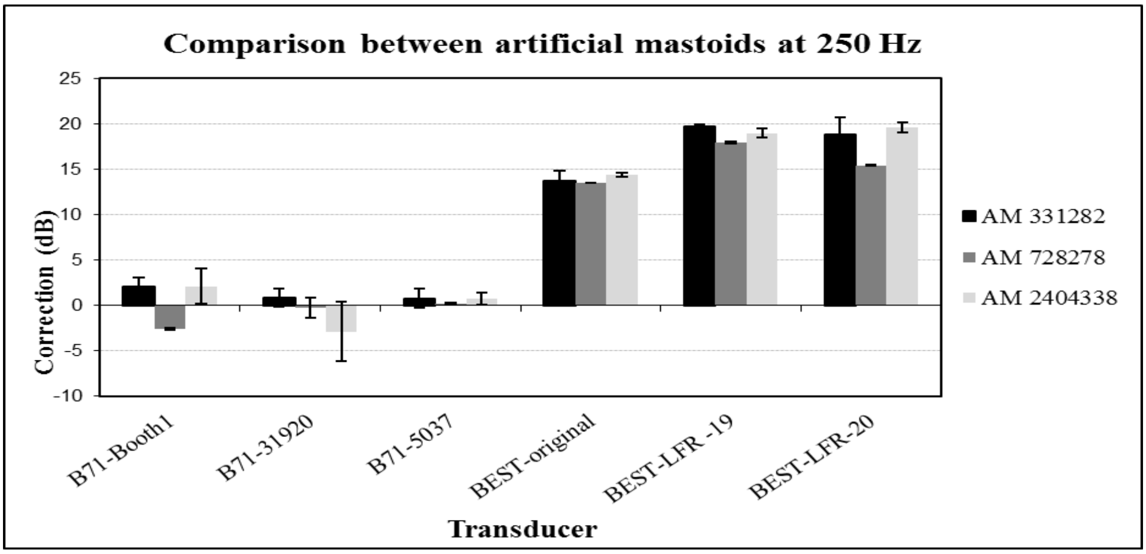

Figure 3.10 Comparison between two artificial mastoids for seven different transducers at 250 Hz (error bars show 95% confidence intervals)

The measurements conducted at 2000 Hz are illustrated in Figure 3.11. The signal on the audiometer was set at 40 dB D and the correction number is the level required for the signal to be in dB HL. It was noticed that the placement on the artificial mastoid was more sensitive at this frequency compared to 250 Hz and the small change in the placement would result in a change in the reading.

It is evident from this graph that the first AM used in the first three studies consistently produced higher levels of correction than all the transducers used. Whereas, the other two AM's showed a different trend which required lower correction values. However, the three artificial mastoids were within the allowed tolerances which are ± 4 dB at 125 to 4000 Hz; ± 5 dB at 6000 Hz and above (IEC 60645-1:2001). Repeated measures ANOVA was conducted with the AM (3) and transducers (7) as factors. The results indicated that the three artificial mastoids were statistically different than each other F2,18= 122.27, p< 0.001, Mauchly's test of sphericity was assumed x2(2)= 0.869, p=0.570. Furthermore, on average, the transducers were significantly different than each other $F_{6, 54}$=69.28, p<0.001. Mauchly's test of sphericity was assumed $x^2(20)$ =0.107, p=0.801.

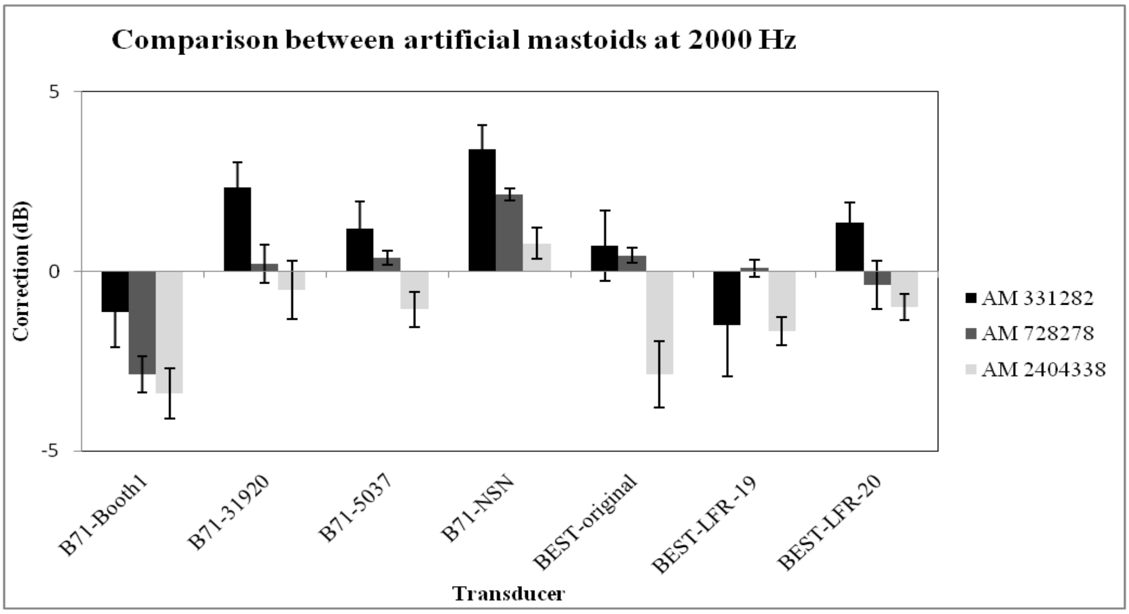

Figure 3.11 Comparison between two artificial mastoids for seven different transducers at 2000 Hz (error bars show 95% confidence intervals).

This graph (Figure 3.11) shows that the last two artificial mastoids are in opposite direction compared to the first artificial mastoid that was used in the first three hearing thresholds studies. In some transducers, the last two artificial mastoids were different. A noted difference (< 3 dB) was with the BEST-original.

Measurement on a second occasion was conducted to evaluate the stability over time influence on the test results using two artificial mastoids and to decide the appropriate correction factors to be used. Figure 3.12 shows the results of the first AM and the artificial mastoid used at the department (AM 2404338) where the measurements were conducted after two months. A discrepancy was noted between the first and the second measurement using AM 331382 and observed with all the transducers with the maximum difference of 5 dB between the measurements seen with the $BEST_{LFR1}$. On the other hand, the second AM 2404338 showed a maximum difference of 2.5 dB between the two measurements seen with the B71. In contrast, the BEST's showed more consistency with the measurements over time with this specific AM.

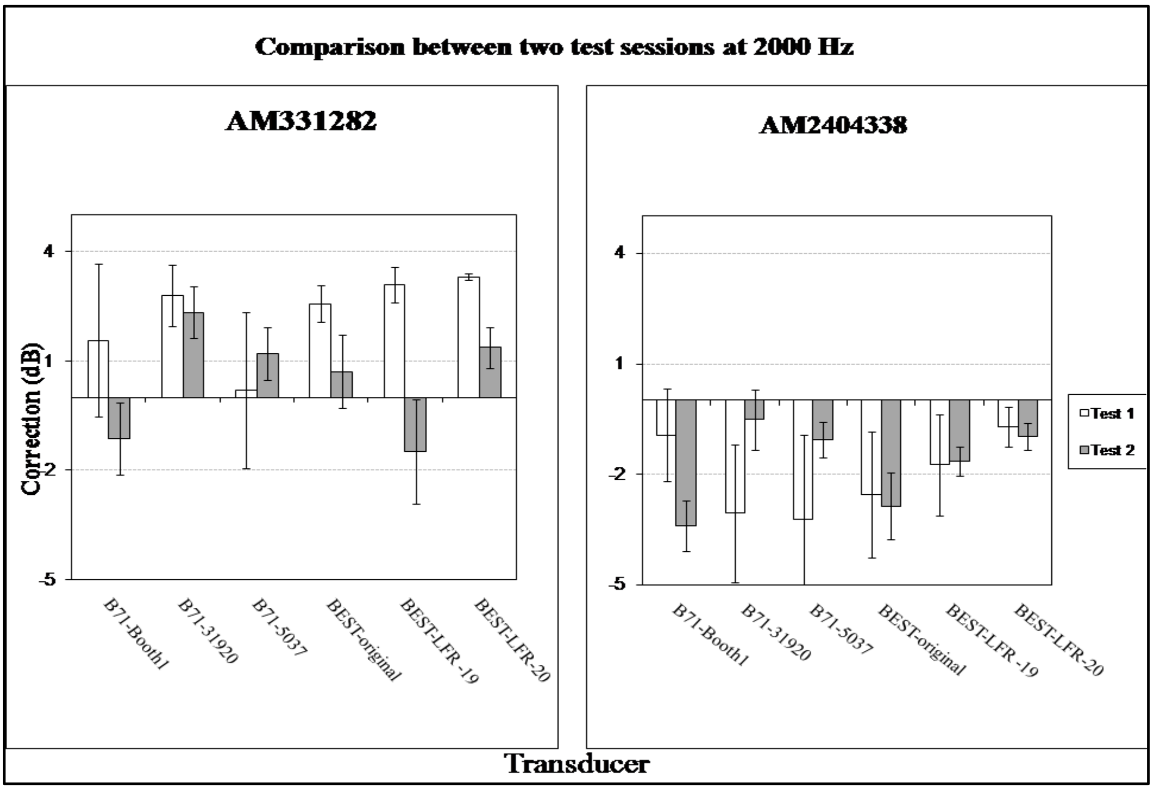

Figure 3.12 Comparison between the two artificial mastoids, measurements were conducted in two different sessions at 2000 Hz. Error bars indicate 95% confidence intervals.

According to these results it was decided to add a correction factor (Figure 3.7) that was transducer specific since the repeated measures ANOVA showed significant difference between the transducers. These correction factors were calculated from the differences between the AM 2404338 and AM 331282. These values were added to the threshold levels at 2000 Hz only in the first three studies.

Table 3.7 Correction factors added to the threshold at 2000 Hz in the first three studies.

B71-Booth1	B71-31920	B71-5037	BEST-original	$BEST_{LFR1}$	$BEST_{LFR2}$
– 5	–2	–3	–4	–4	–2

3.4.1.7 Statistical analysis

The aim of the study was to evaluate the performance of the BESTs in relation to the clinically used B71. The hearing thresholds were measured twice in two sessions measured on different days. Therefore, the statistical analysis included the measurement intraclass (ICC) coefficient to evaluate the quality of the results in the two test sessions and the measurement of precision and the reliability score.

Intraclass correlation (ICC) is used to study the measurement error and observer variation. It provides a measure of the homogeneity among units of analysis and a summary into the variance structure of the data, in other words, it provides a measure of repeatability or the relationship between two variables that measure the same thing (Field, 2009). ICC gives an indication of the measurement and is unit less. A true value should not be affected by the order it was presented in. The interpretation of the ICC is based on the quantitative score given in a ratio between 0 and 1, where ratio close to 0 indicates poor reliability and the closer the ratio to 1, the higher the reliability (Weir, 2005). However there is no consensus to what constitutes a good ICC (Weir, 2005; Graham et al, 2012). There is one disadvantage associated with the results of the ICC especially when there is low variation in the results between the participants which would show as low ICC values despite participants results that are similar to each other (Graham et al, 2012).

The measurement of precision which is the typical error (standard error of the measurement SEM) provides an absolute index of reliability (Weir, 2005). It is measured by calculating the standard deviation of the differences between trails and dividing it by the square root of 2. It can also be calculated by the square root of the mean square error from the one-way ANOVA table. It represents the variability between the measures and is not affected by between-subjects variability as in the ICC. The interpretation of the precision values are based on the previous studies of the threshold measurement where an acceptable variation in threshold from day-to-day would be ±5 dB (British society recommended procedures for pure tone measurement, 2011), therefore results between 1-5 dB would indicate good reliability and results > 5dB would indicate poor reliability.

Repeatability coefficient was reported for the test-retest trials to evaluate the agreement between the sessions. It is generally expected that 95% of the differences are less than two standard deviations (Bland & Altman, 2010). It is measured by taking the sum of the square differences for each participant, dividing it by the number of the participants and then taking the square root (standard deviation of the differences). The coefficient of repeatability is twice the standard deviation of the differences.

To evaluate the differences between the thresholds measured by the two transducers, one way ANOVA was conducted because the four experiments used different groups of participants. The data was examined to check if it followed the assumptions of using parametric testing. The data was normally distributed and the homogeneity of variance was assumed (Field, 2009).

Statistical package used for the analysis was SPSS (version 18) and repeated measures ANOVA because each participant had their thresholds measured in different transducer types across the frequency range (250 to 4000 Hz). This was conducted for the analysis of each experiment separately.

3.4.2 Results

Four experiments were conducted chronologically to evaluate the threshold of hearing using the traditional B71 and the new BESTs. The main aim of the study was to evaluate the performance of the BESTs for clinical use. The BEST has to conform to the current RETFLs for it to be used clinically in terms of the design. The circular tip of the BESTs follows the current standard. However, no psychoacoustical measurements of the hearing thresholds have been reported with the BESTs. Frank et al (1988) claims that the RETFLs should be transducer specific. Therefore, a secondary aim was to evaluate the current RETFLs with the B71 and BEST transducers with a sufficient number of young normal hearing adults.

Exploring the results in the first study led to the decision to measure the AC hearing thresholds as part of the main test procedure. The AC thresholds would help in identifying specific trends in the hearing thresholds of the participants. Furthermore, it would identify the presence of air-bone gaps at the frequencies tested. It would allow the evaluation of the discrepancy between the AC and BC thresholds. The results with the AC will be outlined first, leading to the results with the B71s and finally the results of the hearing thresholds with the BESTs. The relation between the transducers will be explored to investigate the differences between the thresholds from the two transducer types.

Statistical analysis for each study used repeated measures ANOVA as the results were normally distributed based on the results of Kolmogrov-Smirnov test and through visual inspection of the histograms for each test session and transducer in each experiment. Whereas the comparison between the studies will use independent analysis as the results were collected from different participants.

The hearing thresholds are expected to be around 0 dB HL because the four studies followed the recommended procedures to measure the hearing thresholds. The calibration of the audiometers and transducers ensured that the same guidelines were followed in the four experiments. Furthermore, rigorous calibrations between the sessions were performed.

Table 3.8 The mean threshold (dB HL) for each transducer used across the frequency range 250 - 4000 Hz for each study (Experiment 1-4 are indicated by E1-4).

	Frequency (Hz)					
Experiment	**250**	**500**	**1000**	**2000**	**3000**	**4000**
E2_AC		2.3	3.0	3.0*	1.7	–0.8
E3_AC	8.4*	3.9*	3.4*	5.4*	5.4*	2.0
E4_AC	2.6	0.8	1.0	3.3	4.0	–1.1
E1_B71_A	–1.4	3.7	–3.1*	3.1	3.9	3.4
E3_B71_A	1.5	–1.8	–0.5	0.2	3.2	3.6
E2_B71_B		2.5	1.5	6.4*	2.6	–2.9
E3_B71_B	–2.9	0.0	–0.7	3.9	4.3	–1.2
E4_B71_C	2.9	1.0	6.0	2.1	1.0	1.8
E4_B71_D	1.3	0.8	6.0	3.4	0.7	1.4
E1_BEST	–0.4	–3.4	–1.2	6.0*	5.5*	–2.2
E2_BEST		–5.8*	0.8	6.3*	4.9*	–2.0
E3_BEST	2.0	–3.7	–1.2	7.2*	6.0*	–0.3
E1_ $BEST_{LFR1}$	1.2	–3.2	–0.8	6.3*	7.4*	–3.8
E3_ $BEST_{LFR1}$	3.2	–3.6	0.3	7.0*	5.9*	–1.6
E4_ $BEST_{LFR1}$	2.0	–2.3	4.9	7.5*	2.8	–4.7*
E1_ $BEST_{LFR2}$	2.4	–1.6	0.4	9.1*	8.0*	–4.0
E4_ $BEST_{LFR2}$	1.8	–2.0	6.5*	5.1	3.7	–3.3

***** The thresholds were significantly different than 0 dB HL (p<0.002 adjusted for Bonferroni correction)

The mean thresholds (dB HL) for each transducer used are shown in Table 3.8, highlighted in yellow are the thresholds > ±5 dB HL. It can be observed from the table that the highest thresholds (worse) were mainly observed at 2000 Hz with the BESTs (regardless of the type) even after the correction was applied from the second artificial mastoid. A preliminary outcome would hint that the RETFLs are not appropriate with the BESTs at this frequency. The standard deviation of the mean reported in the table ranged between 4 to 9 dB with the majority of the results ranging below 5 dB. The four experiments are labelled from E1-4 based on the time the study took place with E1 being the first study and E4 being the last.

3.4.2.1 Repeatability

The test-retest hearing thresholds were obtained for each participant by calculating the difference between the first and second session for the two test conditions (AC and BC) and for the different BC transducers (bias). The mean and standard deviation of the differences for all the test frequencies and the transducers are displayed in Table 3.9. The averaged differences for the AC thresholds showed a smaller standard deviation of the difference for the second experiment. The results with the AC and BC with the two main types of transducers showed similar trends for the means and standard deviations. The results were similar to the test-retest hearing threshold differences reported by Stuart et al (1991) who measured the AC hearing thresholds in adults using insert earphones (ER 3A).

The average differences of the hearing thresholds between the two test sessions were less than ±2 dB across the different studies and transducer types. The majority of the mean differences clustered around zero indicating good repeatability (Table 3.9). In clinical testing of hearing thresholds, a difference of ±5 dB between sessions is considered to be acceptable. Therefore, the current results indicate consensus. Good agreement was also seen when measuring the absolute differences between the test- retest sessions in Table 3.9. The average differences between the absolute test- retest were less than 5 dB. These results were in line with the results of the test-retest acceptable by the BSA recommended procedures (Audiology, 2004; Swanepoel & Biagio, 2011).

Furthermore, to evaluate the quality of the thresholds for each participant in the two test sessions the ICC was calculated for each test frequency in four experiments for the different types of transducers. The precision was also evaluated by calculating the measurement error. The repeatability shows the degree to which the values cluster around the mean of the distribution of values which was calculated by the method described in Section 3.4.1.7 (Hanneman, 2008). Furthermore, repeated measures ANOVA were calculated to evaluate the statistical significance of the differences in the two test sessions and to check the results of the precision (Appendix E shows the tables for the four experiments).

Examining the AC thresholds showed that the manual method in experiment two resulted in smaller values for the precision compared to the automated method. However, the results for all of the measurements were lower than 4 dB which indicated good stability between the test and retest values. The measurement of the repeatability coefficient ranged between 6-11 dB which means that a true test-retest score would be around this range, with a 95% confidence interval which is larger than the expected test-retest repeatability of ±5 dB.

A second observation was related to the measurements of ICC which was >0.5 for all of the experiments and across the test frequencies. This indicates a medium to good test-retest repeatability. The ICC scores and range of the confidence intervals were distributed in a similar manner for the three experiments. The ICC calculates the F score for repeated measured ANOVA which compares the difference in the means between the test-retest sessions. None of the comparisons was significant which proves that measuring the thresholds in two sessions had no influence on the hearing thresholds.

A similar observation was seen in the four experiments evaluating the BC thresholds through the manual (E1 &E2) and the automated methods (E3 &E4). The precision scores were slightly lower in the manual method compared to the automated method. However, the majority of the scores were lower than 5 dB. The repeatability scores were about ±10 dB for all of the frequencies, which indicates that a true value for 95% of the population would be within this value.

The ICC scores were comparable to the scores achieved with the AC thresholds indicating a good test-rest repeatability, the ICC scores were >0.7 for the majority of the frequencies. Repeated measures ANOVA conducted to evaluate the test-retest thresholds in the two test sessions was not significant in any of the investigations.

Table 3.9 Test-retest audiometric threshold mean differences and absolute differences (dB)

	Frequency (Hz)		AC			B71A		B71 B		B71C	B71D	BEST			BEST LFR1			BEST LFR2	
			E2	E3	E4	E1	E3	E2	E3	E4	E4	E1	E2	E3	E1	E3	E4	E1	E4
Differences	250	M		–1.1	–0.5	–3.0	–0.1		0.2	–1.2	–1.4	–0.4		–0.2	0.4	0.9	–1.3	–1.6	–1.9
		SD		4.8	5.5	4.8	4.7		5.4	7.8	6.9	4.4		5.8	4.4	6.7	8.1	5.2	4.7
	500	M	–1.3	–1.9	–0.2	–0.3	0.9	0.2	–0.5	–1.3	–0.2	0.3	–0.8	–1.4	0.4	–0.6	0.8	0.6	–1.5
		SD	2.5	4.2	3.8	6.7	7.4	5.4	6.4	8.0	5.3	4.2	6.0	7.0	3.7	6.9	5.1	5.6	6.4
	1000	M	–1.2	–0.2	0.8	–0.3	–0.2	0.0	–0.6	1.2	–2.2	3.0	0.1	–0.5	0.7	0.7	–1.6	1.2	0.8
		SD	3.5	3.6	4.9	4.0	4.2	4.7	6.9	7.6	6.9	4.2	6.6	6.0	3.8	5.0	6.9	4.5	7.4
	2000	M	–0.6	0.2	0.8	–0.2	–0.5	–0.5	–1.5	–0.4	–1.0	0.7	–0.3	0.6	–0.1	0.8	0.0	–1.8	–1.4
		SD	2.8	5.5	5.8	5.6	5.4	5.4	7.2	6.7	4.6	4.0	5.3	8.4	3.7	6.1	5.3	5.9	7.1
	3000	M	–0.9	0.6	0.4	–1.0	–0.5	–1.6	–0.3	–0.8	–1.8	–0.8	0.0	–1.7	0.6	0.9	–0.8	0.4	0.0
		SD	3.4	5.9	4.1	3.9	5.0	4.2	4.6	7.2	4.9	3.4	3.7	7.9	4.3	5.4	5.7	3.7	5.8
	4000	M	–0.8	–0.2	0.7	–0.2	–0.6	–0.1	–1.3	–0.4	1.3	–0.2	0.5	0.1	–0.2	–0.7	0.5	–1.2	–0.4
		SD	2.8	5.8	5.5	3.3	5.7	6.8	5.4	5.6	6.3	4.2	5.0	4.9	5.3	4.8	4.3	5.0	5.4
Absolute Differences	250	M		3.4	4.4	4.7	3.6		4.5	5.5	5.0	2.9		4.9	3.6	4.8	5.8	4.2	3.9
		SD		3.5	3.3	3.0	2.9		2.9	5.6	5.3	3.3		3.1	2.5	4.7	5.8	3.1	3.1
	500	M	2.7	3.4	3.0	4.8	5.6	4.0	4.7	6.1	4.2	3.1	4.8	4.8	2.6	5.2	3.2	4.0	4.5
		SD	1.9	3.1	2.3	4.5	4.9	3.6	4.2	5.1	3.2	3.9	3.5	5.2	2.6	4.4	4.3	3.8	5.1
	1000	M	3.5	2.8	4.0	2.9	3.4	3.8	5.3	5.7	5.5	3.8	5.0	4.3	2.7	3.8	5.2	4.1	5.6
		SD	2.6	2.2	2.8	2.7	2.4	2.7	4.4	5.6	4.2	3.4	4.1	4.1	2.7	3.4	5.1	2.1	4.4
	2000	M	2.7	3.1	4.0	4.4	4.2	4.7	5.2	5.1	3.5	3.1	4.0	5.9	3.0	4.1	4.5	4.2	5.1
		SD	1.8	4.5	4.2	3.3	3.3	2.4	5.0	3.5	3.3	2.5	3.4	5.9	2.1	4.5	2.8	4.4	4.7
	3000	M	2.8	3.6	3.4	2.8	3.5	3.7	3.1	5.1	3.6	2.9	3.1	5.3	3.5	3.2	4.5	2.8	4.4
		SD	3.0	4.6	2.3	2.8	3.5	2.4	3.3	5.0	4.1	2.0	2.0	6.1	2.5	4.4	3.4	2.3	3.9
	4000	M	2.7	3.6	3.6	2.5	4.1	4.7	4.1	4.0	4.6	3.0	3.8	3.7	4.3	3.9	3.4	4.0	3.5
		SD	2.1	4.5	4.2	2.1	3.9	4.8	3.4	3.1	4.8	2.9	3.2	3.2	2.9	2.8	2.7	3.0	4.3
	M: Mean (dB)			SD: Standard deviation (dB)						E1–4: Experiment 1 to 4									

The current results indicate that the test session did not influence the hearing thresholds and spread of the results was similar in the four experiments. The typical error measured with the AC was lower than the BC transducers. Nonetheless, the typical error did not exceed 5 dB. The thresholds measured using the BESTs did follow the same trend of the B71s in the two test sessions.

3.4.2.2 Hearing thresholds: air conduction

Air conduction hearing thresholds were tested in last three experiments where the measurement of the hearing thresholds were conducted through insert earphones (ER 3A and 5A). Figure 3.13 plots the mean hearing thresholds obtained from the last three studies. The hearing thresholds from the three studies showed the same pattern of responses. One study (E3) showed a higher threshold average at 250 Hz with an average mean of 8.4 dB. This experiment was conducted in the same method and transducer used in experiment 4.

The hearing thresholds were normally distributed according to the Kolmonogrov-Simernov test and visually inspected with the histograms. A one way ANOVA was conducted to evaluate the overall influence of different experiments and the change of frequency on the hearing thresholds. Significant effects were obtained for the experiment ($F_{2,\ 417}$= 15.15, p <0.001) and the frequency ($F_{5,\ 417}$= 7.84, p <0.001) but not for their interaction ($F_{9,\ 417}$= 1.17, p =0.32). The overall influence of the experiment with the averaged frequencies showed that E3 was significantly different than E2 and E4 with a mean difference of 2.9 and 3.0 dB, respectively.

Multiple comparisons were performed using one way ANOVA because the experiment and frequency factors had more than two conditions. The effect of measuring the hearing thresholds in the three experiments was not significant at the test frequencies 500 – 4000 Hz. The Levenes statistic for the homogeneity of variances was not significant for any of the frequencies which indicate that the variances were equal.

At 250 Hz only E3 and E4 were evaluated because this frequency was not part of the main investigation in E2. All the results are tabulated in

Table 3.10 where the only significant difference between the experiments was observed at 250 Hz.

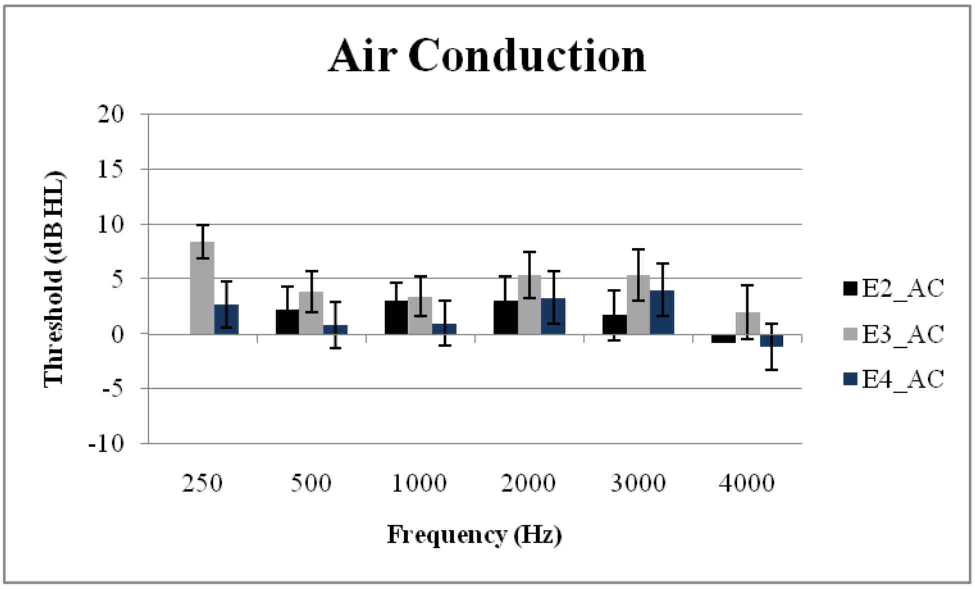

Figure 3.13 The average hearing threshold in AC across three studies (error bars show 95 % confidence intervals), 250 Hz was not tested in E2.

The thresholds were further compared for each frequency between the three experiments and the results indicated that the thresholds were similar and not statistically significant. This indicates that the method for collecting the thresholds did not influence the results and that the participants had similar results. These results also indicate that the hearing thresholds for the three experiments could be pooled.

Repeated measures ANOVA were conducted to evaluate the influence of the change in frequency on the hearing thresholds. The thresholds were found to be significantly different when tested at different frequencies ($F_{5,\ 265}$ =11.75, p<0.001) based on Greenhouse-Geisser because the sphericity was not assumed (x^2 (14) = 0.58 p= 0.02). Post hoc investigation for the change in the frequency was evaluated for each experiment individually through repeated measures ANOVA. E2 showed that the thresholds measured at 4000 Hz were statistically different than 500, 1000 and 2000 Hz with a difference of 3.1, 3.9 and 3.9 dB, respectively. A similar trend was observed with E4 with the thresholds at 4000 Hz differing than 2000 and 3000 Hz by 4.5 and 5.1 dB, respectively. The average high threshold of 8.4 dB in E3 at 250 Hz was statistically different than the majority of the frequencies with the exception of 3000 Hz.

Table 3.10 Results of one way ANOVA for the AC thresholds across the three studies.

Frequency (Hz)	Levene statistic	Sum of squares	Mean square	$F_{(df)}$	Probability (p)
250	0.78, p= 0.38	441.5	441.5	$F_{1,52}$= 22.26	<0.001*
500	0.91, p= 0.41	123.6	61.7	$F_{2,73}$= 2.72	0.07
1000	0.33, p= 0.72	87.6	43.4	$F_{2,73}$= 1.92	0.16
2000	2.27, p= 011	88.8	44.4	$F_{2,73}$= 1.66	0.2
3000	0.49, p= 0.62	171.5	85.8	$F_{2,73}$= 2.60	0.08
4000	2.31, p= 011	166.2	83.1	$F_{2,73}$= 2.56	0.08

* Experiment E3 &E4 resulted in thresholds that were significantly different.

The averaged thresholds for all of the experiments are tabulated in Table 3.20. The thresholds at 250 Hz were significantly different from 500, 1000 and 4000 Hz with a difference of 3.4, 3.3 and 5.6 dB respectively. Furthermore, at 4000 Hz significantly differed than that of 2000 and 3000 Hz with a difference of –3.8 and –3.6 dB, respectively. It is observed that E3 showed statistical significance when compared to 0 dB HL at all of the frequencies with the exception of 4000 Hz. However, only three frequencies resulted in averaged thresholds above 5 dB which was observed at 250, 2000 and 3000 Hz with average thresholds of 8.4, 5.4 and 5.4 dB, respectively.

3.4.2.3 Hearing thresholds: B71

Four different B71 were used in the four studies. The four transducers are labelled by the letters A-D. The B71C and B71D used in the fourth study were not used in any of the previous studies. However, the B71A and B71B were used in E1 and E2, respectively. The third experiment (E3) measured the thresholds using the same transducers used in E1 and E2 to verify the results.

The mean thresholds for each experiment are tabulated in Table 3.8. It is observed that E4 produced the highest thresholds at 1000 Hz compared to the rest of the studies (6 dB produced by the two transducers). It was also observed that B71B produced an average threshold of 6.4 dB at 2000 Hz in E2 which was different than the average results of the same transducer used in E3 (3.9 dB).

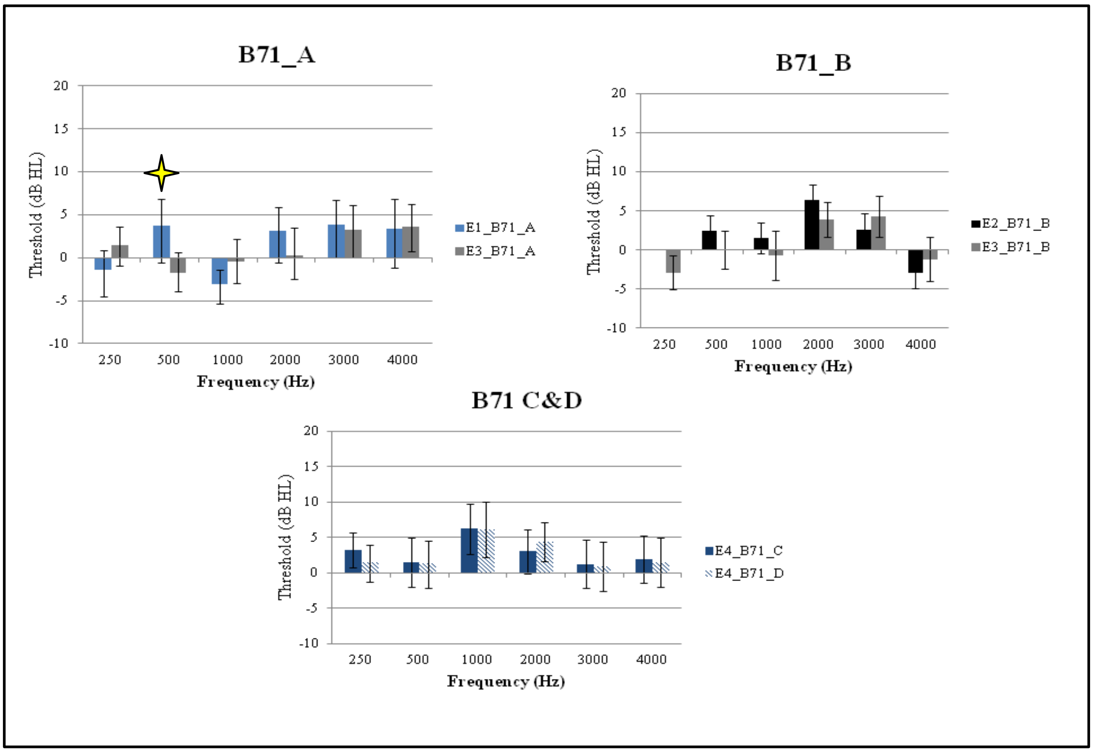

Figure 3.14 BC hearing thresholds with the B71s across the different studies, error bars indicate 95% confidence intervals. The yellow star indicates a significant difference.

The hearing thresholds with the B71 are plotted in Figure 3.14. This figure plots the same version of the transducer used in different experiments with the exception of E4 that used two different versions which were not repeated in other studies. The general trend was that the same version of B71 produced thresholds that were within 3 dB of each other for most of the frequencies. However, comparison of the thresholds between the different versions showed different trends at some of the frequencies. Thresholds measured at 4000 Hz using B71B, for example, were consistently lower than the thresholds measured with the different versions of the B71 even when the thresholds were tested in the same group of participants (E3).

Unrelated ANOVA was conducted for each version of transducer. The threshold difference of 5.4 dB at 500 Hz between E1 and E3 using the B71A was statistically significant ($F_{1, 48}$= 8.35, p=0.006) where Levene statistic was assumed (p= 0.92). The thresholds measured by B71B in E2 and E3 were similar at each frequency measured with no statistical significance observed. Similarly, the thresholds measured in E4 using B71C and B71D were similar (Table 3.11).

Table 3.11 Comparison between each version of the B71 between the experiments.

Frequency	Transducer	Sum of squares	$F_{(df)}$	Probability (p)
250 Hz	**B71A (E1&E2)**	103.8	$F_{1,46}$=3.56	0.060
	B71B (E2& E3)			
	B71 C&D (E4)	30.1	$F_{1,46}$= 0.83	0.370
500 Hz	**B71A (E1&E2)**	360.8	$F_{1,48}$=8.45	0.006*
	B71B (E2& E3)	77.3	$F_{1,50}$=1.62	0.210
	B71 C&D (E4)	0.5	$F_{1,46}$=0.01	0.930
1000 Hz	**B71A (E1&E2)**	79.1	$F_{1,48}$=2.18	0.150
	B71B (E2& E3)	60.1	$F_{1,50}$=1.03	0.310
	B71 C&D (E4)	0.0	$F_{1,46}$=0.00	1.000
2000 Hz	**B71A (E1&E2)**	101.7	$F_{1,48}$=1.70	0.190
	B71B (E2& E3)	77.9	$F_{1,50}$=2.01	0.160
	B71 C&D (E4)	19.4	$F_{1,46}$=0.40	0.530
3000 Hz	**B71A (E1&E2)**	5.3	$F_{1,48}$=0.10	0.750
	B71B (E2& E3)	36.4	$F_{1,50}$=0.75	0.390
	B71 C&D (E4)	0.8	$F_{1,46}$=0.01	0.910
4000 Hz	**B71A (E1&E2)**	0.5	$F_{1,48}$=0.01	0.920
	B71B (E2& E3)	39.6	$F_{1,50}$=0.74	0.390
	B71 C&D (E4)	1.5	$F_{1,46}$=0.02	0.880

One way ANOVA was conducted to evaluate two factors, the influence of the experiment and the transducer on the hearing thresholds (Table 3.12). The results indicate that at 250, 1000 and 4000 Hz, the thresholds were significantly different between the different experiments and between the different transducers. The homogeneity of the variance was assumed for the majority of the frequencies with exception at 1000 Hz.

Post hoc tests were conducted to evaluate the significance between the different versions of the transducers where the significance was corrected to Bonferrni due to multiple comparisons. This means that the thresholds evaluated by the same version of transducer in two excitements were averaged. The results reported earlier showed that this was feasible because there was no significant difference in the thresholds measured by the same version. At 250 Hz an average difference of –5.8 dB between B71B and B71C was significant p= 0.002. As the variance was not similar at 1000 Hz, post hoc examination adjusted to Dunnett T3 showed that a difference of –7.5 dB between B71A and B71C was statistically significant p= 0.003. Similarly, a difference of –7.5 dB between B71A and B71D was statistically significant p=0.006.

A marginal statistical significance was observed between B71B and B71C, p=0.04 with a difference of –5.7 dB. On the other hand, the observed difference in the average hearing thresholds of 5.4 dB between B71A and B71B was statistically significant p=0.002 at 4000 Hz.

Table 3.12 Results of one way ANOVA for the thresholds measured by the different versions of the B71across the three studies, the displayed results are for the experiment and transducer factors.

Factor	Frequency (Hz)	Levene statistic	Sum of squares	Mean square	$F_{(df)}$	Probability (p)
Experiment	**250**	0.42, p= 0.65	274.3	137.2	$F_{2,122}$= 3.96	0.02**
	500	0.89, p= 0.44	401.3	133.8	$F_{3,146}$= 2.59	0.06
	1000	5.71, p= 0.001*	1646.4	548.8	$F_{3,146}$= 9.65	p< 0.001**
	2000	0.24, p= 0.87	305.9	101.9	$F_{3,146}$= 2.01	0.11
	3000	0.83, p= 0.48	260.9	86.9	$F_{3,146}$= 1.61	0.19
	4000	0.35, p= 0.79	478.2	159.4	$F_{3,146}$ = 2.78	0.04**
Transducer	**250**	0.15, p= 0.93	493.2	164.4	$F_{3,125}$ = 4.95	0.003***
	500	0.36, p=0.78	11.4	3.8	$F_{3,146}$ = 0.07	0.98
	1000	3.73, p= 0.01*	1707.9	502.6	$F_{3,146}$ = 8.69	P<0.001***
	2000	0.61, p=0.61	347.2	115.7	$F_{3,146}$ = 2.35	0.07
	3000	0.67, p=0.57	238.3	79.4	$F_{3,146}$ = 1.47	0.34
	4000	0.53, p=0.66	785.1	261.7	$F_{3,146}$ = 4.75	0.003***

*** Levene statistic was significant indicating the variance was not equal**
****The thresholds were significantly different between experiments**
***** The thresholds were significantly different bwithdifferent versions of B71**

Post hoc examination was conducted to evaluate the significant findings between the experiments. At 250 Hz, E4 was significantly different than E1 and E3 with a mean difference of 3.5 and 2.7 dB, respectively (p=0.02 for the two experiments). At 1000 Hz, thresholds measured in E1 were significantly different than E2 and E4 with a mean difference of –4.5 and –9 dB, respectively, with E1 having lower thresholds (p= 0.04 and <0.001). Furthermore, thresholds measured in E3 were significantly different (p=0.001) than E4 with a mean difference of –6.5 dB E3 having lower thresholds. At 4000 Hz, the difference in the hearing thresholds between E1 and E2 of 6 dB was marginally significant (p=0.04).

The results presented here indicated that the hearing thresholds were similar with the same version of the B71 across the different experiments. This trend was observed at the majority of the frequencies. Extending the comparison between the different versions of the B71 showed that the hearing thresholds measured at 500, 2000, and 3000 Hz were similar across the different transducer versions and across the different experiments. Whereas the hearing thresholds measured at 250, 1000 and 4000 Hz with different versions of B71 showed statistical significance. Further comparisons showed that the majority of the differences were observed with B71B at these three frequencies.

This indicated that the differences in the hearing thresholds could have been due to an error of the transducer itself rather than the methodology for data collection. The results in the different studies were carried out by different audiologists and different methodology (automated and manual). Re-analysis of the data was carried out while removing the hearing thresholds results, measured with B71B, to check whether the apparent significance persisted. Table 3.13 displays the results of one way ANOVA.

Table 3.13 Results of one way ANOVA for the thresholds measured by the different versions of the B71across the three studies (excluding B71B), the displayed results are for the experiment and transducer factors.

Factor	Frequency (Hz)	Levene statistic	Sum of squares	Mean square	$F_{(df)}$	Probability (p)
Experiment	250	0.34, p= 0.72	180.1	90	$F_{2,95}$= 2.76	0.07
	500	1.09, p= 0.34	366.1	183	$F_{2,95}$= 3.41	0.04**
	1000	8.82, p< 0.001*	1460.3	730.1	$F_{2,95}$= 12.42	p< 0.001**
	2000	1.28, p= 0.28	147.2	73.6	$F_{2,95}$= 1.37	0.26
	3000	1.05, p= 0.3	175.4	87.7	$F_{2,95}$= 1.53	0.22
	4000	0.67, p= 0.51	94.2	47.1	$F_{2,95}$= 0.84	0.44
Transducer	250	0.22, p= 0.80	106.3	53.2	$F_{2,95}$= 1.59	0.21
	500	0.34, p=0.72	5.8	2.9	$F_{2,95}$= 0.05	0.95
	1000	5.79, p= 0.004*	1381.2	690.6	$F_{2,95}$=11.97	p< 0.001***
	2000	0.49, p=0.61	64.8	32.4	$F_{2,95}$= 0.59	0.55
	3000	0.83, p=0.44	170.9	85.5	$F_{2,95}$=1.49	0.23
	4000	0.70, p=0.49	95.2	47.6	$F_{2,95}$=0.85	0.43

*** Levene statistic was significant indicating the variance was not equal**
****The thresholds were significantly different between experiments**
***** The thresholds were significantly different between the different versions of B71**

The hearing thresholds measured at 250 and 4000 Hz were not significant, while the significance at 1000 Hz was unchanged. It is evident from the current results that the B71B was the main contributor to the significant results with the experiment and transducer observed in the previous analysis. The current results indicated that the only statistical significance remained at 1000 Hz which indicated a real difference between the thresholds between the experiments and transducers.

Based on the findings of this section with the B71 it was decided to carry the comparison between the transducers with the BEST while removing the B71B as it resulted in variation in the thresholds that could not be accounted for. The calibration was conducted in the same manner for the studies. The analysis indicated that for the rest of the frequencies the average thresholds were similar, indicating that the results can be pooled for the main comparison between the transducer (B71 vs. BEST).

3.4.2.4 Hearing thresholds: BEST

Three versions of the BESTs were used in four experiments measuring the hearing thresholds in the normal hearing sample. The hearing thresholds with the BESTs are displayed in Figure 3.15. It is observed that the BESTs in general produced the same trend for hearing thresholds regardless of the version used in the frequency range tested at 250- 4000 Hz. It can be seen from this graph that there was a worsening in thresholds at 2000 and 3000 Hz that was larger than 5 dB in the four studies. At 500 and 4000 Hz, the thresholds were always negative in the four studies.

To investigate the influence of the different versions of the BESTs on the hearing thresholds, one way ANOVA was conducted with two factors, the experiment and the transducer (Table 3.14). Only at 1000 Hz were thresholds significantly different in the two factors. Post hoc examination of the different transducers was conducted by averaging the results of the same versions of the BESTs in the different experiments. The $BEST_{original}$ produced hearing thresholds that were lower than the $BEST_{LFR2}$ with a difference of –4.2 (p=0.005). The two $BEST_{LFR}$s produced similar thresholds that were statistically not significant.

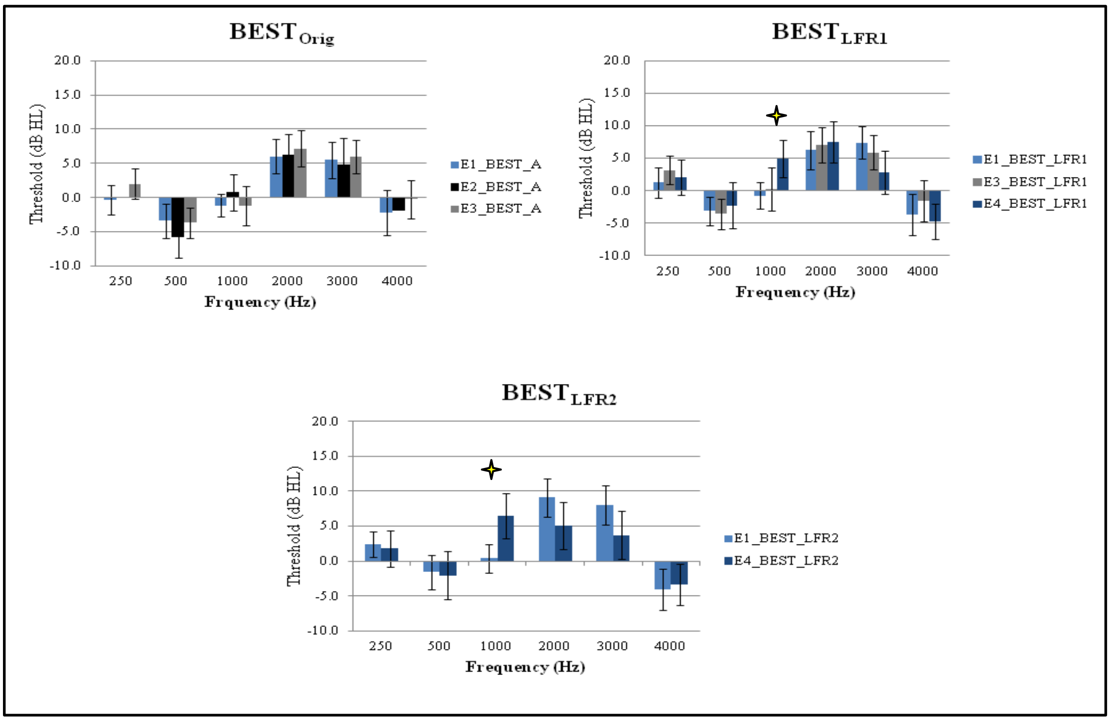

Figure 3.15 BC hearing thresholds with the BESTs across the different studies, error bars indicate 95% confidence intervals. The star indicates a statistical significance.

Table 3.14 Results of one way ANOVA for the thresholds measured by the different versions of the BEST's across the three studies, the displayed results are for the experiment and transducer factors.

Factor	Frequency (Hz)	Levene statistic	Sum of squares	Mean square	$F_{(df)}$	Probability (p)
Experiment	**250**	1.55, p= 0.22	77.7	33.9	$F_{2,165}$= 1.08	0.34
	500	2.63, p= 0.05	231.2	77.1	$F_{3,186}$= 1.85	0.14
	1000	6.06, p= 0.001*	1314.3	438	$F_{3,186}$= 9.68	p< 0.001**
	2000	1.01, p= 0.39	39.6	9.9	$F_{3,186}$= 0.21	0.89
	3000	2.05, p= 0.11	387.4	129.1	$F_{3,186}$= 2.80	0.04
	4000	0.86, p= 0.46	302.9	100.9	$F_{3,186}$= 1.68	0.37
Transducer	**250**	1.25, p= 0.29	47.6	23.8	$F_{2,126}$ = 0.76	0.47
	500	0.22, p=0.80	165.9	82.9	$F_{2,187}$ = 1.98	0.14
	1000	0.97, p= 0.38	509.7	354.8	$F_{2,187}$ = 5.17	P= 0.007***
	2000	0.64, p=0.53	5.9	2.9	$F_{2,187}$ = 0.06	0.94
	3000	0.67, p=0.51	4.5	2.2	$F_{2,187}$ = 0.05	0.96
	4000	0.23, p=0.80	191.7	95.9	$F_{2,187}$ = 1.76	0.18

***   Levene statistic was significant indicating the variance was not equal**

****   The thresholds were significantly different between experiments**

***** The thresholds were significantly different between the different versions of BESTs**

Post hoc comparisons of the experiment was conducted by averaging the thresholds obtained by the different versions of the BEST used in each experiment. The results showed that E1, E2 and E3 produced thresholds that were similar and not statistically significant. One the other hand, the thresholds measured in E4 using two BEST_$_{LFR's}$ were significantly different than E1, E2 and E3. A difference in the average hearing thresholds of 6.2 dB between E4 and E1 was significant at p<0.001. The thresholds were significantly different than E2 (p=0.03) with a mean difference of 4.5 dB. The threshold difference between E4 and E3 was 6.1 dB (0<0.001).

Table 3.15 Comparison between each version of the BEST between the experiments.

Frequency	Transducer	Sum of squares	Mean square	$F_{(df)}$	Probability (p)
250 Hz	**BEST_original (E1, E2, E3)**	67.7	67.7	$F_{1,48}=2.23$	0.14
	BEST$_{LFR1}$(E1, E3,E4)	47.2	23.6	$F_{2,71}=0.68$	0.51
	BEST$_{LFR2}$ (E1,E4)	4.0	4.0	$F_{1,42}=0.15$	0.70
500 Hz	**BEST_original (E1, E2, E3)**	79.4	39.7	$F_{2,69}=1.09$	0.34
	BEST$_{LFR1}$(E1, E3,E4)	23.3	11.7	$F_{2,71}=0.26$	0.77
	BEST$_{LFR2}$ (E1,E4)	2.1	2.1	$F_{1,42}=0.04$	0.84
1000 Hz	**BEST_original (E1, E2, E3)**	57.1	28.6	$F_{2,69}=0.69$	0.50
	BEST$_{LFR1}$(E1, E3,E4)	427.1	213.5	$F_{2,71}=3.96$	0.02*
	BEST$_{LFR2}$ (E1,E4)	406.5	406.5	$F_{1,42}=10.2$	0.003*
2000 Hz	**BEST_original (E1, E2, E3)**	17.8	8.9	$F_{2,69}=0.22$	0.80
	BEST$_{LFR1}$(E1, E3,E4)	17.1	8.5	$F_{2,71}=0.17$	0.84
	BEST$_{LFR2}$ (E1,E4)	181.4	181.4	$F_{1,42}=3.49$	0.07
3000 Hz	**BEST_original (E1, E2, E3)**	16.4	8.2	$F_{2,69}=0.19$	0.82
	BEST$_{LFR1}$(E1, E3,E4)	246.3	123.2	$F_{2,71}=2.55$	0.09
	BEST$_{LFR2}$ (E1,E4)	201.3	201.3	$F_{1,42}=3.84$	0.06
4000 Hz	**BEST_original (E1, E2, E3)**	57.3	28.6	$F_{2,69}=0.48$	0.62
	BEST$_{LFR1}$(E1, E3,E4)	138.9	69.5	$F_{2,71}=1.25$	0.29
	BEST$_{LFR2}$ (E1,E4)	5.5	5.5	$F_{1,42}=0.12$	0.73

The results indicated that the three versions of the BESTs were similar across the frequency range 250-4000 Hz. The only discrepancy to this finding was observed at 1000 Hz (Table 3.15). The transducer and the experiment resulted in different hearing thresholds that were mainly due to the hearing thresholds produced in E4 that were worse compared to the other studies. Similar to the results obtained with the B71's this indicated that the results could be pooled.

3.4.2.5 Difference between transducers B71 and BEST

The hearing thresholds were pooled to conduct the main evaluation between the transducers, the mean and standard deviations are tabulated in Table 3.21 in the last two rows. Comparison between the B71 and BESTs was conducted by exploring the differences between the B71 and BESTs (Table 3.16). A positive value indicates that the B71 was higher in thresholds compared to the BESTs (worse hearing thresholds). On the other hand, a negative value indicates that the B71 was lower in threshold when compared to the BESTs (better hearing thresholds).

The results of the relative differences are plotted in Figure 3.16 based on the type of the BESTs. The general trend in the two graphs is similar, indicating that the BEST in its original form and $BEST_{LFR}$ produced the same thresholds and thus similar differences with the B71 transducers were observed. The results are displayed for each version of the B71 compared with the version of the BEST used in the same experiment. The comparison with the B71B is displayed in the grey rows for information purposes and was not used in the statistical analysis (See Section 3.4.3.2).

Table 3.16 The difference between the B71 and BEST across the different studies in dB. Results highlighted in yellow are the differences > ±5 dB, rows highlighted in grey are for the B71B that was removed from the main comparison between the transducers.

Transducer	250	500	1000	2000	3000	4000 Hz
E1_B71A-BEST	–1.1	7.1	–1.9	–2.9	–1.6	5.6
E1_B71A-$BEST_{LFR1}$	–2.7	6.9	–2.3	–3.1	–3.5	7.2
E3_B71A-$BEST_{LFR1}$	–1.7	1.8	–0.7	–6.7	–2.6	5.2
E1_B71A-$BEST_{LFR2}$	–3.8	5.3	–3.4	–6.0	–4.1	7.5
E3_B71A-BEST	–0.5	1.9	0.7	–6.9	–2.8	3.9
E2_B71B-BEST	0.0	8.3	0.7	0.1	–2.2	–1.0
E3_B71B_BEST	–4.9	3.7	0.5	–3.3	–1.7	–0.9
E3_B71B_$BEST_{LFR1}$	–6.1	3.6	–0.9	–3.1	–1.5	0.4
E4_B71C-$BEST_{LFR1}$	0.9	3.3	1.1	–5.4	–1.8	6.5
E4_B71C-$BEST_{LFR2}$	1.1	3.0	–0.5	–2.9	–2.7	5.1
E4_B71D-$BEST_{LFR1}$	–0.7	3.0	1.1	–4.1	–2.1	6.1
E4_B71D-$BEST_{LFR2}$	–0.5	2.8	–0.5	–1.7	–3.0	4.7
AC _E3-E4	5.8	3.0	2.5	2.1	1.4	3.2
Overall B71- BEST	–0.4	3.8*	1.0	–4.7*	–3.2*	5.2*

* The difference was statistically significant

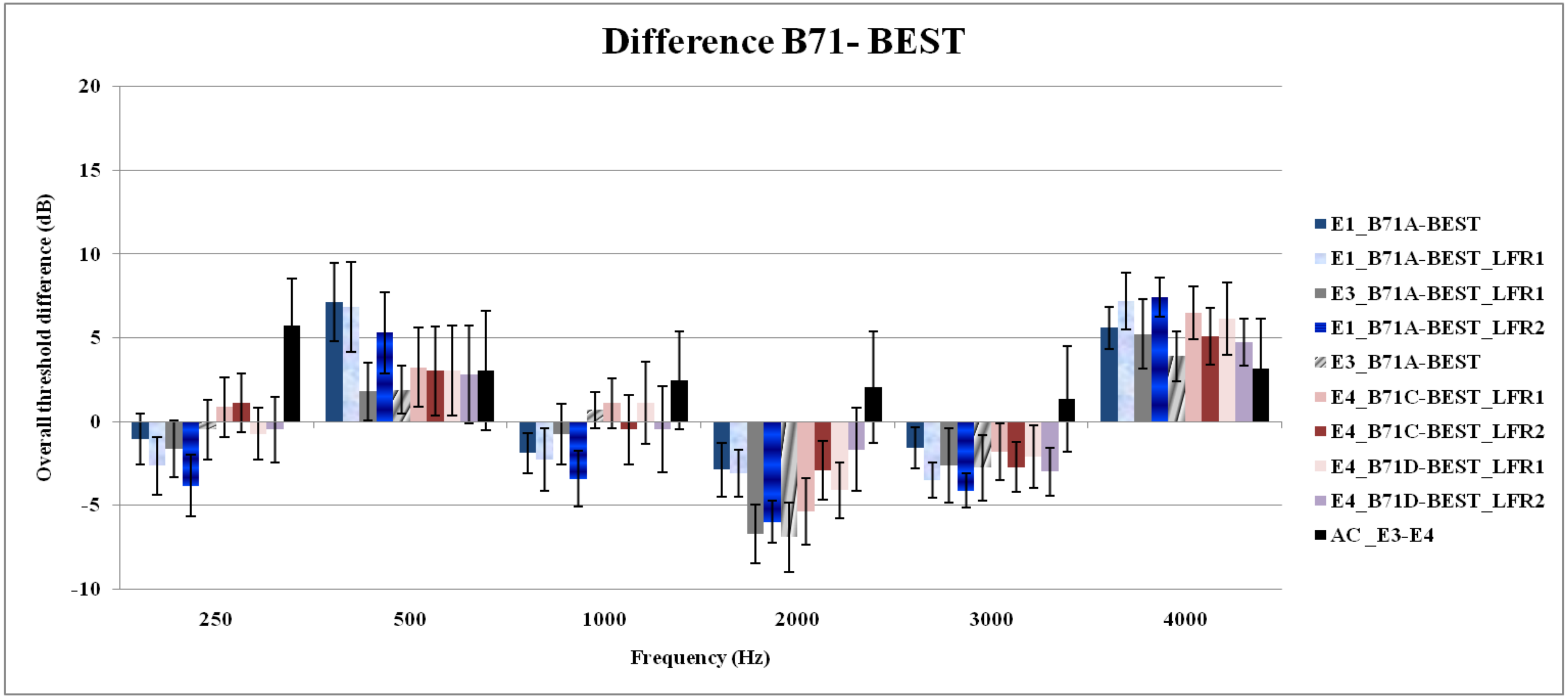

Figure 3.16 Thresholds of the BESTs relative to B71 are plotted for the four experiments. Positive values indicate BEST thresholds were lower than B71 thresholds. Error bars represent 95% confidence interval.

The main observation is that most of the differences between the transducers were lower than ±5 dB, mainly observed at 250, 1000 and 3000 Hz. Another observation, the thresholds measured with the BESTs at 500 and 4000 Hz were consistently lower than the thresholds measured with B71 regardless of the version of the transducer or the experiment, the magnitude of the difference was higher at 4000 Hz. A similar trend was observed but in the opposite direction at 2000 and 3000 Hz where the hearing thresholds measured by the BESTs were consistently higher than the thresholds measured by B71.

Statistical evaluation was conducted using one way ANOVA (Table 3.17) with transducer as the main factor. The results indicate that at 250 Hz and 1000 Hz, the thresholds produced by the BESTs were similar to the B71. However, the differences at the rest of the test frequencies were statistically significant.

Table 3.17 One way ANOVA for the overall influence of transducer on the hearing thresholds.

Factor	Frequency (Hz)	Levene statistic	Sum of squares	$F_{(df)}$	Probability (p)
Transducer	**250**	1.19, p= 0.27	12.4	$F_{1,286}$ = 0.41	0.52
	500	3.33, p=0.07	967	$F_{1,286}$ =20.6	<0.001**
	1000	6.58, p= 0.01*	58.8	$F_{1,286}$ =1.01	0.32
	2000	0.15, p=0.70	1447.9	$F_{1,286}$ =29.7	<0.001**
	3000	1.36, p=0.24	684.7	$F_{1,286}$ =13.4	<0.001**
	4000	0.41, p=0.52	1733.7	$F_{1,286}$ =36.4	<0.001**

*** Levene statistic was significant indicating the variance was not equal**

**** The thresholds were significantly different between the transducers**

The repeatability was evaluated by averaging the results of the B71 and BESTs in E4. Due to the different number of participants in the previous studies and because one of the B71s was removed from E2 and E3, this was the only study that had equal number of transducers and each type of transducer was found to have comparable results which allowed for the thresholds to be averaged.

Table 3.18 shows the results at the frequency range tested. The precision score ranged between 1.9 to 3.9 dB which indicates that the BEST produced thresholds that were comparable to the B71 with similar typical error scores. This degree of precision was comparable to the test-retest values reported in Section 3.4.2.1. The measurement of repeatability which accounts for 95% confidence was 6.1, 7.9 dB at 250 and 1000 Hz.

This result was associated with large ICC >0.9 and non significant ANOVA which indicates that measuring hearing thresholds with the BESTs were close to the B71. However, the results with the rest of the frequencies showed wider confidence limits of the ICC, and larger repeatability scores which indicate that the hearing thresholds measured by the BESTs were not comparable to the thresholds measured with the B71. The ANOVA scores showed that the comparisons were significant. This means that BEST in its current form produce different thresholds compared to the B71.

Table 3.18 Repeatability measures for the averaged results of the B71 and BEST in experiment 4.

Frequency (Hz)	Precision (dB)	Repeatability (dB)	Intraclass correlation				ANOVA	
			ICC	CI		p	F	p
250	2.2	6.1	0.92	0.83	0.97	<0.001	0.08	0.77
500	3.9	12.4	0.83	0.56	0.93	<0.001	7.23	0.01*
1000	2.9	7.9	0.93	0.84	0.97	<0.001	0.14	0.71
2000	1.9	8.7	0.89	0.01	0.97	<0.001	40.95	<0.001*
3000	1.9	7.1	0.94	0.69	0.98	<0.001	19.85	<0.001*
4000	2	12.6	0.82	–0.16	0.96	<0.001	92.13	<0.001*

3.4.2.6 Does the RETFLs require adjustment?

The current RETFLs standard is designed to produce thresholds that should scatter around 0 dB HL. The current results with the two transducers were analysed by comparing the overall means to 0 dB through one sample *t*-test. The significance was adjusted to Bonferroni for multiple comparisons. The results in Table 3.19 show that the hearing thresholds measured by the B71 transducer were above 0 dB HL by a maximum of 2.5 dB. Statistical significant findings were seen at all the frequencies tested above 2000 Hz which indicates that the current RETFL requires adjustment at these frequencies.

The thresholds measured by the BESTs differed than 0 dB by –3.2 to 6.8 dB at the range of frequencies tested. The only frequency that did not show a statistical significance was 1000 Hz, the rest of the threshold differences were statistically significant with the largest difference seen at 2000 Hz. The current results indicated that the current RETFLs should not be used with the BESTs without adjustment.

Table 3.19 One sample *t*-test comparing the average hearing thresholds to 0 dB.

Frequency (Hz)	Transducer	df	t	Probability (p)	Mean difference
250	**B71**	97	2.1	0.04	1.2
	BEST	189	4.3	<0.001*	1.6
500	**B71**	97	0.8	0.4	0.6
	BEST	189	–6.8	<0.001*	–3.2
1000	**B71**	97	2.6	0.01	2.1
	BEST	189	2.3	0.02	1.2
2000	**B71**	97	2.8	0.007*	2.1
	BEST	189	13.8	<0.001*	6.8
3000	**B71**	97	2.9	0.005*	2.2
	BEST	189	10.9	<0.001*	5.5
4000	**B71**	97	3.4	0.001*	2.5
	BEST	189	–4.8	<0.001*	–2.6

* significance level corrected to Bonferroni for multiple comparisons p< 0.008

Hood (1979) pointed that one of the shortcoming in formulating the RETFLs was that the AC hearing thresholds were not take into account. Therefore, the current study measured the AC hearing thresholds as part of the main evaluation. The pooled results for each type of transducer are illustrated in Figure 3.17. It is noted that the BC thresholds measured with the B71 were lower or at the same level of the AC thresholds where with the exception of 4000 Hz, the hearing thresholds were higher than the AC hearing thresholds.

One way ANOVA was conducted to evaluate the trend of the hearing thresholds with the AC and BC (using the B71 transducers). The results showed that the homogeneity of variance was not assumed in most of the frequencies which meant that one of the assumptions of the parametric test was violated. The results were tested with non-parametric analysis using the Kruskal-Wallis test which is equivalent to one way ANOVA.

A difference in hearing thresholds of 4.6 dB was significant at 250 Hz and the results corrected to Bonferroni for multiple comparisons. The rest of the comparisons for the hearing thresholds across the test frequencies of 500-4000 Hz were not significant. This indicated that hearing thresholds for the AC and BC were similar.

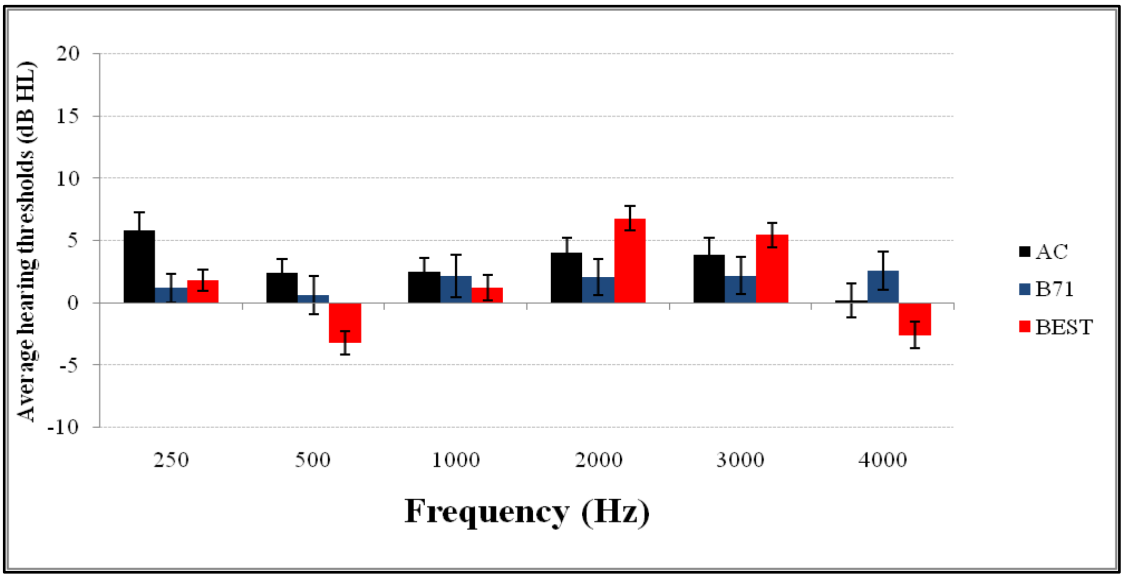

Figure 3.17 Average hearing thresholds for the three main transducers. Error bars show 95% confidence intervals.

The hearing thresholds at 250 Hz were only measured in E3 and E4 therefore post hoc comparison was conducted for each experiment separately to evaluate the significance in finding. Comparing the hearing thresholds through independent sample Kruskal-Wallis test in E3 showed a statistical significant finding $p<0.001$. However, the comparison between the hearing thresholds in E4 were not significant $p=0.79$.

3.4.3 Summary of results

- The measurement of repeatability indicated that the precision of test- retest scores were within 5 dB for all of the measurements (AC and BC). The repeatability coefficient and the ICC scores mimicked those of the precision measurement.
- The AC hearing thresholds were comparable between the different experiments. This indicates that the influence of the change of transducer, tester and method had minimal influence on the hearing thresholds.
- The BC hearing thresholds measured with the B71 transducer were comparable in the studies with the exception of one transducer (B71B) that produced thresholds that were significantly different than the rest of the studies despite rigorous calibration.

- The hearing thresholds measured with the BESTs were comparable in the different studies.
- Comparison between the B71 and BESTs showed that there was a statistical significant difference in the hearing thresholds measured at 4 test frequencies.
- Comparison between the AC and BC hearing thresholds showed a significant difference only at 250 Hz in the third experiment
- The examination of the RETFL showed that it required adjustment at 3 frequencies with the B71 (2000, 3000 and 4000 Hz) and at 5 frequencies with the BEST (all test frequencies except at 1000 Hz). This was based on the results of one way ANOVA.

3.4.4 General discussion

Verification of the transducers was conducted by measuring the hearing thresholds using different versions of the two main transducers (B71 and BEST) across the frequency range between 250 to 4000 Hz in four experiments. The four studies showed a similar trend in the hearing thresholds for each type of BC transducer. Therefore, the hearing thresholds were pooled to conduct the main analysis.

3.4.4.1 Repeatability

The hearing thresholds were measured in two test sessions, separated by a minimum of 24 hours. The measurement of precision showed that on average the test-retest repeatability was within ±5 dB for the absolute differences with a standard deviation averaging around 4 dB for the test frequencies. The results indicated that the thresholds measured in the manual method were slightly lower than the thresholds measured in the automated method. In general 75% of the participants had hearing thresholds within ±5 dB (Appendix F tabulates the distribution of the responses).

The repeatability with AC hearing thresholds showed that 82% of the participants had threshold within ±5 dB while 4% of the participants had thresholds ≥ 10 dB between the two test sessions. The AC threshold repeatability is lower than the results reported by Henry et al, (2001). They measured the hearing thresholds in twenty normal hearing individuals using an automated protocol with insert earphone RE 4B and found that 91.5 % of the repeated hearing thresholds varied within ±5 dB and 98.1% of the repeated thresholds were within ±10 dB. One reason that could explain this discrepancy in the test-retest responses between the present study and Henry et al (2001) could be related to the way the hearing threshold was defined. They defined the threshold as the average of the two minimum responses using 1 dB increments in an ascending manner. The definition of the hearing threshold in the current study was the threshold obtained in 50% of signal presentation in an ascending manner.

The automated and manual methods for data collection were carried out in the different experiments. The change in the test method did not seem to influence the test repeatability in the AC condition. 85% of the participants had their test-retest thresholds within ±5 dB in the manual method compared to 81% in the automated method. The current results are similar to the results reported by Ho et al (2009). They reported that the thresholds measured manually were around 74% compared to 84% with the automated method for AC measurements (ER 5A). The hearing thresholds collected by Ho et al (2009) were evaluated with an automated audiometer (OtogramPTA) and the regular audiometer was used to collect the thresholds manually (16 participants in each group). The BC hearing thresholds showed a repeatability trend that was lower than the AC results, 76% and 73% of the participant had hearing thresholds within ±5 dB between the test and retest sessions for the manual and automated method, respectively, compared to the 64% and 87% of participants who scored within ±5 dB in the manual and automated methods, respectively, measured by Ho et al (2009).

It should be noted that the study of Ho et al (2009) reported the results for groups of patients with different degrees of hearing losses while the present study measured the hearing thresholds in normal hearing participants with no history of hearing loss. The state of hearing loss should not influence the degree of the test-retest scores because differences between an automated method and a manual method in participants with hearing losses were reported to be similar to the test-retest scores by normal hearing participants with AC thresholds (Margolis et al, 2010). Comparison between the results reported by Ho et al (2009) and the current study show that their automated method produced higher test-retest percentage. This could be due to the difference of the device used between the two studies. The small difference could be due the smaller sample size used by Ho et al (2009). Ho et al (2009) concluded that the automated method was similar to the manual method, which was also observed in the results in the current study. This in turn leads to confidence that the variation in the results was not due to the method of threshold measurement.

Margolis et al (2010) reported the test-retest differences using manual audiometry in six normal hearing participants measured by two testers. Their results were used as a control measure of reliability to evaluate the thresholds measured with 25 hearing impaired participants using an automated method. Their results with the AC thresholds (using headphone TDH 49) showed that the reliability (mean absolute difference) with traditional audiometry was between 2.4 to 6.3 dB with the overall mean absolute differences for all the frequencies of 4.1 dB. The results of the absolute difference in the present study ranged between 2.7 to 4.4 dB and the overall mean absolute threshold of 3.3 dB for all of the frequencies.

Thresholds measured with the BC transducers in the current study showed a trend of producing larger test-retest absolute differences compared to the AC thresholds. This was also reported by Margolis et al (2010), their mean absolute differences ranged from 4.6 to 7.6 dB with an overall mean across the test frequencies of 5.8 dB. The results in the present study were lower than those reported by Margolis et al (2010) with a range of 2.5 to 6.1 dB with an overall average of the transducers and frequencies of 4.3 dB. The results reported by Margolis et al (2010) were measured at the forehead whereas the results of the current study were measured by placing the BC transducer on the mastoid bone.

The repeatability with the BESTs was similar to the repeatability with the B71 with 75% of the participants having their test-retest hearing thresholds within ±5 dB. This indicates that the repeatability of the hearing thresholds was not influenced by the transducer type.

The present results are in good agreement with the results of repeatability measured with insert earphones (Stuart et al, 1991) and B71 test-retest thresholds (Ho et al, 2009; Margolis et al, 2010). Using the automated method in the current study produced mean absolute differences that were slightly higher than that of the manual method which was mainly observed when BC transducers were used. A similar observation was reported by Margolis et al (2010).

3.4.4.2 Hearing thresholds: air conduction

The air conduction thresholds were measured in three different experiments by three different audiologists. The pure tone signals were presented by two different types of insert earphones that were calibrated in the same way and in accordance to ISO 389-2 (1997) standard for calibration.

The choice of using insert earphones was determined by the planned masking to be presented at the non-test ear for measuring the BC hearing thresholds. Therefore, the inserts have the advantage of the smaller size and can be placed in the ear-canal without a headband that could interfere with the placement of the BC vibrator on the head. Insert earphones are reported to have less variability in auditory thresholds due to placement of the foam tip in the ear canal, and greater attenuation of ambient noise in the audiometric test environment (Larson et al, 1988).

The averaged results of the hearing thresholds were compared to the results reported in literature (Table 3.20). It is observed that at 250 Hz there is some variation in the hearing thresholds with the mean thresholds ranging from –3.4 to 11.7 dB in the background studies (Smith & Markides, 1981; Clemis et al, 1986; Larson et al, 1988). In the current study it was observed that one of the measurements E3 resulted in an average hearing threshold of 8.4 dB HL which was the statistically significant compared to the thresholds measured in E4. The reason behind this could be due to the sample measured having a worse hearing threshold at this particular frequency. The participants evaluated in E3 were recruited with the same criteria for inclusion and the same calibration method as for the rest of the studies. In general the results are in line with the thresholds reported in the background studies. The standard deviations for all of these studies are similar which gives an indication to the spread of data in each specific sample.

The thresholds reported in the current investigation and background studies show that the current reference zero for the AC thresholds should be re-evaluated at 250 Hz, and possibly at 2000 Hz.

Table 3.20 Mean hearing thresholds (dB HL) in background studies in relation to the current study with AC stimulation.

Study	N.	Ear-phone		250	500	1000	2000	3000	4000 Hz
Clemis et al. (1986)	16	ER 3A	M	–3.4	5	3.4	3.1	NR	3.8
			SD	4.9	4.4	7.7	7.72		8.9
Larson et al. (1988)	90	ER 3A	M	11.7	8.6	5.9	5.6	2.4	–3.2
O'Neill et al. (2000)	12	TDH 39	M	NR	NR	4	3	0.5	4
			SD			3.6	3.6	5	7.3
Smith et al. (1999)	93	TDH 50P	M	5.3	2.9	1.5	3.5	2.7	3.2
			SD	5.5	4.4	5.2	7.1	6	6.9
Swanepoel & Biagio (2011)	60 ears	ER 3A	M	6.2	7.6	9.2	9.6	NR	13.1
			SD	9.4	10.4	10.8	13.2		17.7
Current study	76	ER 3A &ER 5A	M	5.8	2.4	2.5	4.1	3.8	0.2
			SD	5.2	4.8	4.8	5.2	5.8	5.8

M: Mean (dB HL)   SD: Standard deviation (dB)   NR: Not Reported

3.4.4.3 Hearing thresholds: bone conduction

The BC thresholds were measured using two main types of transducers (B71 and BEST) with different versions of each type. The main aim was to evaluate the performance of the BESTs in relation to the B71. The BESTs could be a clinical replacement of the B71s provided that they produced similar hearing thresholds and followed the same international standards. There is no published data that measured the hearing thresholds with the BESTs. Therefore, this section will evaluate the hearing thresholds measured with the B71 as referenced to the background studies (Table 3.21).

The same calibration procedure was used with all the transducers. However, it was found that the B71B constantly produced thresholds that were different than the other three B71's used in the different studies. Therefore, it was decided that the thresholds for that specific transducer be removed from the analysis. This indicates that the B71's have some inconsistencies that are masked in the calibration process.

Comparison between the results reported in the current study and the hearing thresholds reported in literature are presented in Table 3.21. The general trend was similar for the hearing thresholds between the studies with the exception of the thresholds reported by Swanepoen and Biagio (2011). Their study showed greater discrepancy in the results of the current study and also compared to the results reported in other studies. This discrepancy is attributed to the participants used in their sample, only 82% of their sample had normal hearing thresholds.

Table 3.21 Mean hearing thresholds (dB HL) in background studies in relation to the current study with BC stimulation.

Study	N.	Ear phone		250	500	1000	2000	3000	4000 Hz
Richter & Brinkmann (1981)	50	B71	M	1.7	–3.5	–0.6	–4.5	1.8	6.6
			SD	6.1	5.8	7.6	8.0	8.3	8.3
Frank et al(1988)	100	B71	M	–1.2	2.9	–2.0	–1.9	1.5	4.5
			SD	7.5	6.2	7.8	7.3	6.2	6.7
Smith et al.(1999)	93	B71	M	3.3	3.6	3.5	5.0	3.4	2.5
			SD	7.3	7.1	8.0	7.8	6.9	8.0
O’Neill et al. (2000)	12	B71	M	NR	NR	–1.6	5.3	5.5	–1.3
			SD			0.8	10.0	3.3	7.5
Margolis et al. (2010)	6	B71	M	–2	5.0	3.0	17.0	NR	5.0
			SD	6.0	11.0	6.0	7.0		12.0
Swanepoel & Biagio (2011)	60	B71*	M	–5.8	3.7	2.7	10.8	NR	7.2
			SD	6.3	10.5	11.1	14.7		16.2
Current study	98	B71	M	1.2	0.6	2.1	2.0	2.2	2.6
			SD	5.8	7.5	8.4	7.2	7.4	7.5
	190	BEST	M	1.6	–3.2	1.2	6.7	5.4	–2.6
			SD	5.3	6.5	7.2	6.7	6.9	7.4
M: Mean (dB HL) SD: Standard deviation (dB) NR: Not Reported									
* Forehead placement									

The results of the current study are close to the results reported by Smith et al (1999). They measured the hearing thresholds in a large sample of young normal hearing participants and they reported that the ISO 389 (1999) definition of “otologically normal” was vague. Therefore, they set a strict criteria for otologically normal participants that included normal middle ear status, no exposure to loud noise (including gun shots, recreation or occupational), no relevant middle ear problems like tinnitus or vertigo, normal tympanic membrane, and no medications. The results reported in Table Table 3.20 and Table 3.21 are from the sample with the strict definition. The sample in the current study had similar inclusion criteria with an age range of 18-30 years, whereas, the strict criteria of Smith et al (1999) was for the age range of 18-25 years.

The results in the background studies show a tendency for the hearing thresholds to be less acute at 2000 Hz, this was directly linked to a systematic discrepancy with the RETFLs (O'neill et al, 2000). Other studies have showed the results with higher thresholds at 2000 Hz but did not comment on the reason behind the worse hearing thresholds (Margolis et al, 2010).

The variation in the hearing thresholds between the different studies with BC measurement could be attributed to a number of reasons. The first is related to the sampling criteria as more stringent criteria should be used to define the sample, and the inclusion criteria. The placement of the bone vibrator can influence the results because it has to be placed on the most prominent part of the mastoid bone (Weatherton & Goetzinger, 1971). The calibration standards can also influence the results of the hearing thresholds. There have been several reports that indicated that the RETFLs standard should be revised (Frank et al, 1988).

The BC hearing thresholds were measured with the ears not occluded in a sound treated booth. The two doors of the room were closed to ensure that the ambient noise level did not exceed 35 dB A as recommended by the BSA (2004) recommended procedure for pure tone audiometry.

The hearing thresholds measured with the BESTs showed the same trend between the four experiments and across the different versions of the BESTs. This indicates that the BEST as a device was stable to be used clinically. However, the thresholds showed different trends when compared to the B71's (See the next section).

3.4.4.4 Difference between transducers B71 and BEST

The differences between the B71 and BEST were investigated in each study and as an average for all of the studies. The thresholds collected with the BESTs were systematically lower than those of the B71 at 500 Hz and 4000 Hz, and always higher at 2000 and 3000 Hz. At 250 Hz and 1000 Hz the thresholds were similar in the two types of the transducer. The statistical analysis indicated that the differences were statistically significant at 500, 2000, 3000 and 4000 Hz with the differences ranging from –4.7 to 5.2 dB. The results indicate that the most likely reason for the discrepancy in the results could be due to the lack of accuracy of the audiometric zero used for the calibration. It was expected that with a large sample of participants, the averaged thresholds should be around zero dB for the frequencies tested. Frank et al (1988) showed that the current RETFL should be adjusted for different types of transducers, the differences between the two transducers in the current study indicated that this is true with the BEST.

There are a number of factors that contribute to the observed differences with the main factor being related to the design of the BEST. Håkansson (2003) reported that the internal design and weight of the BESTs are different from the B71 making the BESTs better than the B71 (refer to Section 3.2). The frequency response of the BESTs is different from that of the B71 which could explain why the thresholds were different from the B71. The coupling force of the BC transducers is reported to have influence on the hearing thresholds (Lau, 1986). However, it was found that the tension influences the thresholds by about 2 dB (Toll et al, 2011) which would not explain the magnitude of the difference observed in the current study. Therefore, the tension of the headband alone would not be the main factor for the current discrepancy between the two transducers. The results indicate that the calibration values for the reference zero along with the different frequency response are the main contributors to the observed discrepancy.

3.4.4.5 Does the RETFLs require adjustment?

The current RETFL was created using two different transducers (B71, KH70) with the studies reporting the hearing thresholds were from three different laboratories (Dirks et al, 1979; Richter & Brinkmann, 1981; Robinson & Shipton, 1982). The formulation of the RETFLs was criticised for not using different masking levels, a limited number of transducers, and not accounting for the AC hearing thresholds (Hood, 1979; Frank et al, 1988; Lightfoot & Hughes, 1993; Margolis et al, 2010). The present investigation used the same masking noise level in the four experiments and used four versions of the B71 and three versions of the BESTs. Furthermore, the AC hearing thresholds were part of the main investigation.

The comparison between the AC and BC hearing thresholds with the B71 indicated that the thresholds were similar across the frequency range 500-4000 Hz. However, the thresholds were significantly different at 250 Hz with a difference of 4.6 Hz. This is indicative of the similarity in the reference zero for the two test methods, the results also indicated AC hearing thresholds were on average higher than zero dB.

The results indicated that the current RETFL required adjustment for the B71 at high frequencies and for the BESTs at most of the frequencies. Table 3.22 tabulates the results of the four experiments. The thresholds were averaged at each frequency to evaluate

Table 3.22 The current results in the relation to the current RETFLs and the recommendation for correction.

Current study											**Current RETFL**	**RETFL appropriate? ***		**Correction to the current RETFL**	
Experiment	**One**		**Two**		**Three**		**Four**		**Average**						
N ears	**20**		**22**		**30**		**24**		**96**						
N subject	**20**		**22**		**30**		**24**		**96**						
Masking	**None**		**35 dB HL**		**35 dB HL**		**35 dB HL**		**35 dB HL**						
Hearing thresholds (equivalent force levels dB re 1µN)												**B71**	**BEST**	**B71**	**BEST**
Transducer	**B71**	**BEST**	**B71**	**BEST**	**B71**	**BEST**	**B71**	**BEST**	**B71**	**BEST**					
Frequency (Hz) **250 (SD)**	65.5 (4.8)	68.1 (4.6)			66.3 (6.1)	69.6 (6.0)	69.1 (6.0)	68.9 (6.1)	68.2	68.9	67	Yes	No	1.2	1.6
500 (SD)	61.7 (6.6)	55.3 (5.1)	60.5 (7.3)	52.2 (6.70)	57.1 (6.6)	54.4 (6.0)	58.9 (8.0)	55.8 (8.2)	58.6	54.8	58	Yes	No	0	–3.2
1000 (SD)	39.4 (3.5)	42.0 (4.1)	44.0 (6.40	43.3 (6.6)	41.9 (7.8)	42.0 (8.3)	48.5 (8.8)	48.2 (7.2)	44.7	43.7	42.5	Yes	Yes	2.1	1.2
2000 (SD)	34.1 (5.8)	38.1 (6.0)	37.4 (6.4)	37.3 (6.0)	33.1 (7.7)	38.1 (7.1)	33.8 (6.9)	37.3 (7.8)	33.1	37.8	31	No	No	2.1	6.8
3000 (SD)	33.9 (6.1)	37.0 (5.7)	32.6 (6.9)	34.7 (6.9)	33.8 (7.3)	35.9 (6.8)	30.9 (8.0)	33.3 (7.9)	32.2	35.5	30	No	No	2.2	5.5
4000 (SD)	38.9 (7.2)	32.2 (6.7)	32.6 (7.1)	33.5 (8.7)	36.7 (7.5)	34.6 (8.0)	37.1 (7.9)	31.5 (6.7)	38.1	32.9	35.5	No	No	2.5	–2.6

SD standard deviation of the mean (dB re 1µN)
***According to the results of one sample t-test (0 dB HL).**

whether the current RETFLs are appropriate. To evaluate the statistical significance, one sample *t*-test was carried out with the mean set to zero. It was expected that with proper calibration the hearing thresholds will scatter around 0 dB.

The results were different from 0 dB at frequencies > 1000 Hz yet the difference was lower than 2.5 dB when compared to the RETFLs which is an acceptable difference. Margolis et al, (2010) and O'Neill et al (2000) recommend that the RETFLs should be adjusted at 2000 Hz. The present investigation shows that with proper calibration and careful selection of the B71 transducers the discrepancy with the RETFLs is low. It should be noted that the results of one of the B71 were removed because the thresholds were variable (Section 3.4.2.3).

The results with the BESTs were statistically different than audiometric zero at most of the test frequencies which indicates that for it to be used clinically the RETFLs have to be corrected. The difference with the current RETFLs was > 5 dB at 2000 and 3000 Hz. This is supported by the Frank et al (1988) recommendation that the current RETFLs should be transducer specific.

The factors that can influence the RETFLs differences could be related the method of calibration and how the transducers were placed on the artificial mastoid, in addition to the temperature of the artificial mastoid which should not exceed 23ºC. Care was taken in the present study to placing the vibrator on the exact same place on the artificial mastoid and repeating the calibration more than twice per frequency for each transducer. The calibration was carried out on a weekly basis during the data collection. The temperature of the artificial mastoid was measured before the calibration started.3.5 Vibrotactile thresholds

3.5.1 Overview and rationale

The vibration of the transducer causes additional tactual sensation when driven at high intensity levels. The tactual sensation could be interpreted as auditory sensation in clinical investigation of hearing thresholds. Therefore, the use of BC transducers is restricted at low frequencies. The British Standard (ISO 389-4, 1999) defines the vibrotactile threshold level as " level of an alternating force at which a person gives 50%

of correct detection responses on a repeated trials due to the sensation of vibration on the skin."

Boothroyd & Cawkwell (1970) investigated the vibrotactile thresholds in nine unilateral deaf participants. They reported the median of the vibrotactile thresholds at 250 Hz at 35 dB, and at 500 Hz the vibrotactile thresholds were about 60 dB. They have cited a study of Brinkmann & Richter (1983) reporting vibrotactile thresholds at 43, 55 and 72 dB HL at 250, 500 and 1000 Hz, respectively. This indicates that care should be taken when measuring the hearing thresholds in patients with hearing loss in clinical setting.

The low frequency reinforced BESTs are reported to be more suitable for this kind of measurement (Håkansson, personal communication), and are claimed to produce less tactile sensation when compared to the B71. This study aims to investigate this claim in comparison with the clinically used B71. The BEST's are relatively new BC transducers (Håkansson, 2003) there are no reports of their clinical performance including the vibrotactile thresholds, therefore, this study aimed to provide information that previous research lacked. The BESTs are intended to be used in the bilateral masking level difference study. Therefore, the results obtained in this study will give information about the limit of tactility of the device, the results will also lead to the decision of the overall stability of the BESTs.

Evaluation of the BEST in comparison to the B71 by testing the harmonic distortion and the hearing thresholds indicated some advantages of the BESTs, mainly related to the production of less harmonics compared to the B71 especially at 250 Hz. The results of the hearing thresholds showed that on average the thresholds measured with the BESTs were different than the B71 at most of the frequencies tested with the exception of 250 and 1000 Hz. However, the differences between the thresholds using the B71 and BEST did not exceed 5 dB. Measuring the vibrotactile thresholds was aimed at exploring the performance characteristics of the BEST in comparison with the B71 in participants with profound hearing loss who are current users of cochlear implants, in addition to normal hearing participants while providing sufficient masking noise to mask the harmonics.

The vibrotactile thresholds were intended to be measured in deaf participants who are current users of cochlear implants because it was hypothesised that these participants would give more accurate responses to vibrotactile stimuli. They would be able to differentiate between the two types of sensation since they receive auditory stimuli while the cochlea implant is switched on, and are deaf when the cochlear implant is switched off.

Differentiating the two sensations can be difficult in normal hearing participants because the responses could be directly related to hearing. The pilot study proved that differentiating the two sensations was difficult. Furthermore, the hearing sensation could not be eliminated when the broad band noise was presented bilaterally because the level of the second harmonic was always audible. Increasing the level of the masker noise proved to be very loud and uncomfortable. The study aimed to modify the masking noise to cover all the harmonics for the vibrotactile thresholds measured in normal hearing listeners.

Approval from the National Research Ethics Service (NRES) was granted before the commencement of the study (Reference number 10/H0604/43). The Approval of the Institute of Sound & Vibration Research Human Experimentation Safety and Ethics Committee was also granted before initiation of the two studies.

Research question: is the newly designed BEST associated with less sensation of feeling compared to the traditional B71?

In an attempt to answer the research question the following aims are outlined:

- Measuring the vibrotactile thresholds in deaf participants who are current users of cochlear implants at 250, 500 and 750 Hz.
- Measuring the vibrotactile thresholds in normal hearing participants with masking noise applied bilaterally. The masking noise was custom-made for this study to mask the tone and its harmonics at 250 Hz.
- Measuring the vibrotactile thresholds at two masking levels with normal hearing participants, because it was hypothesised that increasing the level of the noise should not affect the vibrotactile threshold if the results are due to sensation. If the threshold increased then it could indicate that hearing could have contributed to the result.

- Measuring the vibrotactile thresholds without making noise with the normal hearing participants to evaluate their baseline vibrotactile threshold and to compare it to the masked thresholds.

3.5.2 Specific methods: normal hearing participants

3.5.2.1 Pilot study

An initial pilot study was performed on 18 normal hearing individuals using an automated test procedure and broad-band masking noise to the non-test ear. This study was performed as a guideline for the study with the cochlear implant participants using only one frequency at 250 Hz. Other frequencies could not be used because the masking noise would be too loud. Masking was used at two levels 60, and 70 dB EML.

The results indicate that the participants did show difficulty in separating the two sensations of hearing and feeling. Furthermore, the results could not confirm that the masking level was sufficient to mask the signal. Some of the participants reported that the signal was still audible in the presence of the bilateral masking noise at the two masking levels. This was further observed by the increase in the vibrotactile thresholds as the masker level was increased (Figure 3.18). Figure 3.18 shows the averaged results obtained from the participants, higher vibrotactile thresholds with the BESTs were observed. The BESTs had lower harmonic distortion compared to the B71 therefore these results are linked to the 250 Hz tone and not to the harmonics, whereas, the harmonic distortion with the B71 is relatively high therefore the responses could be due to the harmonics in addition to the fundamental frequency.

The results showed that the vibrotactile thresholds could not be confirmed with the current masking noise because increasing the masking level resulted in an increase in the vibrotactile thresholds which indicates that the results could be due to audibility more than tactile sensation. The results indicate that further studies were required while adjusting the masking noise to cover all the harmonics. Furthermore, the results indicate that testing deaf participants could be more appropriate for this type of study.

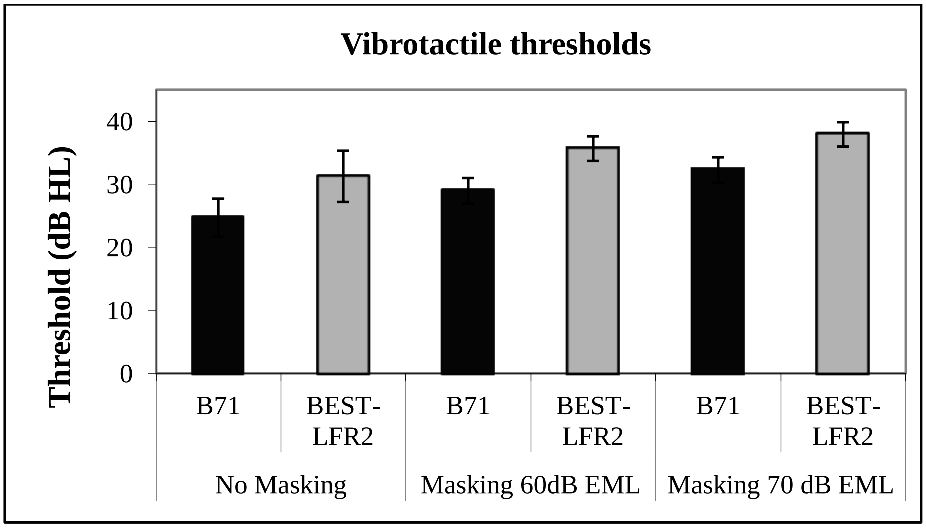

Figure 3.18 Vibrotactile thresholds for 18 participants, error bars indicate 95% confidence intervals.

3.5.2.2 Setup

The test setup and calibration was similar to Experiment 3& 4 (hearing thresholds). 250 Hz tone was generated through MATLAB coupled with a sound card and audiometer KC50 for signal amplification. The pilot study showed that only one frequency could be tested with normal hearing participants. Using higher frequencies would result in the need to use louder levels of masking noise which was above the permissible levels used with normal hearing participants. Four BC transducers were used: two BESTs and two B71s. The order of the transducers was counterbalanced. The vibrotactile threshold was collected through the automated method using 10 down 5 up step size. The start level of the signal presentation was roved by about ±5 dB to start at around 30 dB HL. If the participant did not respond, the level was increased by 10 dB steps until the participant responded then the level was decreased by 10 dB and increased by 5 dB steps till the threshold was calculated.

The participants were instructed to respond when they felt the vibration on the mastoid bone. The threshold was taken as the level the participant responded 3 out of 4 times in an ascending manner. The vibrotactile threshold was measured twice in each test condition in each transducer. The order of the test presentation of noise condition and transducer was randomised.

The masking noise was fixed in level to either 60 or 65 dB EML delivered to the two ears via insert earphones (Etymotic Research ER2). According to the manufacturer specifications these inserts are specifically designed to be used in auditory research as they create approximately flat frequency response at the eardrum. In addition to the high IA achieved with these inserts (70 dB), they are capable of producing a maximum undistorted output of 89-107 dB HL in the frequency range 0.25- 8 kHz as measured in a Zwislocki coupler, particularly useful for broadband stimuli (Etymotic-Research, 2013).

Disposable foam tips were coupled to the insert plastic tip, the size of the foam tip was chosen according to the size of the ear canal of the participants, three different sizes were available (small, medium and large).

3.5.2.3 Masking noise

The pilot study showed that NBN and the regular broad band noise were not practical to be used in the current study because the NBN did not provide sufficient coverage to mask the signal or its harmonics at 250 Hz. Whereas, the broad band had to be too loud to mask the signal and harmonic. Therefore, the masking noise was made to cover the main tone and its harmonics.

The masking noise was generated through MATLAB and copied to a compact disc and the MATLAB code was fed correction factors. The calculation was based on the reference equivalent threshold sound pressure level (RETSPL) at 250 Hz (fundamental frequency), added to reference NBN according to the ISO 389-4 (1994), the harmonics produced by BC transducers, and the calculation was also made for the first three harmonics. The difference to the fundamental was added to the harmonics to get more masking energy at each harmonic. Collectively the overall level was 82 dB SPL. This appeared to be sufficient to mask the signal during the pilot study, and was not uncomfortably loud for the participants.

3.5.2.4 Participants

Twenty normal hearing participants took part in the study, recruitment and exclusion criteria were based on the guidelines outlined in Section 3.4.1.2. The participants were students at the University of Southampton recruited through email invites circulated in the department. They volunteered to take part in a one hour test session and were not paid for their participation. Participants were excluded if they had excessive wax in their ear canal, pervious history of ear infections, head injuries or surgeries and complaints of persistent tinnitus.

3.5.3 Specific methods: cochlear implant participants

The present investigation used the same apparatus used to measure the vibrotactile thresholds in normal hearing participants. However, the masking noise was not required because the participants suffered from profound hearing loss when the cochlear implant was switched off. More frequencies were added to the evaluation that included 250, 500, and 750 Hz.

The transducers were the same as the transducers used with the normal hearing participants. The frequencies were generated through MATLAB coupled to a sound card and amplified through an Audiometer (KC 50). The BC transducers were placed on the prominent part of the mastoid process of the ear opposite to the side of the implant and special care was taken to guard against the BC steel band touching the cochlear implant site. Frequent breaks were given to the participants to minimise the tension of the headband.

3.5.3.1 Participants

Ethical standards involving patients requires approaching potential participants through invitation letters. Identification of potential participants was facilitated by the staff of the South of England Cochlear Implant Centre (SOECIC) through automated filtering of their patient system files.

The criteria fed to the system included the AC hearing thresholds, patients targeted should not have residual hearing at low frequencies, they should have bilateral hearing loss, and their ears free of tinnitus. The age range included participants between 18- 70 years. The outcome resulted in a number of potential participants. Another screening process then took place by manually inspecting the BC thresholds in the patient files-if reported. 100 letters were sent out to the potential participants. 25 participants responded and they were sent the health questionnaires to confirm the inclusion criteria. 11 were excluded as they had continuous tinnitus and the rest did not send the health questionnaire back.

Four participants attended the testing, they were not paid for their participation. They attended one session that lasted no longer than one hour.

3.5.4 Results: normal hearing participants

The vibrotactile thresholds were measured in 20 normal hearing participants using two versions of B71's and two $BEST_{LFR}$. The aim of this study was to evaluate the performance of the $BEST_{LFR}$ in relation to the B71 at 250 Hz.

The pilot study indicated that distinguishing between hearing and feeling was problematic this led to the design of a custom made masking noise that took account of the harmonics produced at 250 Hz mainly by the B71. Therefore the current testing used two levels of masking noise to ensure that the response was due to sensation rather than hearing. A trial without making noise was conducted to evaluate the level that the participants thought was tactile, a summary of the averaged results are tabulated in Table 3.23.

The results showed that the participant's judgment of the vibrotactile thresholds was always lower in the no masking condition compared to the thresholds obtained with masking which was observed using the two types of the transducers. This indicates that the judgment of the participants could be linked to the loudness of the signal, as the sound increases in level they would judge the threshold as vibrotactile. The thresholds were measured twice in the same session while removing the transducer and replacing it on the mastoid according to the randomised order. The results show that the average of the two trials was almost equal in all of the test conditions and using the two different types of bone vibrators.

The results were normally distributed according Kolmonogrov- Simernov and by visual inspection of the histograms. Therefore, the results were analysed using repeated measures ANOVA with Green-house Geisser as the sphericity was not assumed. Paired samples *t*-tests were used when two conditions were compared.

Table 3.23 The mean vibrotactile thresholds (dB HL) measured in 20 normal hearing participants, using four transducers at two masking conditions and a two no masking trials. Between brackets are the standard deviations (dB).

Transducer		No masking		Masking level 60 dB EML		Masking level 65 dB EML	
		Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Sessions	B71C	29.9 (8.4)	29.6 (9.8)	35.9 (8.6)	35.2 (8.6)	35.4 (9.4)	35.7 (8.7)
	B71D	29.1 (8.7)	30.0 (8.9)	33.2 (8.5)	32.3 (8.4)	33.9 (7.9)	34.5 (6.6)
	$BEST_{LFR1}$	30.3 (10.0)	30.4 (10.0)	33.7 (8.6)	35.3 (8.4)	35.2 (7.8)	35.2 (8.8)
	$BEST_{LFR2}$	30.6 (8.3)	30.5 (9.5)	32.8 (6.6)	32.6 (8.2)	35.7 (5.8)	35.5 (8.1)
Average	B71C	29.9 (8.3)		35.5 (8.1)		35.6 (8.9)	
	B71 D	29.5 (8.7)		32.8 (8.2)		34.2 (7.2)	
	$BEST_{LFR1}$	30.2 (8.6)		34.5 (8.3)		35.2 (7.9)	
	$BEST_{LFR2}$	30.6 (8.6)		32.6 (6.9)		35.6 (6.8)	

3.5.4.1 Repeatability

The vibrotactile thresholds were measured twice in the same test session to evaluate the repeatability of the measurement. The order of the presentation was randomised and the transducer was completely removed and re-positioned on the prominent part of the mastoid bone.

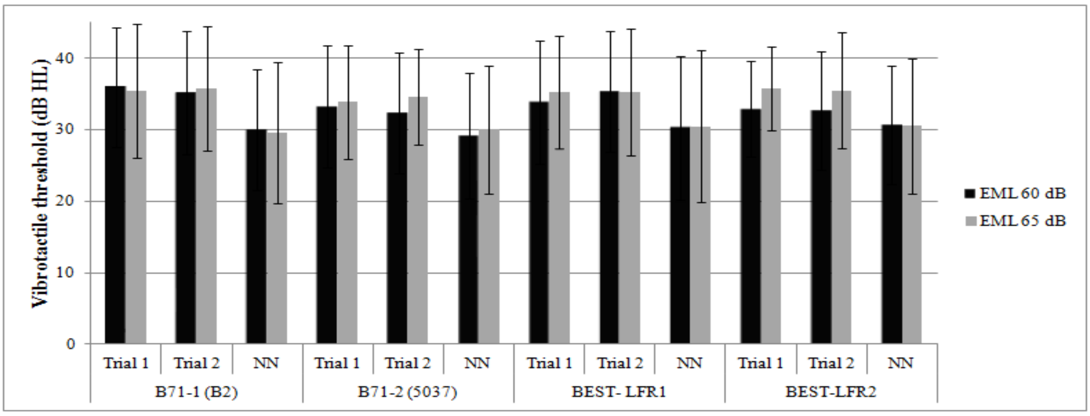

Figure 3.19 Average vibrotactile thresholds for 20 participants measured in two trials, NN is for a no noise trial, and error bars indicate the standard deviation.

Figure 3.19 plots the vibrotactile thresholds measured in the three test conditions using four BC transducers. It can be observed that the responses were similar in the two test trials. Introducing the masking noise resulted in response to the sensation increasing the masking noise did not influence the average thresholds indicating that the results were due to feeling the vibration rather than hearing the signal.

The test-retest variability was measured by calculating precision, repeatability and ICC tabulated in Table 3.24. The precision measurement was lower than 4 dB for all of the transducers in the test and retest measurements which indicates that the test-retest scores for the participants were parallel. The repeatability was within ±7 dB for most of the comparisons and of a maximum of ±10 dB. The ICC scores indicated that the test-retest thresholds were in very good agreement (>0.8) with small range of confidence intervals. The results of ANOVA for the average test-retest scores were not significant for any of the comparisons. The results indicate that it was safe to pool the results of the test-retest thresholds to compare the results for the two transducers.

Table 3.24 Evaluation of the test-retest repeatability of the vibrotactile thresholds in the three test conditions using four transducers in 20 normal hearing participants.

			Intraclass correlation			ANOVA	
Condition	**Precision**	**Repeatability**	**ICC**	**CI**	**p**	**F**	**p**
B71C_NN	2	5.5	0.97	0.94 to 0.99	<0.001	0.9	0.59
B71D_NN	2.3	6.7	0.96	0.91 to 0.99	<0.001	1.48	0.24
BEST_LFR1_NN	2.1	5.7	0.98	0.95 to 0.99	<0.001	0.05	0.82
BEST_LFR2_NN	3.4	9.4	0.92	0.81 to 0.97	<0.001	0.02	0.89
B71C_60	3.2	8.8	0.93	0.82 to 0.97	<0.001	0.49	0.49
B71D_60	2.7	7.6	0.94	0.87 to 0.98	<0.001	1.14	0.29
BEST_LFR1_60	2.9	8.6	0.93	0.83 to 0.97	<0.001	2.86	0.11
BEST_LFR2_60	3.8	10.5	0.85	0.64 to 0.94	<0.001	0.03	0.87
B71C_65	2.4	6.7	0.96	0.91 to 0.98	<0.001	0.21	0.65
B71D_65	1.9	5.3	0.96	0.92 to 0.99	<0.001	1.03	0.32
BEST_LFR1_65	3.9	10.7	0.88	0.71 to 0.96	<0.001	0	1
BEST_LFR2_65	2.8	7.7	0.92	0.8 to 0.97	<0.001	0.08	0.78

3.5.4.2 Comparison between B71 and BEST

The vibrotactile thresholds were evaluated for each type of transducer to evaluate the vibrotactile thresholds with different versions of the same transducer. The average thresholds are tabulated in Table 3.23. Statistical evaluation was conducted with paired samples *t*-tests to evaluate the performance of each type of transducer at the three test conditions. The results are tabulated in Table 3.25. Comparison of the vibrotactile thresholds using the B71's in the three test conditions (No noise, 60 dB EML and 65 dB EML) resulted in no significant differences between the B71C and B71D in any of the test conditions, additionally, the significance level was corrected to Bonferroni adjustment for multiple comparisons. These results indicate that the two versions of BC transducers resulted in similar hearing thresholds, which shows that the results of the two transducers can be pooled for the investigation of the BEST in relation to the B71.

The two versions of the BESTs resulted in a similar trend to the B71. The results indicate that none of the comparisons were statistically significant when the significance was adjusted to Bonferroni adjustment for multiple comparisons. The results indicate that the vibrotactile thresholds can be pooled.

The effect size (r) was calculated and reported in the last column of Table 3.25. The effect size was lower than 0.5 for all of the comparisons for the two types of the transducers, which is consistent with the non-significant findings.

Table 3.25 Comparison between the two versions of each type of transducer through paired samples *t*-test s in 20 normal hearing participants.

Condition	Mean difference	*t*	p	r
B71C and B71D at 60 dB EML	2.8 dB	2.63	0.017	0.5
B71C and B71D at 65 dB EML	1.4 dB	1.67	0.112	0.4
B71C and B71D at NN	1.8 dB	1.37	0.188	0.3
$BEST_{LFR1}$ and $BEST_{LFR2}$ at 60 dB EML	–0.4 dB	0.39	0.697	0.1
$BEST_{LFR1}$ and $BEST_{LFR2}$ at 65 dB EML	0.4 dB	0.79	0.437	0.2
$BEST_{LFR1}$ and $BEST_{LFR2}$ at NN	–0.2 dB	0.16	0.874	0.03

Repeated measures ANOVA were conducted to evaluate the vibrotactile thresholds with the two main types of BC transducers and the three test conditions. The results indicated that the condition was significantly different $F_{2.78}=32.3$, $p<0.001$. The results were adjusted to Greenhouse_Geisser because the sphericity was not assumed $x^2(2) = 0.51$, $p< 0.001$. This indicates that the changing the level of the masking noise had a significant influence on the vibrotactile thresholds. However, the interaction between the condition and transducer was not significant $F_{2.78}=0.78$, $p= 0.467$, the sphericity was assumed $x^2(2) = 0.98$, $p=0.616$.

The condition was further investigated through paired samples *t*-tests for each type of transducer (Table 3.26) then between the transducers. The results showed that with the B71, increasing the masker noise by 5 dB resulted in a non-significant influence on the vibrotactile hearing thresholds and the effect size was small which is consistent with the non-significant findings. The comparison between the vibrotactile thresholds measured without masking noise and the two masking levels was significant with a large effect size. The BESTs on the other hand, showed a significant influence of the increase in the masking noise on the vibrotactile thresholds with a mean difference of –1.8 dB, the effect size was medium. The comparison between the two masking levels and the thresholds measured without masking noise was significant showing a similar trend of the B71.

Statistical analysis was conducted to evaluate the vibrotactile thresholds using the two types of transducers at the three test conditions (last three rows in Table 3.26). The results showed that the vibrotactile thresholds were similar for the two types of transducers and not statistically significant. This was also confirmed by the small effect size.

Table 3.26 Investigating the influence of masking on the vibrotactile thresholds for each type of transducer using paired samples *t*-test's.

Condition	Mean difference	*t*	p	r
B71 at 60 and 65 dB EML	–1.4 dB	2.07	0.046	0.3
B71 at 60 dB EML and NN	4.4 dB	5.4	<0.001	0.7
B71 at 65 dB EML and NN	5.8 dB	6.5	<0.001	0.7
BEST at 60 and 65 dB EML	–1.8 dB	3.4	0.002	0.5
BEST at 60 dB EML and NN	3.3 dB	3.4	0.002	0.5
BEST at 65 dB EML and NN	5.0 dB	4.9	<0.001	0.6
B71_60 and BEST_60 dB EML	0.5 dB	0.5	0.598	0.1
B71_65 and BEST_65 dB EML	0.2 dB	0.2	0.847	0.03
B71_NN and BEST_NN	–0.6 dB	0.9	0.386	0.1

These results indicate that the judgement without noise produced vibrotactile thresholds that were lower than the thresholds obtained with masking noise. The vibrotactile thresholds without masking were always significantly different than the vibrotactile thresholds measured with masking noise regardless of the transducer type. Increasing the masking noise by 5 dB did not result in a 5 dB increase in the vibrotactile thresholds indicating that the results were due to the sensation of the vibration rather than hearing. A significant difference of 1.8 dB with the BESTs was observed with when the masking noise was increased by 5 dB. However, the effect size was medium indicating that the sample size should be increased to confirm the current results. The confidence intervals were concentrated around the thresholds (Figure 3.20) which indicates that the results are likely to represent the population. The vibrotactile thresholds with the BEST's were comparable to the thresholds obtained with the B71 in the three test conditions. These results indicate that the BEST was not better than the B71 in producing vibrotactile thresholds as claimed.

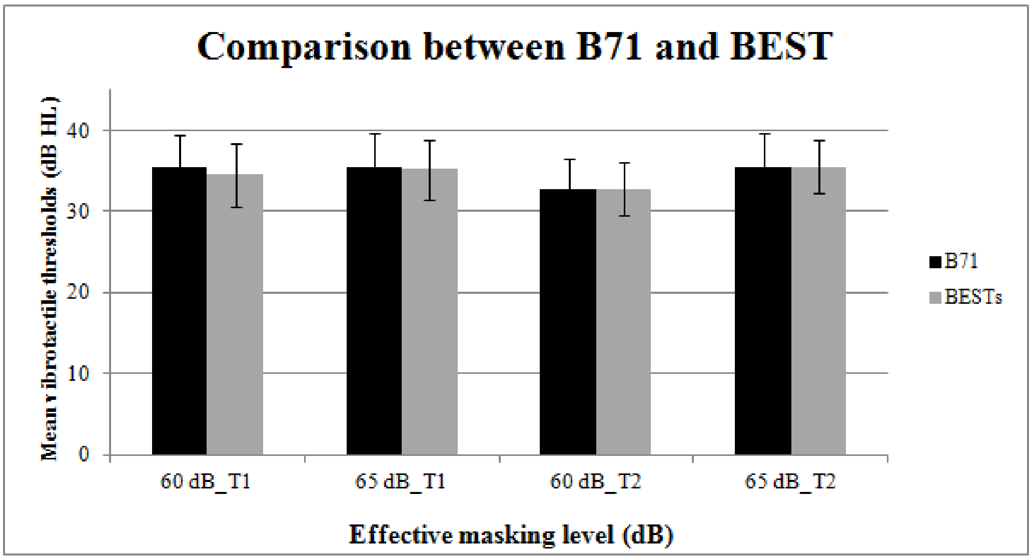

Figure 3.20 The averaged vibrotactile thresholds for B71 and BEST. T1 is for the first transducer, T2 is for the second transducer, error bars indicate 95% confidence intervals.

3.5.5 Results: cochlear implant participant

The results presented in this section is the outcome of the vibrotactile thresholds measured from four patients to evaluate the performance of the BESTs in comparison to the B71s by measuring the vibrotactile thresholds at 250, 500 and 750 Hz. All of the participants did not respond up to the maximum level used (70 dB HL) at 750 Hz, therefore the results reported in this section are for 250 and 500 Hz.

Descriptive results of the means and standard deviations are tabulated in Table 3.27. It is observed that the vibrotactile thresholds measured in the second trial resulted in similar vibrotactile thresholds in the first trial with the two versions and two types of the BC transducers. This was similar to the results obtained with the normal hearing participants. The vibrotactile thresholds were higher when the frequency was increased. This trend is similar to the results reported in literature (Boothroyd & Cawkwell, 1970; Dean & Martin, 1997).

Furthermore, the vibrotactile thresholds measured with the BESTs at 500 Hz were lower than the thresholds measured by B71 by almost 10 dB which was observed with the two versions of the BESTs.

Table 3.27 The mean vibrotactile thresholds (dB HL) measured in 4 deaf participants, using four transducers. The vibrotactile thresholds were measured at 250 and 500 Hz. The results between brackets are the standard deviations (dB).

Transducer		250 Hz		500 Hz	
		Trial 1	Trial 2	Trial 1	Trial 2
Session	B71C	42.0 (9.1)	42.2 (8.2)	62.8 (2.2)	62.0 (4.9)
	B71D	42.3 (6.0)	42.8 (7.3)	65.0 (4.1)	66.0 (3.4)
	$BEST_{LFR1}$	42.3 (6.9)	45.0 (9.1)	53.3 (1.7)	52.5 (4.1)
	$BEST_{LFR2}$	42.0 (11.1)	43.5 (9.1)	52.3 (5.5)	54.5 (6.8)
Average	B71C	42.1 (8.6)		62.4 (3.4)	
	B71 D	41.5 (6.5)		65.5 (3.7)	
	$BEST_{LFR1}$	44.1 (8.0)		52.9 (2.5)	
	$BEST_{LFR2}$	42.8 (10.0)		53.4 (6.2)	

3.5.5.1 Repeatability

The vibrotactile thresholds were measured twice in the same session. The transducer was completely removed and replaced on the prominent part of the mastoid bone. Only four participants participated in this study, a number of participants were excluded due to persistent tinnitus which could influence their judgment or exacerbate the tinnitus.

The small sample could result in biased statistical analysis. Therefore, the current results would be used as a preliminary investigation with the two types of the transducers. And the interpretation would be conducted with caution, the measurement of repeatability and ICC were not conducted.

Individual vibrotactile thresholds are plotted in Figure 3.21 and Figure 3.22 at 250 and 500 Hz respectively in the two test trials. The vibrotactile thresholds in the first participants measured at 250 Hz were higher with the two versions of the B71 compared to the BESTs. Participant number 4 showed lower vibrotactile thresholds with the two types of the BC transducers. The participants seemed to have similar thresholds in the two test trials.

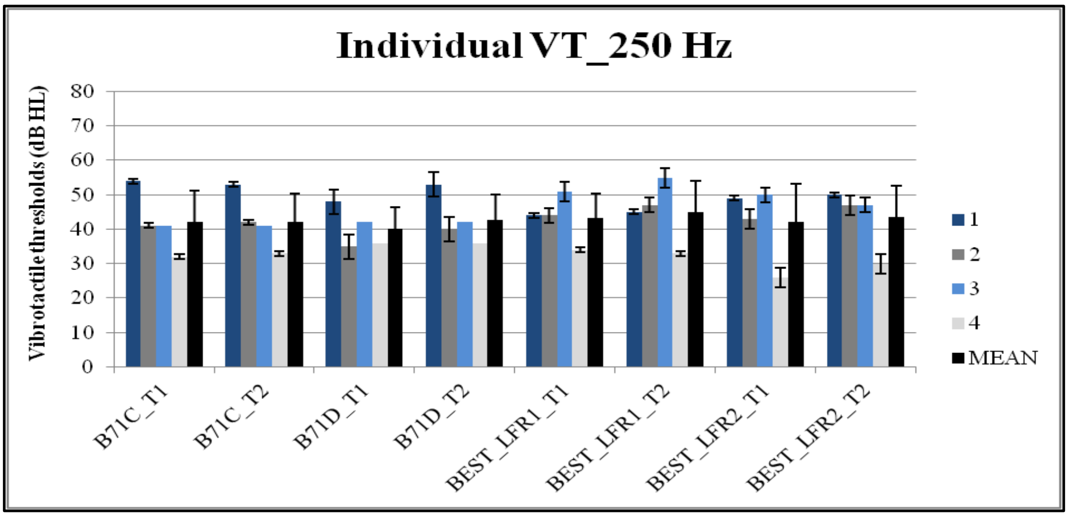

Figure 3.21 The individual vibrotactile thresholds at 250 Hz for the two B71's and two BESTs (Participant 1 to 4), error bars indicate the standard deviation.

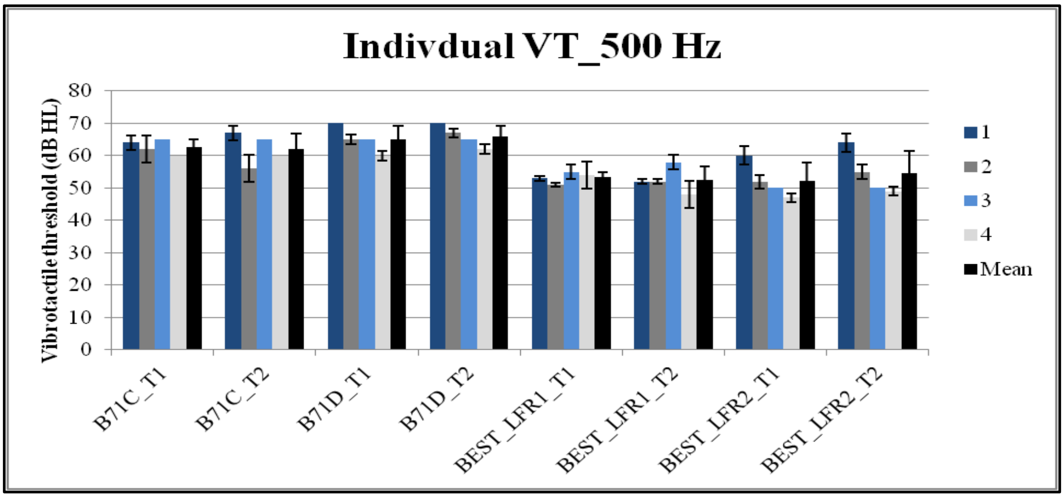

Figure 3.22 The individual vibrotactile thresholds at 250 Hz for the two B71's and two BESTs, error bars indicate the standard deviation.

At 500 Hz, the four participants had the same trend of higher vibrotactile thresholds with the B71's and lower vibrotactile thresholds measured with the BESTs. When compared to the thresholds measured at 250 Hz, the vibrotactile thresholds were higher with the two types of transducers. The second trial had little influence on the vibrotactile thresholds.

Figure 3.23 shows the averaged vibrotactile thresholds for the four participants using the two versions of each transducer in two test sessions. The graph shows that the results were similar for the two types of the transducers as observed earlier. The left side of the graph plots the results at 250 Hz, while the right side displays the results at 500 Hz.

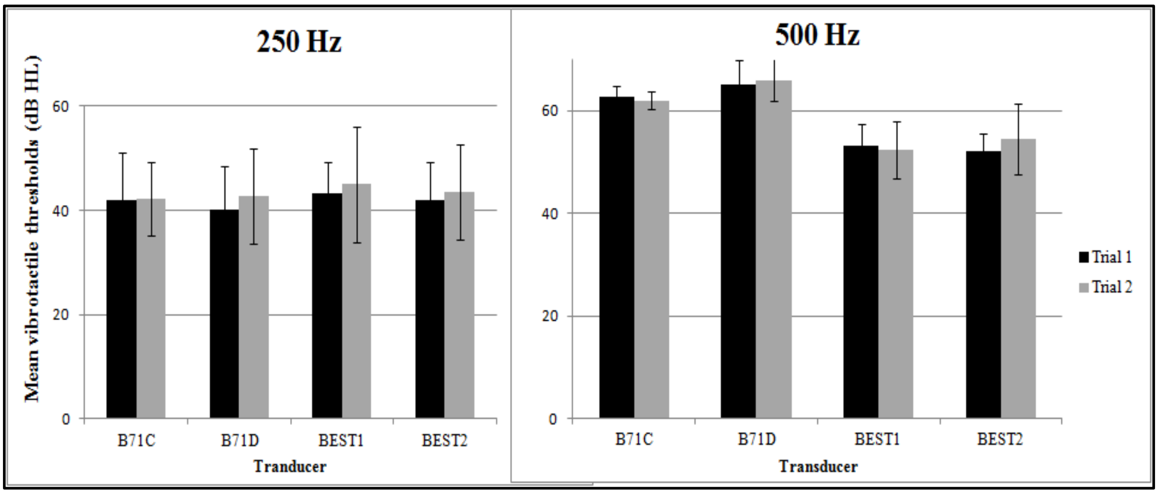

Figure 3.23 The mean vibrotactile thresholds at 250 Hz and 500 Hz for the two transducers in the two sessions, error bars indicate the standard deviation of the mean.

Table 3.28 Comparison between the two trials for each type of transducer through paired samples *t*-tests.

Condition	**Mean difference**	***t***	**p**	**r**
B71C_250 Hz	–0.3 dB	0.52	0.863	0.3
B71D_250 Hz	–2.5 dB	1.73	0.182	0.7
$BEST_{LFR1}$_250 Hz	–1.7 dB	1.58	0.213	0.7
$BEST_{LFR2}$ _250 Hz	–1.5 dB	0.91	0.432	0.5
B71C_500 Hz	0.8 dB	0.39	0.718	0.2
B71D_500 Hz	–1.0 dB	1.73	0.182	0.7
$BEST_{LFR1}$_500 Hz	0.8 dB	0.39	0.724	0.2
$BEST_{LFR2}$ _500 Hz	–2.3 dB	2.63	0.078	0.8

Paired sample *t*-test was conducted to evaluate the vibrotactile thresholds in the two test sessions and the results indicate that none of the comparisons were significant. However, the effect size was large for most of the cases indicating that the differences have high effect but due to the small sample size these results cannot be generalised.

3.5.5.2 Comparison between B71 and BEST

The vibrotactile thresholds were compared in the two versions of each transducer before conducting the comparison between the two main types of bone vibrators. Paired sample *t*-test s indicated that the vibrotactile thresholds were similar between the two versions of the B71's and the two BESTs at 250 and 500 Hz (Table 3.29). These results indicated that the vibrotactile thresholds could be pooled.

Table 3.29 Comparison between the two versions and two types of BC transducers through paired samples *t*-test s in four deaf participants.

Condition	Mean difference	*t*	p	r
B71C and B71D at 250 Hz	0.6 dB	0.36	0.744	0.2
$BEST_{LFR1}$ and $BEST_{LFR2}$ at 250 Hz	1.4 dB	0.58	0.604	0.3
B71C and B71D at 500 Hz	–3.1 dB	1.94	0.148	0.7
$BEST_{LFR1}$ and $BEST_{LFR2}$ at 500 Hz	–0.5 dB	0.14	0.895	0.1
B71 and BEST at 250 Hz	–1.6 dB	0.47	0.672	0.3
B71 and BEST at 500 Hz	10.8 dB	28.97	<0.001	0.9

The statistical evaluation comparing the B71 and the BEST revealed that at 250 Hz the vibrotactile thresholds were similar with a difference of –1.6 dB (Best higher vibrotactile thresholds). However, at 500 Hz the BESTs had lower vibrotactile thresholds compared to the B71 by about 10.8 dB which was statistically significant.

3.5.6 Summary of results

- Normal hearing participants showed difficulty in separating the sensation of feeling from the sensation of hearing, indicated by the vibrotactile thresholds measured with and without masking noise.
- The BESTs produced vibrotactile thresholds that were comparable to the B71 in normal hearing and deaf participants at 250 Hz.
- The vibrotactile thresholds measured at 500 Hz with the deaf participants were significantly different between the two transducers. All four participants had lower vibrotactile thresholds with the BESTs compared to the B71.

3.5.7 General discussion

3.5.7.1 Vibrotactile thresholds with B71

The vibrotactile thresholds obtained in this study were comparable to the results reported by Boothroyd& Cawkwell (1970) for the placement on the mastoid process. The no noise trial was significantly different than the conditions with the masking noise which indicates that the participants were not able to accurately differentiate the two sensations, this was apparent with the 4 transducers. The judgment of the sensation level was always lower with the no masking trial indicating that the participants tended to respond when the sound was intense. It was interesting to note that the method the participants used seemed to be consistent between the test-retest trials.

There are limited background studies reporting the vibrotactile thresholds because of the difficulty in distinguishing the tactile sensation from the auditory sensation leading to difficulty in recruiting normal hearing participants and even participants who have residual hearing. The BSA (2004) recommended procedures cite the Boothroyd & Cawkwell (1970) study stating the possibility of large subject variation. The results with the normal hearing and deaf participants showed variation between the individual responses.

Investigating the repeatability with the normal hearing participants showed that the results were congruent in the two trials. The testing was conducted in one session and although the order of the testing was counterbalanced, the placement of the transducer was the same due to the visibility of transducer mark on the participant's head resulting from the tension of the transducer. This would lead to the possibility of having different results if the testing was conducted on a different day.

Two masking noise levels were used in the current study to ensure that the vibrotactile thresholds were due to sensation rather than hearing. The increase in the level did not result in an increase in the vibrotactile thresholds strongly indicating that the results were tactile.

The results with the B71's are tabulated in Table 3.30, the results are in line with the thresholds measured with Boothroyd & Cawkwell (1970) at 250 Hz and 500 Hz. This shows that the masking was sufficient to eliminate hearing because the results of the normal hearing participants (present study) was comparable to the results of children with profound unilateral hearing loss reported by Boothroyd & Cawkwell (1970). Dean & Martin (1997) participants showed lower vibrotactile thresholds at 250 Hz compared to the present investigation and to the results reported by Boothroyd & Cawkwell (1970). They have used a similar method to the one used in the present study with the exception that they used the American National Standards Institute (1994) correction factors for calibration. The current study, on the other hand, calibrated the BC transducers using ISO 389-3 (1999) standard. Frank & Crandell (1986) reported that the method for deriving the two standards were different and they used different participants. This may have led to the lower vibrotactile thresholds reported by Dean and Martin (1997).

The vibrotactile thresholds measured at 250 Hz in the four deaf participants were slightly higher compared to the background studies and to the results reported with normal hearing participants in the present investigation. The sample size was too small to generalise the results as the effect size indicated that more participants were required for this evaluation. However, the vibrotactile thresholds measured from deaf participants is more ideal than measurements with hearing participants, the variation in the responses of the deaf participants was small. At 500 Hz the participants showed similar vibrotactile thresholds to that reported in the literature.

Table 3.30 Vibrotactile thresholds (dB HL) reported in background studies.

Study	**N.**	**Ear-phone**	**250 Hz**	**500 Hz**
Boothroyd & Cawkwell (1970)	9	B71	~ 35	60
Dean & Martin (1997)	12	B71	29.2	61.6
		B72	44.1	53
Current study (normal hearing)	20	B71	34.8*	NM
		BEST	34.5*	
Current study (deaf participants)	4	B71	41.8	63.9
		BEST	43.4	53.1

* The thresholds were averaged from the two masking levels

NM: Not measured

3.5.7.2 Comparison between B71 and BEST

The vibrotactile thresholds with the BESTs were similar to the B71 at 250 Hz with the two groups of participants. However, the normal hearing group of participants had lower vibrotactile thresholds compared to the deaf group using the BEST's and the B71's. The normal hearing participants showed that an increase in the overall masking level resulted in a significant increase in the vibrotactile thresholds with the BESTs but not with the B71's. However, the difference was lower than the hypothesised 5 dB, it was 1.8 dB and the effect size was medium indicating that this difference accounts for half of the cases. Possible explanations for the higher results obtained with the deaf group could be due to the small sample size. The vibrotactile thresholds are known to vary with different individuals (Boothroyd .A & Cawkwell, 1970; Dean & Martin, 1997).

The vibrotactile thresholds measured at 500 Hz with the deaf participants resulted in vibrotactile thresholds that were lower than the B71 and similar to the vibrotactile thresholds reported by Dean & Martin (1997) with the B72. The BESTs were calibrated using the current RETFLs (1990), and there was no attempt to correct the results. The results obtained with the hearing thresholds in the normal hearing participants (Section 3.4.4.5) indicated that the participants had lower hearing thresholds at 500 Hz measured by the BEST by about –3.2 dB. If the vibrotactile threshold was corrected to this level it is predicted that the vibrotactile threshold would be around 56.3 dB. This indicates that some of the difference can be accounted for by adjusting the RETFLs for the BEST.

The thresholds should be repeated with a larger sample using the correction factors suggested in Section 3.4.4.5.

3.6 Conclusions

The current study was conducted to verify the performance of the BC transducers using the newly designed BEST with the aim of answering the following questions:

Does the BEST perform better than the B71?

- Sensitivity: it was verified that the BEST was more sensitive than the B71 providing wider dynamic test range at 250 Hz by about 20 dB.

- Total harmonic distortion: the BESTs produced significantly lower harmonics at 250 Hz compared to the B71s. For example, at a presentation level of 40 dB HL at 250 Hz the BESTs produced an average of 0.4 % THD compared to 33% produced by the B71. This gives confidence that when testing low frequencies the result would be from the test frequency rather than the harmonics.
- Hearing thresholds: the BEST produced hearing thresholds that are different than the B71. However, this difference did not exceed 5 dB between the two transducers. Compelling evidence was shown that the current RETFLs should be changed at high frequencies.
- Vibrotactile thresholds: the BESTs performed similar to the B71 at 250 Hz. However, at 500 Hz the BESTs were significantly poorer than the B71's (small sample size). Correcting to the suggested RETFLs can decrease the difference in the vibrotactile thresholds between the two transducers.

Based on the above points there is a trade-off between the acoustical and psychoacoustical outcomes. Acoustically the BESTs are superior to the B71 at low frequencies. However, psychoacoustically the BEST perform similarly to the B71. The limitations associated with the B71 have not been resolved with the BESTs. The limitations include better vibrotactile performance, wider frequency range and lower airborne radiation. The acoustical performance would be of value for future research planned because testing is intended to be performed at low frequencies. Furthermore, correction factors can be used to adjust the thresholds and the sensitivity. The stability of the BESTs also weighs in for the choice of transducer for the future testing. The BESTs were shown to be stable and reliable over time, whereas, two of the B71 transducers showed inconsistencies in the thresholds despite having the same calibration as the rest of the transducers.

Are the current RETFLs applicable with the BEST?

- No. The current results indicate that the RETFLs require adjustment for the majority of frequencies with the BESTs especially at 2000 and 3000 Hz where the difference with the current RETFLs exceeded 5 dB.

The current RETFLs have been criticised because they did not account for AC thresholds (Hood, 1979; Frank et al, 1988). The present results show that there was no discrepancy between the AC and BC thresholds except at 250 Hz. This suggests that the RETSPLs and RETFLs should be revised at 250 Hz.

It is noted that the difference between the BEST and B71 was less than 5 dB indicating that the current RETFLs can be applied with the BESTs, However, it is recommended that more investigation should be carried out with the BESTs at high frequencies.

Are the BESTs consistent enough to be used in the planned future research?

- Yes. The BESTs have been used in a number of studies across a period of three years. Test-retest repeatability showed that the transducers were consistent over time and there were no signs of fluctuation in performance. Therefore, the BESTs can be used in future research while accounting for the differences with the RETFLs.

Chapter four. Masking level differences with bone conduction stimulation: preliminary investigation

4.1 Overview and rationale

This chapter provides a preliminary investigation of binaural hearing with bilateral bone conduction stimulation in normal hearing participants. The main aim was to develop a methodology that is suitable for investigation of MLDs with AC vs. BC such a way as to relate their performance. Part of this involves ensuring the test-retest repeatability is sufficiently high. The BC measurement is affected with large inter-subject variability, the development of the methodology aimed to reduce the variability by carefully selecting the signals, consistent placement of the BC transducers. A second aim was to compare the AC and BC MLDs at several frequencies and across different individuals with probably different transcranial characteristics.

Binaural benefit with bilateral bone conduction stimulation have been reported in studies investigating binaural MLDs in patients suffering from bilateral symmetrical conductive hearing loss (Bosman et al, 2001; Priwin et al, 2004). The MLDs have been evaluated through tonal signals at a range of frequencies, the magnitude of the MLDs described in these studies was small when compared to the AC MLDs reported in other studies under same conditions. The observed MLDs reported were associated with wide variability between the participants. Furthermore, the MLDs were measured in normal hearing participants with tonal (Tompkins, 2008) and chirp tone (Stenfelt & Zeitooni, 2013) using the same phase conditions (So and Sπ). The reported results are almost in the same direction. The BC MLDs were smaller than the AC MLDs measured in the same group. One reason that could explain this variability is the cross-talk of the signal in the two ears, i.e. interference of the signal at each cochlea (Zurek, 1986), it could also be an indication of binaural benefit.

Cross-talk of signal is assumed to influence binaural hearing due to the contribution of the TA and TD (refer to Section 2.6.1 for more detail). This might explain the large variability between the participants because the TA is known to differ from one person to another (Nolan & Lyon, 1981; Stenfelt, 2012). Furthermore, measurements of the TD showed variation between the participants (Jahn & Tonndorf, 1982). The TA and TD are anticipated to influence the magnitude and direction of the MLD in a complex manner. As the BC signal behaviour in the head does not follow the same pattern as the AC studies (Hausler et al, 1983), caution should be taken when interpreting the results of MLD studies conducted through BC stimulation. Therefore, it is important to identify the factors that contribute to the presence of the MLD with bone conduction stimulation (Stenfelt, 2011).

The BC transducers are associated with a number of limitations (Section 2.2.2.1) that would influence the cross-talk to the signal. For example, BC transducers have limited frequency response. Therefore, it would be ideal to separate the noise signal from the tone in MLD studies with bilateral bone conduction stimulation. This would limit the degree of distortion between the two types of signals (Noise and tone) that have unpredictable influence on the outcome (Sorenson & Schubert, 1976). Another reason could be to ensure excitation associated with all stimuli is the same for the AC and BC.

Furthermore, development of the methodology in the present study included the measurement of reliability. The MLDs were measured in different sessions separated by different days. The reliability of the measurements could be influenced by a number of factors. For example, BC thresholds can be influenced by the placement of the transducer (Studebaker, 1962; Mcbride et al, 2008; Stenfelt, 2011). Therefore, special care was taken to maintain the same placement in the three test sessions. The change in placement from session to session can have unpredictable influence on the phase of the signal which can also influence the reliability. The repeatability of BC MLD was investigated by repeating the measurement twice in each session and over three different sessions as outlined in Figure 4.1. The degree of repeatability of ±5 dB was considered suitable for this test based on previous studies, Stubblefield & Goldstein (1977) reported the test-retest reliability within the subject of about 3 dB.

To evaluate the second aim two phase conditions were used (SoNo and SπNo) and the resultant MLDs were a calculation of the difference between SoNo and SπNo. MLDs have been extensively measured with AC using two phase conditions the diotic (in-phase) and dichotic (180° out-of-phase conditions) in the background studies, the difference between these two phase conditions was shown to be maximal (Green &

Yost, 1975; Gelfand, 1998; Yost, 2007). Studies measuring BC MLD's in patient using bilateral BAHAs have also used these two phase conditions (refer to Section 2.6.3.2) and reported the presence of binaural hearing when the signal was inverted by 180°. Therefore, these two main phase conditions were chosen in this study to evaluate the experimental procedure as they were used in many background studies investigating AC MLD's, which in turn, would provide stability of the testing. These phase conditions are unique in that the inter-cochlear phase. The assumption is that the manipulated IPD is similar to the internal IPD (provided that the TA and TD are not symmetrical). For other IPDs when the TA is low, the measured MLD would be associated with the manipulated phase difference.

Studies investigating AC MLD have reported that the MLDs magnitude decreases with the increase in frequency. The low frequencies are associated with large MLD's with the largest MLD's reported at 250 Hz. Whereas, frequencies at and above 2000 Hz result in a uniform MLD of 3 dB (Levitt & Voroba, 1980; Yost, 2007). Therefore, it was decided in the present investigation to evaluate the AC and BC MLD's at 250, 500, and 1000 Hz. It was expected that 250 Hz would produce the largest MLD in particular for the AC MLD as described in the literature. The MLD was expected to reduce as the frequency increased from 500 Hz to 1000 Hz (Durlach, 1963).

Addressing these aims was required before a more detailed investigation was carried out to investigate the effects of cross-talk.

The following hypotheses were made in this study:

1. It is hypothesised that a change in the phase for the BC signal will result in an MLD that is different from zero dB, based on the interference model (Section 2.6.1.3), it is assumed that an MLD up to 6 dB could be the result of monaural interference (provided that the TA is 5 dB or less). BC MLD equal to AC MLD is hypothesised to be associated with larger TA values indicating binaural benefit.

2. It is hypothesised that the change in the frequency from low to high would influence the BC MLD in a similar way that it influences the AC MLD. This is indicated by the fact that AC and BC stimulate the Basilar membrane in the same manner (Bekesy, 1948). Moreover, it is indicated by lateralisation studies that humans are capable of lateralising

with two bone vibrators placed on the head with careful adjustment of the signals time difference (Jahn & Tonndorf, 1982). The degree at which the interference of the two signals would affect the BC MLD is not known.

4.2 Specific methods

This section includes the methods specific to MLD experiment with AC and bone conduction stimulation. Approval of the institute of Sound & Vibration Research Human Experimentation Safety and Ethics Committee (Reference number 1213) was obtained before commencing with the study (Appendix A).

The thresholds in each condition were measured in three sessions. Each session was conducted in a separate day to investigate the day to day variability, in addition to investigating the repeatability of the threshold. The sessions were approximately an hour long, the first session included a screening session that was lasted approximately 15 minutes.

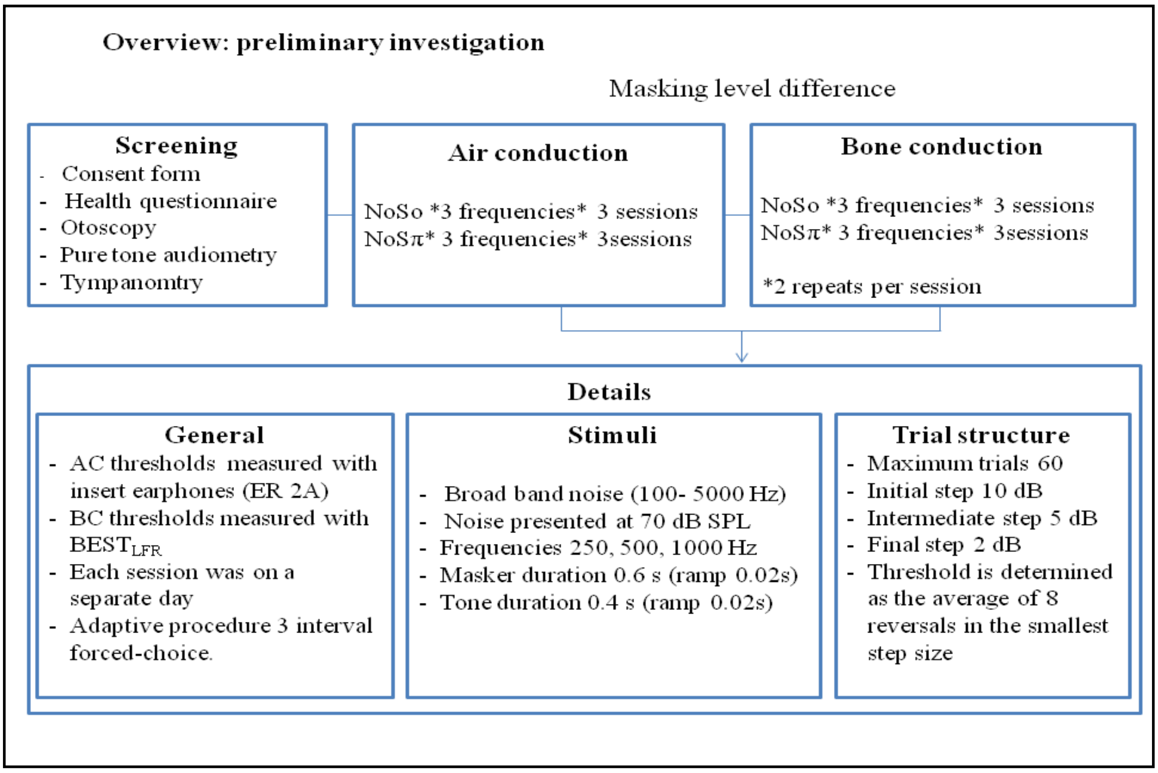

Figure 4.1 Overview of the experimental design for the preliminary investigation.

In summary, each participant undertook a total of 54 measurements across the three sessions where each test trial lasted approximately three minutes, 18 trials for the AC measurement and 36 trials for the BC. It was decided to repeat the measurement of the BC in the same session to check the performance with the bone transducers in the same placement.

The thresholds were measured at three frequencies (250, 500 and 1000 Hz) masked by broadband noise (100-5000 Hz) for the AC and BC conditions. Three interval forced choice (3IFC), two down one up procedure was used in estimating the threshold. Figure 4.1 outlines the design of the study.

4.2.1 Participants

Ten participants took part in the study, all of which have passed the screening guidelines for inclusion as described in Section 3.4.1.2. The upper age limit was extended to 45 years. It has been shown that age does not influence the MLD within this range (Dubno et al, 2008) .

The participants were recruited through opportunistic sampling (mean age of 26.8 years, age range 20-32 years), 6 females and 4 male. They were recruited by advertising through emails and posters from the university student population either under- or post-graduate students and were not paid for their participation. All participants were screened by filling in a health questionnaire and by testing the middle ear function and their hearing was evaluated to ensure, as far as possible, no hearing impairment or asymmetry in thresholds between the two ears. Any person with occluding wax, history of middle ear infections, thresholds ≥ 20 dBHL, asymmetry between the two ears of ≥ 10 dBHL was excluded. One participant was excluded in the screening stage due to excessive wax in both ears which was contraindicated with the use of insert earphones. Another participant was later excluded due to poor concentration during the testing and high variability in results between the sessions (results were always outliers to the group).

Otoscopy and tympanometry were repeated in each session. Participants were asked about their general health on each session. Questions included if they had common colds, or were exposed to loud noise in the previous 48 hours, if the participant replied positively he/she was asked to come on a different day. Seven of the participants were audiology students with some experience in psychophysical studies including MLD studies. The remaining three were naïve to this type of experiment.

All testing was performed in a sound-treated test booth with the door closed to ensure that the ambient noise of the room was lower than 35 dB A (IEC 60645-1, 2001). The participants were observed through an observation window at all times and were notified to inform the tester if they experienced any discomfort.

4.2.2 Apparatus

The apparatus used for the main testing is schematically presented in Figure 4.2. A laptop was used to run MATLAB (Math works Inc.), a custom-written program that generates the digital signal for MLD threshold measurement and collects responses. The signal was routed to Creative extigy sound card through its stereo output. Two audiometers were used for each type of stimuli to provide control of the signal level and the required amplification. Due to the different nature of the transducers and the need for four different channels for signal presentation, that setup was found to be the best to minimise signal distortion.

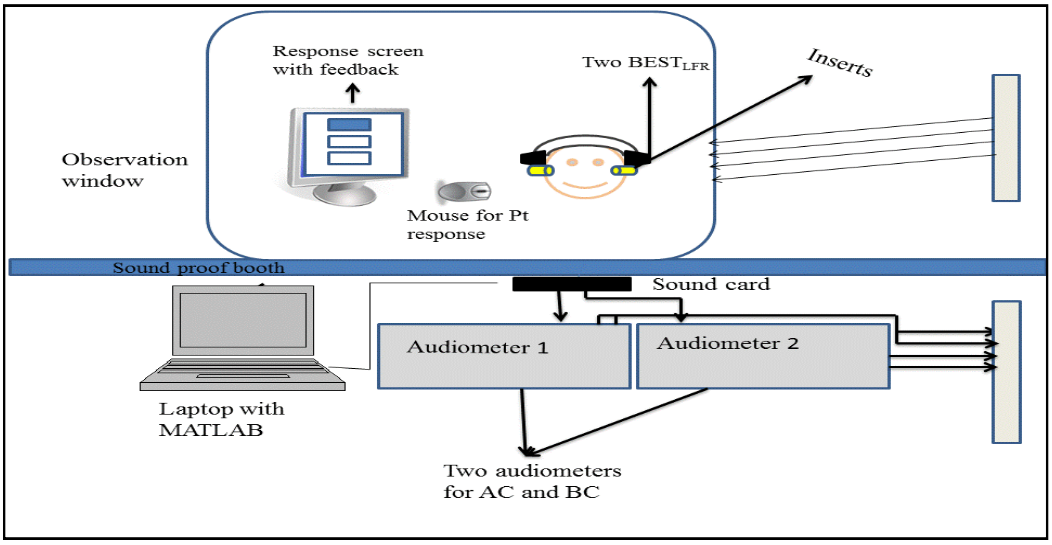

Figure 4.2 Representation of equipment setup for MLD testing through AC or BC data collection. The BC transducers were removed when the AC MLDs were measured.

A mouse (left click) was used for subject responses and a feedback monitor indicated the correct response. Participants were able to abort the test trial if they needed to by pressing the “abort” button present on the response screen.

4.2.3 Transducers

Two insert earphones were used for AC measurements (Etymotic Research ER2). According to the manufacturer specifications these inserts are specifically designed to be used in auditory research as they create approximately flat frequency response at the eardrum. In addition to the high IA achieved with these inserts (70 dB), they are capable of producing a maximum undistorted output of 89-107 dB equivalent HL in the frequency range 0.25- 8 kHz as measured in a Zwislocki coupler, which is particularly useful for broadband stimuli (Etymotic-Research, 2013).

Disposable foam tips were coupled to the insert plastic tip. The size of the foam tip was chosen according to the size of the ear canal of the participants. Three different tip sizes were available at the clinic (small, medium and large).

Two matched $BEST_{LFR}$ were chosen for BC MLD measurement (See below). Chapter 3 evaluated the performance of the $BEST_{LFR}$ in relation to the B71. These transducers showed superiority in the production of total harmonic distortion at low frequencies (Section 3.3.2). This was important in this study because 250 Hz was planned to be measured and using B71 would have resulted in large harmonics at this frequency leading to inaccurate results. Furthermore, the BESTs provide a wider dynamic range for testing at low frequencies enabling them to produce signals at higher presentation levels, this meant that testing could be performed at levels up to 60 dB HL, if needed at 250 Hz. The evaluation of the BESTs showed them to be reliable and consistent over time while using the same RETFLs used in the ISO 389-3 standard (1999) (Section 3.6). There was some discrepancy with the current RETFL. However, this did not exceed 5 dB. The vibrotactile thresholds measured with the BESTs were about 35 dB and 53 dB at 250 and 500 Hz, respectively, indicating that the MLD thresholds would not be influenced by vibrotactile sensation because the noise spectrum level of the tone was about 33.1 dB.

The BC transducers were used for the signal presentation and the inserts were used for the broadband masking noise. The noise level was constant while the level and phase of the tone was changed depending on the test condition. Rigorous calibration was performed to ensure that the level of the tone and noise were correct and stable over time to within ±4 dB as outlined by the tolerance levels accepted in IEC 60645-1(2001). Calibration of the phase was also performed to ensure that the two inserts and BC transducers were matched in phase to within 5° at the test frequency. The calibration was conducted twice per week and whenever the knobs of the volume control were moved due to speech testing with patients in the clinic.

4.2.4 Stimuli

Pure tone frequencies were used for MLD threshold measurements at: 250, 500 and 1000 Hz. The level set on the MATLAB calibration was at 45 dB HL presented through insert earphones ER2 for AC condition and $BEST_{LFR}$ for the BC condition. Testing binaural hearing with stationary signals was reported to add constructively or destructively to the resultant signal and was considered inappropriate by Stenfelt (2011). However, this claim was not supported by research. The frequencies were chosen on the basis that AC MLD has been shown to be larger at lower frequencies compared to a uniform MLD of 3 dB at frequencies above 2000 Hz. Therefore, measurement of the MLDs with different frequencies with bilateral BC stimulation will allow the observation of the presence of similar trends with the AC or lack of it. Furthermore, the same frequencies were reported in the investigations measuring bilateral BC stimulation (Bosman et al, 2001; Priwin et al, 2004). Even though, the current study recruited normal hearing participants the results can be looked at in relation to the results reported with patients fitted with BAHAs.

Broadband Gaussian noise (bandwidth 100-5000 Hz) was presented at 70 dB A (spectrum level 33 dB A). The masking noise was presented via insert earphones in both conditions (i.e. AC and BC). Hall & Harvey (1985) reported that the MLD increases as a function of the masker noise level until the noise spectrum level is about 30-50 dB A, MLD studies have usually used masking levels around 50- 80 dB SPL (Quaranta & Cervellera, 1974; Hall & Harvey, 1985; Wilson et al, 2003). The wideband noise used in the current study was judged in the pilot study to be sufficiently loud to be used with the participants in the three test sessions (it was at a comfortable level). MLD measured with wideband noise have been shown to produce lower MLD’s compared to MLD produced with narrow band noise (Hall & Harvey, 1985). Furthermore, lower inter-subject variability was found with broad-band noise (Bernstein et al, 1998).

The masking noise was always presented via insert earphones even when the stimulus was presented through BC transducers. Separating the masking from the tone allows the separation of the effect of cross-talk on tone (single frequency) and the masker (range of frequencies) noting that the effect of cross-talk may differ with the frequency. Presenting the noise via inserts allows the noise source to be constant and uninfluenced by the limitation of the BC transducers. The frequency response of the BESTs is limited to an upper limit of 4000 Hz (Håkansson, 2003). The broadband Gaussian noise was checked to have equal energy across the frequency range but it is known that the actual spectrum reaching the participant would be influenced by the shape of the device used to deliver the signal (Gelfand, 1998). Therefore, the use of the BEST to deliver the noise would have influenced the level and quality of the noise signal. In addition to the limitation of the transducer, presenting the noise through the BC could have resulted in unpredictable interference pattern at the cochlea (Sorenson & Schubert, 1976).

Separating the noise from the tone with BC testing meant that masking noise could be used at a higher level without being influenced by the performance of the transducer. Using the BESTs enabled testing at 250 Hz without the presence of distortion products that could have influenced the response of the participants. The study of the vibrotactile thresholds showed that the BESTs become vibrotactile at around 35 dB HL. This was envisaged not to influence the overall threshold in both phase conditions (Section 3.5).

Using the masking noise with insert earphones introduced an occlusion effect when BC MLD was tested. Occlusion effect is known to be more prominent at lower frequencies (Section 2.1.2.1). The inserts were placed in both ears symmetrically and care was taken to ensure that they are fully inserted. Therefore, it was expected that the influence was uniform and would affect both NoSo and NoSπ conditions to the same degree (Jahn & Tonndorf, 1982) where the calculated difference should not be influenced. However, the occlusion effect may have an influence on the transcranial transmission characteristics (TA and TD) due to the removal of the natural high pass filter of the ear canal (Tonndorf, 1966). Pilot work has shown that it was not possible to cut the tips of the insert foam as the masking noise would leak affecting the overall level.

4.2.5 Trial structure

The stimulus was presented in a 3 alternative forced choice (AFC) two-down-one-up procedure, i.e. the stimulus was presented in one of the three noise presentations. The participant had to indicate the interval containing the stimulus. The level was reduced after two consecutive correct responses at the same presentation level. Temporal structure for the signal presentation is illustrated in Figure 4.3. The expected probability of responding only by chance was 0.33%.

Signal duration of the pure tone was set to 0.4s with an onset-offset ramps of 0.02s allowing the signal to increase gradually preventing the onset transient cue that occur when the rise time is less than 0.001s (Jahn & Tonndorf, 1982). The noise was presented for duration of 0.6s and 0.02ms onset- offset ramps.

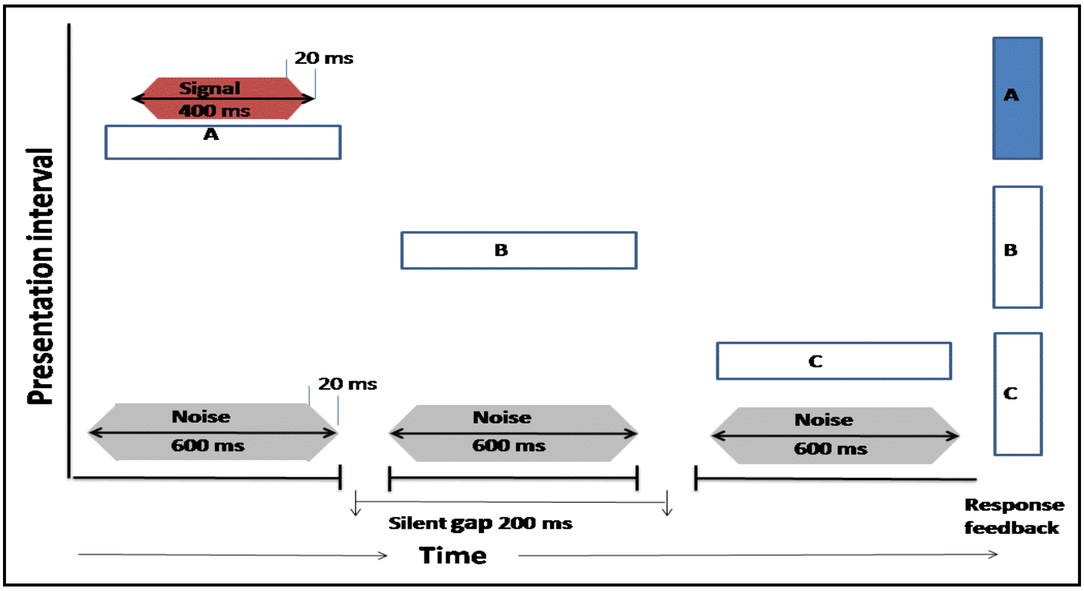

Figure 4.3 Temporal structure of a given trial. The noise was presented on three intervals with one tone presented in one of these intervals. Upon a participants response a blue light will flash indicating the interval that carried the tone. In this example it is centred in interval A.

The signal and masker durations were considered appropriate based on the reports that showed that the signal duration barely affect the MLDs results. It could influence the threshold of the signal in noise in the two phase conditions but not the overall level of MLD (Henning & Zwicker, 1984; Zwicker & Zwicker, 1984). It was reported that an increase in the MLD from about 5 to 10 dB was observed when the masker duration increased from 5 to 200 ms (Zwicker & Zwicker, 1984). Therefore, the masking duration used in the current study was chosen to be 600 ms so as not to influence the overall MLDs.

Visual feedback accompanied the testing was presented through a computer monitor by an illuminating blue light indicating the interval that contained the signal after the participant had chosen the interval that they thought contained the signal. Feedback was given throughout the testing to keep the participants motivated and maintain their concentration through the testing. Participants were not given training sessions because Trahiotis et al (1990) and Bernstein et al (1998) concluded that training has little if any effect on the MLDs. However, familiarization with the test setup was conducted through the first and second step sizes (Section 4.2.6) and the results were not included in the reported thresholds.

4.2.6 Adaptive procedure

The MLD was measured through a 3AFC procedure with a two-down-one-up adaptive staircase that theoretically estimates a threshold that asymptotes to 70.7% correct on a psychometric function (Levitt, 1971). Adaptive methods for MLD data collection have proven to be stable with no change in performance over time (Trahiotis et al, 1990).

The adaptive procedure uses a series of trials and runs which adapt according to the participant response in descending or ascending manner. It is characterised by reversals or turning points. All these points and step sizes are decided before starting the test.

Figure 4.4 illustrates an example of the MLD threshold collection method through the use of an adaptive staircase procedure. A correct score is indicated with a ‘cross’ and an incorrect response is indicated with a ‘circle’, participants responding to the interval containing the signal scored a correct response. A two-down-one-up method meant that it was required to get the signal correct at the same level two times for the signal level to be decreased, if the response was incorrect then the signal level was increased.

The parameters were set at three main step sizes governing the magnitude of signal level change in consecutive trials. The first step size was set at 10 dB to aid in getting to the threshold quicker and this lasted for one reversal. A reversal occurs when an incorrect response occurs and the level of the signal is changed (i.e. when the direction of response changes). The second intermediate step size was set at 5 dB and lasted for two reversals. The final step size was set at 2 dB for the rest of the reversals.

The testing was stopped after eight scored reversals and was set to a maximum of 60 trials so the testing not to go indefinitely if the participants responses were random. The threshold was defined as the average of the last 8 reversals, and the first reversal was discarded.

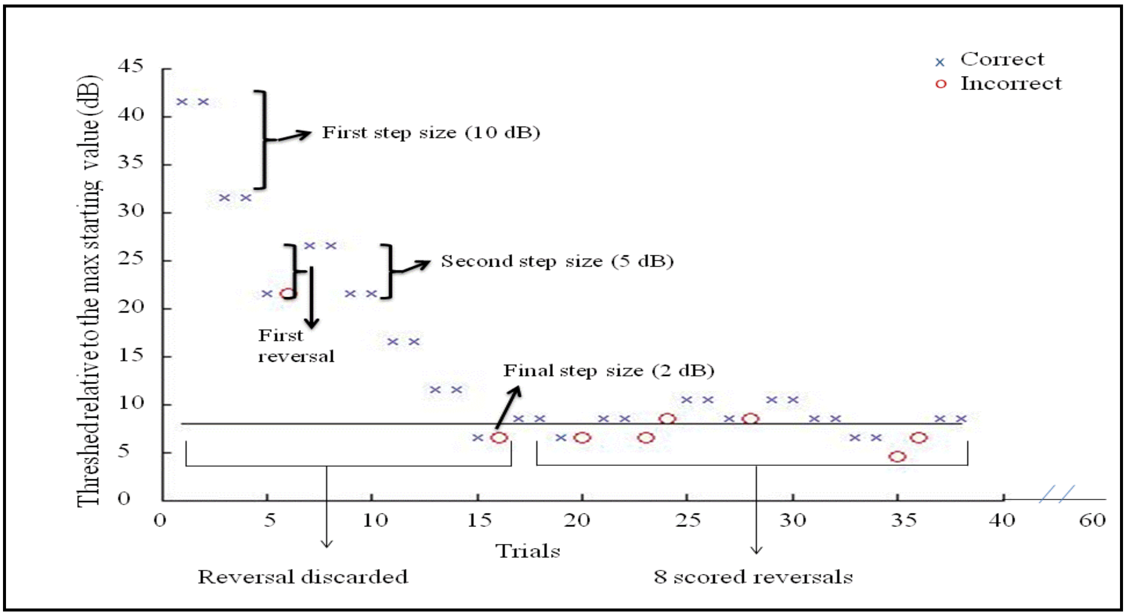

Figure 4.4 Adaptive procedure used with two-down one-up procedure illustrating the three step sizes used and the reversals for all the test blocks. A correct response is indicated with an "x", while an incorrect response is marked with an "o".

4.2.7 Statistical analysis

The study was mainly designed to evaluate MLDs with BC stimulation through the use of two matched $BEST_{LFR}$. The outcome was planned to be compared with the AC MLDs in order to establish if there is a relation between the two measures under the same test conditions while changing the stimulation source from inserts to BC transducers for the tone stimulation. To estimate the number of sample required to test, sample power calculation was conducted using G*Power (version 3.1.2) package.

A significant difference between the AC and BC MLD of 6 dB or more would be of interest. Based on the calculations reported by Tompkins (2008) (the only study measuring the MLDs with AC and BC stimulation in the same sample at 1000 Hz test frequency) an AC MLD 8.4 dB (SD: 1.7 dB) and a BC MLD of 2.2 dB (SD: 5.9 dB) result in an effect size of 1.17. With a two sided significance of 0.05 and a power of 0.8, a total of 7 participants were required.

It was important to evaluate the performance of the participants in the study by measuring the repeatability of their performance in two measures: the precision and the intraclass correlation (ICC). The precision (typical error) measurement obtained from one way ANOVA represents the variability between the measures and is not affected by between-subjects variability; an acceptable value of precision would be ±5 dB based on day-to-day variation in threshold measurement. The ICC scores gives an indication of the measurement and is unit-less, the interpretation of the ICC is based on the quantitative score given in a ratio between 0 and 1, where ratio close to 0 indicate poor reliability and the closer the ratio to 1 the higher the reliability (Weir, 2005). Furthermore, the ICC calculates the confidence intervals (CI) which indicates the spread of the results for the test-retest scores. The comparison between the means of the two variables was evaluated through ANOVA which measures the significance of the mean difference between the test-retest thresholds (refer to Section 3.4.1.7 for more details of ICC and precision measurements). The MLD’s have been shown to provide good test-retest scores with AC stimulation (Stubblefield & Goldstein, 1977). Results of the patients collected with bilateral BAHAs have shown wide variability with no consistent trend in the individual responses although the contribution of the test-retest reliability was not reported (Bosman et al, 2001; Priwin et al, 2004).

The data obtained from the present study were statistically analysed through the statistical package (SPSS v19). Repeated measure analysis of variance (ANOVA) was chosen to analyse the overall trend on the participants as a group. Post-hoc pairwise comparisons were adjusted to Bonferroni adjustment for multiple comparisons. This test was performed to evaluate how the two conditions differed from each other for example the AC and BC performance for a specific frequency and a specific phase.

The distribution of the threshold measurements in the two phase conditions for the AC and BC were normal based on Shapiro-Wilk tests of normality, histograms were also visually checked to confirm these results. Therefore, parametric tests were used for the statistical analysis.

4.3 Results

The results described in this section were collected from nine participants in total. All participants attended three test sessions on different days. One participant was later excluded from the analysis because he showed a large amount of variability, this participant had struggled to stay focused during the test sessions (S9). Three frequencies were tested in each session. AC thresholds were measured once per session in each phase condition, while the BC thresholds were repeated twice per session per frequency and phase. Therefore, a total of six measurements were collected for the AC condition, three in each phase measurement per frequency. The BC masked thresholds were collected twelve times per frequency, six times in each phase measurement. In other words the resultant MLD was calculated three times per frequency in the AC while in the BC, it was measured six times per frequency in the three test sessions.

The overall mean and standard deviation (SD) of the threshold and MLD's is outlined in Table 4.1, in addition to the range of the responses and the confidence intervals of the mean (CI). The table outlines the overall results for the three test frequencies (250, 500 and 1000 Hz) when the signal was tested in phase (SoNo) and the overall thresholds for the signal measured with inverting the phase 180° (SπNo) for the AC and BC conditions, respectively. The third section of the table covered the results of the calculated MLD which was the outcome of subtracting the SπNo from SoNo conditions for each frequency and condition separately.

Individual responses are illustrated in Appendix H. The figures show the results of participant 9 who was later excluded because of the wide variations in his responses. The graphs show that the participants showed stability in their responses across the different sessions. It can also be observed that inverting the phase resulted in slightly more variation in the participants' responses as indicated in Table 4.1.

Table 4.1 Descriptive statistics for the whole sample (n=9) in terms of thresholds and MLD's for the AC and BC results at the three frequencies tested, thresholds for SoNo, SπNo are given in dB HL, and MLD's and SD are reported in dB.

	Condition	Mean[a]	SD[b]	Min[a]	Max[a]	95 % CI on mean Low[a]	95 % CI on mean High[a]
SoNo	AC_250	17.8	1.6	15.7	22.1	17.2	18.4
	AC_500	25.4	1.7	22.2	29.1	24.8	26.1
	AC_1000	31.8	1.9	27.4	35.6	31.1	32.6
	BC_250	-4.1	8.3	-25.2	14.2	-8.3	-1.5
	BC_500	4.7	8.2	-14.6	19.0	2.5	7.0
	BC_1000	21.8	6.7	8.7	41.2	19.9	23.6
SπNo	AC_250	6.0	3.1	-1.0	14.2	4.8	7.2
	AC_500	13.8	2.5	9.0	19.6	12.8	14.8
	AC_1000	21.7	2.2	15.0	25.5	20.9	22.6
	BC_250	-6.6	8.3	-21.3	11.9	-10.1	-3.5
	BC_500	-0.2	7.8	-15.1	13.2	-2.4	1.9
	BC_1000	15.2	7.9	0.6	34.9	13.1	17.4
MLD**	AC_250	11.8	2.9	6.1	20.0	11.7	13.0
	AC_500	11.7	2.6	6.4	18.0	10.7	12.7
	AC_1000	10.1	2.6	6.3	15.9	9.1	11.1
	BC_250	2.4	7.5	-10.0	16.2	0.4	4.5
	BC_500	5.0	7.1	-11.0	19.0	3.0	6.9
	BC_1000	6.5	4.1	-3.17	13.9	5.4	7.7

[a] dB HL for thresholds; dB for MLD [b] dB

** Minimum and maximum results for the MLD is based on the three sessions

4.3.1 Repeatability

The thresholds of the signal in noise were measured in two main phase conditions (SoNo and SπNo), e.g. the signal was either presented by insert earphones or through two matched $BEST_{LFR}$. Each threshold measurement was calculated once per session for the AC condition and twice per session for the BC stimulation. Testing was conducted in three test sessions on separate days to evaluate the stability of the measurements for the AC and BC stimulation.

The standard deviations of the individual mean thresholds across the three sessions were calculated to observe how the individuals performed in the different sessions (Table 4.2).

The individual SD of the mean in the AC measurements was within 2 dB for 78 % of the participants for the three test frequencies and two phase conditions. Furthermore, all the participant individual performance did not exceed 3 dB SD. Moreover, the SD of the individual performance in the six BC masked threshold measurement, SoNo and SπNo at the three test frequencies, showed greater variability compared to the AC (bottom half of Table 4.2). The individual SD for their individual mean was within 5 dB for 80% of the participants which was also consistent with the precision measurement. The BC pure tone thresholds are associated with wider variation when compared with the AC thresholds which was observed in Chapter Three.

Table 4.2 Individual standard deviation of the mean (dB), measured from three test sessions (3 threshold measurement in AC and 6 threshold measurement in the BC condition).

Condition		Frequency (Hz)	Participant								
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Air conduction	**SoNo**	**250**	1.9	0.8	0.6	0.6	0.7	0.8	0.5	0.8	0.9
		500	1.7	0.8	1	1.4	3.2	0.4	1.8	0.9	1.5
		1000	0.4	3.1	0.7	0.7	1.3	2.5	1.1	1	1.8
	SπNo	**250**	2.8	1.1	1	1.2	1.8	2.5	2.7	4.4	0.5
		500	1.6	2.3	1	0.3	3.1	1.7	1.5	2.7	3.9
		1000	0.5	0.5	1.4	3.1	0.8	0.7	0.9	2.1	3.9
Bone conduction	**SoNo**	**250**	4.8	5.1	4.1	5.2	4.5	3.4	4.4	4.7	7.5
		500	4.6	5	9	6.8	2.4	5.4	6.1	1.8	4.8
		1000	3	4.1	4.1	1.6	3.9	3.4	3.9	4.9	1.9
	SπNo	**250**	8	3.6	4.6	1.8	5.9	2.4	3.2	4.5	7.1
		500	4.7	3.7	8.4	6.6	3.2	1.9	2.4	10.7	2.2
		1000	2	1.8	5.7	2.7	3	4.2	1.3	4.5	3

The results indicate that the repeatability performance for the participants were good with the AC measurement when the thresholds were compared between the three test sessions indicating that the test was repeatable for all the participants taking part in the study. Furthermore, the scores in each session did not significantly differ from each other as indicated by the ANOVA results. Table 4.3 tabulates the results of precision, repeatability, intraclass correlation and ANOVA. The table is composed of four main columns. The first indicates the precision (typical error) measurement as obtained from one way ANOVA. The second column, is the repeatability measure (Rep.), it indicates the agreement between the sessions. The third column tabulates the results of the ICC scores. Table 4.3 is divided into three main sections. Section 1 displays the results of the

BC thresholds for the repeat thresholds per session at the three test frequencies. Section 2 reports the test-retest repeatability for the AC thresholds in the three test sessions. Finally, Section 3 reports the test-retest repeatability for the BC thresholds measured in the three test sessions (6 measurements).

The investigation of the test-retest scores with AC thresholds (Section2) showed small precision scores < 2.5 dB and the repeatability was < 4.5 dB. These results indicate that the test-retest score was within the acceptable limits used in pure tone audiometry. The ICC on the other hand, was very small indicating that this test was not good in identifying differences within the individual responses, the confidence intervals were wide. One of the disadvantages associated with the ICC is when the sample has low variation in their scores, the resultant ICC would be small, which is expected to be the case in the current results (Graham et al, 2012). This is further confirmed by the low SD of the mean for the individual responses. The presence of any differences could be related to random error. On an average the test-retest thresholds were not significant at any of the test frequencies as indicated by ANOVA results (corrected to Bonferroni adjustment).

The precision scores measured with bilateral BC stimulation (section 1) were <5.5 dB for all the conditions with the majority of conditions' results below 3 dB. The repeatability coefficient was lower than 5 dB, the repeatability was largest at 500 Hz. The precision and repeatability results indicate good repeatability when the thresholds were repeated in the same session showing that the test-retest repeatability was acceptable. The ICC scores were > 0.8 with a wide spread of the confidence intervals at the test frequencies which indicated fair repeatability. On average the test-retest thresholds were similar as indicated by the non significant results obtained with ANOVA.

The precision scores measured with bilateral BC stimulation for the three sessions combined (section 3) were <5.5 dB for all of the test frequencies. However, the repeatability was between 6- 11 dB. The results of the precision and repeatability show that the thresholds measured in the three test sessions were higher than the thresholds measured in the same session. The ICC scores were > 0.5 with a wide spread of the confidence intervals at the test frequencies, this indicated fair repeatability. On average the test-retest thresholds were similar as indicated by the non significant results obtained with ANOVA.

Table 4.3 Precision measurements and the interclass correlation in the preliminary investigation.

	Test	Precision (dB)	Rep. (dB)	Intra-class correlation			ANOVA	
				ICC	Confidence intervals	p	F	p
Section 1	BC_250_So_S1	2.9	5.7	0.8	(0.3 to 0.9)	0.002	1.2	0.305
	BC_250_So_S2	1.8	3.7	0.9	(0.5 to 1.0)	<0.001	0.7	0.430
	BC_250_So_S3	4.6	9.2	0.7	(0.3 to 0.9)	0.003	2.8	0.131
	BC_250_Sπ_S1	1.7	3.5	0.9	(0.7 to 1.0)	<0.001	2.2	0.172
	BC_250_Sπ_S2	1.8	3.7	0.4	(–0.2 to 0.8)	0.100	1.5	0.248
	BC_250_Sπ_S3	2.9	5.8	0.9	(0.8 to 1.0)	<0.001	1.1	0.315
	BC_500_So_S1	2.2	4.3	0.9	(0.7 to 1.0)	<0.001	0.4	0.554
	BC_500_So_S2	1.7	3.4	1.0	(0.8 to 1.0)	<0.001	1.7	0.223
	BC_500_So_S3	3.1	6.3	0.9	(0.5 to 1.0)	<0.001	1.5	0.245
	BC_500_Sπ_S1	3.5	7.0	0.8	(0.5 to 1.0)	<0.001	2.5	0.146
	BC_500_Sπ_S2	5.5	10.9	0.8	(0.4 to 0.9)	0.001	0.7	0.430
	BC_500_Sπ_S3	1.2	2.5	0.9	(0.8 to 1.0)	<0.001	0.1	0.782
	BC_1000_So_S1	1.4	2.9	0.9	(0.8 to 1.0)	<0.001	0.4	0.529
	BC_1000_So_S2	2.6	5.2	0.9	(0.6 to 1.0)	<0.001	0.4	0.557
	BC_1000_So_S3	1.6	3.1	0.9	(0.8 to 1.0)	<0.001	1.5	0.257
	BC_1000_Sπ_S1	1.7	3.4	1.0	(0.9 to 1.0)	<0.001	0.7	0.436
	BC_1000_Sπ_S2	1.7	3.4	0.6	(0.1 to 0.9)	0.017	1.1	0.317
	BC_1000_Sπ_S3	0.9	1.7	1.0	(0.9 to 1.0)	<0.001	6.5	0.032
Section 2	AC_250_So_3S	0.9	1.9	0.7	(0.3 to 0.9)	<0.001	3.8	0.044
	AC_500_So_3S	1.6	3.2	0.1	(-0.3 to 0.6)	0.36	1.3	0.289
	AC_1000_So_3S	1.6	3.3	0.3	(-0.1 to 0.7)	0.070	1.5	0.247
	AC_250_Sπ_3S	2.3	4.6	0.5	(0.1 to 0.8)	0.012	2.1	0.160
	AC_500_Sπ_3S	2.3	4.5	0.2	(-0.2 to 0.7)	0.170	1.1	0.342
	AC_1000_Sπ_3S	1.9	3.9	0.3	(-0.1 to 0.7)	0.104	3.1	0.073
Section 3	BC_250_So_6S	5.0	9.9	0.7	(0.4 to 0.9)	<0.001	0.7	0.596
	BC_500_So_6S	5.5	11.0	0.6	(0.4 to 0.9)	<0.001	0.7	0.608
	BC_1000_So_6S	4.2	8.3	0.7	(0.4 to 0.9)	<0.001	1.0	0.433
	BC_250_Sπ_6S	5.0	9.9	0.5	(0.2 to 0.8)	<0.001	1.0	0.417
	BC_500_Sπ_6S	5.7	11.3	0.7	(0.4 to 0.9)	<0.001	0.9	0.468
	BC_1000_Sπ_6S	3.4	6.8	0.7	(0.5 to 0.9)	<0.001	1.9	0.121

AC: Air conduction BC: Bone conduction Rep.: Repeatability
S1,2,3: Session 1 or 2 or 3 3S: the three sessions 6S: the six sessions

The results indicate that the repeatability performance for the participants were good with the AC measurement when the thresholds were compared between the three test sessions indicating that the test was repeatable for all the participants taking part in the study. Furthermore, the scores in each session did not significantly differ from each other as indicated by the ANOVA results.

Two main conclusions are made for the BC masked threshold measurements. The first relates to the participant performance in the two repeats per session showing good repeatability. The second is the repeatability results in the different sessions that showed greater variation but were within an acceptable range, possibly indicating that the placement of the transducer may have influenced the results.

4.3.2 Air conduction: thresholds

Thresholds were measured in two phase conditions, the signal in phase (SoNo) and the signal inverted 180° out-of-phase (SπNo) across three test frequencies (250, 500 and 1000 Hz). The mean threshold, in dB HL, calculated from the three test sessions for the frequencies tested (in Hz) are displayed in Figure 4.5. Box plots show the spread of responses of the participants: boxes (this and remainder box plot figures) represent the median (black horizontal line), lower and upper quartiles (end of boxes), minimum and maximum values (end of whiskers), and outliers (values between 1.5 and three times the inter-quartile range bellow the first quartile or above the third quartile-circles).

The mean masked thresholds calculated for the three test session in SoNo condition was 17.8, 25.4 and 31.8 dB HL at 250, 500 and 1000 Hz, respectively. The thresholds obtained in the SπNo condition were 5.9, 13.7 and 21.7 dB HL at 250, 500 and 1000 Hz, respectively. These results indicate that inverting the phase by 180° produced smaller thresholds of hearing at the three test frequencies as expected (Bernstein et al, 1998; Yost, 2007).

Figure 4.6 illustrates the thresholds measured in three sessions at the two phase conditions, the general overall performance was similar as indicated by the small box

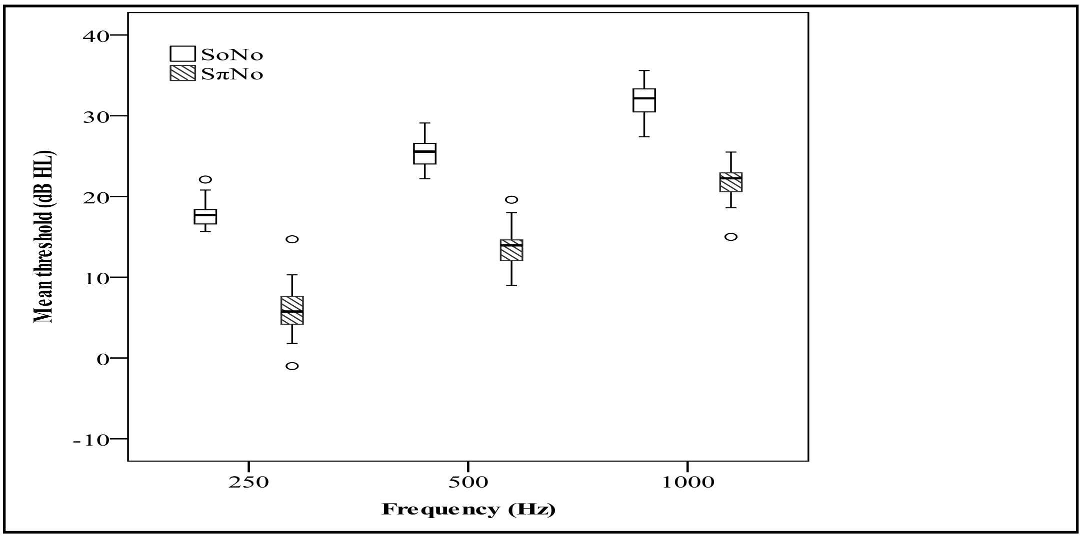

Figure 4.5 Mean AC thresholds in the diotic condition (SoNo, white bars) and in the dichotic condition (SπNo, striped bars), in dB HL, measured at three test frequencies in Hz. Boxes in this and following figures represent the median (thick horizontal line), lower and upper quartiles (ends of boxes), minimum and maximum values (ends of whiskers), outliers (values between 1.5 and 3 times the interquartile range below the first quartile or above the third quartile –circles), and extreme values (values more than 3 times the interquartile range below the first quartile or above the third quartile – asterisks).

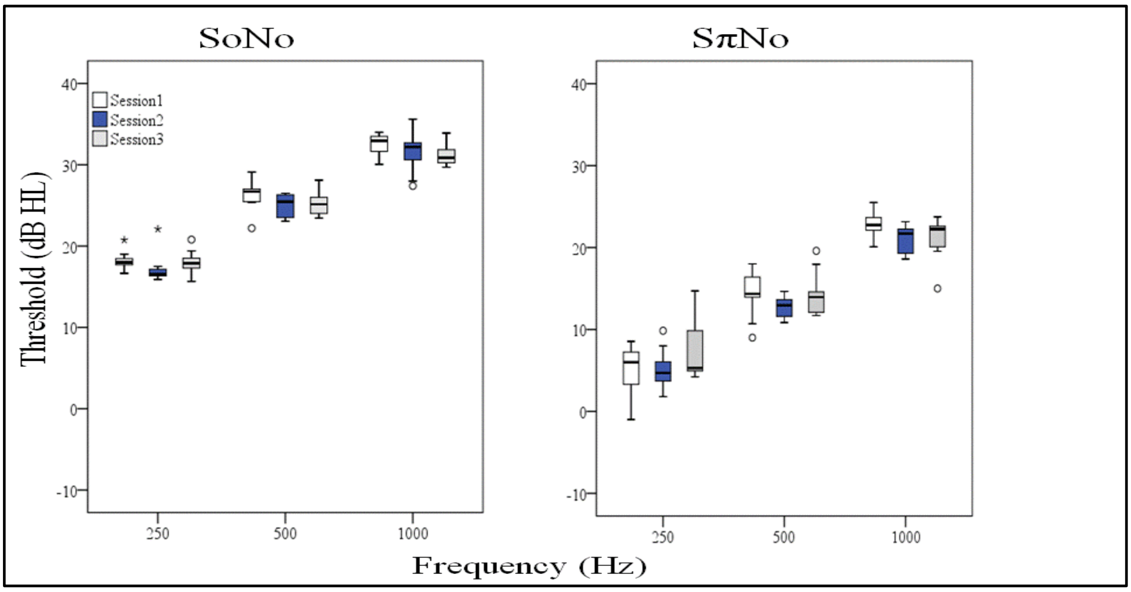

Figure 4.6 AC tthresholds, in dB HL, measured in three test sessions: first session (white bar), second session (blue bar) and third session (grey bar), measured at three test frequencies in Hz. The two panels show: the diotic (SoNo, left panel) and dichotic conditions (SπNo, right panel). For description of the feature of a box plot refer to Figure 4.5

plots. The first session in the two phase conditions appear to produce higher thresholds (worse) compared to the two sessions performed on different days. Inverting the phase produced better hearing thresholds which indicate that the test method was in line with the previous measurements.

Repeated measures ANOVA for SoNo was performed deploying within subject factors of session (3 sessions) and frequency (3 frequencies) to investigate the overall influence of the mean results. Statistical analysis was followed by pairwise comparison to investigate the relation between the pairs corrected to Bonferroni adjustment for multiple comparisons. The repeated measure would investigate the overall difference between the means, thus it might conceal significant effects within the participants.

Table 4.4 tabulates the results of the repeated measures ANOVA at the two phase conditions. The sphericity was assumed in all of the comparisons. The results indicate that the change in frequency influenced thresholds significantly in the two phase conditions (SoNo and SπNo). However, interaction between the frequency and session did not influence the thresholds measured in SoNo and SπNo conditions.

Table 4.4 Results of repeated measures ANOVA in the two AC phase conditions

Test		**Mauchly's test of sphericity**	**ANOVA**	
			F	**P**
SoNo	Frequency x Session	$x^2(9)$= 10.6, p= 0.32	$F_{4,32}$= 0.42	0.79
	Frequency	$x^2(2)$= 1.1, p= 0.58	$F_{2,16}$=565.3	<0.001*
SπNo	Frequency x Session	$x^2(9)$= 5.4, p= 0.80	$F_{4,32}$= 0.73	0.25
	Frequency	$x^2(2)$= 0.4, p= 0.82	$F_{2,16}$= 180.5	<0.001*

The trend observed in first session producing worse thresholds in the three test frequencies observed in Figure 4.6 was not statistically significant. The slight difference could be due to the learning effect as the AC was always tested first so the first session could have resulted in slightly higher (worse) thresholds but it did not reach statistical significance. At 250 Hz the largest difference between the mean thresholds was observed between the first and third sessions with a magnitude of –1.8 dB, while the difference between the first and second session was –0.1 dB, and finally the difference between the second and third session was –1.7 dB. None of these differences were statistically significant. At 500 Hz, pairwise comparisons between the sessions did not result in a significant difference in the thresholds with the largest difference amounting to –1.4 dB between the second and third session. Similar results were observed at 1000 Hz with the greatest difference between the first and second session of 1.8 dB.

4.3.3 Air conduction: MLDs

The MLDs were calculated from the difference between the SoNo and SπNo conditions. The mean results are plotted in Figure 4.7 (left panel). The mean MLDs were 11.8, 11.6 and 10.1 dB at 250, 500 and 1000 Hz, respectively. The right panel of Figure 4.7 plots the calculated MLDs at each test session at the three test frequencies. It can be observed from the figure that the distribution of the participants' MLDs were similar at the three test frequencies.

The change of frequency is known to influence the magnitude of the MLDs (Durlach, 1963; Yost, 2007). This was also confirmed in the current study where the MLDs differed significantly with the change in frequency (Table 4.5), the MLD at 1000 Hz differed significantly from 250 and 500 Hz. Whereas, MLDs measured at 250 and 500 Hz were similar, pairwise comparisons were not significant. The interaction between the frequency and the session was not statistically significant (Table 4.5). This can also be observed from the distribution of the results in Figure 4.7 right panel. The MLDs collected at the three test sessions were distributed in the same manner with no remarkable trends.

The AC MLDs were evaluated to observe the influence of the session at each frequency as indicated in Table 4.5, none of the comparisons were significant. Post-hoc examination showed that at 250 Hz the largest averaged difference was between the first and third session with an average difference of 2.1 dB. Similarly, at 500 Hz the largest difference of 1.3 dB was observed between the second and third sessions. At 1000 Hz, the largest difference in mean MLD between the sessions was –1 dB between the first and second session.

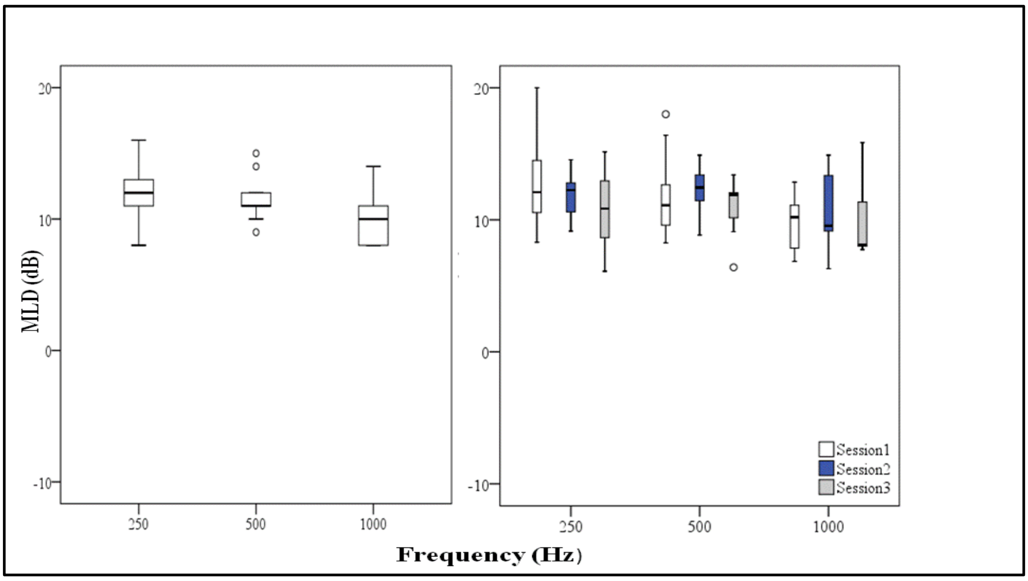

Figure 4.7 The difference between AC SoNo and SπNo thresholds: masking level difference (MLD), in dB, at the three test frequencies in Hz. The left panel shows the overall MLD calculated from three sessions, the right panel shows the MLD in each session. For description of the features of the box plots refer to Figure 4.5.

Table 4.5 Results of repeated measures ANOVA for AC MLD measured in the three sessions.

Test		**Mauchly's test of sphericity**	**ANOVA**	
			F	**p**
Frequency		$x^2(2)$ = 0.33, p= 0.847	$F_{2, 16}$= 7.2	0.006*
Frequency x session		$x^2(9)$ = 4.85, p= 0.853	$F_{4, 32}$= 1.2	0.313
AC MLD session	250 Hz	$x^2(2)$ = 0.19, p= 0.907	$F_{2, 16}$= 1.7	0.202
	500 Hz	$x^2(2)$ = 1.45, p= 0.484	$F_{2,}$ 16= 0.8	0.469
	1000 Hz	x^2 (2) = 1.95, p= 0.378	$F_{2, 16}$= 0.5	0.538

Individual responses of the MLD in the three test sessions are displayed in Appendix I, the error bars indicate the SD for the three sessions calculated for each participant. All participants performed in a similar manner and showed small variation between the sessions.

4.3.4 Bone conduction: thresholds

Binaural hearing with bone conduction stimulation was measured with two matched bone transducers ($BEST_{LFR}$) placed on the most prominent part of the two mastoid bones. The threshold in noise in the two phase conditions was measured twice per session and in three different test sessions.

The thresholds obtained in the SoNo condition were –4.1, 4.7 and 21.7 dB HL at 250, 500 and 1000 Hz, respectively. The thresholds obtained in SπNo condition were –6.6, –0.2 and 15.2 dB at 250, 500 and 1000 Hz, respectively (Figure 4.8). These values were lower than what was expected as it was hypothesised that the signal-in-phase would be similar or equal to AC results. Figure 4.8 shows two main observations. The first is related to the distribution of the participants in the SoNo and SπNo which were wide indicated by the whiskers of the box plots. The second observation is that the increase in the frequency resulted in higher (worse) thresholds for the two phase conditions.

The thresholds for the participants in the three test sessions with the repeats per session are illustrated in Figure 4.9. It is observed that the thresholds followed the same pattern of responses in the three test session for each test frequency in the twp phase conditions. The wide box plots show that there was variation in the participants responses which is similar to the observation of the averaged thresholds. There seems to be slightly less variation in the overall performance toward the last test session mainly observed at 500 and 1000 Hz, this could be attributed to the participants getting more familiar with the test procedure but this was not statistically significant, sphericity was always assumed.

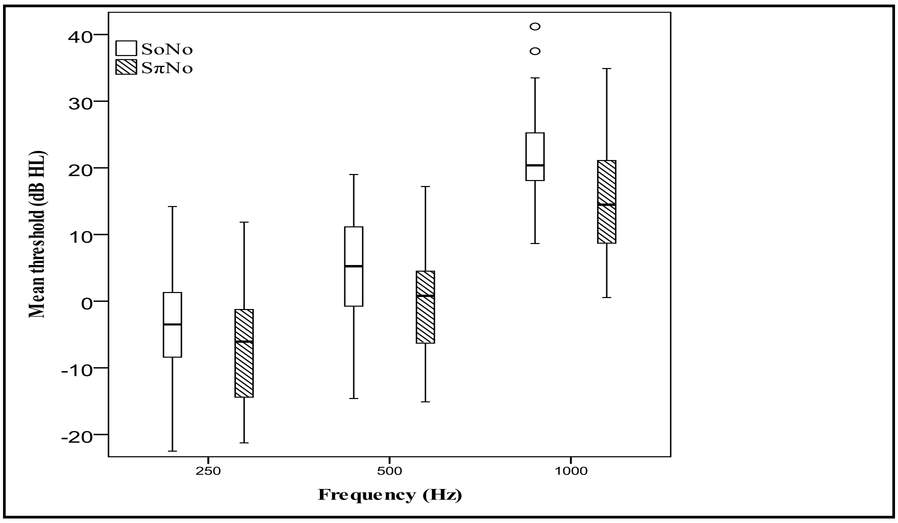

Figure 4.8 Mean BC thresholds in the diotic condition (SoNo, white bars) and in the dichotic condition (SπNo, striped bars), in dB HL, measured at three test frequencies in Hz. For description of the features of box plots refer to Figure 4.5.

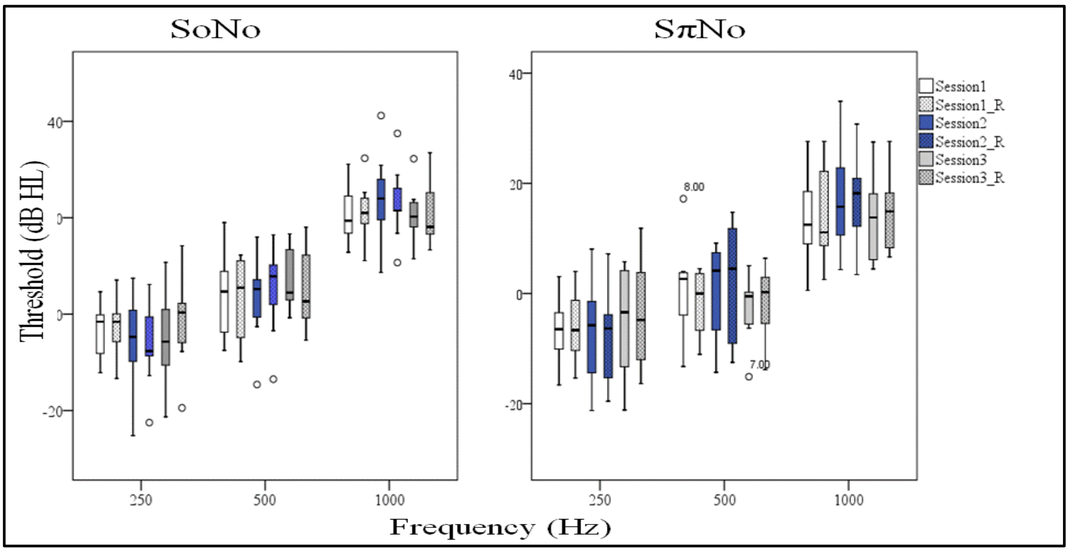

Figure 4.9 BC thresholds, in dB HL, measured in three test sessions: first session (white bar& repeated in white dotted bar), second session (blue bar & repeated in blue dotted bar) and third session (grey bar & repeated in grey dotted bar), measured at three test frequencies in Hz. The two panels show: the diotic (SoNo, left panel) and dichotic conditions (SπNo, right panel). . For description of the feature of a box plot refer to Figure 4.5.

The statistical analysis for this section followed the same procedure used in with the AC thresholds. Repeated measures ANOVA for SoNo was performed with the within subjects factors of session (3 sessions) and frequency (3 frequencies) to investigate the overall influence of the mean results. Statistical analysis was followed by pairwise comparison to investigate the relation between the pairs adjusted to Bonferroni for multiple comparisons. The repeat per session was averaged and the main effect of the session was compared because the results of ANOVA (Section 4.3.1) indicated that the thresholds in the two repeats were repeatable.

Table 4.6 tabulates the results of the repeated measures ANOVA at the two phase conditions. The results indicate that the thresholds significantly differed in the two test conditions. The results indicate that the change in frequency influenced thresholds significantly in the two phase conditions (SoNo and SπNo). However, interaction between the frequency and session did not influence the thresholds measured in SoNo and SπNo conditions. For the SoNo condition, the difference in the mean threshold between 250 Hz and 500 Hz of about –8.8 dB was statistically significant $p<0.001$ as indicated by the pairwise comparisons, the significance level was adjusted to

Bonneferoni. The magnitude of the difference between 250 Hz and 1000 Hz of about –25.8 dB was statistically significant p< 0.001. The difference of –16.9 dB between 500 and 1000 Hz was also significant. These results show that the threshold increment (worsening) as the frequency increased was significant for the three test frequencies.

Table 4.6 Results of repeated measures ANOVA in the two BC phase conditions

Test		**Mauchly's test of sphericity**	**ANOVA**	
			F	**P**
SoNo	Frequency x Session	$x^2(9)$= 21.9, p=0.01**	$F_{4,32}$= 1.8	0.19
	Frequency	$x^2(2)$= 6.9, p= 0.003**	$F_{2,16}$= 218.2	<0.001*
SπNo	Frequency x Session	$x^2(9)$= 6.8, p= 0.67	$F_{4,32}$= 1.4	0.25
	Frequency	$x^2(2)$= 1.9, p= 0.91	$F_{2,16}$= 91.6	<0.001*
** Sphericity not assumed, the results were adjusted to Greenhouse- Geisser				

Furthermore, pairwise comparisons were conducted to evaluate the significant thresholds differences between the frequencies in SπNo condition. The difference of –6.3 dB in threshold between 250 Hz and 500 Hz was statistically significant p<0.01 as indicated by the pairwise comparisons. The magnitude of the difference between 250 Hz and 1000 Hz increased to –21.9 dB which was statistically significant p< 0.001 as indicated by the pairwise comparisons adjusted to Bonferroni. The difference of – 15.5 dB between 500 and 1000 Hz was also significant. These results indicate that the threshold increment (worsening) as the frequency increased was significant for the three test frequencies.

The influence of session was evaluated for each frequency separately as it was mentioned earlier that the repeated measures ANOVA would conceal the main effects. Statistical comparison revealed that the thresholds were not influenced by the change in session in each phase condition (SoNo and SπNo). SoNo thresholds measured at 250 Hz in the three test session were not significant $F_{2, 16}$=1.27, p> 0.05. The SπNo produced similar non-significant results $F_{2, 16}$=0.586, p> 0.05. Thresholds measured at in SoNo 500 Hz of the three sessions (repeats averaged) were not significantly different $F_{2, 16}$=0.427, p> 0.05. Similarly, inverting the phase was not significant $F_{2, 16}$=0.799, p> 0.05. Finally, at 1000 Hz the session effect was not significant with $F_{2, 16}$=1.66, p> 0.05 and $F_{2, 16}$=2.22, p> 0.05 at the SoNo and SπNo conditions, respectively.

4.3.5 Bone conduction: MLD

The release from masking was calculated through subtracting SπNo from SoNo, the results indicated that MLD were present with the magnitude of 2.4, 4.9 and 6.5 dB at 250, 500 and 1000 Hz, respectively. The SD was around 7 dB at the three frequencies. The trend observed from these results is that the MLD increases as the frequency is increased which was not expected.

Figure 4.10 left panel illustrates the BC MLD trend at the three frequencies. It can be observed from the graph that the variation in the participants results were wider at the lower frequencies compared to 1000 Hz. It appears that the participants MLD at 1000 Hz were more condensed as a group. The right panel plots the calculated MLD at the three test sessions and the repeats per session. The spread of the participants responses was similar to the averaged MLD.

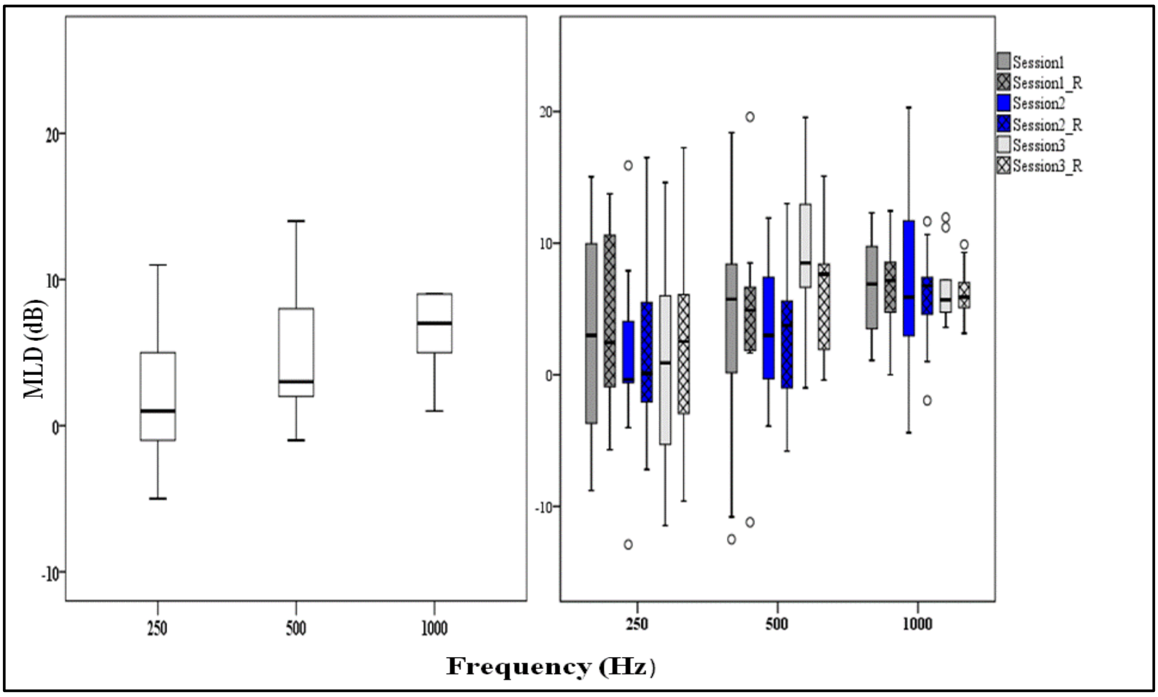

Figure 4.10 The difference between BC SoNo and SπNo thresholds: masking level difference (MLD), in dB, at the three test frequencies in Hz. The left panel shows the overall MLD calculated from three sessions, the right panel shows the MLD in each session. For description of the features of the box plots refer to Figure 4.5

Statistical evaluation was conducted through repeated measures ANOVA for the influence of the frequency and session on the BC MLD (

Table 4.7). The MLD measured at the three frequencies was found to be similar with no statistical significance. Furthermore, the interaction between the frequency and session was not statistically significant. Further analysis of the effect of the session on each frequency also resulted in none significant findings. At 250 Hz, the first session produced the highest MLD with a mean difference of 2 dB compared with the second session. At 500 Hz, the largest mean difference was –4.6 dB between the second and third sessions. At 1000 Hz, the largest mean difference in MLD was between the first and second session with a difference of –0.4 dB.

Table 4.7 Results of repeated measures ANOVA for BC MLD measured in the three sessions

Test		**Mauchly's test of sphericity**	**ANOVA**	
			F	**p**
Frequency		$x^2(2) = 0.51$, p= 0.773	$F_{2, 16}= 2.4$	0.120
Frequency x session		$x^2(9) = 10.20$, p= 0.0.343	$F_{4, 32}= 1.2$	0.313
BC MLD session	250 Hz	$x^2(2) = 7.39$, p=0.025**	$F_{2, 16}= 0.4$	0.594
	500 Hz	$x^2(2) = 1.61$, p= 0.446	$F_{2, 16}= 1.8$	0.192
	1000 Hz	$x^2 (2) = 4.59$, p= 0.101	$F_{2, 16}= 0.03$	0.973
** Sphericity not assumed, the results were adjusted to Greenhouse- Geisser				

Refer to Appendix I for the individual responses in the MLD at the three test frequencies.

4.3.6 Comparison between AC and BC: thresholds

The comparison between the AC and BC thresholds in phase and out of phase serves to explore the relation between the two conditions. A comparison between the AC and BC thresholds for the two phase conditions is illustrated in Appendix F. The BC thresholds in the SoNo condition was always lower in magnitude compared to the AC thresholds, whereas the BC thresholds showed wider variation in the participant responses as a group.

Statistical analysis between the AC and BC was conducted in each phase condition using repeated measures ANOVA with within subject factors of session (3 sessions) and condition (AC,BC) and frequency (250, 500, and 1000 Hz) the thresholds as the dependent variable. Table 4.8 tabulates the results for each phase condition separately.

Table 4.8 Results of repeated measures ANOVA for comparison between the AC and BC thresholds in SoNo and SπNo conditions.

Test			Mauchly's test of sphericity	ANOVA	
				F	p
SoNo	Frequency		$x^2(2) = 3.09$, p= 0.213	$F_{2,16}$= 369.8	<0.001*
	Condition		$x^2(0) = 00$, p= /	$F_{1,8}$= 66.0	<0.001*
	Session		$x^2(2) = 1.03$, p= 0.597	$F_{2, 16}$= 0.1	0.864
	Frequency x condition		$x^2(2) = 7.86$, p= 0.02**	$F_{2, 16}$= 56.2	<0.001*
	Condition x session		$x^2(2) = 1.87$, p= 0.391	$F_{4, 32}$= 0.7	0.580
	Frequency x condition x session		$x^2(9) = 26.31$, p= 0.002**	$F_{2, 16}$= 1.4	0.280
	Condition *frequency	250 Hz	Comparison between two conditions	$F_{1, 8}$= 79.45	<0.001*
		500 Hz		$F_{1,8}$= 93.96	<0.001*
		1000 Hz		$F_{1, 8}$= 22.74	<0.001*
SπNo	Frequency		$x^2(2) = 0.34$, p= 0.843	$F_{2,16}$= 202.5	<0.001*
	Condition		$x^2(0) = 00$, p= /	$F_{1,8}$= 25.9	<0.001*
	Session		$x^2(2) = 8.56$. p= 0.014**	$F_{2, 16}$= 0.01	0.946
	Frequency x condition		$x^2(2) = 0.59$, p= 0.744	$F_{2, 16}$= 9.6	0.002*
	Condition x session		$x^2(2) = 5.66$, p= 0.059	$F_{4, 32}$= 1.1	0.342
	Frequency x condition x session		$x^2(9) = 7.44$, p= 0.604	$F_{2, 16}$= 1.0	0.401
	Condition *frequency	250 Hz	Comparison between two conditions	$F_{1, 8}$= 24.34	<0.001*
		500 Hz		$F_{1, 8}$= 58.35	<0.001*
		1000 Hz		$F_{1, 8}$= 5.65	<0.05*

** Sphericity not assumed, the results were adjusted to Greenhouse- Geisser
/ Not calculated due to two conditions

Table 4.8 shows that the thresholds measured in the three test sessions were not influenced by the condition (AC and BC) which is expected based on the results in the previous sections. Furthermore, the change in frequency has resulted in a significant difference in the thresholds measured in SoNo and SπNo conditions which was observed in the statistical analysis in for the AC and BC threshold presented in the previous sections. The condition that compares the AC and BC thresholds was significant at the two phase conditions. Therefore, further analysis was conducted in the SoNo and SπNo phase conditions at each frequency (last row in each condition). The results indicate that the difference in SoNo between the AC and BC of 21.9, 20.7, 10.1dB at 250, 500, and 1000 Hz, respectively, were statistically significant. Similarly, the differences in the SπNo between the AC and BC thresholds of 12.5, 14, 6.5 dB at 250, 500 and 1000 Hz respectively were statistically significant.

4.3.7 Comparison between AC and BC: MLDs

The comparison between the AC and BC MLDs was carried out to investigate the relation between the two conditions. Figure 4.11 displays box plots for the distribution of the results of the AC and BC MLDs.

Comparison between the AC and BC MLD thresholds was conducted through repeated measures ANOVA to evaluate the frequency (3 frequencies) and condition (AC and BC). The influence of the change in frequency on AC and BC MLD was not significant $F_{2, 16}$= 0.72, p =0.503, Mauchly's test of sphericity was assumed $x^2(2)$ =0.59, p= 0.78. The AC and BC MLD was positive for all the participants at 500 and 1000 Hz. However, three participants had negative BC MLD at 250 Hz (participants 4, 8 and 9). The difference between the AC and BC MLD's was statistically significant for the pooled data from the three frequencies, the AC was always larger in magnitude compared to the BC MLD ($F_{1, 8}$= 42.9, p<0.001). The interaction between the frequency and the condition was statistically significant $F_{2, 16}$= 4.7, p=0.024 sphericity was assumed $x^2(2)$ = 0.51, p=0.773.

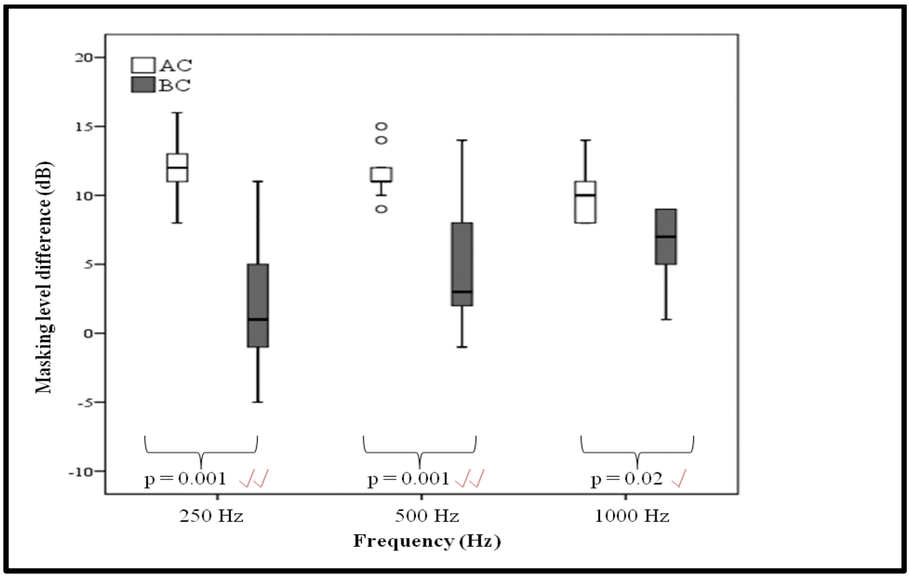

Figure 4.11 The difference between BC SoNo and SπNo thresholds: masking level difference (MLD), in dB, between the AC (white bars) and BC (grey bars), measured at the three test frequencies in Hz. The p values indicate the significance of the comparison. For description of the features of the box plots refer to Figure 4.5.

Further analysis was conducted at each frequency separately to evaluate the difference between the AC and BC MLD. Student *t*-test was used because two paired conditions were tested. The independent variable was the mean MLD and the dependent variable was the condition (AC and BC). The analysis revealed that the AC MLD was greater than the BC MLD at the two test frequencies 250 and 500 Hz, the difference was statistically significant and a marginal significant difference was found at 1000 Hz (Table 4.9).

Table 4.9 Comparison between the AC and BC MLD at each test frequency using paired *t*-test.

Condition	Mean difference (dB)	*t*	df	p
250 Hz	9.4	5.1	8	0.001*
500 Hz	6.7	5.3	8	0.001*
1000 Hz	3.6	6.5	8	0.024*

A trend of an increase in the BC MLD was observed with the increase in frequency, this is contrary to the AC MLD which is known to decrease as the frequencies increase (Figure 4.12).

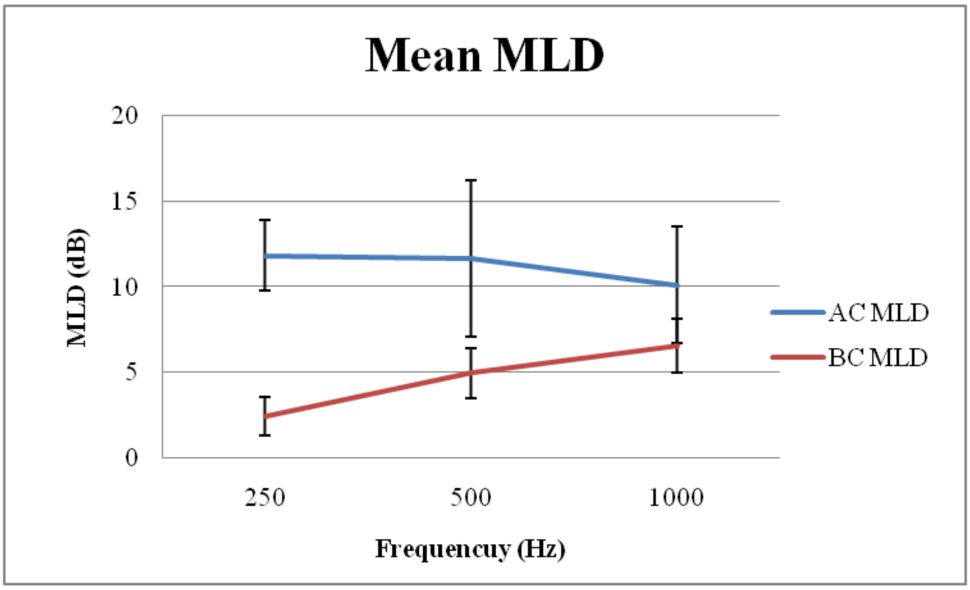

Figure 4.12 Mean AC and BC MLD at the three frequencies. Error bars represent 95% confidence intervals.

Pearson correlations were conducted to evaluate the relationship between the AC and BC MLD at the three test frequencies. There was no relationship between the AC and BC MLD at 250 Hz (r= 0.25, p= 0.51), 500 Hz which was significant (r= 0.66, p= 0.05), and 1000 Hz (r= –0.36, p= 0.32).

Individual MLD data at 250 Hz indicates the all the participants had positive AC MLD (Appendix I). Whereas, the BC MLD had smaller magnitude compared to the AC MLD and three participants had negative MLD (participant 4, 8, 9). Two participants had almost similar magnitude of AC and BC MLDs (participant 2 &7). The rest of the participants had large discrepancy between the AC and BC MLD >5 dB. The calculated confidence intervals were small for the AC MLD indicating that the responses in the three test sessions for each participant was close thereby lending credibility to the measurement. Whereas, the CI were wide in the BC MLD suggesting that the individual responses varied between the three test sessions.

The MLD comparison at 500 Hz indicates that all participants showed positive MLD in the AC and BC stimulation (Appendix I). Two participants had almost equal magnitude of AC and BC MLD (participant 5 &7), while the rest of the participants had large discrepancy between the AC and BC MLD >5 dB. The confidence intervals with the AC MLD's at 500 Hz were small, while the BC MLD CIs was wider.

The discrepancy between the AC and BC MLD at 1000 Hz was the smallest compared to 250 and 500 Hz. Seven of the participants had almost equal AC and BC MLD <4 dB (1, 2, 3, 4, 5, 7, 8), the largest discrepancy at 1000 Hz was 12.6 dB (participant 9).

The current results indicate that the measurable BC MLD was different than the AC MLD. The increase in frequency resulted in a smaller discrepancy between the AC and BC MLD, which was mainly observed at 1000 Hz. Large discrepancies were observed at 250 and 500 Hz supporting the lack of correlation between the AC and BC MLD.

4.3.8 Summary of results

The study aimed at investigating the MLD in BC and AC stimulation as a preliminary investigation. The main findings of this study are summarised in the following points:

- Reliability of thresholds was evaluated in AC and BC stimulation, the results are summarised as follows:
- AC thresholds in SoNo and SπNo measured in three sessions appeared to have good test-retest results as indicated by precision and repeatability coefficient measurements. Furthermore, it was indicated by the confidence intervals of the participants' responses at the three test frequencies. ICC was not a good measure of repeatability due to the small variations in the individual responses.
- BC thresholds repeated in the same session showed precision and repeatability scores that were comparable to the AC results.
- Averaged BC thresholds from the three sessions produced higher precision and repeatability scores. However, the differences in the mean SoNo and SπNo thresholds measured in the three test sessions were not statistically significant.
- The change in frequency had a statistical significant impact on the AC and BC thresholds in the two phase conditions (SoNo and SπNo). Similarly, this was observed with the BC thresholds in the two phase conditions (SoNo and SπNo). The AC thresholds were always higher in magnitude compared to the BC thresholds at the three test frequencies.
- The magnitude of the BC MLD was about 2.4, 5.0, and 6.5 dB compared to the AC MLD of 11.8, 11.7, and 10.1 dB at 250, 500, and 1000 Hz, respectively. The difference between the AC and BC MLD was statistically significant at the three test frequencies with a marginal significant difference at 1000 Hz. Some participants had almost equal AC and BC MLDs.
- The magnitude of the BC MLD appeared to increase with the increase of the frequency from 250 to 1000 Hz. This was contrary to the AC MLD that decreases with the increase in frequency (Levitt & Voroba, 1980).

4.4 General discussion

4.4.1 Repeatability

4.4.1.1 Within-subject variability

The repeatability of the thresholds measurement was evaluated using a number of statistical methods for the AC and BC conditions. Due to the small inter-subject variation with the AC thresholds at the three test frequencies, the ICC scores were not a strong indicator of the repeatability as it resulted in small ICC scores despite the small precision and repeatability scores. The opposite trend was observed with BC thresholds, the ICC scores were high while the precision and repeatability scores were high. The low ICC observed with the AC thresholds can be attributed to the low variability between the thresholds (Graham et al, 2012).

Measurement of the individual standard deviation of the mean showed that 78% of the participants had their AC SD within 2 dB, whereas 80% of the participants had their BC SD was within 5 dB. Some of the participants showed larger individual SD at the lower frequencies. The thresholds measured at1000 Hz produced the lowest BC thresholds for the individual SD deviations. The maximum SD for the BC thresholds of the individual responses was 10.7 dB at 500 Hz. It was noticed that some individuals had higher SD particularly at 500 Hz in the diotic and dichotic phase conditions (participant 3 and 4). The maximum SD for the individual BC at 1000 Hz was 5.7 dB which was comparable to the result reported by Tompkins (2008) of 5.4 dB at 1000 Hz. This indicates that the within-subject variation was comparable between the two studies. Within-subject variation could not be compared to previous background studies reporting BC MLD because their methodology was not repeated in different sessions (Bosman et al, 2001; Priwin et al, 2004; Stenfelt & Zeitooni, 2013).

The mean SD of the BC individual thresholds showed the same trends for the diotic and dichotic conditions in both AC and BC stimulation, this was contrary to the reported results of Tomkins (2008). Tompkins (2008) found that the participants in her study had lower SD in the SoNo condition compared to the SπNo and SoNπ conditions. The reasons for this discrepancy could be due to the different methodology used by

Tompkins, she introduced the signal and noise from the BC transducers which could have resulted in more within-subject variation when the phase of the signal was inverted.

The wider test-retest thresholds with BC stimulation could be related to a number of factors:

1. BC thresholds have been reported to produce wider variability and higher standard deviations compared to the AC thresholds (Ho et al, 2009; Margolis et al, 2010).

2. The placement of the BC transducers between the test-sessions could have resulted in poorer repeatability due to the change in the placement between the sessions despite the care taken to ensure that the placement of the BC vibrators was as consistent as possible between the test sessions.

3. The use of insert earphones occludes the ear canal, care was taken to ensure consistent placement of the foam tip inside the ear canal, and the variation in the degree of occlusion between the two ears and the different sessions was not predictable.

4.4.1.2 Inter-subject variability

The inter-subject variation evaluated by the SDs of the pooled data was lower than 3 dB SD, inverting the phase of the signal tended to producer slightly higher SD of the pooled data at the three test frequencies. The inter-subject variation with AC was comparable to the results reported by Tompkins (2008) at 1000 Hz, for the SoNo condition (SD 1.9 dB) and SπNo (SD 1.8). Furthermore, the SD reported by Stenfelt & Zeitooni (2013) in the AC threshold measurement was around 2 dB in SoNo condition and 3 dB in SπNo using chirp signals. The inter-subject variability results in the present study were close to the background studies indicating that the AC thresholds provides a good and reliable measure to compare the BC results to.

The BC inter-subject variability was characterised with higher SD for the pooled data with no obvious change in trend with frequency or phase. Stenfelt & Zeitooni (2013) and Tompkins (2008) results showed that the SoNo condition produced lower SD which was comparable to the AC thresholds, this was not observed in the current investigation. However, inverting the phase of the signal showed comparable results between the present study 7.9 dB and Tompkins (2008) at 1000 Hz. Stenfelt & Zeitooni (2013) reported that the SD deviation of their pooled data was around 4 dB when the phase of the chirp signal was inverted. The reason for the discrepancy between the present study and that of Tomkins (2008) and Stenfelt & Zeitooni (2013) could be related to the difference in the methodology between the studies. Tomkins (2008) and Stenfelt & Zeitooni (2013) presented the tone and the noise signal through the BC transducers, whereas the current study presented the noise through insert earphones resulting in an occlusion effect which may have contributed to the larger inter-subject variation. Twenty participants took part in Stenfelt & Zeitooni (2013) whereas the preliminary investigation had nine participants which may have led to more detectable inter-subject variation.

The test-retest thresholds with AC stimulation were within the acceptable range of ±5 dB in the two phase conditions. Test-retest thresholds with adaptive test method was reported to produce repeatable thresholds (Trahiotis et al, 1990). Furthermore, the results from this measurement were comparable to the measurement of the AC hearing thresholds (Section 3.4.2.2).

On the other hand, the repeatability measurement with bilateral BC stimulation showed two trends. The precision and repeatability scores were within ±5 dB when the thresholds were measured in the same session, this was comparable to the AC results. The second observation was wider precision and repeatability scores (±10 dB) when the results were compared between the six measurements in the three test sessions. This was comparable to the results of the hearing threshold with BC stimulation measured in Section 3.4.2.4.

4.4.2 Air conduction: thresholds and MLDs

The AC thresholds were measured in two phase conditions (SoNo and SπNo) at 250, 500, and 1000 Hz, where the signal was centred in a broadband Gaussian noise presented diotically at spectrum level of 33.1 dB. Inverting the signal's phase by 180° resulted in better thresholds (5.9, 13.7 and 21.7 dB HL) compared to the SoNo condition (17.8, 25.4 and 31.8 dB HL) at 250, 500 and 1000 Hz, respectively. The change of frequency from low to high resulted in higher (worse) thresholds in the two phase conditions. Hawkins & Stevens (1950) and Yost (2007) reported that thresholds get worse as the frequency increased because the tones needs more energy to be detected thus resulting in higher thresholds. The thresholds measured in the current study were consistent with the results reported by Bernstein et al (1998).

The AC MLD measured by the difference between the SoNo and SπNo thresholds. A number of background studies with similar experimental setup are tabulated in Table 4.10 for comparison purposes with the present investigation.

Table 4.10 Background studies reporting MLD results.

Study	Masker noise	Level (dB SPL)	Masking level difference (dB)			
			250 Hz	500 Hz	1000 Hz	2000 Hz
Bernstein et al (1998)	BB (100-8500 Hz)	50**	NR	13.6	NR	NR
Durlach (1963)	BB	Not indicated	15	12	8-10	3-4
Hall & Harvey (1985)	BBN (2000 Hz wide)	50	NR	14.2 dB	NR	3 dB
Van Deun et al., (2009)	BBN (200- 1000 Hz)	75	NR	13*	NR	NR
Webster (1951)	BB	60	16	11	8	4
Wilmington et al.(1994)	BB (100-3000 Hz)	45	NR	12.8	NR	NR
Preliminary investigation	BB (100-5000 Hz)	70	11.82	11.66	10.12	NR
Interference investigation (Chapter 5)	BB (200-4000 Hz)	75	NR	15.2	11.0	6.6

* Median NR: not reported BB: broadband
** Spectrum level

It is noticed that the current results followed the reported literature at 500 and 1000 Hz. Although, the MLD at 250 Hz was lower than expected. The MLD is sensitive to the signal and tone manipulations (Durlach, 1963; Green & Yost, 1975). The masker level is the most plausible reason for the low MLD compared to literature at 250 Hz, it is reported that an increase in the MLD is observed with noise level increment up to an effective level of 40-50 dB after which it becomes stable (Levitt & Voroba, 1980).

Dolan (1968) reported that the increase in the spectrum level of the noise leads to an increase in the magnitude of the MLD which was investigated at 150 and 300 Hz. Henning & Zwicker (1984) also reported that the magnitude of the MLD increases with the increase in the masking level.

Table 4.11 tabulates MLD results from different investigations using BB masking noise at different spectrum level at 500 Hz. This frequency has extensive literature studies compared to 250 and 1000 Hz.

Table 4.11 Comparison of the MLD (SoNo- SπNo) in studies at 500 Hz (limited to broadband noise).

Study	Noise spectrum level (dB)	MLD (dB)
Quaranta & Cervelle.G (1974)	28 dB	8.2
Van Deun et al. (2009)	46 dB	13
Hall & Harvey (1985)	50 dB	14.2
Trahiotis et al. (1990)	50 dB	15
Current study	33 dB	11.6

4.4.3 Bone conduction: thresholds and MLD

The BC thresholds were measured in SoNo with averaged thresholds of -4.1, 4.7, and 21.8 dB at 250, 500, and 1000 Hz, respectively. Inverting the phase of the signal resulted in improvement in hearing thresholds of about -6.6, -0.2 and 15.2 dB, respectively. These results indicate that the SoNo thresholds were different than expected. It was expected that the SoNo would be comparable to the magnitude of the AC SoNo thresholds because the sound stimulates the basilar membrane in the same manner and the calibration was similar. One reason could have influenced the level of the thresholds would be related to the overall level of the masking noise which could have been low for the mask the BC signal.

The BC MLD calculated from the difference between the SoNo and SπNo was significantly different than zero with magnitude of 2.4, 5.0 and 6.5 dB at 250, 500 and 1000 Hz respectively, indicating that the MLD was measureable. The presence of BC MLD at the three test frequencies might be due to an actual binaural hearing and in this case the level of the MLD is expected to be similar to the AC MLD in addition to the presence of a high TA and high TD. Another explanation could be due to the contribution of monaural effect as a result of the cross-talk of the signal at the cochlea. The signal presented in the So condition is expected to be lower than the AC So because the interference of the contralateral ear would be dependent on the TA and TD, whereas the signal in the Sπ condition will be influenced by an external IPD and internal TA and TD leading to a possible enhancement in the thresholds. For example, the application of the model described in Section 2.6.1.3 show that the resultant MLD could be between –11 to 11 dB if the TA is about 5 dB.

The results in the present study can be explained by the cross-talk model because three participants had negative MLD at 250 Hz which is an indication of cross-talk of signal described above. The observed trend that the BC MLD increased with the increase in frequency is an indication that the cross-talk leads to an enhancement in the level of the BC MLD. Furthermore, the wide inter-subject variations indicate that the internal TA and TD are different for each participant. However, these explanations are speculations because the TA and TD were not measured.

Few investigations have reported measuring BC MLD in normal hearing participants. Stenfelt & Zeitooni (2013) reported an average MLD of 4.9 dB in 20 normal hearing participants using a chirp tone masked by white noise presented at 60 dB SPL (spectrum of 27 dB). This threshold is similar to the result obtained in the current study with pure tone at 500 Hz of 4.9 dB, despite their argument that the interference should be measured with non-stationary tone and not a pure tone. However, it seems that the BC MLD was influenced in the same manner for the stationary and non-stationary signal. They concluded that cross-talk may have partly influenced their thresholds.

Tompkins (2008) reported a BC MLD of 2.2 dB at 1000 Hz, this was lower than 6.5 dB BC MLD measured in the present investigation. The difference between the two studies includes the use of BEST and the masking noise was always present by insert earphones in the present investigation compared to the B71 and presenting the signal and noise from the BC transducer in Tompkins (2008) investigation. The use of different transducers is unlikely to be the reason for this discrepancy because the verification of transducers (Chapter three) found that the two transducers were similar at 1000 Hz. It is more likely the presenting the noise source from the BC transducer was the reason for the difference between the two studies because of the limitation of the transducers frequency response. Furthermore, presenting the noise and tone from the same transducer can cause signal distortion that have unpredictable influence on the outcome (Sorenson & Schubert, 1976).

4.4.4 Comparison between the AC and BC: thresholds

The AC was always significantly different than the BC thresholds whether the signal was in-phase or out-of-phase. The difference was reduced as the frequency of the signal was increased but the gap was never closed (i.e. the AC and BC were never equal). The thresholds with the BC were always lower (better) than the AC thresholds in the two phase conditions across the three test frequencies. This can be explained by the occlusion effect as the two inserts were placed in the ear canal for the noise presentation. The influence of the occlusion would result in the enhancement of the hearing thresholds, the magnitude of the enhancement is supposed to influence the SoNo and SπNo in the same way thus the resultant difference (MLD) should not be affected. The occlusion may influence the quality of the signal by changing the phase or level of the tone. Reducing the occlusion effect by trimming the tips of the inserts was advised by (Stenfelt & Reinfeldt, 2007). However, the pilot study showed that the level of the masking noise would be compromised and it was difficult to place the tip in the ear. Therefore, it was decided to place the foam tips without modification.

4.4.5 Comparison between the AC and BC: MLD

The magnitude of the BC MLD was lower than the AC MLD despite the fact that all the participants had normal hearing and they had access to binaural cues in their daily lives. The difference between the AC and BC MLD was statistically significant at the three test frequencies. The BC MLD was compared to the MLD results for patients with CHL measured either through AC or BC stimulation (Table 4.12). Patients with CHL were targeted because bilateral BCI is mainly fitted to patients with CHL. The MLD measured with AC stimulation in patients with CHL was higher in magnitude compared to the results of the BC MLD measured in normal hearing participant (Quaranta & Cervellera, 1974; Hall & Grose, 1994). This indicates that the BC route contributes to the smaller MLD magnitude; this further supports the cross-talk hypothesis.

Hausler et al (1983) used bilateral bone vibrators with four participants suffering from CHL and two normal hearing participants. Their results with the CHL participants were similar to the results obtained with earphones. However, the normal hearing participants scored as if they had hearing loss. Especially the just noticeable difference in time was above normal range with bone vibrators when compared to earphones. The just noticeable difference in level was within the normal range for the headphones when the bone vibrators were placed on the two ears, it was above the normal range when one bone vibrator was used on one ear and an earphone on the other. This indicates that the transmission of the sound through the bone in normal hearing participants has a negative influence on the binaural cues.

Table 4.12 Comparison of the MLD (SoNo- SπNo) in various studies with CHL patients and normal hearing participants.

Study	Condition	Noise level (dB SPL)	Frequency (Hz)	MLD (dB)
Quaranta & Cervelle.G (1974)	Earphone	Broadband noise at 60 dB SPL	500	8.1
Hall & Grose (1994)	Inserts	NBN	500	10.4
Bosman et al (2001)	BAHAs	NBN at patient comfort level	125 250 500 1000	6.1 6.0 6.6 4.1
Stenfelt & Zeitooni (2013) NORMAL	BESTs	Band-limited white noise at 60 dB SPL	Chirp tone	4.9
Current study (NORMAL)	BESTs	Wide band noise 70 dB SPL	250 500 1000	2.4 4.9 6.5

Comparison between the BC MLD measured in normal hearing participants and patients fitted with bilateral BAHA (Bosman et al, 2001) showed that the MLD was within 2 dB between the studies at 500 and 1000 Hz and within 4 dB at 250 Hz. The results were similar despite the differences between the participants and the difference in methodology. This further supports Hausler et al (1983) observation and indicates that the results are more likely to be due to monaural interference rather than binaural hearing.

These results indicate that normal hearing participants perform differently when tested with bone vibrators compared to earphones, whereas the patients performed in the same manner when tested with headphones and bone vibrators. This clearly indicates that more testing is required with normal hearing participants to allow for proper explanation of the results. Furthermore, patients suffering from CHL (similar to the majority of patients fitted with BCI) are reported in some studies to perform similar to normal hearing participants when MLD is tested with AC stimulation at 500 Hz masked with wide band noise (Quaranta & Cervellera, 1974) whereas other studies reported lower magnitude of MLD (Hall & Grose, 1994) when compared to normal hearing control group (CHL 10 dB compared to 17 dB with normal hearing). The magnitude of the MLD with bilateral BAHAs was even lower in magnitude compared to these two studies, again this indicates that the BC transmission could have an influence on the quality of the signal and also supports that the interference of the signal might be a plausible explanation to the degradation of the MLD.

The results in literature with bilateral BAHAs measured the MLD with the patients without control groups. Therefore, there are several factors influencing the understanding of the MLD processing through bone conduction stimulation. For example, patients have pathologies so they don't represent what occurs with normal hearing participants. The location of the placement of the BAHA is different than the position where the regular BC is placed so their results could have been influenced by the change in phase due to the position. Procedural variables of the studies could have influenced the outcome of the measurements like small sample size and low number of repetitions.

The factors that may have influenced the results at low frequencies include the BC transducer producing tactile sensation especially at 250 Hz. This reason can be excluded in the current study because the $BEST_{LFR}$ were shown to produce vibrotactile thresholds at levels of 35 dB HL and above. The thresholds in the current study were measured at levels much lower than this level. Another main factor that may have caused the discrepancy in the thresholds in the two phase conditions between the AC and BC is the occlusion effect. It is the improved hearing threshold observed when the ear canal is occluded (Stenfelt & Reinfeldt, 2007). It is acknowledged in the current study that the presentation of the noise by insert earphones will cause occlusion effect. However, it was hypothesised that since the two ears are occluded then the influence should be symmetric and would not affect the overall difference in phase. Furthermore, it is not anticipated that the occlusion would have influenced the MLD because the current finding is similar to the BC MLD reported by Stenfelt & Zeitooni (2013) who presented the tone and noise from the vibrator without occluding the ears.

Shifts in the vibrator position as large as 4 cm have been shown to have very little effect on the strength of the received stimulation (Studebaker, 1962; Dirks, 1964). On the other hand, Stenfelt (2012) reported different results of TA with two different positions with patients with unilateral hearing aids and concluded that studies with mastoid results should not be compared to the positioning of the BAHA as the results showed that the TA was systematically lower at this position. The results in the current study measured the thresholds with the vibrators placed on the mastoid bone so the different placements on the different sessions may have influenced the variation in the results. However, the MLD in different sessions was not significantly different indicating that small changes in the placement do not affect the overall MLD.

The AC MLD is sensitive to the signal and masker manipulations (Green & Yost, 1975; Hall & Harvey, 1985; Grose et al, 1997; Buss et al, 2007). However, due to the limited background studies with bilateral BC stimulation, little is known about the effect of the signal and masker manipulation with BC MLD. The present results are similar to Bosman et al (2001) despite using different masker bandwidths and normal hearing participants against pathological ears, indicating that studies with a different test setup would be of interest.

The current results with the normal hearing participants were similar to the results reported with the bilateral stimulation with bone conduction with BAHA users which could mean that in both cases the responses were due to the interference pattern of the BC signals inside the head rather than the result of BC benefit this indicates that further investigation is required to evaluate the interference of the signals by measuring the TA and the monaural bone conduction thresholds.

4.5 Conclusions

- The current methodology was sufficient to produce significant AC and BC MLD. The AC MLD and BC MLD were comparable to the reported literature (Bernstein et al, 1998; Bosman et al, 2001; Van Deun et al, 2009; Stenfelt & Zeitooni, 2013). The results were in line with a recent study that investigated the MLD with non-stationary signal (Stenfelt & Zeitooni, 2013).

- Significant discrepancy between the AC and BC MLD was observed at the three test frequencies. The largest discrepancy was observed at 250 Hz with individual trends in the opposite direction.
- The BC MLDs evaluated at different frequencies showed a small trend of an increase in the magnitude as the frequency increased. This is contrary to the expectations with AC MLD.
- The observations in this study can be explained by the monaural effect due to the cross-talk of the signal. The monaural effect is influenced by the individual TA and TD and can result in an apparent MLD due to the stimulation at one cochlea rather than binaural hearing.
- The study concludes that further investigation is required to evaluate the monaural effect and the TA and TD.

Chapter five. Masking level difference with bone conduction stimulation: investigation of interference

5.1 Overview & rationale

Discrepancy between the AC and BC MLD was observed in the preliminary investigation (Chapter four). The results indicated that the methodology applied was sufficient to produce significant levels of BC MLD at the frequencies evaluated (250, 500 and 1000 Hz). However, the BC MLD was lower in magnitude compared to the AC MLD at the three test frequencies. Evaluation of the repeatability showed that within-subject and inter-subject variation was lower in the AC results compared to BC MLD indicating better repeatability with AC MLD. Furthermore, it was observed that the change in frequency resulted in an increase in the BC MLD contrary to the AC MLD.

One explanation for discrepancy between the AC and BC MLD could be related to the cross-talk of the bilateral signal at the cochlea. With bilateral stimulation each cochlea will receive the signal from the two BC transducers due to the small acoustical separation. This would result in an unknown enhancement or destruction of the resultant signal due to the involvement of the TA and TD. To evaluate the cross-talk of the signal Zurek (1986) proposed a mathematical model that assumes negligible AC contribution because of interaural separation between the cochlea of 60-80 dB (Zwislocki, 1953), the model also assumes symmetry between the two ears. The model explored in Section 2.6.1.3 shows that the sound can be amplified if the two signals are received at one cochlea are in the same phase, otherwise if the sound arrives from one ear out of phase to the other ear, this will lead to destruction of the signal, the difference between the in phase and the out of phase would be large (i.e. equal to the reported binaural benefit).

The cross-talk model was applied to a range of frequencies to evaluate the MLD resulting from stimulating one cochlea i.e. MLD due to the monaural effect. Figure 5.1 plots the predicted results based on a TD of 0.5 ms (Bekesy, 1948; Stenfelt & Goode, 2005) and TA values ranging from 2-10 dB based on literature results (Nolan & Lyon, 1981; Vanniasegaram et al, 1994; Stenfelt, 2012). The signals presented through the two BC in phase are the result of the ipsilateral minus contralateral signal transmission. While inverting the phase in one BC transducer would be the result of ipsilateral plus contralateral signal transmission. The figure indicates that the increase in TA would result in smaller monaural effect compared to lower TA values. Furthermore, the monaural effect could have a different direction (negative values) at some frequencies if compared to the AC MLD. Variation in the participants responses are expected because of the variation in the TA and TD values (Section 2.6.1).

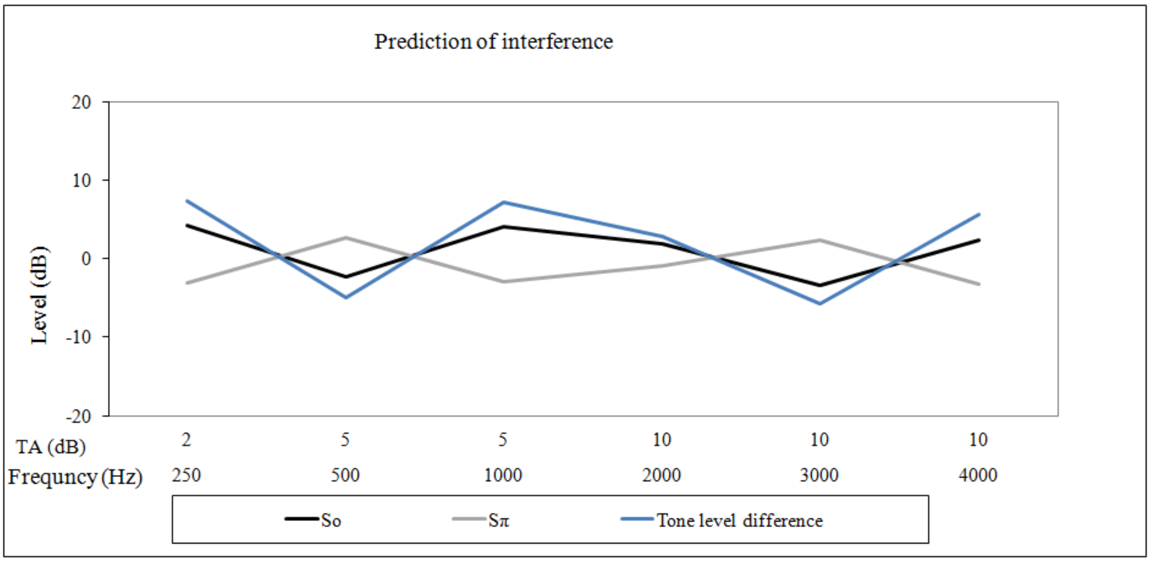

Figure 5.1 The predicted monaural interference effect as a function of frequency, in Hz, the level of the TA used at each frequency is indicated.

This chapter aimed to investigate the influence of signal interference at each cochlea that could have resulted in the discrepancy between the AC and BC MLD. It builds on the preliminary investigation by measuring the bilateral BC MLD with modified test conditions. Furthermore, it aimed to investigate the origin of the BC MLD by investigating the monaural interference effect in the right and left ears. The monaural interference effect was measured by presenting the signal through bilateral BC stimulation in two phase conditions, similar to the BC MLD measurement, while the masking noise was only presented to the non-test ear to mask the signal. The resultant tone difference was envisaged to be due to signal arriving at one cochlea rather than a binaural benefit. The measurement of the monaural interference effect was intended to explain the observed discrepancy between the AC and BC MLD. An additional aim was to investigate the influence of the transcranial attenuation (TA) on the discrepancy between the AC and BC MLD. The assumption was that small TA would be associated with a large difference between the AC and BC MLD, while a large TA would result is greater isolation between the cochlea leading to smaller differences between the AC and BC MLDs.

An overview of the study design is illustrated in Figure 5.2. The participants attended three test sessions, and each session was divided into three sections. The order of the testing was counterbalanced, the screening was always part of the first session. The session structure shows the specifics of a given test session.

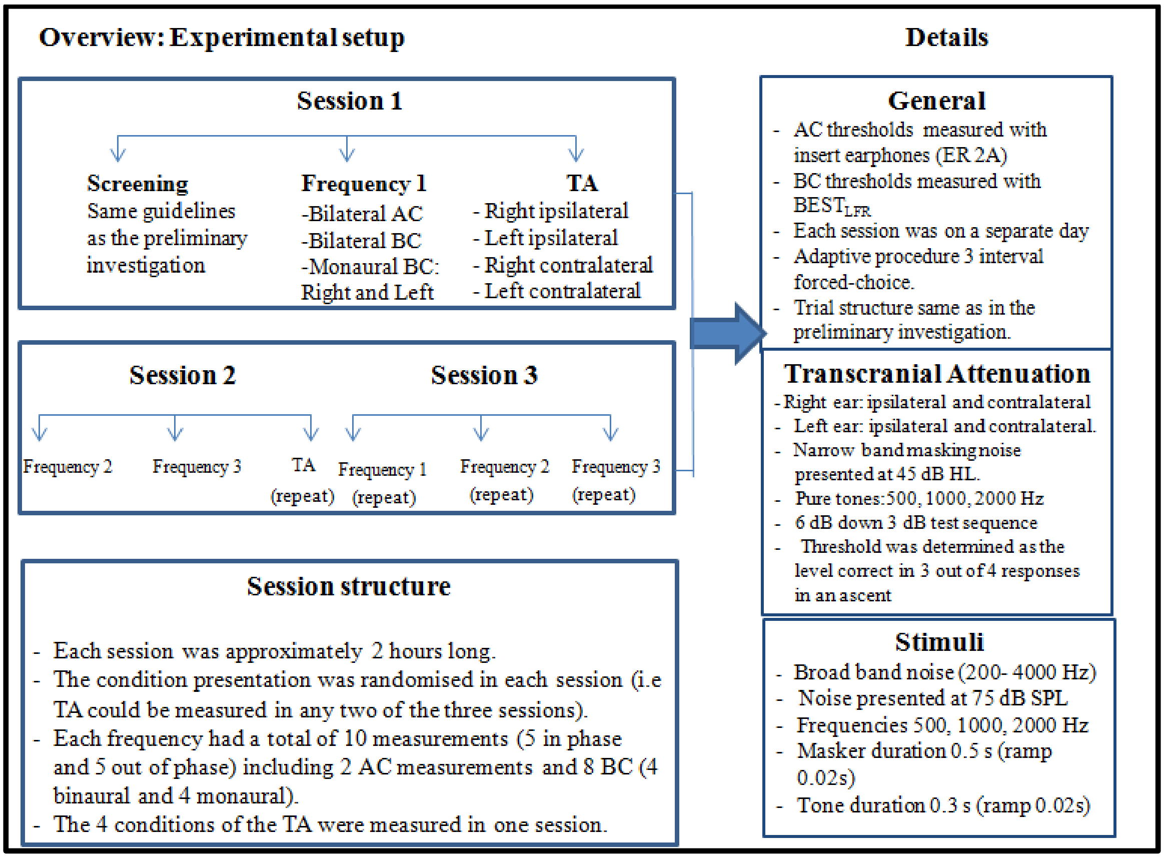

Figure 5.2 Overview of experimental design and structure.

The following hypotheses were made in this study:

1. The hypothesis for the AC and BC MLD were passed from the preliminary investigation for the main effects. The additional frequency presented at 2000 Hz is hypothesised to produce a smaller discrepancy between the AC and BC MLD compared to 500 and 1000 Hz because the reported TA is reported to be larger at higher frequencies (Nolan & Lyon, 1981). Based on the trend observed in the preliminary

investigation that the MLD increases with the increase in frequency it is hypothesised that the MLD at 2000 Hz would be larger than the MLD at 1000 Hz. AC MLD is expected to be small at 2000 Hz.

2. It is hypothesised that TA measured at each frequency would clarify the variation in the BC MLD seen in the preliminary investigation. Participants with low TA would have large monaural interference and large binaural MLD discrepancy between the AC and BC, which would indicate that the binaural results are due to the interference of the signals at the cochlea. Whereas, participants with large TA would have low monaural interference and small binaural MLD discrepancy between the AC and BC MLDs indicating that the binaural MLD is due to binaural hearing and not due to interference.

3. The monaural effect measured by the difference between the Sπ and So is hypothesised to vary in direction depending on the TA and TD values. This effect is expected to have high inter-subject variability. Furthermore, it is expected to have an apparent MLD without binaural processing.

Ideally, the measurement of TD and additional phase conditions would be included in this study. However, the measurement of TD was shown to require tremendous amount of time and it was associated with a number of procedural variables as reported by a PhD researcher working on measuring the TD while this present study was conducted. Measurement of different phase conditions was not feasible due to the time constraints.

5.2 Specific methods

The broad methodology was similar to the preliminary MLDs measurement described in the Chapter 4 in terms of the transducers used, in addition to the general setup and the participant response. Slight adjustments were made to the choice of signals and levels (Section 5.2.3). This study aimed to investigate the interference of signals at the cochlea by measuring the monaural tone level difference and the transcranial attenuation.

The current methodology ensured consistent placement of the two BC transducers on the mastoid bone. The preliminary investigation showed that the repeatability of the measurements was affected by the change in the test session. The placement of the BC transducers can influence the phase and loudness of the signal which could contribute to the variability of the participants performance between the sessions. Therefore, extra care was given to place the transducers where the left BC transducer was always placed first. The band of the right transducer was covered with foam to decrease the effect of the steel bands touching thus causing signal interference and increasing comfort.

All participants taking part in the study followed the same screening guidelines in Section 3.4.1.2. All the participants signed an informed consent prior to taking part in the study.

5.2.1 Participants

Eighteen normal-hearing participants were recruited in this study (age range 19- 33 years, 4 males and 15 females) with a mean age of 27 years. Participants were recruited through email invitations sent to the department. Eight of the participants were audiology students and participated previously in hearing experiments. Four participants participated in the preliminary investigation (see Section 5.3.6.3).

The results obtained from the first participant were discarded from the analysis because the test setup was later changed by using an amplifier instead of the audiometer for BC sound delivery (participant 19). In order to keep the methodology consistent for all the participants it was decided to remove the results of the first participant.

Participants were paid £10 for their participation which was given at the completion of the three sessions. Two participants were given £30 as a bonus for taking part in the study and were chosen through a raffle.

Participants attended three testing sessions, each lasting approximately 2 hours, the order of the testing was counterbalanced (Appendix K).

5.2.2 Apparatus

The same apparatus used in the preliminary investigation were used for the current study. A laptop with a MATLAB program installed was used to route the signal to a sound card (Creative extigy). The signals were then amplified and controlled through an audiometer (KC 50) used for the inserts. The second audiometer used for routing the signal to the two BESTs in the preliminary investigation was replaced with an amplifier (OBH 21/21

SE headphone amplifier). Calibration indicated that the amplifier did not influence the quality of the signal. Furthermore, it did not produce harmonics or distortion. The volume control of the amplifier was secured with tape to make sure that it did not move between testing. Calibration was also performed at the beginning and middle of the week to ensure that the levels were stable. The reason behind replacing the audiometer with an amplifier was because it was noticed that the volume control unit on one of the channels was not stable which could lead to signal distortion without noticing.

A second amplifier was used for the TA measurements because the test setup was different than the MLD and a different MATLAB file was used. Using a second amplifier ensured that the calibration for the TA remained consistent without manipulation of the volume control of the device.

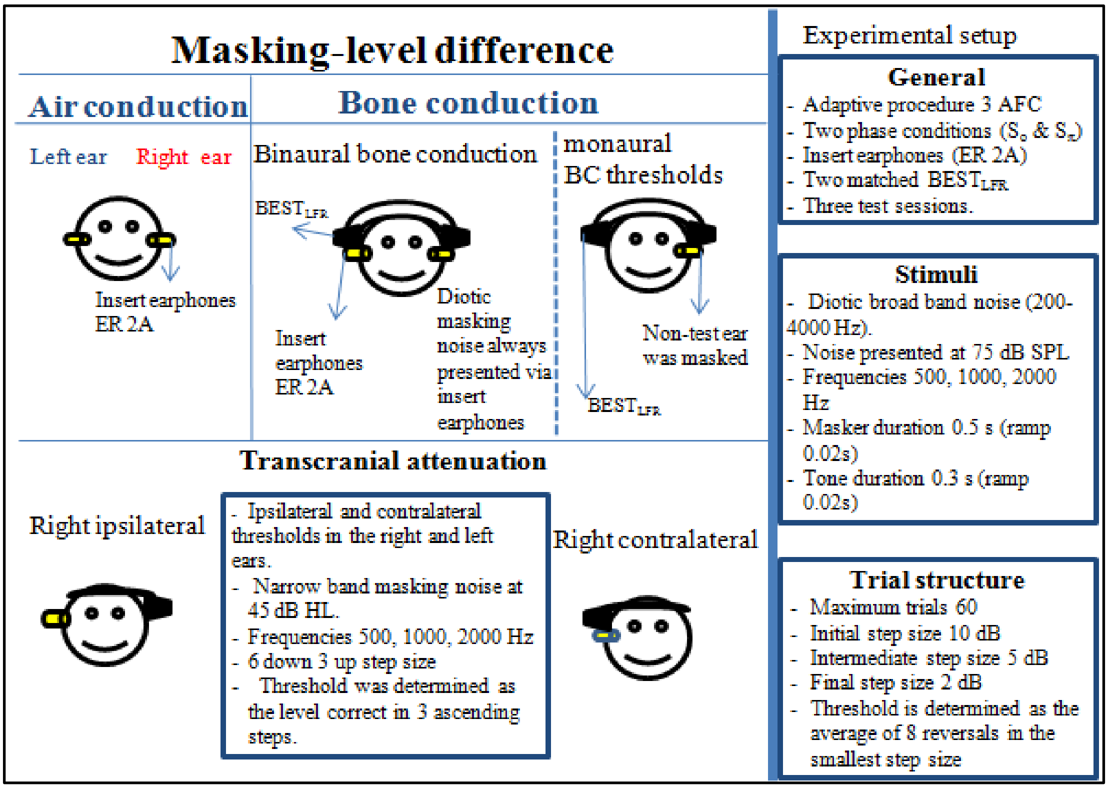

Figure 5.3 Investigation of interference: illustration of the three main test conditions (MLD, monaural interference effect and TA).

Figure 5.3 illustrates the main test conditions. The first test was the AC MLDs it used the same inserts (2A) as in the preliminary investigation, the insert tips were deeply inserted as instructed by the manufacturer with less than approximately 1mm of foam being visible. For the BC testing the two matched BESTs were used for the bilateral and monaural conditions.

The participant response pattern was also the same as the preliminary investigation. A mouse (left click) was used for subject responses and a feedback monitor indicated the correct response, participants were able to abort the test trial if they needed to by pressing the “abort” button present on the response screen (refer to Figure 4.2).

Measurement of the TA used one BEST and NBN masking noise delivered through the one insert earphone to the non-test ear. A computer mouse was used as a response button.

5.2.3 Stimuli

Pure tone frequencies were presented: 500, 1000 and 2000 Hz at a start level of 55 dB HL. This level was adaptively decreased while the level of the masking noise was constant. The signals presented by the AC insert earphones and the BC transducers were calibrated to produce the same hearing level. Unlike the preliminary investigation, 250 Hz was not measured in the present investigation of interference because it was associated with large variability in the preliminary investigation in addition to the time constraints.

The masker noise used was broadband Gaussian noise (bandwidth of 200 to 4000 Hz). The broadband Gaussian noise was checked to have equal energy across the frequency range through the calibration. The masking noise was presented through MATLAB and routed to a SLM and spectrum analyser “HP 3582”. The masking noise was presented at a constant level of 75 dB SPL which was equivalent to a pressure spectrum level of 39.1 dB. This could address the lower AC thresholds compared to the literature found in the preliminary investigation, most of the studies have used a pressure spectrum of over 40 dB SPL (Bernstein & Trahiotis, 1993; Bernstein et al, 1998; Wilson et al, 2003). The masker bandwidth was decreased compared to the preliminary investigation. The decrease in the overall bandwidth aided in the increase in the overall level of masking that was within the permissible levels and was comfortable for the listeners. The masking noise remained wide to cover the targeted test frequencies.

The testing followed the preliminary investigation by presenting the masking noise always from the insert earphones for the signal presentation by inserts and BC transducers (refer to Section 4.2.4 for justification).

5.2.4 Trial structure MLD testing

The trial structure was presented through 3AFC two-down one-up procedure which was similar to the method used in the preliminary investigation. The signal duration was adjusted to 0.3s (0.4s in the preliminary investigation) with cosine-squared onset-offset ramps of 0.02s. The noise duration was presented for duration of 0.5s (0.6s in the preliminary investigation) and 0.02s cosine-squared onset- offset ramps. These changes were not expected to cause any difference in the results of the preliminary results because it was reported that the duration of the signal and masker scarcely influence the MLD outcome, but it is expected that the thresholds in the two phase conditions to be dependent on the signal duration in the same way (Henning & Zwicker, 1984; Zwicker & Zwicker, 1984). Feedback was presented to the participants to keep them motivated.

This study has used the same adaptive method used in the preliminary investigation with the same threshold definition and stopping rule (Section 4.2.6). The masking noise was always constant in level while the tone presented by either the inserts or the BC transducers was varied in level. The MLD was measured through 3 AFC procedure was used with a two-down, one-up adaptive staircase.

5.2.5 Transcranial attenuation

TA was measured in the same participants taking part in this study (N=18). Previous studies reporting TA used participants with single sided deafness (SSD) (Nolan & Lyon, 1981; Vanniasegaram et al, 1994; Stenfelt, 2005). The method used for measuring the TA in these studies was through threshold measurement with the transducer placed on the normal hearing ear then (named as the ipsilateral side) after the threshold was obtained the transducer was placed on the contralateral side and the threshold was measured again. The difference between the contralateral and ipsilateral thresholds is the transcranial attenuation.

Due to the nature of the investigation and because the participants had normal hearing it was decided to measure the transmission of sound in the two sides of the head to investigate the symmetry between the ears and if it contributes to the monaural interference. Therefore, ipsilateral thresholds were measured with the transducer in the test ear (either right or left) and masking noise in the non-test ear. For the contralateral thresholds, the transducer was placed on the non-test ear and the masker remained in that ear.

Pure tone frequencies of 500, 1000 and 2000 Hz were used, the threshold was collected automatically using MATLAB to generate the signals. In general, the method followed the BSA recommended procedures with modification to the step size. A 6 dB down 3 dB up test sequence was used to allow for more measurement precision. The threshold was determined based on the lowest level the participant responds to in 3 out of 4 correct responses in an ascending manner.

The masking noise was narrow band noise centred at the frequency of interest. The masking noise ensured that the threshold measured was for the test ear. It was presented at 45 dB EML through insert earphones ER 2A. The level of the masking noise was considered sufficient to mask the non-test ear based on ISO 389-3 (1999) which recommends that the masking noise is presented at 35 dB HL when measuring hearing thresholds with BC stimulation. Furthermore, Nolan & Lyon (1981) presented the masking noise at 45 dB HL when measuring TA in normal hearing participants. The examiner placed the foam tip in the ear safely and accurately following the recommendation of the manufacturer.

Each session consisted of four measurements: right and left ipsilateral, right and left contralateral threshold measurement. The session lasted approximately 40 minutes and was repeated in a second session. The order of testing was counterbalanced to minimise any order effect (Appendix K).

The equipment setup was similar to the MLD measurement. The signals were generated through MATLAB software from a laptop connected to a sound card which was connected to an amplifier (OBH 21/21 SE headphone amplifier) for signal amplification. The narrow-band noise was generated from the audiometer (KC 50).

One BC transducer ($BEST_{LFR1}$) was used throughout the testing. It was positioned according to the test condition by the examiner and placed on the most prominent part of the mastoid bone. Participants were instructed to alert the examiner if the transducer slipped at any point during the testing.

Participants responded through a left click on a computer mouse, and computer screen was placed in front of the participant to alert them to the start and end of the test.

5.2.6 Monaural interference effect

To investigate the interference of the signals at each cochlea, it was decided to measure the monaural interference effect through bilateral BC stimulation at the right and left ears while masking the non-test ear. It was assumed that masking one ear would result in the exclusion of that ear and the tones from the two bone transducers would be measured at one cochlea (test ear). The testing used the same setup of the binaural MLD testing with the exception that the masking noise was removed from the test ear during the testing.

The two bone conduction transducers were placed on the mastoid bone in the same way as in the binaural measurement while only one insert earphone was placed in the non-test ear and provided the same broad-band Gaussian masking noise used in the binaural condition to mask that ear. It was assumed that the two signals will interact according to the phase of the tone (So or Sπ) and the calculated monaural tone level difference (MTLD) would provide an estimate of the signal interference at the cochlea.

5.2.7 Statistical analysis

The statistical analysis followed the same guidelines used in the analysis of the preliminary investigation (Section 4.2.7). As the measurements were conducted in two different sessions, the repeatability was investigated.

Repeated measures ANOVA were carried out to investigate the influence of the session (2 sessions), frequency (3 frequencies), phase (2 phase conditions) and condition (AC, BC, and MTLD). Pairwise comparisons with Bonferroni adjustment for the significance were carried out to investigate the any significant effects in the conditions.

5.3 Results

The results described in this section were collected from 18 participants, each participant attended three sessions. AC thresholds were measured once per session in SoNo and SπNo conditions at 500, 1000 and 2000 Hz. While, the BC thresholds measured in the SoNo and SπNo phase conditions were repeated twice per session per frequency. A total of four estimates of thresholds were gathered for the AC and monaural conditions (two SoNo, and two SπNo) at each test frequency leading to two measurements of AC MLD and MTLD. Eight estimates of thresholds (four SoNo, and four SπNo) were gathered in BC condition at each test frequency, leading to four BC MLD measurements.

TA was measured through placing the BC transducer on the mastoid bone and measuring the ipsilateral and contralateral thresholds for the right and left ears in two test sessions at the three test frequencies.

Table 5.1 Descriptive statistics for the whole sample (n=18) in terms of thresholds and MLD's for the AC and BC results at the three frequencies tested. Thresholds for SoNo, SπNo are given in dB HL, and MLD/ MTLD and SD are reported in dB.

Cond.	Freq. (Hz)	AC	BC	Mon_Rt	Mon_Lt	TA dB
SoNo dB HL	500	35.0 (2.3)	23.3 (5.1)	2.2 (9.1)	–0.8 (8.4)	7.0 (7.3)
	1000	41.1 (2.0)	36.5 (5.3)	9.7(12.1)	8.2 (9.4)	2.4 (5.1)
	2000	40.8 (1.7)	41.4(5.2)	6.3 (7.6)	5.1 (6.7)	8.4 (5.6)
SπNo dB HL	500	19.9 (2.7)	14.1 (4.6)	2.0(10.7)	0.4 (9.5)	
	1000	30.1(2.8)	27.4 (5.4)	3.1 (9.0)	5.8 (9.7)	
	2000	34.2(2.1)	37.4(4.4)	7.0 (8.1)	4.5 (8.1)	
MLD dB	500	15.2 (2.6)	9.2 (3.7)	0.0 (6.4)	–1.2 (6.4)	
	1000	11.0 (2.1)	9.2 (3.2)	6.6 (6.7)	2.4 (6.1)	
	2000	6.6 (1.8)	4.0 (3.2)	–0.7 (4.5)	0.5 (5.9)	

The overall mean and standard deviation of the threshold and MLDs is outlined in Table 5.1 for each condition across the three frequencies tested. Visual inspection of the histograms in addition to the results of Shapiro-Wilk tests indicated that the thresholds were at least approximately normally distributed leading to the choice of parametric tests for statistical analysis.

5.3.1 Repeatability

The test-retest repeatability was evaluated by measuring intraclass correlation (ICC), precision, repeatability and repeated measures ANOVA (refer to Section 3.4.1.7 for more details). The results for each measure at the three test frequencies are tabulated in Table 5.2.

Table 5.2 is composed of four main columns. The first indicates the precision (typical error). The precision was calculated from the standard deviation of the differences between the mean divided by the square root of two, it represents the variability between the measures and is not affected by between-subjects variability. An acceptable value of precision would be ±5 dB based on day-to-day variation in threshold measurement. The second column is repeatability measure (Rep), it indicates the agreement between the sessions. It is expected that 95% of the population would fall within 2 SD. The third column plots the results of the ICC scores, it gives an indication of the measurement and is unit-less, the interpretation of the ICC is based on the quantitative score that can be given between 1 and 0. Results closer to 1 indicate good agreement while results closer to 0 indicate poor agreement. Furthermore, the ICC calculated the confidence intervals which indicate the spread of the results for the test-retest scores. The final column is the comparison between the means of the two variables through ANOVA which measures the significance of the mean difference between the test-retest thresholds.

The repeatability with AC thresholds showed small precision scores < 2.3 dB indicating that the repeatability was good between the two sessions and showing that the test-retest repeatability was relatively small. The repeatability measure shows that 95% of the population would have a test-retest score of <6.5 dB which is acceptable. The ICC on the other hand was very small indicating that this test was not good in identifying differences between individuals, the confidence intervals were wide. One of the disadvantages associated with the ICC is when the sample has low variation in their scores, the resultant ICC would be small, which is expected to be the case in the current results (Graham et al, 2012), since most participants performed in a similar manner, there was small variation between individuals performance. The presence of any difference could be related to random error. On an average, the test-retest thresholds were not significant at any of the test frequencies as indicated by ANOVA results.

Table 5.2 Test-retest repeatability, cells in bold are the results of the two sessions with bilateral BC.

Test	Precision (dB)	Rep. (dB)	Intraclass correlation			ANOVA	
			ICC	Confidence intervals	p	F	p
AC_So_500	2.3	6.5	0.0	(–0.5 to 0.4)	0.558	0.2	0.673
AC_Sπ_500	1.8	5.0	0.6	(0.2 to 0.8)	0.005	0.1	0.713
BC_S1_So_500	2.9	8.1	0.8	(0.5 to 0.9)	<0.001	0.1	0.799
BC_S2_So_500	2.2	7.0	0.9	(0.8 to 1.0)	<0.001	4.9	0.041
BC_2S_So_500	**5.3**	**10.6**	**0.4**	**(0.2 to 0.7)**	**<0.001**	**0.7**	**0.610**
BC_S1_Sπ_500	3.3	9.1	0.7	(0.3 to 0.9)	0.001	0.3	0.077
BC_S2_Sπ_500	2.5	7.4	0.8	(0.5 to 0.9)	<0.001	3.5	0.645
BC_2S_Sπ_500	**3.9**	**7.8**	**0.5**	**(0.5 to 0.7)**	**<0.001**	**1.3**	**0.404**
BC_MR_So_500	4.8	13.4	0.7	(0.4 to 0.9)	<0.001	0.2	0.749
BC_MR_Sπ_500	4.8	13.4	0.8	(0.6 to 0.9)	<0.001	0.7	0.514
BC_ML_So_500	4.4	12.2	0.7	(0.5 to 0.9)	<0.001	0.1	0.103
BC_ML_Sπ_500	5.4	15.0	0.7	(0.4 to 0.9)	<0.001	0.4	0.378
AC_So_1000	2.0	5.8	–0.1	(–0.5 to 0.4)	0.606	3.0	0.990
AC_Sπ_1000	2.3	6.5	0.3	(–0.1 to 0.7)	0.084	0.8	0.468
BC_S1_So_1000	2.0	5.4	0.9	(0.7 to 1.0)	<0.001	0.0	0.483
BC_S2_So_1000	1.6	4.5	0.9	(0.8 to 1.0)	<0.001	0.6	0.354
BC_2S_So_1000	**3.5**	**7.2**	**0.6**	**(0.4 to 0.8)**	**<0.001**	**0.1**	**0.710**
BC_S1_Sπ_1000	1.5	4.3	0.9	(0.8 to 1.0)	<0.001	0.5	0.574
BC_S2_Sπ_1000	1.3	3.6	1.0	(0.9 to 1.0)	<0.001	0.9	0.783
BC_2S_Sπ_1000	**2.8**	**5.5**	**0.7**	**(0.6 to 0.9)**	**<0.001**	**0.2**	**0.821**
BC_MR_So_1000	6.9	19.1	0.7	(0.4 to 0.9)	<0.001	0.1	0.683
BC_MR_Sπ_1000	6.4	17.7	0.5	(0.1 to 0.8)	0.009	0.3	0.654
BC_ML_So_1000	4.8	13.3	0.8	(0.5 to 0.9)	<0.001	0.1	0.009
BC_ML_Sπ_1000	4.1	11.2	0.8	(0.6 to 0.9)	<0.001	0.1	0.625
AC_So_2000	1.6	4.4	0.2	(–0.3 to 0.6)	0.180	0.2	0.180
AC_Sπ_2000	2.2	6.0	0.0	(–0.5 to 0.4)	0.512	0.2	0.070
BC_S1_So_2000	1.3	4.4	0.9	(0.8 to 1.0)	<0.001	8.6	0.789
BC_S2_So_2000	1.7	4.7	0.9	(0.8 to 1.0)	<0.001	0.2	0.864
BC_2S_So_2000	**3.0**	**6.0**	**0.7**	**(0.5 to 0.9)**	**<0.001**	**0.6**	**0.556**
BC_S1_Sπ_2000	1.7	4.8	0.9	(0.8 to 1.0)	<0.001	2.0	0.606
BC_S2_Sπ_2000	1.4	4.1	0.9	(0.8 to 1.0)	<0.001	3.7	0.673
BC_2S_Sπ_2000	**2.7**	**5.5**	**0.7**	**(0.5 to 0.8)**	**<0.001**	**0.6**	**0.713**
BC_MR_So_2000	3.6	9.8	0.8	(0.5 to 0.9)	<0.001	0.1	0.799
BC_MR_Sπ_2000	4.3	11.9	0.7	(0.4 to 0.9)	<0.001	0.0	0.041
BC_ML_So_2000	3.3	9.3	0.8	(0.5 to 0.9)	<0.001	0.4	0.610
BC_ML_Sπ_2000	3.7	10.4	0.8	(0.6 to 0.9)	<0.001	0.3	0.077

AC: Air conduction BC: Bone conduction S1,2: Session 1 or 2
2S: results from two sessions MR: Monaural right ML: Monaural left

The precision scores measured with bilateral BC stimulation were <3.3 dB, indicating that the repeatability was good between the repeats per session and showing that the test-retest repeatability was relatively small. The repeatability measure was similar to the results of the AC thresholds which was acceptable. A trend of lower scores appeared as the frequency increased. The ICC scores were > 0.7 with small spread of the confidence intervals at the test frequencies which indicates good repeatability. The averaged mean for the sessions were not significantly different in each condition, as indicated by ANOVA.

The four BC thresholds measured in the two test sessions were measured for repeatability as indicated in Table 5.2 by (2S) in each test condition. The precision and repeatability results followed the same trend of the repeat per session, and AC measurement. The ICC scores were above 0.5 indicating a fair inter-subject variability between the four threshold measurements at the three test sessions. None of the comparisons for the average results was significant as indicated by repeated measures ANOVA.

The repeatability with the monaural thresholds showed poorer precision and repeatability compared to the bilateral BC results. These results indicated wider variation in the participants performance in the test-retest thresholds. The ICC scores were not consistent with the above findings, the scores were >0.7 indicating good repeatability. However, the confidence intervals were wide supporting the variation in test-retest scores. The comparison between the average thresholds at the three test frequencies was not significant as indicated by the ANOVA results. The overall results of the repeatability with the various measures indicate fair test-retest scores.

5.3.2 Air conduction

5.3.2.1 Thresholds

Thresholds were measured in two phase conditions, the signal in phase (SoNo) and the signal inverted 180° out-of-phase (SπNo) across three test frequencies (250, 500 and 1000 Hz). The mean thresholds, in dB HL, calculated from the three test sessions for the frequencies tested (in Hz) are displayed in Figure 5.4. The box plots in Figure 5.4 show the spread of the results for the 18 participants taking part in the study was small. The mean thresholds calculated for the two test sessions in SoNo condition was 35.0, 41.1 and 40.8 dB HL at 500, 1000 and 2000 Hz, respectively. The signals presented bilaterally in phase were –4, 2, 1 dB lower than the masking noise level (39.1 dB) at 500, 1000 and 2000 Hz, respectively, which is consistent with the reported literature (Bernstein et al, 1998; Yost, 2007). Inverting the phase of the test signal (SπNo) resulted in mean thresholds of 19.9, 30.1 and 34.2 dB HL at 500, 1000 and 2000 Hz respectively. The gap between the two phase-conditions appeared to decrease as the frequency is increased from 500 Hz to 2000 Hz which was expected. Individual responses in the two phase conditions at the three test frequencies are displayed in Appendix M.

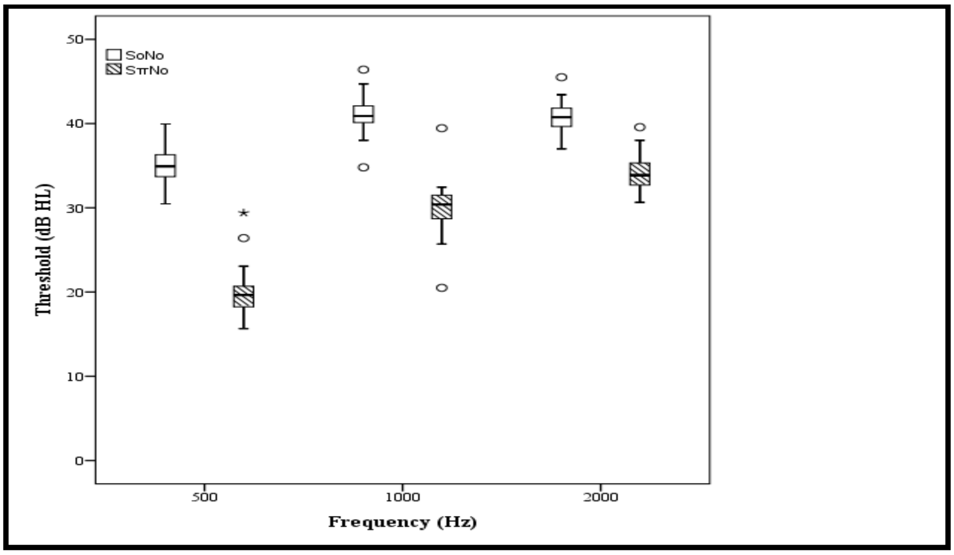

Figure 5.4 Mean AC thresholds in the diotic condition (SoNo, white bars) and in the dichotic condition (SπNo, striped bars), in dB HL, measured at three test frequencies in Hz. For description of the features of box plots refer to Figure 4.5.

Repeated measures ANOVA for SoNo was performed with the within subjects factors of session (2) and frequency (3) to investigate the overall influence of the mean results which are tabulated in Table 5.3. Statistical analysis was followed by pairwise comparison to investigate the relation between the pairs adjusted to Bonferroni for multiple comparisons. The interaction of the frequency and session was not significant in the SoNo and the SπNo phase conditions. This meant that the thresholds measured in each session were not influenced by the frequency. However, thresholds measured at the three frequencies were significantly different than each other.

Pairwise comparisons with Bonferroni adjustment to the significance (p value) were conducted to evaluate the threshold change with frequency in SoNo, the difference of –6.0 dB between 500 Hz and 1000 Hz was statistically significant $p<0.001$. Similarly, the difference of –6 dB between 500 Hz and 2000 Hz was statistically significant $p<0.001$ as indicated by the pairwise comparisons adjusted to Bonferroni. The difference of about 0.3 dB between 1000 and 2000 Hz was not significant $p>0.05$. These results show that the threshold increment (worsening) as the frequency increased was significant when the higher frequencies 1000 and 2000 Hz were compared to 500 Hz. But the difference between 1000 and 2000 Hz was not statistically significant.

Table 5.3 Results of repeated measures ANOVA in the two AC phase conditions

Test		Mauchly's test of sphericity	ANOVA	
			$F_{2,34}$	P
SoNo	Frequency x Session	$x^2(2)= 0.57$, p= 0.75	1.2	0.292
	Frequency	$x^2(2)= 2.2$, p= 0.05	153.0	<0.001*
	Session	Not calculated	0.7	0.403
SπNo	Frequency x Session	$x^2(2)= 0.89$, p=0.39	0.7	0.488
	Frequency	$x^2(2)= 0.91$, p=0.50	385.6	<0.001*
	Session	Not calculated	0.1	0.701

The difference in threshold in SπNo phase condition between 500 Hz and 1000 Hz was –10.22 dB which was statistically significant $p<0.001$ as indicated by the pairwise comparisons. The magnitude of the difference between 500 Hz and 2000 Hz was about –14.3 dB which was statistically significant $p<0.001$ as indicated by the pairwise comparisons adjusted to Bonferroni. The difference of about –4.1 dB between 1000 and 2000 Hz was also significant $p<0.001$. These results show that the threshold increment (worsening) as the frequency increased was significant between the three test frequencies.

5.3.2.2 Masking level difference

The MLD was calculated from the difference between the SoNo and SπNo conditions. The mean MLD was 15.2, 11.0 and 6.6 dB at 500, 1000 and 2000 Hz, respectively. The mean results are plotted in Figure 5.5 (right panel). It can be observed that MLD reduced in magnitude as the frequency increased and the distribution of the participants MLD was similar at the three test frequencies. The left panel of Figure 5.5 plots the calculated MLD at each test session at the three test frequencies, the boxes and the median results in the two test sessions were similar at the three test frequencies. Differences between the maximum and minimum results were observed as indicated by the whiskers.

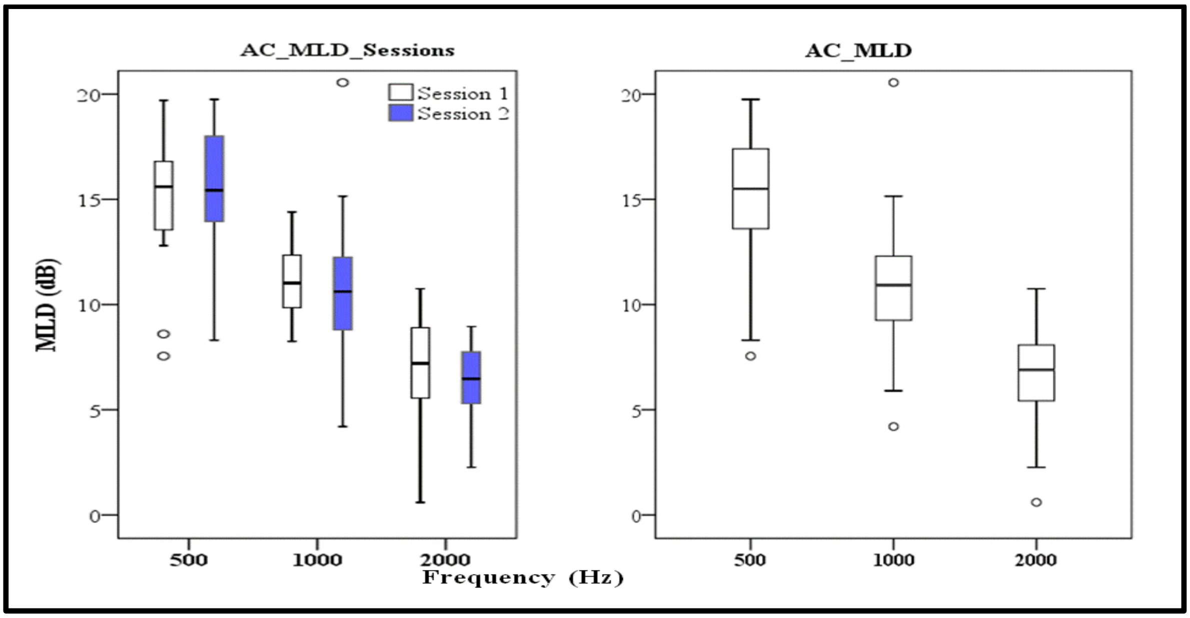

Figure 5.5 The difference between AC SoNo and SπNo thresholds: masking level difference (MLD), in dB, at the three test frequencies in Hz. The right panel shows the overall MLD calculated from two sessions, the left panel shows the MLD in each session. For description of the features of the box plots refer to Figure 4.5

The differences in the thresholds in two test sessions was not statistically significant at the three test frequencies as indicated by the results of repeated measured ANOVA ($F_{1, 17}$=0.07, p=0.78). None of the pairwise comparisons between the two sessions were statistically significant. Student *t*-tests were conducted at 500 Hz (*t*(17)=0.68, p=0.50), 1000 Hz (*t*(17)=0.45, p=0.65) and at 2000 Hz (*t*(17)=–0.80, p=0.43) indicating that the results could be averaged.

The influence of the change of frequency on the MLD was significant ($F_{2, 34}$= 101, p<0.001), Mauchly's test of sphericity was assumed $x^2(2)$ =6.11, p=0.05. Post-hoc examination was statistically significant (p<0.001) for all the frequency comparisons. The difference between 500 and 1000 Hz was 4.1 dB, the difference of 8.5 dB between 500 and 2000 Hz. Finally, 4.4 dB difference between 1000 and 2000 Hz was significant.

The interaction between the frequency and session was not significant ($F_{2,\ 34}$= 0.58, p=0.56), Mauchly's test of sphericity was assumed $x^2(2)$ =2.69, p=0.26.

5.3.3 Transcranial attenuation

Measurements were conducted in 18 normal hearing participants on the right and left ears, the data was normally distributed according to visual inspection of the histograms and by Shapiro-Wilk test of normality for all the test conditions. Therefore, parametric tests were used for the statistical analysis.

The averaged results for all the participants are presented in Table 5.1. TA was calculated from the difference between the ipsilateral and contralateral thresholds for the right or left ear separately. On average, the difference in TA for the right and left ear was around 2 dB with higher TA values in the right ear at 500 and 2000 Hz, whereas at 1000 Hz the results showed symmetry between the two ears.

The measurements were conducted in two different sessions for each participant. Test-retest thresholds were evaluated through the measurement of precision, ICC and repeated measures ANOVA.

Table 5.4 is divided into two main sections: the first section (first 6 rows) displays the average TA calculated from the two test sessions for the right and left ears at the three test frequencies. The second section of the table displays the average thresholds of the two test sessions for each condition separately (i.e. for the ipsilateral thresholds and contralateral thresholds) to evaluate the performance of the participants.

The results of the first section indicate that precision score was lower than 7.8 dB. It was noticed that the high precision scores were associated with low ICC (highlighted in yellow). The TA showed variation between the right and left ears at the three test frequencies indicating that the individual responses varied between the two sessions. Repeated measures ANOVA was not significant for any of the comparisons indicating that the averaged thresholds in the two test sessions were similar.

The results of the raw data in the second section of Table 5.4 indicate that precision for almost all the conditions the result was below 5 dB indicating good test/retest repeatability. Only three conditions (highlighted) resulted in variation up to 7 dB these conditions were associated with small ICC. However, the results of the ICC showed an overall medium agreement between the two sessions. Repeated measured ANOVA was not significant for any of the comparisons.

Table 5.4 test-retest repeatability measured by precision, ICC and ANOVA.

	Test	Precision (dB)	Interclass correlation			ANOVA	
			ICC	Confidence intervals	p	F	p
Section 1	TA_500_Right	6.8	0.6	(0.1 to 0.8)	0.006	1.3	0.263
	TA_500_Left	4.8	0.7	(0.3 to 0.9)	0.001	0.1	0.810
	TA_1000_Right	4.4	0.5	(0.1 to 0.8)	0.008	0.0	0.882
	TA_1000_Left	7.7	–0.1	(–0.5 to 0.4)	0.653	0.2	0.685
	TA_2000_Right	7.8	0.0	(–0.4 to 0.5)	0.497	1.4	0.255
	TA_2000_Left	4.9	0.5	(0.0 to 0.8)	0.018	0.5	0.503
Section 2	Rt_ipsi_500	4.5	0.7	(0.3 to 0.9)	<0.001	2.9	0.108
	Rt_contra_500	6.8	0.2	(–0.2 to 0.6)	0.155	0.1	0.753
	Lt_ipsi_500	5.6	0.9	(0.7 to 0.9)	<0.001	0.1	0.807
	Lt_contra_500	5.5	0.7	(0.3 to 0.9)	0.001	0.2	0.657
	Rt_ipsi_1000	3.1	0.9	(0.7 to 0.9)	<0.001	0.3	0.621
	Rt_contra_1000	4.7	0.6	(0.3 to 0.8)	0.001	0.2	0.663
	Lt_ipsi_1000	6.0	0.5	(0.1 to 0.8)	0.010	0.0	0.855
	Lt_contra_1000	7.8	0.3	(–0.2 to 0.7)	0.095	0.8	0.392
	Rt_ipsi_2000	4.7	0.6	(0.2 to 0.8)	0.004	0.2	0.662
	Rt_contra_2000	4.9	0.4	(0.0 to 0.7)	0.026	3.8	0.068
	Lt_ipsi_2000	4.2	0.6	(0.3 to 0.8)	0.001	1.1	0.305
	Lt_contra_2000	4.3	0.3	(–0.1 to 0.7)	0.078	0.0	0.858

Table 5.5 TA mean and (standard deviations), in dB, for the right and left ears. Measured at 500, 1000, and 2000 Hz.

Condition	500 Hz		1000 Hz		2000 Hz	
	Right	Left	Right	Left	Right	Left
Session 1	7.3 (7.8)	5.7 (7.1)	2.1 (6.3)	3.2 (6.7)	7.9 (8.6)	6.8 (7.1)
Session 2	9.5 (8.9)	5.4 (8.6)	2.3 (6.3)	2.2 (7.7)	11 (6.9)	7.9 (6.0)

Evaluation of the difference between the right and left ears indicated that TA was not statistically significant between the two ears based on the results of paired sample *t*-test at 500 Hz (t= 1.86, p >0.05), 1000 Hz (t= 0.28, p >0.05), and 2000 Hz (t= 1.56, p >0.05).

This indicates that the results could be averaged together (Table 5.1). The averaged TA for the three test frequencies was < 10 dB with the lowest averaged TA at 1000 Hz.

Figure 5.6 explores the results through box plots. It shows the variation of the data distribution at the three frequencies with the largest spread of participants present at 500 Hz as can be seen with the wide whiskers. It can be observed from this graph that the two sessions shared similar trends.

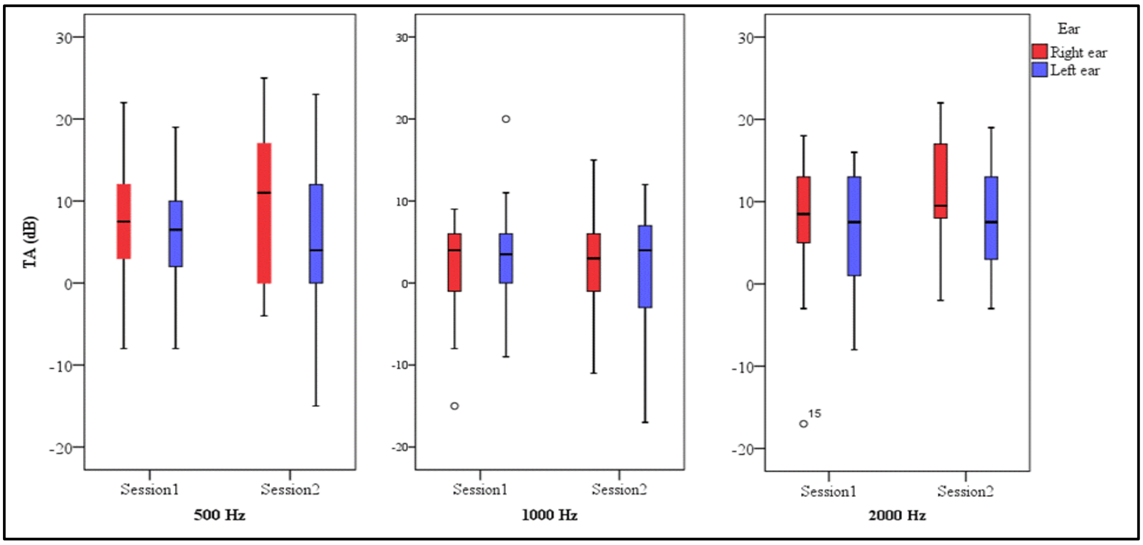

Figure 5.6 TA results measured from the difference between the ipsilateral and contralateral thresholds, in dB, for the right (red bars) and left (blue bars) ears, in two test sessions. For description of the feature of a box plot refer to Figure 4.5.

5.3.4 Bilateral bone conduction

5.3.4.1 Thresholds

The test conditions were similar to the AC threshold measurement. The thresholds were measured in two phase conditions (SoNo and SπNo) with bilateral matched BESTs placed on the mastoid bone. The noise was always presented through insert earphones. The thresholds were collected in two test sessions (twice per session).

Figure 5.7 show box plots of the averaged four threshold measurements, in the SoNo and SπNo at 500, 1000 and 2000 Hz. The spread of the participants responses was wider at 500 Hz compared to 1000 and 2000 Hz indicated by the whiskers of the box plots. The mean thresholds calculated for the two test sessions in SoNo condition was 23.3, 36.5

and 41.4 dB HL at 500, 1000 and 2000 Hz, respectively. The signals presented bilaterally in phase were –16, –2.6, 2.3 dB lower than the masking noise level (39.1 dB) at 500, 1000 and 2000 Hz, respectively. Inverting the phase of the test signal (SπNo) resulted in mean thresholds of 14.1, 27.4 and 37.4 dB HL at 500, 1000 and 2000 Hz respectively.

Individual responses in the two phase conditions at the three test frequencies are displayed in Appendix M.

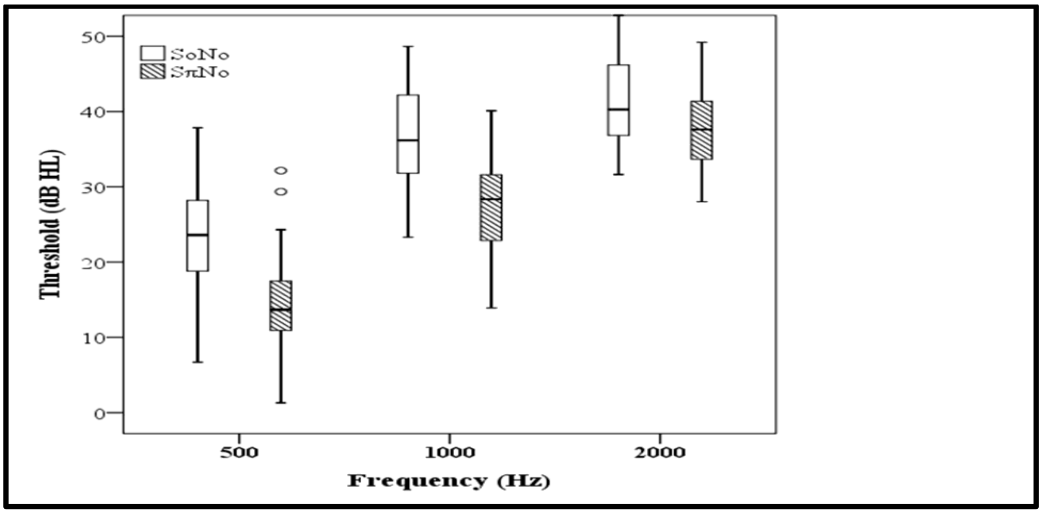

Figure 5.7 Mean BC thresholds in the diotic condition (SoNo, white bars) and in the dichotic condition (SπNo, striped bars), in dB HL, measured at three test frequencies in Hz. For description of the features of box plots refer to Figure 4.5.

Figure 5.8 represents the box plots for the two test sessions: two measurements per session in the SoNo (Left panel) and SπNo (right panel) conditions at the three test frequencies. The main observations are that the thresholds increase as the frequency increases from 500 to 2000 Hz in the two phase conditions. It is observed that the range of responses for the group of participants was relatively wide. The repeat per session and the change in the sessions appears to be similar.

Repeated measures ANOVA are tabulated (Table 5.6) showing the main effects of frequency (3 frequencies), session (2 sessions) and repeat per session (2 repeats). The overall interaction between the frequency, session and repeat was not significant in the two phase conditions which indicates that the threshold measured in any of the test frequencies was not influenced by the change of session or in the repeat per session.

However, the thresholds measured at the three test frequencies were significantly different at the two phase conditions. The overall influence of session at the three test frequencies was not significant as reported in Section 5.3.1. The interaction between the repeat per session and the two test sessions was not statistically significant at the three test frequencies. It can be observed from Figure 5.8 that the repeat per session was similar and the overall wide distribution of the participants was expected as observed in the preliminary investigation and in the studies of bone conduction (Chapter 4).

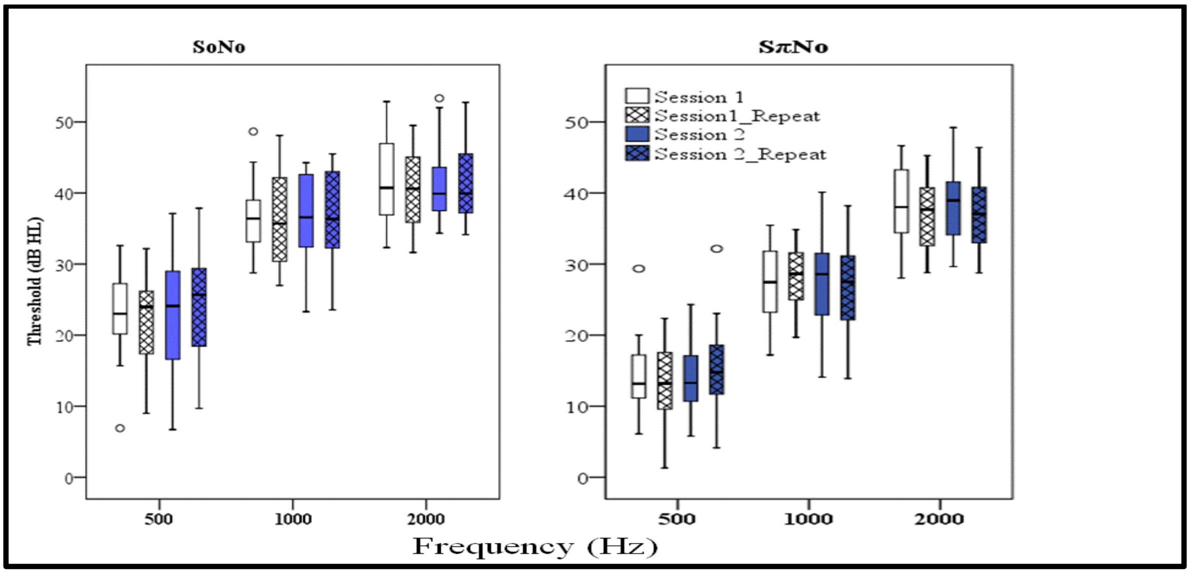

Figure 5.8 BC thresholds, in dB HL, measured in two test sessions: first session (white bar& repeated in white crossed bar), second session (blue bar & repeated in blue crossed bar), measured at three test frequencies in Hz. The two panels show: the diotic (SoNo, left panel) and dichotic conditions (SπNo, right panel). For description of the feature of a box plot refer to Figure 4.5.

The influence of the frequency was further investigated by post-hoc tests. The difference in threshold in the SoNo condition between the averaged thresholds at 500 Hz and 1000 Hz was –13.3 dB which was statistically significant $p < 0.001$ as indicated by the pairwise comparisons adjusted to Bonferroni correction for the significance. The magnitude of the difference between 500 Hz and 2000 Hz was increased to –18.1 dB which was statistically significant $p < 0.001$ as indicated by the pairwise comparisons adjusted to Bonferroni. The difference of –4.8 dB between 1000 and 2000 Hz was also significant. These results show that the threshold increment (worsening) as the frequency increased was significant for the three test frequencies.

Table 5.6 Results of repeated measures ANOVA in the two BC phase conditions

Test		Mauchly's test of sphericity	ANOVA	
			$F_{2,34}$	P
SoNo	Frequency x session x repeat	$x^2(2)$=1.05 , p=0.590	0.73	0.48
	Frequency x session	$x^2(2)$= 10.4 , p=0.006	0.5	0.60
	Frequency x repeat	$x^2(2)$= 1.9 , p=0.381	1.8	0.16
	Session x repeat	Not calculated	4.6	0.05
	Frequency	$x^2(2)$= 7.04 , p=0.03	82.3	<0.001*
	Session	Not calculated	0.1	0.76
	Repeat	Not calculated	0.2	0.67
	Session x Repeat 500	Not calculated	1.38	0.25
	Session x Repeat 1000	Not calculated	0.26	0.61
	Session x Repeat 2000	Not calculated	1.48	0.24
SπNo	Frequency x Session x repeat	$x^2(2)$= 0.82 , p=0.21	2.7	0.08
	Frequency x session	$x^2(2)$= 0.1 , p=0.945	1.1	0.32
	Frequency x repeat	$x^2(2)$= 8.7 , p=0.013	1.4	0.24
	Session x repeat	Not calculated	1.1	0.29
	Frequency	$x^2(2)$= 6.5 , p=0.04	147	<0.001*
	Session	Not calculated	0.09	0.76
	Repeat	Not calculated	0.149	0.70
	Session x Repeat 500	Not calculated	0.35	0.29
	Session x Repeat 1000	Not calculated	1.39	0.18
	Session x Repeat 2000	Not calculated	0.17	0.84

Inverting the phase in one ear showed lower thresholds at 500 Hz and the thresholds increased with the increase in the frequency similar to the SoNo observation, it was also similar to the trend observed with AC. The difference in threshold between the averaged thresholds at 500 Hz and 1000 Hz was –13.3 dB which was statistically significant p<0.001 as indicated by the pairwise comparisons adjusted to Bonferroni for multiple comparisons. The magnitude of the difference between 500 Hz and 2000 Hz was increased to –23.3 dB which was statistically significant p< 0.001 as indicated by the pairwise comparisons adjusted to Bonferroni. The difference of –10 dB between 1000 and 2000 Hz was also significant. These results show that the threshold increment (worsening) as the frequency increased was significant for the three test frequencies.

Observation of the SD for each individual for the two repeats can be seen in Appendix L, it can be observed that the SD was small in the bilateral BC stimulation indicating that the repeats per session were similar which could be related to the placement of the BC transducers.

5.3.4.2 Masking level difference

The MLD calculated from the difference between the two phase conditions is displayed in Figure 5.9. The right panel plots the box plots of the averaged results 9.1, 9.1 and 3.9 dB at 500, 1000 and 2000 Hz, respectively. The left panel plots the box plots for the two sessions and two repeats at the three frequencies tested, it is observed that the most noticeable variation between subjects was observed at 500 Hz in the second test session.

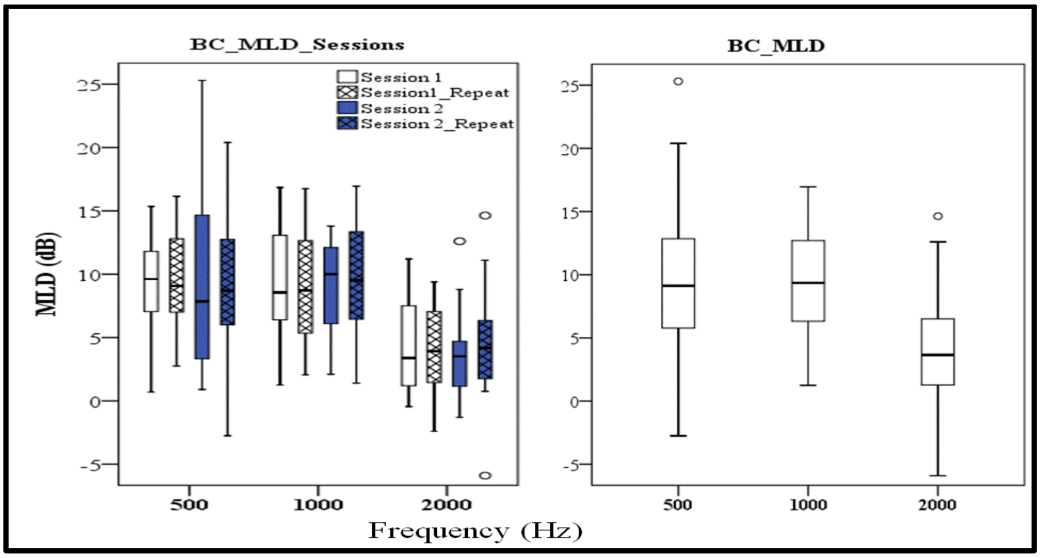

Figure 5.9 The difference between BC SoNo and SπNo thresholds: masking level difference (MLD), in dB, at the three test frequencies in Hz. The right panel shows the overall MLD calculated from two sessions, the left panel shows the MLD in each session. For description of the features of the box plots refer to Figure 4.5.

Repeated measures ANOVA was conducted to evaluate the influence of the frequency change (3 frequencies), change in session (two sessions) and influence of repeat per session on the calculated MLD. The interaction between the frequency, session and repeats per session was not significant $F_{2, 34}$=0.719, p=0.49, Mauchly's test of sphericity was assumed $x^2(2)$ =0.97, p=0.799. However, the MLDs were found to be significantly different with the change in the frequency $F_{2, 34}$= 17.5, p<0.001, the sphericity was assumed $x^2(2)$ =0.83, p=0.23. Post hoc examination showed that 2000 Hz significantly differed than 500 Hz (mean difference of – 5.1, p< 0.001) and 1000 Hz (mean difference of – 5.1, p= 0.001). The difference in the averaged MLD at 500 and 1000 Hz was similar.

The influence of the repeats and sessions were evaluated at each frequency. The influence of the repeat per session on the MLD was not significant at 500 Hz ($F_{1, 17}$= 0.06, p=0.797) 1000 Hz ($F_{1, 17}$= 0.15, p=0.699) and 2000 Hz ($F_{1, 17}$= 0.40, p=0.534). Similarly, the session did not influence the averaged thresholds at 500 Hz ($F_{1, 17}$= 0.01, p=0.947) 1000 Hz ($F_{1, 17}$= 0.02, p=0.893) and 2000 Hz ($F_{1, 17}$= 0.01, p=0.971). These results indicate that the average MLD was comparable for the repeats and sessions and could be averaged to evaluate the overall MLD.

One sample statistics was conducted to evaluate the resultant MLD compared to 0 dB at the three test frequencies. The results indicated a statistical significant difference at 500 Hz (t(17) = 10.3, p<0.001), 1000 Hz (t(17)= 11.9, p<0.001), and 2000 Hz (t(17)= 5.3, p<0.001) confirming measurable MLDs.

5.3.5 Monaural interference effect

5.3.5.1 Thresholds

Monaural interference effect was measured in the same setup for the bilateral BC testing. However, the masking noise was only used to mask the non-test ear keeping the test ear not masked. The tone was presented bilaterally through the BC transducers.

The variation between the two test sessions was wide for the right and left ears in the two phase conditions at the three test frequencies. However, there was no statistical significance between the two sessions as reported in Section 5.3.1. The participants thresholds in the monaural condition was similar across the three frequencies in both the phase conditions which indicated that inverting the phase had no clear influence on the averaged thresholds. The right and left ears produced similar thresholds in both of the phase conditions.

The effect of the session was further evaluated statistically by paired sampled *t*-tests. None of the comparisons were statistically significant (Table 5.7) indicating that the thresholds in the two test sessions could be averaged (Figure 5.10).

Table 5.7 Comparison between the thresholds in the two test sessions using paired sample *t*-tests, for the right and left thresholds at the three test frequencies in SoNm and SπNm conditions.

Condition		Mean difference (dB)	*t*	p
SoNm	Right_500 Hz	–0.75	0.47	0.645
	Left_500 Hz	–0.47	0.32	0.749
	Right_1000 Hz	–0.87	0.37	0.710
	Left_1000 Hz	–0.45	0.28	0.783
	Right_2000 Hz	–0.32	0.27	0.789
	Left_2000 Hz	–0.66	0.60	0.556
SπNm	Right_500 Hz	–1.36	0.85	0.404
	Left_500 Hz	1.19	0.66	0.514
	Right_1000 Hz	1.2	0.57	0.574
	Left_1000 Hz	0.31	0.23	0.821
	Right_2000 Hz	0.25	0.17	0.864
	Left_2000 Hz	0.65	0.52	0.606

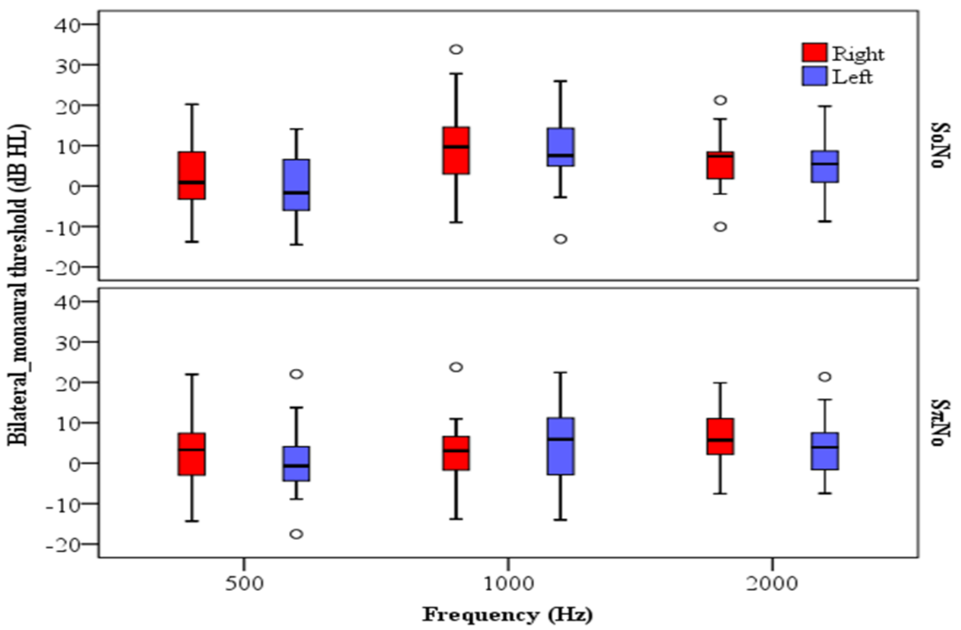

Figure 5.10 Comparison between the BC Bilateral-monaural thresholds, in the right (red bars) and left (blue bars) in the diotic condition (SoNo, top panel) and in the dichotic condition (SπNo, bottom panel), in dB HL, measured at three test frequencies in Hz. For description of the features of box plots refer to Figure 4.5.

The thresholds were compared between the right and left ears by paired sample *t*-tests for the averaged thresholds from the two sessions. The results presented in Table 5.8 showed that none of the comparisons were statistically significant indicating that the thresholds were similar for the right and left ear, thus the results could be pooled for comparison of the main effects.

Table 5.8 Comparison between the thresholds between the two ears using paired sample *t*-tests, at the three test frequencies in SoNm and SπNm conditions.

Condition		Mean difference (dB)	*t*	p
SoNm	**500 Hz**	2.9	2.05	0.055
	1000 Hz	1.5	0.75	0.462
	2000 Hz	1.2	1.17	0.255
SπNm	**500 Hz**	1.6	0.92	0.368
	1000 Hz	-2.7	1.98	0.063
	2000 Hz	2.4	1.14	0.267

Repeated measures ANOVA showed that the thresholds significantly differed in the SoNm condition with the change in frequency ($F_{2,\ 34}$=6.52, p=0.004), sphericity was assumed x^2(2) =3.9, p=0.140. Pairwise comparisons with Bonferroni adjustment for the p value were conducted: the difference in threshold of –8.2 dB between 500 Hz and 1000 Hz was statistically significant p=0.001. However, the difference of –5 dB between 500 Hz and 2000 Hz and 3.2 dB between 1000 and 2000 Hz were not statistically significant with significance values of 0.106 and 0.781 respectively. The thresholds were similar at the three test frequencies when the phase of the signal was inverted ($F_{2,\ 34}$=2.31, p=0.114), sphericity was assumed x^2(2) =1.16, p=0.558.

5.3.5.2 The monaural interference effect: tone level difference

The monaural tone level difference (MTLD) was calculated in the same way as for the binaural condition. The results indicated that the averaged MTLD were close to zero at 500 and 2000 Hz in the two ears. However, at 1000 Hz a measurable tone level difference in the two test ears (Right = 6.6 dB and Left= 2.5 dB) was detected.

The variation in the between and within the participants responses was wide. Figure 5.11 shows the individual responses at the three test frequencies error bars illustrate the SD of the mean for each individual. Panel A represents the monaural tone level difference at 500 Hz. Nine of the participants had positive tone level difference responses while the rest has negative responses and the SD of the mean of the individual responses was wide indicating within-subject variation. A negative MTLD indicates that the Sπ thresholds were higher (worse) than the So thresholds.

At 1000 Hz, four participants had negative tone level difference s and the general trend was a comparable right and left tone level differences. Four of the participants had negative tone level differences and the SD was wide for most of the participants (Figure 5.11B). At 2000 Hz, the majority of the participants showed small tone level differences, 14 of the participants had negative tone level differences (Figure 5.11C).

Repeated measure ANOVA was conducted with the frequency (3) and ear (2) as factors and the monaural tone level difference as the independent variable. Mauchly's test of sphericity for the frequency was assumed, the overall influence of the frequency was significant ($F_{2, 34}$= 4.76, $p<0.05$) this indicates that the change in the frequency results in MLDs that were different than each other. The ear factor was not significant $F_{1, 17}$= 2.61, $p> 0.05$ which indicates that the tone level difference at the right ear was similar to the left ear.

The interaction between the frequency and ear was marginally significant $F_{2, 34}$= 3.34, p= 0.045, indicating that the difference between the right and left ears was influenced by the frequency. Student *t*-test was performed to evaluate this significance. The MTLDs were similar ($p>0.05$) between the right and left ears at 500 and 2000 Hz (*t*(17)= 0.96 and *t*(17)=0.75, respectively). Whereas the MTLDs for the right and left ears were significantly different at 1000 Hz with a mean difference of 4.25 dB (*t*(17)= 2.85). One sample statistics were conducted to evaluate the resultant MTLD compared to 0 dB at the three test frequencies. The results indicated a statistical significant difference at 1000 Hz (*t*(17)= 3.5, p=0.002). Whereas, the MTLD was not different than zero at 500 Hz (*t*(17)= 0.4, p=0.675) and 2000 Hz (*t*(17)= 0.1, p= 0.934).

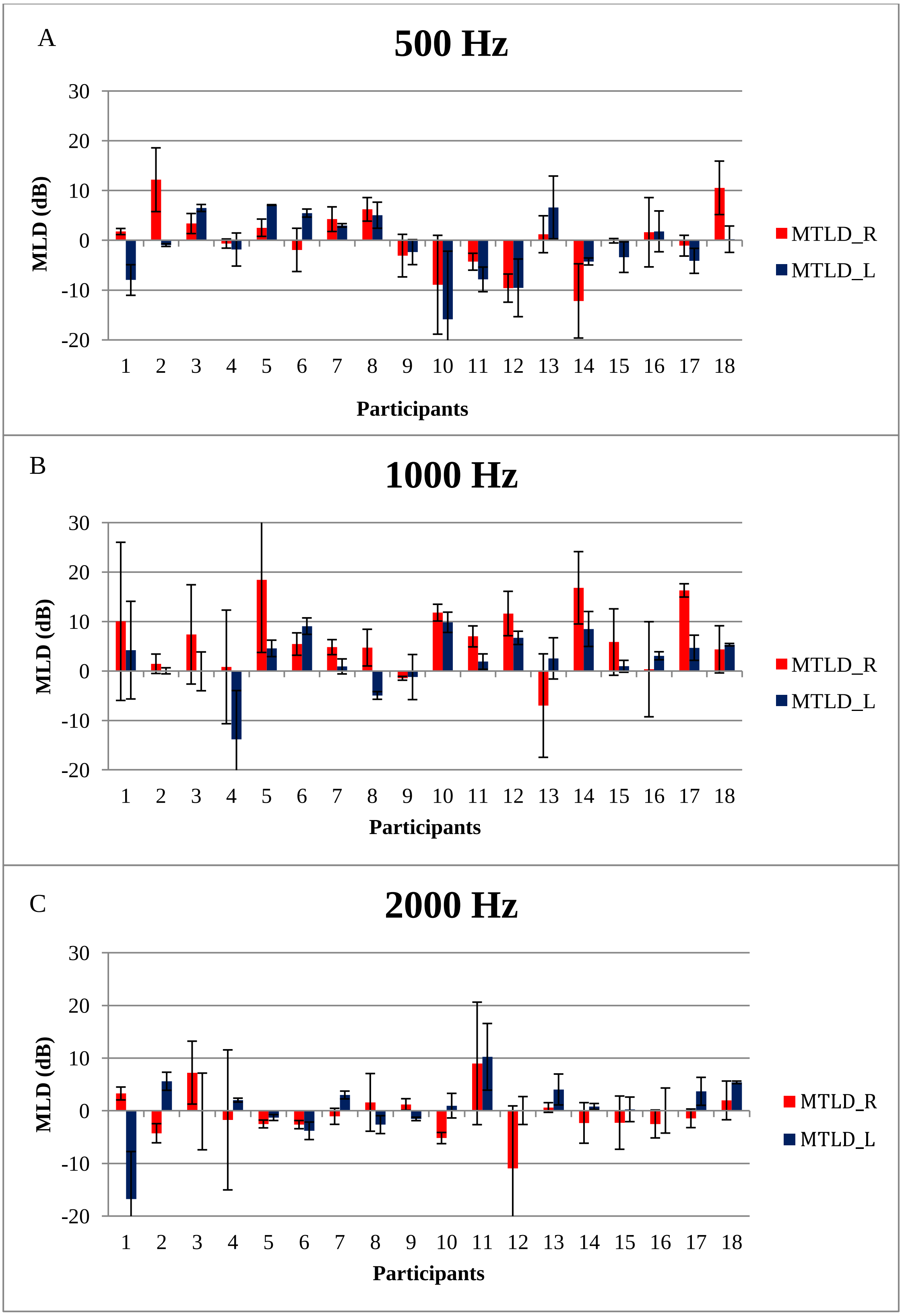

Figure 5.11 Individual monaural tone level difference (MTLD) at 500 (A), 1000 (B) and 2000 (C) Hz, for the right and left ears. Error bars represent SD of the mean for each individual.

Due to the change in the direction of the MTLD between the participants (participants having Sπ thresholds worse than the So thresholds), the averaged results appeared to cancel the observed MTLD (Figure 5.11). Therefore, the results were split into two groups based on the MTLD. Group A included the participants with negative MTLD (–5.2, –2.5 and –2.3 dB at 500, 1000 and 2000 Hz respectively) and Group B including the participants with positive MTLD (4.1, 6.4, 2.7 dB at 500, 1000 and 2000 Hz, respectively) (Figure 5.17).

One sample statistics were conducted in the two groups to evaluate if the MTLD was significantly different than zero dB. Group A showed a significant difference at 500 Hz ($t(8)= 4.0$, $p=0.004$) and 2000 Hz ($t(9)= 3.3$, $p=0.009$). Whereas, the MTLD was not different than zero dB at 1000 Hz ($t(3)= 1.8$, $p=0.162$). Group B had statistically significant positive MTLD at 500 Hz ($t(8)= 8.1$, $p< 0.001$), 1000 Hz ($t(13)= 6.2$, $p< 0.001$) and 2000 Hz ($t(7)= 2.5$, $p=0.039$). These results were opposite to the averaged results indicating that the MTLD was significantly different than zero dB.

5.3.6 Comparison between AC and BC

5.3.6.1 Thresholds

AC results were repeatable, Table 5.9 summarises the results of the AC and BC thresholds and MLDs. The main observations in this table are that the SD is smaller with AC threshold results compared to the BC results. But it should be noted that the studies with BC usually yields a high deviations and a SD of 7 is usually reported with hearing thresholds studies (refer Chapter Three).

Figure 5.12 illustrates the average results and the main differences between the AC and BC results within the two phase conditions. The BC results followed the same trend of the AC but the distribution of the participants was wider. Statistical comparisons based on paired sample *t*-test are indicated in the graph by the p values. The thresholds collected by inserts were statistically different that the BC thresholds at all the test frequencies in the two phase conditions with only one exception of SoNo at 2000 Hz the thresholds in the AC and BC were similar and insignificant. It was observed that the BC thresholds followed the same trend as the AC thresholds in the SoNo and SπNo phase conditions. The Magnitude of the difference in thresholds between the AC and BC was largest at 500 Hz compared to the other test frequencies. The BC thresholds were higher than the AC thresholds at 2000 Hz in two phase conditions.

Table 5.9 Mean results for the AC and BC showing the standard deviation, range and confidence intervals

Condition		Mean[a]	SD[b]	Min[a]	Max[a]	95 % CI Low	High
SoNo (dB HL)	AC_500	35.03	1.56	32.53	37.50	34.25	35.81
	AC_1000	41.08	1.36	37.47	43.35	40.40	41.76
	AC_2000	40.75	1.36	36.64	43.45	40.07	41.43
	BC_500	23.26	5.14	13.52	30.34	20.70	25.81
	BC_1000	35.57	5.27	26.74	46.23	33.94	39.19
	BC_2000	41.40	5.15	33.15	52.11	38.84	43.97
SπNo (dB HL)	AC_500	19.86	2.38	16.68	27.90	18.67	21.05
	AC_1000	30.09	2.25	24.80	35.67	28.96	31.21
	AC_2000	34.18	1.48	31.65	36.65	33.44	34.92
	BC_500	14.09	4.58	6.65	22.84	11.81	16.37
	BC_1000	27.37	5.42	17.79	36.15	24.67	30.07
	BC_2000	37.40	4.63	30.49	46.18	35.10	39.71
MLD (dB)	AC_500	15.16	2.56	9.05	19.55	13.89	16.43
	AC_1000	10.99	2.07	6.9	16.75	9.95	12.02
	AC_2000	6.57	1.80	3.01	9.05	5.67	7.46
	BC_500	9.165	3.7	1.51	15.49	7.29	11.03
	BC_1000	9.19	3.2	3.21	14.58	7.57	10.81
	BC_2000	3.99	3.18	–1.61	10.56	2.41	5.581

[a] dB HL (SoNo and SπNo)
[b] dB

A difference of 11.7, 4.5 dB between the AC and BC for the threshold in-phase was statistically significant at two test frequencies (500 and 1000 Hz respectively) as evaluated by paired sample *t*-test. On the other hand, at 2000 Hz the difference was not significant between the two conditions (–0.6 dB). Inverting the phase of the signal in one ear resulted in a significant difference between the AC and BC in the three test frequencies; the magnitude of the difference was 5.7, 2.7 and –3.22 dB at 500, 1000 and 2000 Hz, respectively.

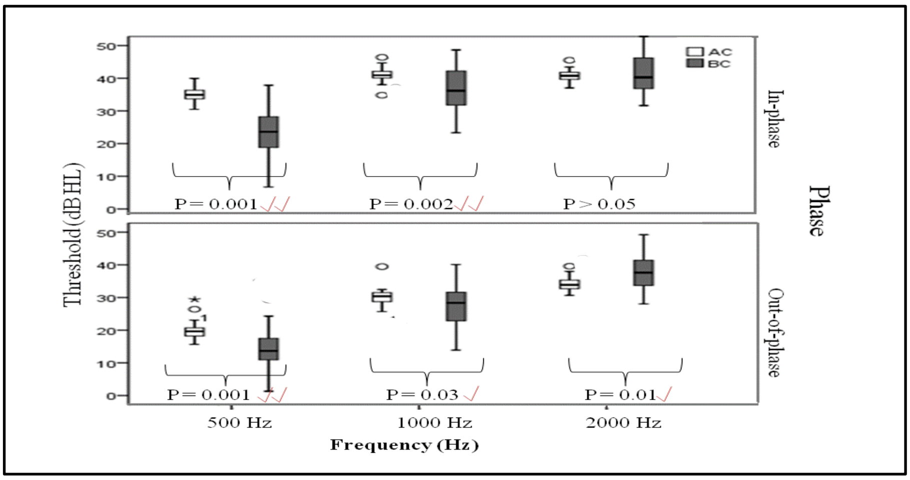

Figure 5.12 Comparison between the mean of the two sessions AC (white bars) & BC (grey bars) thresholds in the diotic condition (in-phase SoNo, top panel) and in the dichotic condition (out-of-phase SπNo, bottom panel), in dB HL, measured at three test frequencies in Hz. For description of the features of box plots refer to Figure 4.5.

5.3.6.2 Masking level difference

The MLD was measurable and repeatable in the AC and BC conditions. Figure 5.13 plots the distribution of the MLD in the two conditions. The AC MLD was always higher in magnitude compared to the BC MLD. Paired sample *t*-tests were significant for the comparison between the conditions with a difference between the AC and BC MLD of 5.9, 1.7, 2.6 dB at 500, 1000 and 2000 Hz.

Comparison between the AC and BC MLD thresholds was conducted through repeated measures ANOVA to evaluate the frequency (3 frequencies) and condition (AC and BC). The influence of the change in frequency on AC and BC MLD was significant $F_{2, 34}$= 64.6, p <0.001, Mauchly's test of sphericity was assumed $x^2(2)$ =3.1, p= 0.21. The AC and BC MLD was positive for all the participants at 500 and 1000 Hz. However, one participant had negative BC MLD at 2000 Hz (participant 12). The difference between the AC and BC MLD's was statistically significant for the pooled data from the three frequencies, the AC was always larger in magnitude compared to the BC MLD ($F_{1, 17}$= 43.6, p<0.001). The interaction between the frequency and the condition was statistically significant $F_{2, 34}$= 8.1, p=0.001 sphericity was assumed $x^2(2)$ = 1.7, p=0.416.

Pearson correlations were conducted to evaluate the relationship between the AC and BC MLD at the three test frequencies. There was no relationship between the AC and BC MLD at 500 Hz (r=0.09, p= 0.70), a positive relation was observed at 1000 Hz which was significant (r= 0.53, p=0.02). The correlation between the AC and BC MLD was not significant at 2000 Hz (r=0.26, p=0.29).

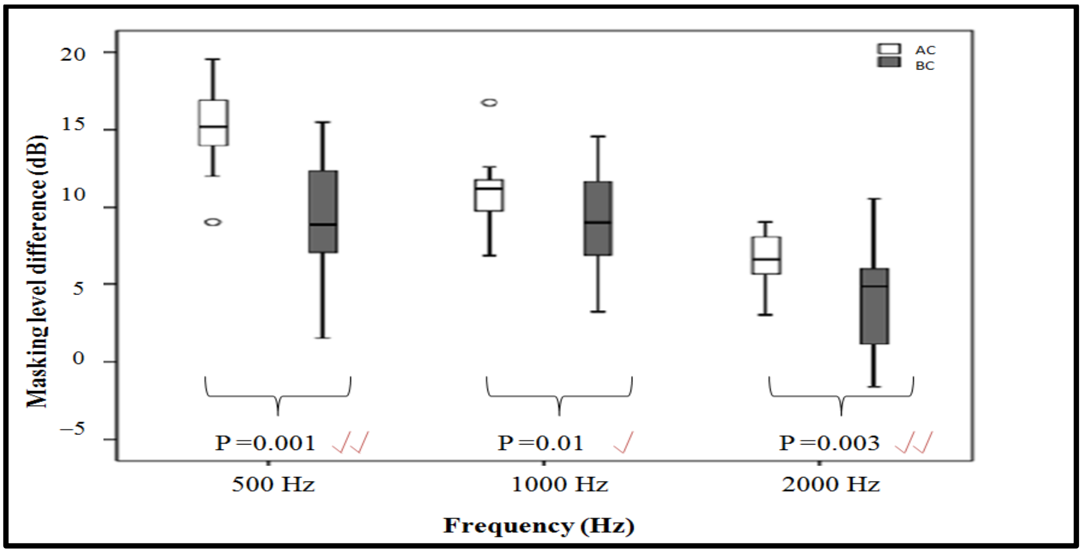

Figure 5.13 The difference between BC SoNo and SπNo thresholds: masking level difference (MLD), in dB, between the AC (white bars) and BC (grey bars), measured at the three test frequencies in Hz. The p values indicate the significance of the comparison. For description of the features of the box plots refer to Figure 4.5.

The individual results were evaluated (Appendix M). The MLD was considered similar if the difference between the AC and BC MLD was between ±2.5 dB. This figure was based on the standard deviation of the mean for the AC measurements. At 500 Hz, four participants had almost equal MLDs between the AC and BC (S 2, 6, 8 17*), subject 17 had the BC threshold higher than the AC threshold. At 1000 Hz, ten participants had equal or lower than 2.5 dB or slightly higher (*) BC MLDs compared to the AC MLDs (S 2, 3, 4*, 6, 9*, 11, 12*, 16*, 17*, 18). Similarly, nine participants had similar AC and BC MLDs at 2000 Hz (S 2*, 3*, 5, 8, 10, 13*, 15, 17, 18). It was noticed that the largest discrepancy between the AC and BC MLD was at 500 Hz (average of 5.9 dB), eleven out of the 18 participants had differences > 5 dB. The difference between the AC and BC MLD was 1.7 dB at 1000 Hz, only three participants had discrepancy >3 dB. Similarly, three participants had discrepancy >5 dB at 2000 Hz, the average difference was 2.5 dB.

The current results are encouraging indicating that the BC MLD was similar to the AC MLD in the majority of the participants. The averaged BC MLD followed the same pattern of responses of the AC MLD (Figure 5.16).

5.3.6.3 Comparison with preliminary investigation

Evaluation of the methodology used in the present investigation was conducted by comparing the mean AC and BC MLD with the results reported in the preliminary investigation (Figure 5.14). The MLD can be compared at 500 Hz and 1000 Hz between the two studies. An increase in the AC and BC MLD was observed at the two test frequencies.

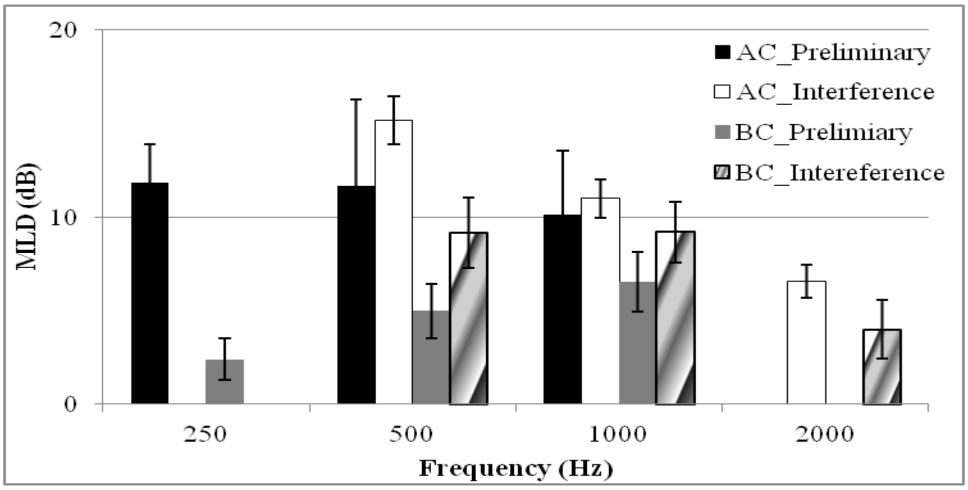

Figure 5.14 The mean AC and BC MLD (dB) measured in the preliminary investigation and the present investigation (interference). Error bars represent 95% confidence intervals.

Independent sample t-test showed that the observed discrepancy between the preliminary and the present investigation was significant at 500 Hz, the magnitude of the difference for the AC MLD was 3.4 dB ($t(25)= 3.6$, p= 0.001), similarly a 4.1 dB difference in the BC MLD was significant ($t(25)= 2.5$, p= 0.019) MLD. However, the smaller discrepancy between the two studies was not significant at 1000 Hz. The difference in the AC MLD was 0.9 dB ($t(25)= 1.0$, p= 0.311) and the difference with the BC MLD was 2.6 dB ($t(25)=2.1$, p= 0.045). Despite the significant difference at 500 Hz the mean discrepancy did not exceed 5 dB, which indicate the methodology produced repeatable values of

MLD. This increase in the MLD was expected to be due to the increase in the overall level of the masking noise in the present investigation.

Four participants took part in the preliminary investigation and the investigation of interference. Their results are presented in Figure 5.15. It is observed that the AC MLD showed similar thresholds between the two studies with a trend for the present study to produce higher thresholds. The effect of the increase in the overall noise level was more notable with the BC MLD. Participant three had BC MLD that was higher in the preliminary investigation compared to the interference at 500 and 1000 Hz. This was different than the trend observed with the other three participants.

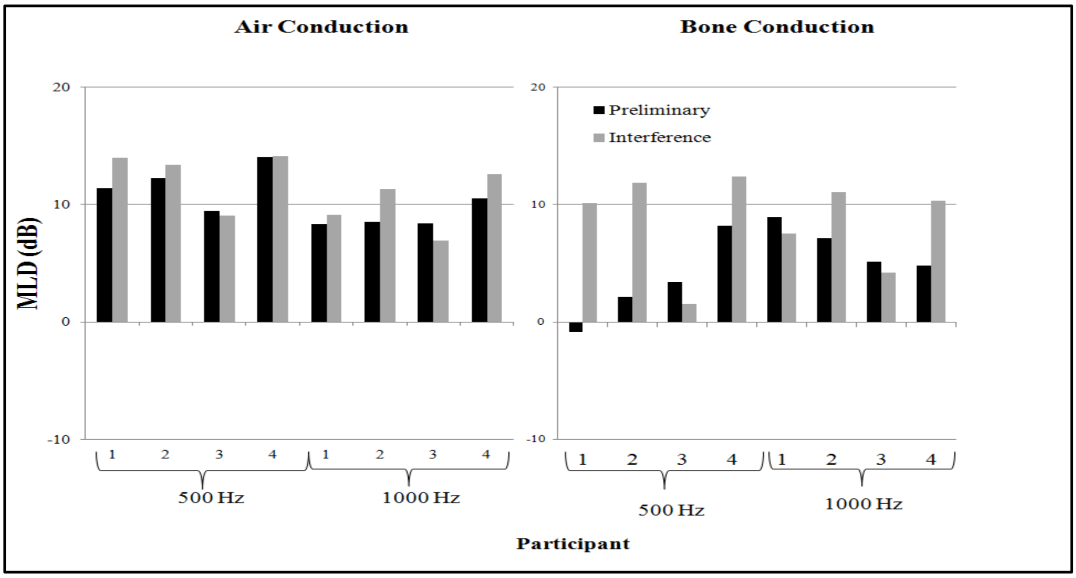

Figure 5.15 The mean AC (left panel) and BC (right panel) MLD, in dB, measured in the preliminary investigation and the present investigation (interference) for four participants as a function of frequency (Hz).

5.3.7 Investigation of interference

Investigation of interference was conducted to evaluate whether the BC MLD can be explained by the monaural effect and the TA contribution to the results. The relation of the measured TA to the BC MLD and the discrepancy between the AC and BC MLD was evaluated. It was assumed large TA would result in small MTLD and small discrepancy between the AC and BC MLD.

The averaged results were evaluated first to investigate the overall trends. Due to the inter-subject variation the results were further evaluated to observe individual trends that may have been concealed by the averages.

5.3.7.1 Group results

The averaged results in all the test conditions are explored in Figure 5.16: the error bars show 95% confidence intervals. The discrepancy bars represent the difference between the AC and BC MLD. An average discrepancy was about 6.0, 1.8, 2.5 dB and the MTLD averaged about –0.5, 4.4, –0.1 dB with a TA of 7.0, 2.5, 8.4 dB at 500, 1000, 2000 Hz, respectively. An association between the MTLD and the TA was observed in the averaged results and a small TA was associated with a high MTLD mainly at 1000 Hz. Opposite trend was observed at 500 and 2000 Hz, high TA was associated with smaller MTLD and a larger discrepancy in the overall results between the AC and BC.

Repeated measured ANOVA was conducted to evaluate the condition (BC MLD, MTLD, TA and discrepancy) and frequency (500, 1000 and 2000 Hz). The interaction between the frequency and condition was statistically significant $F_{6, 102}= 10.22$, $p< 0.001$. Furthermore, pairwise comparisons were conducted at each frequency to evaluate the main effects. The average MTLD significantly differed than the BC MLD at 500 Hz (difference= –9.7 dB, $p< 0.001$), 1000 Hz (difference= –4.7 dB, $p=0.011$) and 2000 Hz (difference= –6.6 dB, $p< 0.001$). The averaged TA significantly differed than: the MTLD at 500 Hz (difference= 7.5 dB, $p< 0.001$), BC MLD at 1000 Hz (difference= –6.7 dB, $p< 0.001$) and BC MLD at 2000 Hz (difference= –2.5, $p=0.02$).

The statistical association between the observed trends was investigated through Pearson correlations to evaluate the assumption that the discrepancy between the AC and BC MLD is associated with a large MTLD and a small TA (Table 5.10). No significant relationship was found between the TA and the discrepancy, MTLD and BC MLD at the three test frequencies. The discrepancy was negatively correlated with the BC MLD at the three test frequencies which is expected as the discrepancy increased in the BC MLD decreased. The MTLD was negatively correlated with the discrepancy which was contrary to the expectation, this was only observed at 2000 Hz. The BC MLD was positively correlated with the MTLD at 2000 Hz.

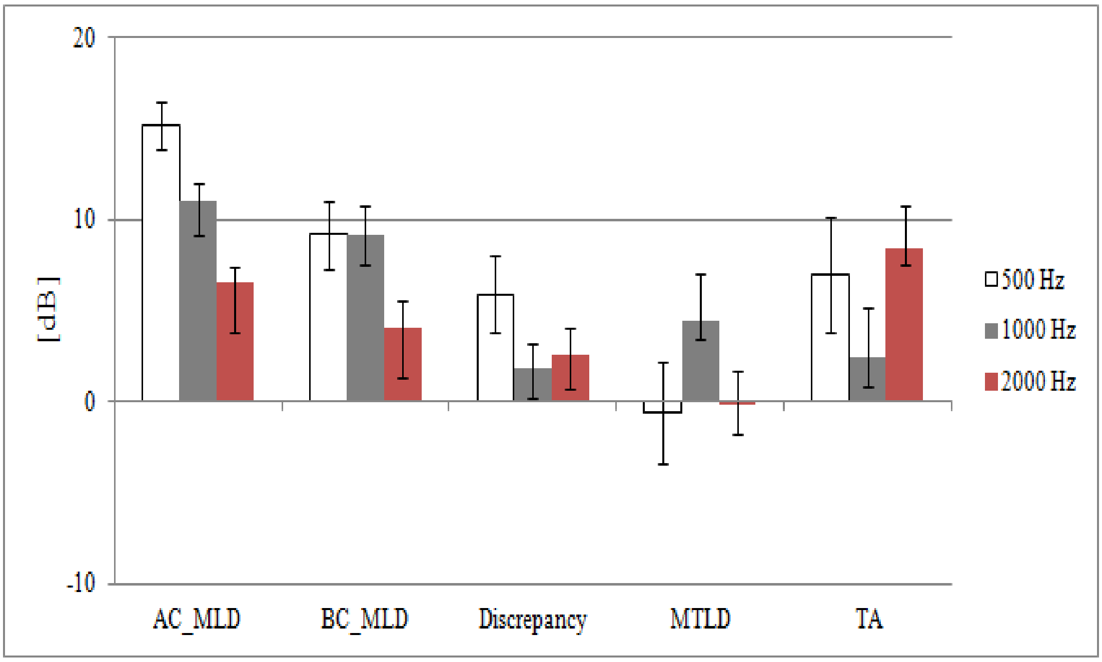

Figure 5.16 Overall conditions error bars showing 95% confidence intervals.

Table 5.10 Correlation matrix across variables measured in 18 participants, at three test frequencies (Hz).

	Variable	**Discrepancy**		**MTLD**		**TA**		**BC MLD**	
		r	**p**	**r**	**p**	**r**	**p**	**r**	**p**
500 Hz	**Discrepancy**	1.00		-0.10	0.69	0.09	0.74	-0.81	<0.001
	MTLD	-0.10	0.69	1.00		0.19	0.46	-0.16	0.52
	TA	0.09	0.74	0.19	0.46	1.00		0.02	0.94
	BC MLD	-0.81	<0.001	-0.16	0.52	0.02	0.94	1.00	
1000 Hz	**Discrepancy**	1.00		-0.01	0.98	-0.23	0.36	-0.78	<0.001
	MTLD	-0.01	0.98	1.00		0.08	0.75	0.26	0.30
	TA	-0.23	0.36	0.08	0.75	1.00		0.14	0.57
	BC MLD	-0.78	<0.001	0.26	0.30	0.14	0.57	1.00	
2000 Hz	**Discrepancy**	1.00		-0.52	0.03	0.18	0.48	-0.84	<0.001
	MTLD	-0.52	0.03	1.00		-0.07	0.79	0.55	0.02
	TA	0.18	0.48	-0.07	0.79	1.00		-0.29	0.25
	BC MLD	-0.84	<0.001	0.55	0.02	-0.29	0.25	1.00	

5.3.7.2 Individual results

Further analysis was conducted to evaluate the interference pattern based on the direction of the MTLD (Figure 5.17). The MTLD results were divided into two groups Group A and B, the results were then analysed using paired sampled *t*-tests. It can be noticed from the Figure 5.17 (Group A) that the MTLD magnitude was almost equal to the discrepancy but in the opposite direction. The difference between the MTLD and discrepancy about –11 and –5.1 dB was statistically significant at 500 Hz ($t(8)=5.9$, $p< 0.001$) and 2000 Hz ($t(12)= 5.1$, $p=0.002$), respectively. Whereas the difference of –5.3 dB at1000 Hz was not significant ($t(3)= 2.5$, $p=0.08$). On the other hand, Group B had positive MTLD values at the three test frequencies,1 the MTLD appeared to be associated with smaller AC and BC discrepancy at 1000 and 2000 Hz. The difference of 4.9 dB ($t(13)= 4.4$, $p=0.001$) at 1000 Hz was statistically significant. Whereas, the difference between the MTLD and discrepancy of -1.3 and 2.1 dB was not statistically significant at 500 Hz ($t(8)=0.8$, $p= 0.413$) and at 2000 Hz ($t(7)=1.7$, $p=0.118$), respectively.

The MTLD significantly differed than the BC MLD in Group A at 500 Hz ($t(8)= 6.0$, $p< 0.001$), 1000 Hz ($t(3)= 3.3$, $p= 0.039$) and 2000 Hz ($t(9)= 6.6$, $p< 0.001$). Similarly, Group B showed significant differences at 500 Hz ($t(8)= 4.7$, $p= 0.002$) , 1000 Hz ($t(13)= 2.7$, $p= 0.017$). However, the difference of 2.8 dB at 2000 Hz was not statistically significant ($t(7)= 2.1$, $p=0.078$). The results followed the averaged trend in that the difference between the BC MLD and the MTLD was statistically significant regardless of the direction of the MTLD, except for the MLD measured at 2000 Hz in Group B.

TA was similar in the two groups across the three test frequencies. Comparison between the mean values was conducted through independent *t*-tests with TA as the test variable and the data was grouped based on the MTLD. None of the comparisons were statistically significant at 500 Hz ($t(16)=0.48$, $p= 0.632$), 1000 Hz ($t(16)=0.69$, $p=0.496$) and 2000 Hz ($t(16)=0.44$, $p=0.661$). These results indicate that the change in the MTLD direction was not influenced by the TA because he TA was similar in the two groups.

The discrepancy between the AC and BC MLD was statistically significant in the two groups expect at 1000 Hz in Group A ($t(3)= 1.2$, $p= 0.304$) and at 2000 Hz in group B ($t(7)= 0.7$, $p=0.500$). A significant correlation between AC and BC MLD was only found in Group B. A negative correlation was observed at 500 Hz (r= –0.718, p= 0.029) indicating that a high AC MLD was associated with a low BC MLD. The relation was positive at 1000 Hz (r= 0.656, p= 0.011) and at 2000 Hz (r= 0.723, p=0.043), indicating that a high AC MLD was associated with a high BC MLD.

The discrepancy between the AC and BC MLD may have been due to the monaural effect due to cross hearing. Therefore, the BC MLD was corrected by adding the absolute MTLD to BC MLD for the participants with positive AC and BC discrepancy, the results of the BC MLD was not changed for the participants who had same AC and BC thresholds. The results were then compared to the AC MLD. The thresholds were similar at 500 Hz ($t(17)=1.1$, p=0.077), 1000 Hz ($t(17)=1.8$, p=0.086) and at 2000 Hz ($t(17)=1.2$, p=0.223). These, results indicate that the cross-talk have contributed to the discrepancy between the AC and BC MLD.

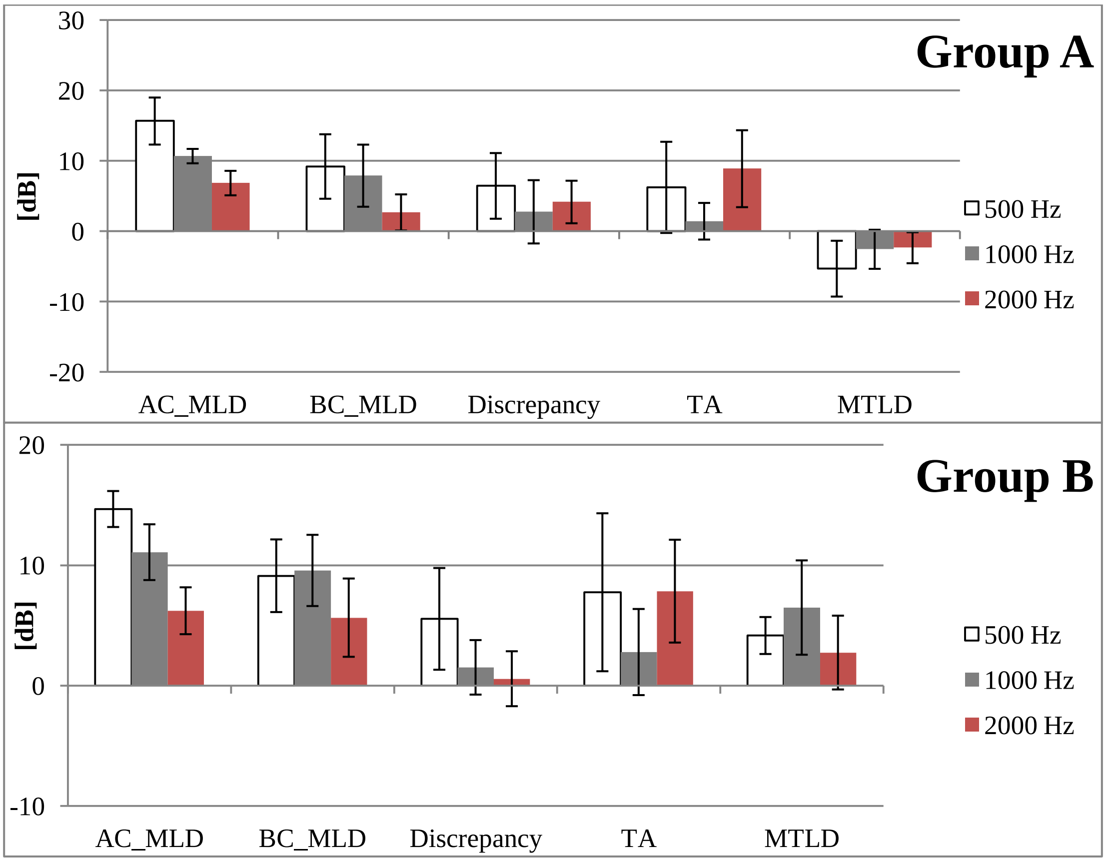

Figure 5.17 Overall conditions, measured at the three test frequencies (Hz), for group A (negative MTLD) and Group B (positive MTLD). Error bars represent the SD of the mean.

Furthermore, the results were evaluated for the participants with small AC and BC discrepancy. The question raised is would the small discrepancy be due MTLD? The MTLD was subtracted from the BC MLD for the group of participants with small discrepancies. The results were then compared to the BC MLD for the rest of the participants without correcting the results. The corrected thresholds were similar at 500 Hz ($t(16)= 0.55$, $p=0.586$), 1000 Hz ($t(16)= 0.48$, $p= 0.637$) and at 2000 Hz ($t(16)=2.27$, $p= 0.037$), the significance was corrected to Bonferroni adjustment due to the multiple comparisons.

Some participants had MTLD that was equal in magnitude of the BC MLD. This would suggest that in some participants the BC MLD can explained entirely by the MTLD. This was observed at 500 Hz (participant 10, 11, 12, 14), 1000 Hz (participant 5, 10, 12, 14 and 17) and at 2000 Hz (participant 1, 6, 11, 12, 16). Participant 12 was present in the three frequencies.

5.3.8 Summary of results

- The current methodology appeared to be reliable in measuring AC MLDs and BC MLD. The within-subject variation in the present investigation is good and indicates that the thresholds were repeatable in the AC and BC thresholds. Inter-subject variation was wider with the BC MLD compared to the AC MLD. However, the results were comparable to background studies.
- BC MLDs followed the same trend of the AC MLD at the three test frequencies. However, the magnitude was lower than the AC MLD. The discrepancy between the AC and BC MLDs was wider at 500 Hz compared to 1000 and 2000 Hz.
- TA results were lower than 10 dB at the three test frequencies. The lowest TA was observed at 1000 Hz. Furthermore, the TA was observed to be symmetrical between the right and left ears. The results were comparable to background studies indicating that the current methodology was acceptable.
- The monaural effect evaluated by measuring the difference between the So and Sπ resulted in a number of observations:

1. The within-subject variation was wider than the BC MLD. However, the repeatability was fair.

2. Some of the participants had MTLD results in the opposite direction (i.e. Sπ having worse thresholds than the So). This was observed at the three test frequencies. Therefore, the participants were grouped based on the results of the MTLD.

3. Some participants had MTLD that was equal in magnitude of the BC MLD, indicating that in some participants the BC MLD can be explained entirely by the MTLD.

- The discrepancy between the AC and BC MLD can be partially explained by the cross-talk model. Because of the following reasons:

1. The BC MLD was always higher in magnitude compared to the MTLD in the two test groups (Figure 5.15).

2. The TA was small at the three test frequencies compared to the IA with AC reported in literature (Moore, 1997; Gelfand, 1998), supporting the small acoustical separation with BC stimulation and supporting the measurable MTLD at the three test frequencies.

5.4 General discussion

5.4.1 Repeatability

5.4.1.1 Within-subject variability

The repeatability of the test conditions were evaluated in the same manner as the preliminary investigation. The within-subject variability can be evaluated by the ICC scores and the individual SD in the different conditions.

The results of the ICC scores showed a trend of high ICC with the BC thresholds in noise while the AC thresholds showed very small ICC < 0.5 for the three test frequencies. This was similar to the findings reported in the preliminary investigation. Low ICC can be produced when there is low variation between the responses, which is one of the main disadvantages of the ICC test (Graham et al, 2012).

The within-subject SD for the various test conditions are presented in Appendix L. 71% of the participants had SD lower than 2 dB in the AC thresholds in noise compared to 78% of the participants in the preliminary investigation. 74% of the participants had a

SD lower than 2 dB for the BC threshold in noise measured in the same test session. Comparing the thresholds in the two test sessions resulted in 70% of the individual SD being at or lower than 3 dB this is compared to 37% in the preliminary investigation. The MTLD measured with bilateral BC stimulation showed that 76% of the participants had SD at and below 5 dB.

Similar to the preliminary investigation that found lower SD for the individual responses at 1000 Hz, it was observed in the present study that the SD were lower at 1000 and 2000 Hz compared to 500 Hz. This indicates that the increase in frequencies leads to lower within-subject variability.

The within-subject variation in the present investigation is good and indicates that the thresholds were repeatable in the AC and BC thresholds. The within-subject SD was lower than the results reported in the preliminary investigation for the same frequencies (500 and 1000 Hz). This could be due to the enhancement in the methodology of placing the two transducers, better audibility due to the control of the level on the tone and masker. Monaural MLD resulted in a wide within-subject variation. However, the repeatability was fair. The reason for the wider variation could be related to the placement of the transducer that could have been different between the sessions. The occlusion effect being more pronounced in MTLD because one ear was un-occluded influencing the level of the tone.

5.4.1.2 Inter-subject variability

The evaluation of the inter-subject variability was performed in a similar manner to the preliminary investigation. The SD of the pooled data was analysed. The SD of the mean for the AC thresholds was < 2.8 dB for the two phase conditions at the three test frequencies, which was similar to the preliminary investigation. Furthermore, the results were comparable to the background studies (Bernstein et al, 1998; Stenfelt & Zeitooni, 2013; Tompkins, 2008). Therefore, the AC thresholds were reliable and can be compared to the BC thresholds.

The SD of the mean for the BC thresholds was approximately 5 dB for the thresholds in the two phase conditions at the three test frequencies. These results are lower than the SD of the pooled mean reported in the preliminary investigation indicating better inter-subject variability. Furthermore, the variability in the present study was comparable to the reported results by Tompkins (2008) and Stenfelt & Zeitooni (2013).

5.4.2 Air conduction

The AC thresholds were measured in SoNo and SπNo phase conditions at 500, 1000 and 2000 Hz. The signal was embedded in broadband masking noise presented at a constant level equivalent to a spectrum level of 39.1 dB. Inverting the phase of the signal resulted in improved thresholds in the SπNo (19.1, 30.1 and 34.2 dB HL) condition compared to SoNo (35, 41.1 and 40.8 dB HL) condition at 500, 1000 and 2000 Hz respectively. The SoNo thresholds were within 5 dB of results reported in literature (Hawkins & Stevens, 1950; Hall & Grose, 1994).

The AC MLD will now be considered by comparing the results in the current experiment to those reported previously, Table 4.10 presented in Chapter four reports the comparisons. It is observed that AC MLD at 500 and 1000 Hz followed the same pattern of the reported literature (Durlach, 1963; Hall & Harvey, 1985; Bernstein et al, 1998; Van Deun et al, 2009). The results in the current investigation were compared to the AC MLD reported in the preliminary investigation (Section 5.3.6.3). A statistical significant difference between the two studies was observed at 500 Hz, but not at 1000 Hz. This difference can be explained by the level of the masking noise. Yost (1988) reported that a change in the masker level (up to a spectrum level of 50 dB) would result in a change in the MLD (See Table 4.11). Furthermore, Hall & Harvey (1985) reported an increase in the MLD as a function of the masking noise which was noticed with NBN maskers. The change in the masking level affected the 500 Hz more than 1000 Hz, this has also been observed in Hall & Harvey's (1985) results. They showed that the MLD increased by 3 dB with the increase in the spectrum level from 50 to 60 dB at 500 Hz, compared to 1 dB increase at 2000 Hz.

The AC MLD of 6.5 at 2000 Hz was higher than the expected MLD of 3-4 dB (Hall & Harvey, 1985). Background studies report that the AC MLD is expected to decrease to a constant level around 3 dB. This is because the firing pattern of the auditory nerve is phase locked to the stimulus which is more pronounced at low frequencies and decreases with higher frequencies (Gelfand, 1998). The reasons that may explain the higher AC

MLD at 2000 Hz could be related to the use of insert earphones. For example, Yost (1988) reported a small difference about 2 dB between the headphones and inserts at the spectrum level of 40 dB at 200 Hz, with the inserts resulting in higher thresholds. However, Hall & Grose (1994) found no difference between the insert and earphones at 500Hz when the NBN was presented at spectrum level of 60 dB. The observation of Yost (1988) that inserts produced higher MLD was due to the contribution of the internal noise when presented at low masking levels. Whether it is the insert earphones that resulted in higher thresholds is uncertain because rigorous calibration was conducted and the AC MLD at 500 and 1000 Hz appeared to be consistent with the reported literature.

5.4.3 Transcranial attenuation

The TA was the result of the difference in masked thresholds between the ipsilateral and contralateral ear measured in two test sessions. The significance of measuring the TA in the present investigation was to evaluate the relation of the TA and the monaural effect to possibly infer the success of fitting BCI. The acoustical-separation between the two ears is dependent on the TA and TD. A large TA is expected to be associated with lower AC and BC discrepancy and lower effect of signal cross-talk.

The results in the present investigation were lower than 10 dB for the three test frequencies. The measurement of TA was conducted for the right and left ears, to evaluate the symmetry between the two ears. The results indicated that the TA was symmetrical between the two ears with an average difference of 2 dB which was not statistically significant. Background studies have mainly measured TA in unilaterally deaf patients. Therefore, their measurements were only related to one ear (Nolan & Lyon, 1981; Vanniasegaram et al, 1994; Stenfelt, 2012). Studies that measured the TA with normal hearing participants have also measured it in one test ear (Nolan & Lyon, 1981; Stenfelt & Zeitooni, 2013).

Figure 5.18 plots the results of the present study in comparison to background studies. It is observed that the TA measured by Nolan and Lyon (1981) was the highest at the three test frequencies compared to the rest of the studies while Stenfelt (2012) reported the lowest TA across the three test frequencies. The TA in the present study followed the same trend as the reported literature at 500 and 2000 Hz. However, the present study and the reported literature seem to report different results at 1000 Hz, a number of studies had higher TA (Nolan & Lyon, 1981; Vanniasegaram et al, 1994) than the rest of the studies (Stenfelt, 2012; Stenfelt & Zeitooni, 2013) including the present investigation.

The methodology for threshold collection was different in the studies which may have led to the lower and higher TA levels. For example, studies with high TA used a 5 dB step size to collect the thresholds whereas the lower TA studies used a 3 dB step size in the present investigation and 1 dB step size in Stenfelt (2012) and 2 dB step size in Stenfelt & Zeitooni (2013). The smaller step sizes indicate that the measurement was conducted with more precision leading to the smaller thresholds. The difference in methodology also included a manual (B71) (Nolan & Lyon, 1981; Vanniasegaram et al, 1994; Stenfelt, 2012) and automated method (BEST) (Stenfelt & Zeitooni, 2013) and the present study. Based on the transducer verification study (Chapter Three) this factor is not expected to have influenced the results of the TA because no difference was found at 1000 Hz between the manual or automated method. Similarly the BESTs and B71 produced similar thresholds at 1000 Hz. All of the studies reported wide range (inter-subject variability) of TA that may have influenced the findings.

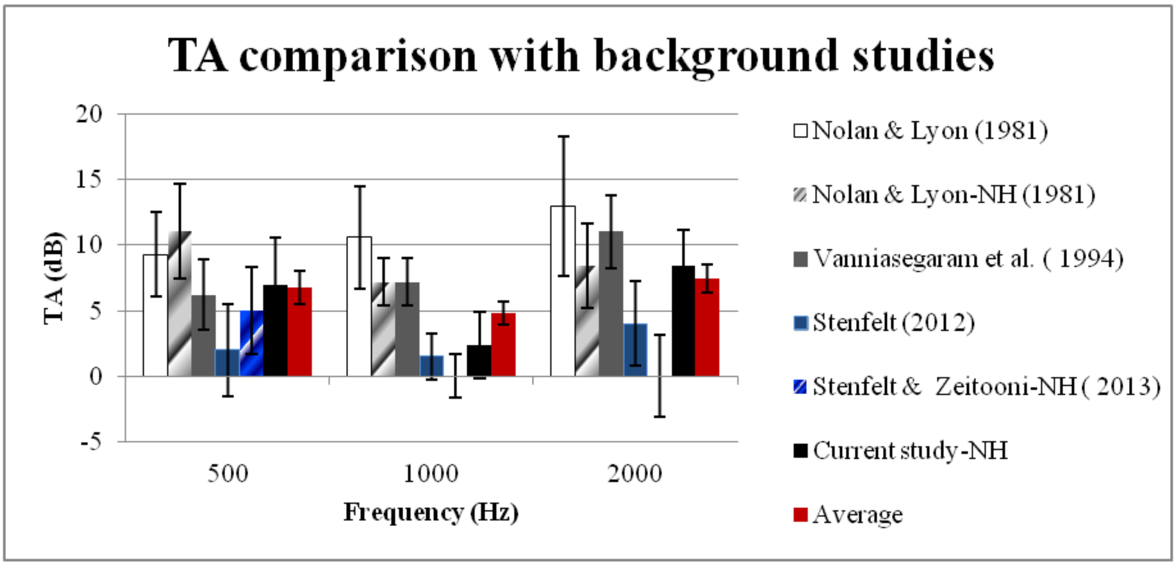

Figure 5.18 TA (dB) results across different frequencies reported in the literature, NH indicates studies with normal-hearing participants. Error bars show 95% confidence intervals.

5.4.4 Bilateral bone conduction

The measurements of the BC thresholds were conducted in the SoNo and SπNo phase conditions. An inversion of the phase of the signal resulted in better hearing thresholds of 14, 27 and 37 dB at 500, 1000 and 2000 Hz respectively, compared to 23, 36 and 41 dB, respectively, at the same test frequencies. These results indicate that the participants were able to detect the change in phase. Comparison of the thresholds to the preliminary investigation showed that the increase in the overall level of the masking noise resulted in higher thresholds in the two phase conditions. This observation was expected and was in line with the previous reports that showed that the masker phase and overall level would influence the thresholds (Hall & Harvey, 1985; Yost, 1988). Furthermore, the change in frequency influenced the test results in the same manner reported in preliminary investigation (Section 4.4.3).

The MLD calculated from the difference between the two phase conditions was significantly different than zero with an average of averaged results 9.1, 9.1 and 3.9 dB at 500, 1000 and 2000 Hz respectively. It was noticed that the magnitude of the MLD was larger than the magnitude reported in the preliminary investigation. The manipulation of the signal and noise parameters seemed to influence the MLD in the same manner reported to influence the AC MLD (Green & Yost, 1975; Hall & Harvey, 1985; Grose et al, 1997; Buss et al, 2007). Refer to Section 4.4.3 for more discussion of BC MLD in relation to background research.

5.4.5 Monaural effect

The measurement of the MTLD with bilateral BC stimulation is one of the novel features of the present investigation. To the knowledge of the investigator, there is no previous published research conducted on this part of the study. The results appeared to be affected by the inter-subject variation in addition to the within-subject variation. However, the averaged results did not show any significant differences for the change in session of ear on the thresholds in the two phase conditions. The change in the phase of the signal had minimal affect on the averaged thresholds.

The difference between the two phase conditions was calculated. The average MTLD was about –0.5, 4.5 and –0.1 dB at 500, 1000 and 2000 Hz, respectively. The average results indicate that the MTLD was only significantly different than zero dB at 1000 Hz. In other words, inverting the phase of the signal was not measurable. Therefore, the BC MLD appears to be due to binaural hearing rather than due to cross-talk. However, clear trends for the individual participants were observed indicating that the averaged results concealed important trends due to large number of participants having MTLDs in the negative region. The MTLD in the opposite direction indicate that the Sπ had a higher threshold than So, which was consistent with the cross-talk model, this trend was observed at the three test frequencies.

The MTLD was measurable in the two groups and was significantly different than zero at the three frequencies. The negative MTLD averaged about –5.2, –2.5 and –2.3 dB at 500, 1000 and 2000 Hz, respectively, while the positive MTLD averaged about and 4.1, 6.4, 2.7 dB at 500, 1000 and 2000 Hz, respectively.

Tompkins (2008) measured the MTLD at 1000 Hz and found the majority of the participants had measurable MTLD in the negative direction (average -4.7 dB). The present investigation had only four participants with negative MTLD, whereas the majority of the participants had positive MTLD. The average of the negative MTLD was comparable to the result reported by Tompkins (2008).

5.4.6 Comparison between AC and BC

The discrepancy between the AC and BC MLD was significant at 500, 1000 and 2000 Hz. Similar to the preliminary investigation the lower frequencies had the largest discrepancy. This can be explained by the occlusion effect influencing the level of the signal in the two phase conditions mainly observed at 500 Hz. Another explanation could be related to the overall level of the masker. The increase in the overall masking level in the present investigation led to smaller discrepancies between the AC and BC MLD at 500 and 1000 Hz compared to the preliminary investigation.

Section 4.4.5 discussed the AC and BC MLD discrepancy in relation to the background research with CHL measured either by AC or BC stimulation. It appears that at 500 Hz the BC MLD follows the same pattern of the AC MLD measured in patients with CHL

(Quaranta & Cervellera, 1974; Hall & Grose, 1994). Furthermore, these results are in line with Hausler et al (1983) observation that normal hearing participants perform similar to patients with CHL.

5.4.7 Cross-talk effect

The results indicate the measured BC MLD was significant, indicated by one sample *t*-test. However, the magnitude of the BC MLD was lower than the AC MLD under the same test conditions. The MTLD evaluated, based on the direction, was significantly different than zero dB at the three test frequencies in Group A and B, except in Group A at 1000 Hz the average of four participants was not statistically different than zero dB. Only at 2000 Hz, was a positive correlation observed between the BC MLD and the MTLD indicating that cross-talk can account for the magnitude of the BC MLD.

The change in the direction of the MTLD was present at the three test frequencies. However, the number of participants in each group was not equal. The reason for the change in the MTLD direction could be related to the TD value. Figure 5.19 plots the MTLD prediction, as a function of TD, based on the cross-talk model (Zurek, 1986). The MTLD results in the present study follow the prediction in the model. This means that the TD is likely to be the cause for the inter-subject variation.

The average TA did not exceed 10 dB at the three test frequencies, with the smallest TA observed at 1000 Hz, indicating that the acoustical separation between the two ears was small and the possibility of cross-talk was present.

Based on the interference model (Figure 5.1) it was expected that TA of magnitude reported in the present investigation would be associated with cross-talk of the signal which was expected to be lower at 500 and 2000 Hz compared to 1000 Hz because TA was lowest at this frequency (average 2.4 dB). The results in the present investigation appeared to confirm the observation in the cross-talk model. The averaged results showed an association between the TA and MTLD results (Section 5.3.7.1), a small TA at 1000 Hz was associated with a higher averaged MTLD while TA that was higher in magnitude at 500 and 2000 Hz was associated with low MTLD. However, these results were not confirmed statistically and there was no relation between the results.

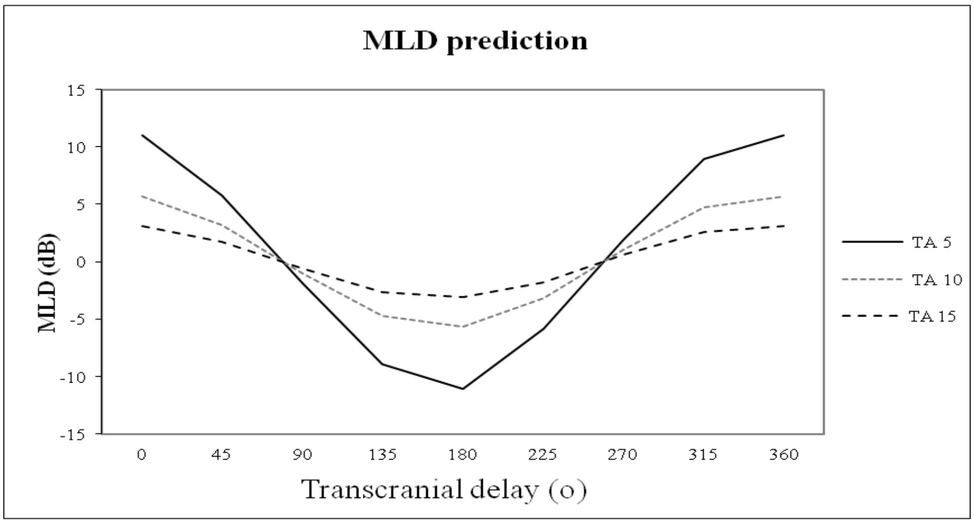

Figure 5.19 The prediction of the MTLD, in dB, as a function of the transcranial delay (°).

The correction of the BC MLD was conducted by adding the MTLD to the participants with positive AC and BC discrepancy. Participants with equal AC and BC MLD their results were unchanged. The corrected results were then compared to the AC MLD and the results were found to be similar. This gives evidence that the MTLD contribute to the discrepancy between the AC and BC MLD.

5.5 Conclusions

- The methodology for measuring the MLD was sensitive to the increase in the noise level. The AC MLD was higher than the preliminary investigation at 500 Hz and the average was comparable to the reported literature (Durlach, 1963; Hall & Harvey, 1985; Bernstein et al, 1998; Van Deun et al, 2009). Similarly the BC MLD increased with the increase in level at 500 and 1000 Hz.
- BC MLD followed the same pattern as with AC across the frequencies tested but with more variability and was always lower in magnitude compared to the AC MLD.
- The discrepancy between the AC and BC could not be explained solely by the results of the bilateral-monaural thresholds. However, the current MTLD results support that cross-talk contributes to the discrepancy between the AC and BC MLD.

- A link has been observed between the TA and the bilateral- monaural thresholds but not the AC-BC discrepancy. This could be explained by TD which needs further studies to investigate it.

Chapter six. Summary

The main aim of this study was to evaluate binaural hearing with bone conduction stimulation. To produce accurate results it was important to evaluate the performance of the transducers given that a new BC transducer has been introduced, the BEST (Håkansson, 2003). The aims are listed below:

1. Is the balanced electromagnetic separation transducer (BEST) more suitable for investigation of binaural tests than the clinically used B71? Specifically, does it have lower total harmonic distortion? Does it have wider dynamic range? Is it suitable to be used under the current calibration standard (ISO 389-3, 1999)?

The performance of the BEST in comparison to the B71 was evaluated through measuring the sensitivity and total harmonic distortion. The measurement of the sensitivity showed that the BESTs were more sensitive than the B71 providing wider dynamic range of testing at lower frequencies. The improvement in sensitivity was between 14 to 19 dB. Furthermore, the results indicated that the BEST was less sensitive than the B71 by 9 dB at 4000 Hz. The results of the total harmonic distortion showed that the BEST produced significantly lower harmonic distortion compared to the B71 at 250 Hz. However, the results of the THD at the rest of the frequencies were comparable between the two types of transducer.

The results of the sensitivity indicate the superiority of the BESTs compared to the B71 at low frequencies. This is clinically promising because the dynamic range of testing would be increased and the threshold measurement can include 250 Hz. The thresholds at 250 Hz could be clinically confirmed by testing rather than inferred which is currently done in the clinics. The results of the THD further confirm that the testing at 250 Hz can be tested with confidence that the threshold is for this frequency rather than its harmonics. The sensitivity results followed the same pattern of results reported by Håkansson (2003) at the frequency range evaluated in the current study. The THD results obtained in the current study were within the IEC 60645-1 (2001) permissible limits for the B71 and BESTs at the frequencies between 250 – 4000 Hz.

The hearing thresholds were measured to evaluate the performance of the BEST in relation to the B71. The results are in good agreement with the results of repeatability measured with insert earphones (Stuart et al, 1991) and B71 test-retest thresholds (Ho et al, 2009; Margolis et al, 2010). The thresholds collected manually were comparable to the thresholds collected through the automated method, a similar observation was reported by Margolis et al (2010)

The results of the hearing thresholds measured by the two types of the BC transducer (B71 and BEST) are indicative of a discrepancy with the current RETFL at frequencies >1000 Hz with the B71 and at the majority of the test frequencies (except 1000 Hz) with the BESTs. The suggested correction factors are tabulated in Table 3.22 based on the results of one sample *t*-test with a mean of 0 dB HL. The results also showed statistical significant differences between the B71 and BEST at 500, 1000, 2000 and 4000 Hz. However, this difference was less than 5 dB.

Measurement of the vibrotactile thresholds in normal and deaf participants demonstrated that the BEST was similar to the B71. The BEST and the B71 produced comparable vibrotactile thresholds in normal hearing participants at 250 Hz. At 500 Hz the thresholds were only measured in deaf participants, the preliminary results indicate that the BEST was more tactile compared to the B71. However, the results of the deaf participants in the current investigation cannot be generalised due to the small sample and wide inter-subject variability.

The better sensitivity and THD makes the BEST a good research and clinical replacement of the B71 because it will enable the testing of the low frequencies with reliability. However, correction factors must be applied in clinical setup especially at 250 and 4000 Hz. Due to the BESTs different design and lighter weight, further research is recommended to address the coupling force and the airborne radiation. It is recommended that the current RETFLs are adjusted for the BESTs to account for the sensitivity and the threshold differences found at 2000 and 4000 Hz.

The preliminary results with the vibrotactile thresholds suggest that the BESTs were not different than the B71 at 250 Hz. However, initial investigations with deaf patients at

500 Hz suggest that the BEST performed worse than the B71. More research with more participants is recommended as the current observation was from only four patients

2. How does the binaural MLD compare between the AC and BC under otherwise identical conditions? This was important because it will aid in understanding the cues normal hearing participants use with bilateral BC stimulation. It will also address the question of whether generalisation from the AC studies can be extended to BC.

The magnitude of the BC MLD was always lower than the AC MLD in the two investigations (preliminary and interference investigation). Testing was conducted in normal hearing participants with natural access to binaural cues. Furthermore, the measurements were conducted under identical test setup with the only difference in stimulation pathway.

The MLD test is sensitive to the manipulation of the signal and noise parameters (Hall & Harvey, 1985; Bernstein et al, 1998). Similarly, it was found that measurement of the MLD with bilateral BC stimulation was sensitive to the manipulation of the test parameters. The signal and noise parameters were adjusted in the investigation of interference to provide higher levels of masking noise and care was taken to adjust the signals of the AC and BC signals as close as possible in the hearing level. This resulted in a decrease in the AC and BC MLD discrepancy. However, a significant difference remained at the three test frequencies. Variation in the participants responses was evident. It was noted that some individuals had almost equal AC and BC MLD at a given frequency. However, the change in frequency would affect the individual performance resulting in a greater discrepancy. In other words, if a person had no discrepancy between the AC and BC MLD at 1000 Hz, it does not mean that the same individual would have no discrepancy at 2000 Hz. This indicates that the use of the binaural cues was influenced by the change in frequency, favouring the cross-talk hypothesis.

The assumption that the results with AC MLD can be generalised to interpret the BC MLD is invalid. The present results indicate that normal hearing participants performed similar to patients with CHL at the frequencies tested (Quaranta & Cervellera, 1974;

Bosman et al, 2001) which is similar to the observation reported by Hausler et al (1983). This indicates that future testing of binaural hearing with patients with CHL should test a control group of normal hearing to interpret the results. Furthermore, the interpretation of the results should be conducted with caution.

The preliminary investigation and the interference investigation reported similar BC MLD values between 500 and 1000 Hz. This could be due to the sensitivity of the transducer. The BESTs were reported to produce lower hearing thresholds than the standard at 500 Hz which means that the overall level should have been adjusted to correct the discrepancy which could result in higher BC MLD score at this frequency.

3. How does the frequency of the tone affect the binaural MLD with BC compared to AC? This was important because AC binaural MLD is known to decrease as the frequency is increased from low to high. Would an increase in the frequency result in a decrease in the overall BC binaural MLD?

The preliminary investigation showed a trend of an increase in the BC MLD as the frequency increased from 250 to 1000 Hz. However, further investigation in the subsequent study showed that the BC MLD followed the same pattern as the AC MLD (i.e. MLD decreased with the increase in frequency). This indicates that the trend observed in the preliminary investigation was probably due to the control of the test setup. Controlled placement of the BC transducers, rigorous calibration and the increase in the masking noise resulted in an increase in the overall magnitude of the BC MLD and the decrease in MLD with the increase in frequency.

The AC MLD has been extensively reported with different frequencies. The magnitude is reported to be the largest at low frequencies and decreases to a constant 3 dB at higher frequencies (Hall & Harvey, 1985; Gelfand, 1998; Yost, 2007). Similarly, the BC results were comparable to the reported literature in the preliminary investigation (Bosman et al, 2001; Stenfelt & Zeitooni, 2013; Tompkins, 2008) and in the investigation of interference (Quaranta & Cervellera, 1974; Hall & Grose, 1994).

The reduced discrepancy with the increase in the frequency could be attributed to the binaural cues used to interpret frequencies. It is well known that the low frequencies are interpreted by ITD while the ILD is responsible for interpreting high frequencies (Gelfand, 1998). Since the participants results in the present investigation were similar to the BC MLD reported with patients (Bosman et al, 2001; Priwin et al, 2004) it would be reasonable to assume that the coding of the binaural cues would follow the same reports with patients with CHL. Hausler et al (1983) reports that patients with CHL have degraded ITDs while the ILDs are preserved. The BC MLD at low frequencies in the present study had the highest discrepancy with the AC MLD which indicates that in normal hearing participants the ITDs were degraded (assuming the results were due to binaural hearing).

The reason for the degraded ITD is attributed to the cross-talk of signal with BC stimulation (Zurek, 1986). The cross-talk of signal is mainly due to the relatively small transcranial attenuation and the transcranial delay which lead to loss of isolation between the two cochlea with bilateral BC stimulation. TA results are reported to have very wide variation between individuals but as a general trend the TA increases with the increase in frequency (Nolan & Lyon, 1981; Vanniasegaram et al, 1994; Stenfelt, 2012; Stenfelt & Zeitooni, 2013). This could explain the larger discrepancy between the AC and BC MLD at low frequencies and low discrepancy at high frequencies. Stenfelt & Zeitooni (2013) report that the results of the precedence test in normal hearing participants were most similar between the AC and BC stimulation at high frequency stimulation. Whereas, the low frequency resulted in the least correspondence between the AC and BC stimulated precedence function.

Bosman et al (2001) and Priwin et al (2004) reported that their participants had advantageous localisation performance with bilateral BCI compared to unilateral condition. The localisation performance was conducted using two different frequencies 500 and 2000 Hz. The accuracy of the localisation was lower than expected with normal hearing participants. However, the change in the frequency did not influence the overall performance. This indicates that the use of the binaural cues was effective in the low and high frequency sounds. The participants were able to locate the sound source within 45º and the result was well above chance level.

4. Is there a relation between the transcranial attenuation and the binaural MLD? This was important because it will address the hypothesis that the magnitude of the transcranial attenuation is related to the magnitude of the discrepancy between the AC and BC binaural MLD.

The magnitude of the TA measured was relatively small < 10 dB at the three test frequencies. The TA at 1000 Hz was the smallest. There was no statistical relation between the TA and the BC MLD at any of the test frequencies.

The model of cross-talk proposed by Zurek (1986) explored in the Section 2.5.3 predicts the influence of signal at each cochlea. A number of assumptions have been made before the application of the model. The first assumption is that the two cochlea are symmetric. The second assumption is related to the noise, it assumes that the noise is identical between the two ears, thus it will be constant to the results. For example, assuming that the TA is 0 dB and TD is 0° in the SoNo condition the signals are in phase and the resultant signal will be twice the magnitude of the direct stimuli indicating that the result obtained should be better than the AC. The average magnitude of the SoNo BC thresholds were lower than the AC thresholds at 500 Hz, while at 1000 and 2000 Hz the thresholds were within 5 dB of the AC thresholds. Individual results (Appendix M) show that a number of participants had slightly better thresholds compared to the AC thresholds.

Inverting the phase of the signal SπNo is assumed to cause a reduction in the magnitude of the resultant stimuli because the direct and interfering signal will almost cancel each other resulting in thresholds that are worse than the AC condition. The results in the current study with the bilateral BC presentation were not better than the AC thresholds at 500 and 1000 Hz. However, the averaged thresholds were better in the BC SπNo condition compared to the AC thresholds at 2000 Hz. The variability in the responses and magnitude suggest that the combination of TA and TD must be different than 0 dB and 0°.

Based on the model the interference pattern can be observed when the TA is assumed to be 10 dB. In which case the SoNo will lead to reduction in the amplitude of the resultant signal, and also to a less reduction in the SπNo condition. This will result in a detectable difference between the two conditions leading to the prediction of MLD due to monaural hearing alone. This could be the cause of the discrepancy in the current results between the AC and BC MLD's.

The model also predicts wide inter-individual variability because of the influence of the TA and TD on the results of the MLD (Nolan & Lyon, 1981; Stenfelt & Reinfeldt, 2007). This prediction seems to be evident in the small number of studies that investigated MLD in patients fitted with bilateral BAHA's (Bosman et al, 2001; Priwin et al, 2004). The current study showed variability in the responses across the different frequencies and across the phase conditions indicating that the TA and TD should be measured to explain the results.

5. Is it possible to measure binaural MLD with monaural BC hearing and can this account for the discrepancy between the AC and BC binaural MLDs? This was important because it will allow in the understanding of the effect of cross-talk of the signal and its contribution to the overall binaural MLD.

The BC MTLD was a novel feature of this study. The results show that it was measurable in all the participants. However, the direction was variable between the participants. Some participants had positive MTLD while the rest have negative MTLD. Therefore, the results were grouped based on the direction. It was observed that some participants had MTLD results that were almost equal to the BC MLD. This indicates that in some participants the binaural MLD can be explained entirely by the cross-talk model. However, the majority of the participants had MTLD that was significantly lower in magnitude compared to the BC MLD.

Correcting the results of the BC MLD to the absolute difference of the MTLD resulted in non-significant differences between the AC and BC MLD. The results indicate that the MTLD can partially account to the discrepancy between the AC and BC MLD.

The question that remains to be answered: is the measurable BC MLD a binaural phenomenon? This investigation shows that the cross-talk of signals is evident by the presence of the MTLD. The TA results on thier own could not explain the magnitude of the MTLD. It is assumed that the TD does influence the results which can be viewed from Zurek (1986) model (Figure 5.19).

The background studies with patients reveal benefits with bilateral fitting compared to unilateral fitting with better performance in speech in noise tests, better localisation scores, better quality of life (Bosman et al, 2001; Dutt et al, 2002b; Priwin et al, 2004). The results of the cross-talk measured by the MTLD can account for the discrepancy between the AC and BC MLD. However, the BC MLD cannot be explained entirely by the cross-talk and some of the results could be due to binaural hearing.

Chapter seven. Conclusions and future research

7.1 Conclusions

1. The verification of the transducers concluded that the BEST performed better than the B71 acoustically. Psychoacoustical measurements showed that the measurement with the BEST were reliable and repeatable.

The BEST was different than the B71 in hearing threshold measurements, the difference did not exceed 5 dB and the direction differed with frequency. Furthermore, the BEST was similar to the B71 in the vibrotactile thresholds measured with normal hearing participants.

2. Significant BC MLD was found in the preliminary investigation and in the investigation of interference.

The magnitude of the BC MLD was influenced by the overall masking level. The results in the preliminary investigation were comparable to the BC MLD reported in literature (Bosman et al, 2001; Stenfelt & Zeitooni, 2013; Tompkins, 2008), the magnitude of the BC MLD in the interference investigation was comparable to the results of AC MLD in patients with CHL (Quaranta & Cervellera, 1974; Hausler et al, 1983).

3. The change in the test frequency resulted in lower BC MLD. It is concluded that the BC MLD follows the same pattern as the AC MLD.

The discrepancy between the AC and BC MLD was largest at lower frequencies. BC MLD followed the same pattern as with AC across the frequencies tested, but with more variability and was always lower in magnitude compared to the AC MLD.

4. Monaural interference effect supports that cross-talk partially contributes to the discrepancy between the AC and BC MLD.

Correcting the BC MLD to the MTLD resulted in similar results to the AC MLD. This shows that the cross-talk can partly explain the discrepancy between the AC and BC MLD.

5. A link has been observed between the TA and the bilateral- monaural thresholds but not the AC-BC discrepancy.

On average high TA resulted in low MTLD observed at 500 and 2000 Hz. However, low TA was linked with high MTLD at 1000 Hz.

7.2 Limitations

The limitations of this study include:

- The vibrotactile thresholds with deaf participants did not recruit sufficient amount of participants, furthermore, the frequencies could not be extended to include frequencies > 500 Hz. Recruiting deaf participants for this type of experiment is ideal because they will not confuse the two sensations, which was observed when testing normal hearing participants. It was unfortunate that low responses were received for the present study. Thus the preliminary results at 500 Hz cannot be generalized.

- The masking level difference is limited in the frequency and levels used to acquire the MLD, only pure tones were used. The study was limited to two phase conditions.

  The use of stationary signals for this type of experiment can result in addition and destruction of the resultant outcome due to cross-talk (Stenfelt, 2011). However, the results presented in the present investigation were similar to the results reported by Stenfelt & Zeitooni (2013) with non-stationary chirp tone.

  The study is also limited to the use of only two phase conditions, and it is more ideal to investigate more phase conditions to evaluate the influence on the BC MLD.

- The wide inter-subject variability in the TA and MTLD studies.

  Despite the measures taken to reduce the influence of variability reported in literature, variability was also observed in the present investigation.

- This study did not correct for the occlusion effect in both the preliminary investigation and the investigation of interference.
  The placement of the insert earphones to produce the masking noise could have introduced an occlusion effect. However, the influence would have affected the two ears in the same manner. It was attempted to cut the foam of the insert earphones in the pilot investigation, but this influenced the level of the masking noise and it was difficult to keep in place.

- The BEST was used without correction to the RETFLs in the preliminary and interference investigations.
  The lack of correction of the RETFLs may have influenced the BC MLD at 500 Hz and 2000 Hz by producing lower thresholds at 500 Hz. However, at 2000 Hz the influence is expected to be minimal because the overall signal will start at a more intense level, whereas at 500 Hz the level would have started at a lower level.

7.3 Future research

Binaural hearing with bone conduction stimulation provides a great deal of scope to work with. The current results and observations suggest some directions for future work which are discussed in this section.

7.3.1 Verification of transducers

The methodology for threshold collection can be optimised by including participants with different types of hearing losses to evaluate the performance of the BEST. Furthermore, the performance can be evaluated in children. Two of the studies used an automated method for data collection employing a MATLAB code. The use of automated method did not influence the results of the hearing thresholds. Future studies can optimise the MATLAB code to include easier access to change the duration of the signal presentation during the testing. The automated method will provide a portable method that required a sound card and amplifier with proper test environment this system will reduce the test space.

Measurement of the airborne radiation was not conducted in the present investigation. For a complete profile about the use of the BEST as a clinical replacement of the B71 the results of the airborne radiation measurements should be conducted acoustically and psychoacoustically. Preliminary investigation of the airborne radiation with BEST conducted by a PhD researcher at the ISVR indicates that the airborne radiation with the BEST was similar to the B71.

The present investigation of the BEST indicated that the RETFLs should be corrected for some frequencies for the B71 and for most of the frequencies with the BEST. This observation has been previously been reported with the B71s (Frank et al., 1988; Margolis et al., 2010). Further investigation should be carried out with different types of BC transducers to confirm the current results that suggested that the RETFLs should be transducer specific. Moreover, the BC transducer itself should be enhanced to reduce the limitations associated with the vibrotactile thresholds and more importantly the frequency range.

Follow-up investigation on the vibrotactile thresholds is suggested with more deaf-participants either patients with cochlear implants or completely deaf participants. For example, people who are users of sign language with no residual hearing. Participants with no residual hearing are good candidates because the test frequencies can be extended. Furthermore the results would then be reported with confidence. The present study was not able to recruit more than four deaf participants

7.3.2 Binaural hearing with bone conduction

The results in the current investigation indicate that binaural hearing can be achieved with bilateral BC stimulation in normal hearing participants. Evidence of cross-talk was noticed that affected the magnitude of binaural hearing. Further testing is required by optimising the methodology for measuring the monaural interference effect with bilateral bone conduction stimulation. This could be achieved with manipulation of the signal level of the tone. Patients with single sided deafness would be suitable for this type of testing as they have no hearing in one ear, therefore, no making would be required.

Furthermore, future research should include more manipulation of the test parameters because the MLD is known to be sensitive to the signal and noise parameters. Stenfelt (2012) reported cutting the foam tip to reduce the occlusion effect. This could not be performed in the present investigation because the level of the noise would be compromised. Microphone placed near the ear canal could be used in future research to control the noise level.

Future research measuring the BC MLD with the noise presented through the BC vibrators is advised. This is particularly useful for testing patients with CHL where the AC route is occluded. It is anticipated that the presenting the noise and tone from the BC transducer may be influenced by the limitation of the transducer which may affect the quality of the signal resulting in low BC MLDs. It is noticed from Table 4.12 that the studies that presented the tone and noise from the BC transducer resulted in similar BC MLDs in normal and CHL groups (Bosman et al, 2001; Stenfelt & Zeitooni, 2013). These results were comparable to the BC MLD collected in the preliminary investigation with the noise and tone separated. However, the manipulation of the level of the noise and in the interference investigation resulted in higher BC MLDs that were comparable to the BC MLDs reported in patients with CHL using insert earphones.

Based on the above results it is recommended that further research is conducted while presenting the noise through speakers in an anechoic chamber to exclude the occlusion effect. The results should be compared with BC MLDs collected by presenting the noise and the tone through the BC transducer.

Further research is required to evaluate the trends observed in this study to relate that include optimizing the methodology to test the monaural effect. This includes measurement of the TA and TD in the same participants which may facilitate the prediction of binaural benefit prior to the fitting of bilateral hearing aids.

The MLDs could be measured with different types of signals, for example, clicks or frequency modulated signals, or with chirp tones at different frequency ranges. More importantly with MLD should be evaluated with speech signals which can be translated into real-world benefit of bilateral fitting. Stenfelt & Zeitooni (2013) did report the results of the BILD in 20 normal hearing participants. Their BC BILD was lower than the AC BILD and similar to the binaural MLD. The origin of this discrepancy should be evaluated in more detail.

It is recommended that future research investigate the BC and AC MLD in patients bilaterally fitted with BCI with control group of normal hearing under the same test conditions.

7.3.3 Clinical implications

The MLD measured with tonal signals provides basic information about the binaural hearing for AC and BC. However, it is a laboratory test that may not reflect real world benefit of binaural hearing. Patients with bilateral symmetrical hearing loss should be evaluated with tonal and speech signals in controlled test environment. Control test environment is suggested to include patients and control group of normal hearing participants. The current results provide provisional novel data about binaural hearing with bilateral BC stimulation. Despite the discrepancy between the AC and BC MLDs the present results indicate that normal hearing participants can utalise bilateral BC input to extract binaural cues.

The results obtained with normal hearing participants. Therefore, caution should be taken when comparing the results to patients or even in predicting the benefit of bilateral fitting in patients due to a number of reasons that include:

- The BC sound transmission in patients can differ than normal hearing participants because the BCI is placed above the ear compared to behind the ear in normal hearing participants.

- The fitting of the BCI hearing aids through an abutment differs than the fitting of the BC transducer over the skin in normal hearing participants. The skin and surrounding tissue can influence the quality of the signal and thus the results.

- Patients with bilateral hearing losses have a period of deprivation of the binaural benefit which influences the interaural cues. However, normal hearing participants have access to the interaural cues. However, studies have shown that patients with CHL can adapt to binaural input even after a period of deprivation (Section 3.3.2).

Appendices

Appendix A: Ethical approval for all the studies

UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

HUMAN EXPERIMENTATION SAFETY AND ETHICS COMMITTEE

Human Experimentation Safety and Ethics Approval Number: 992

Title of Experiment: Comparison study of the performance of two bone-vibration transducers for hearing research

submitted by: Alison Vaughan and Hala Al Omari **on** 22nd April 2009

The Human Experimentation Safety and Ethics Committee has found the planned study satisfactory and confirm that it can proceed.

Please observe the following:

1. ***Record the Human Experimentation Safety and Ethics Approval Number on the subject consent forms. This number can be found at the top of this page.***
2. ***The subject consent forms, to be completed by all the subjects who participate in this study, must be provided to the Secretary of the Human Experimentation Safety and Ethics Committee by 2nd September 2009.***
3. ***You must not make any changes to the study without obtaining the approval of the Human Experimentation Safety and Ethics Committee.***
4. ***You must inform the Human Experimentation Safety and Ethics Committee immediately if any subject experiences a problem or makes a complaint related to this study.***

Date: 2nd June 2009

Signed: ......pp. C Hewitt......
Professor M.J. Griffin
Chair, Human Experimentation Safety and Ethics Committee

cc: Supervisor: Daniel Rowan and Ken Frampton

Safety and Ethics Approval Form Issue 1.0 06/02/2006

UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

HUMAN EXPERIMENTATION SAFETY AND ETHICS COMMITTEE

Human Experimentation Safety and Ethics Application Number: 1213

Title of Experiment: Masking level differences measurements through bone and air conduction

submitted by: Hala Al Omari **on** 06 May 2011

The Human Experimentation Safety and Ethics Committee has found the planned study satisfactory and confirm that it can proceed.

Please observe the following:

1. ***Record the Human Experimentation Safety and Ethics Approval Number on the subject consent forms. This number can be found at the top of this page.***
2. ***The subject consent forms, to be completed by all the subjects who participate in this study, must be provided to the Secretary of the Human Experimentation Safety and Ethics Committee by 27 August 2011***
3. ***You must not make any changes to the study without obtaining the approval of the Human Experimentation Safety and Ethics Committee.***
4. ***You must inform the Human Experimentation Safety and Ethics Committee immediately if any subject experiences a problem or makes a complaint related to this study.***

Date: 27 May 2011

Signed: ....

Professor M.J. Griffin
Chair, Human Experimentation Safety and Ethics Committee

cc: Supervisor: Dr D Rowan

Safety and Ethics Approval Form Issue 1.0 06/02/2006

UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

HUMAN EXPERIMENTATION SAFETY AND ETHICS COMMITTEE

Human Experimentation Safety and Ethics Application Number: 1120

Title of Experiment: Comparison study of the performance of two bone-vibration transducers for hearing research (continuation of experiment S&E application 992)

submitted by: Hala Al Omari and Hannah Semeraro **on** 18/06/2010

The Human Experimentation Safety and Ethics Committee has found the planned study satisfactory and confirm that it can proceed.

Please observe the following:

1. ***Record the Human Experimentation Safety and Ethics Approval Number on the subject consent forms. This number can be found at the top of this page.***
2. ***The subject consent forms, to be completed by all the subjects who participate in this study, must be provided to the Secretary of the Human Experimentation Safety and Ethics Committee by 21st September 2010.***
3. ***You must not make any changes to the study without obtaining the approval of the Human Experimentation Safety and Ethics Committee.***
4. ***You must inform the Human Experimentation Safety and Ethics Committee immediately if any subject experiences a problem or makes a complaint related to this study.***

Date: 21st June 2010

Signed: ....

Professor M.J. Griffin

Chair, Human Experimentation Safety and Ethics Committee

cc: Supervisor: Dr Daniel Rowan

Safety and Ethics Approval Form Issue 1.0 06/02/2006

UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

HUMAN EXPERIMENTATION SAFETY AND ETHICS COMMITTEE

Human Experimentation Safety and Ethics Application Number: 1245

Title of Experiment: Comparison study of the performance of two bone-vibration transducers for hearing research (continuation of experiment S&E application 1120)

submitted by: Hala Al Omari **on** 27 July 2011

Chairs Action Approved - extension of application 1120 until 30/12/2011, noted that 3rd year BSc Student (Caroline Chalke) would be assisting in collection of data.

The above application submitted to the Human Experimentation Safety and Ethics Committee has been considered under Chairman's Actions and has been approved. The study can now commence.

Please observe the following:

1. ***Record the Human Experimentation Safety and Ethics Approval Number on the subject consent forms. This number can be found at the top of this page.***
2. ***The subject consent forms, to be completed by all the subjects who participate in this study, must be provided to the Secretary of the Human Experimentation Safety and Ethics Committee by 30 December 2011.***
3. ***You must not make any changes to the study without obtaining the approval of the Human Experimentation Safety and Ethics Committee.***
4. ***You must inform the Human Experimentation Safety and Ethics Committee immediately if any subject experiences a problem or makes a complaint related to this study.***

Date: 29 July 2011

Signed: ....
Professor M.J. Griffin
Chair, Human Experimentation Safety and Ethics Committee

cc: Supervisors Dr D Rowan

Safety and Ethics Approval Form Issue 1.0 06/02/2006

UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

HUMAN EXPERIMENTATION SAFETY AND ETHICS COMMITTEE

Human Experimentation Safety and Ethics Application Number: 1260

Title of Experiment: Masking level differences measurements through bone and air conduction

submitted by: Hala Al Omari **on** 09 January 2012

The Human Experimentation Safety and Ethics Committee has found the planned study satisfactory and confirm that it can proceed.

Please observe the following:

1. ***Record the Human Experimentation Safety and Ethics Approval Number on the subject consent forms. This number can be found at the top of this page.***
2. ***The subject consent forms, to be completed by all the subjects who participate in this study, must be provided to the Secretary of the Human Experimentation Safety and Ethics Committee by 09 May 2012.***
3. ***You must not make any changes to the study without obtaining the approval of the Human Experimentation Safety and Ethics Committee.***
4. ***You must inform the Human Experimentation Safety and Ethics Committee immediately if any subject experiences a problem or makes a complaint related to this study.***

Date: 9 February 2012

Signed: ....

Professor M.J. Griffin

Chair, Human Experimentation Safety and Ethics Committee

cc.Supervisor: Dr Daniel Rowan

Safety and Ethics Approval Form Issue 1.0 06/02/2006

UNIVERSITY OF SOUTHAMPTON

INSTITUTE OF SOUND AND VIBRATION RESEARCH

HUMAN EXPERIMENTATION SAFETY AND ETHICS COMMITTEE

Human Experimentation Safety and Ethics Application Number: 1048

Title of Experiment: Evaluation of two type of bone transducer for auditory research by measuring the sensation thresholds

submitted by: Hala Al Omari and Hannah Semararo **on** 25th January 2010

The Human Experimentation Safety and Ethics Committee has found the planned study satisfactory and confirm that it can proceed – SUBJECT TO NHS ETHICAL COMMITTEE APPROVAL.

Please observe the following:

1. ***Record the Human Experimentation Safety and Ethics Approval Number on the subject consent forms. This number can be found at the top of this page.***
2. ***The subject consent forms, to be completed by all the subjects who participate in this study, must be provided to the Secretary of the Human Experimentation Safety and Ethics Committee by 1st June 2011.***
3. ***You must not make any changes to the study without obtaining the approval of the Human Experimentation Safety and Ethics Committee.***
4. ***You must inform the Human Experimentation Safety and Ethics Committee immediately if any subject experiences a problem or makes a complaint related to this study.***

Date: 30th March 2010

Signed: ....

Professor M.J. Griffin
Chair, Human Experimentation Safety and Ethics Committee

cc: Supervisor: Dr Daniel Rowan

Safety and Ethics Approval Form Issue 1.0 06/02/2006

NHS
National Research Ethics Service
Oxfordshire REC A
Room 002
TEDCO Business Centre
Rolling Mill Road
Jarrow
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Telephone: 0191 428 3561
Facsimile: 0191 428 3432

14 July 2010

Miss Hala AlOmari
PhD Student
University of Southampton
Rayleigh Building Room 2019
University of Southampton
Hants
SO17 1BJ

Dear Miss AlOmari

Study Title:	**Evaluation of two types of bone transducer for auditory research by measuring the sensation thresholds**
REC reference number:	**10/H0604/43**
Protocol number:	**7183**

Thank you for your letter of 23 June 2010, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information has been considered on behalf of the Committee by the Chair and Lyndsay Hills.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Ethical review of research sites

The favourable opinion applies to all NHS sites taking part in the study, subject to management permission being obtained from the NHS/HSC R&D office prior to the start of the study (see "Conditions of the favourable opinion" below).

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study.

Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.

For NHS research sites only, management permission for research ("R&D approval") should be obtained from the relevant care organisation(s) in accordance with NHS research governance arrangements. Guidance on applying for NHS permission for research is available in the Integrated Research Application System or at http://www.rdforum.nhs.uk.

Where the only involvement of the NHS organisation is as a Participant Identification Centre, management permission for research is not required but the R&D office should be notified of the study. Guidance should be sought from the R&D office where necessary.

Sponsors are not required to notify the Committee of approvals from host organisations.

It is the responsibility of the sponsor to ensure that all the conditions are complied with before the start of the study or its initiation at a particular site (as applicable).

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*
Investigator CV	Hala ALOmari	06 May 2010
Protocol	Version #1	06 May 2010
Human Experimentation Safety and Ethics Application	Number 1048	30 March 2010
REC application	IRAS Version 2.5 46232/118586/1/9	30 March 2010
Letter from Sponsor	Martina Prude Southampton University	08 April 2010
Questionnaire: Health Questionnaire	Version #1	06 May 2010
Letter of invitation to participant	Version #2	23 June 2010
Participant Information Sheet	Version #2	23 June 2010
Response to Request for Further Information	Hala AlOmari	23 June 2010
Participant Consent Form	Version #2	23 June 2010
Supervisor CV	Dr Daniel Rowan	01 May 2010
Evidence of insurance or indemnity	Ruth McFadyen Southampton University	08 April 2010

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees (July 2001) and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Now that you have completed the application process please visit the National Research Ethics Service website > After Review

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website.

The attached document *"After ethical review – guidance for researchers"* gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Adding new sites and investigators
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

We would also like to inform you that we consult regularly with stakeholders to improve our service. If you would like to join our Reference Group please email referencegroup@nres.npsa.nhs.uk.

10/H0604/43	Please quote this number on all correspondence

Yours sincerely

Dr Brian Shine
Chair

Email: anne.taylor7@nhs.net

Enclosures:	"After ethical review – guidance for researchers"
Copy to:	Dr Martina Prude University of South Hampton Corporate Services Highfield Campus Southampton SO17 1BJ

Appendix B_1: Health questionnaire- normal- hearing participants

Health questionnaire

Please complete the following questionnaire. Responses will be held in a confidential manner, and used for the purpose of the experiment by the researcher only

Name :

Address :

Date of Birth :

Sex : Male ☐ Female ☐

1 Do you have any difficulty in hearing? Yes ☐ No ☐

If yes, specify
………………………………………………………………………………......................

………………………………………………………………………………..........

2 Do you have tinnitus (ringing in the ears) Yes ☐ No ☐

If yes, describe
………………………………………………………………………………...................

………………………………………………………………………………....

Which ear is it in? Right ☐ Left ☐

Both ☐

it is continuous Yes ☐ No ☐

3 Have you been exposed to loud sounds in the past week Yes ☐ No ☐

If yes, specify
………………………………………………………………………………...................

………………………………………………………………………………....................

4 Have you ever had ear surgery Yes ☐ No ☐

If yes, specify
……………………………………………………………………………………..................

……………………………………………………………………………………....

5 Have you ever had ear drum perforations? Yes ☐ No ☐

If yes, when ……………………………………………………………………….

which ear is it in Right ☐ Left ☐

Both ☐

has there been any recent discharge Yes ☐ No ☐

6 Have you experienced head injury or head surgery Yes ☐ No ☐

If yes, specify
……………………………………………………………………………………..................

……………………………………………………………………………………....

7 Describe your general health………………………………………………………………

…………………………………………………………………………………….....

8 Are you on any medications? Yes ☐ No ☐

If yes, specify
……………………………………………………………………………………..................

………………………………………………………………………………………

9 Do you have common cold, flu or nasal congestion, today? Yes ☐ No ☐

If yes, specify
……………………………………………………………………………………...................

……………………………………………………………………………………

Appendix B_2: Health questionnaire- cochlear implant

Please complete the following questionnaire. Responses will be held in a confidential manner, and used for the purpose of the experiment by the researcher only

Name : ____________________

Address : ____________________

Date of Birth : ____________________

Sex : Male ☐ Female ☐

1 How long have you had you cochlear implant?

……………………………………………………………………………………

……………………………………………………………………………………
……………………………………………………………………………………
…………………………………………………………………………………..

- Are you aware of any residual hearing without the cochlear implant? Yes ☐]No ☐

2 Which ear has the cochlear implant? Right ☐ Left ☐

3 Do you have tinnitus (ringing in the ears) Yes ☐ No ☐

If yes, describe
………………………………………………………………………………............

……………………………………………………………………………………

Which ear is it in? Right ☐ Left ☐
Both ☐

Is it continuous? Yes ☐ No ☐

4 Have you ever had ear surgery other than the implant? Yes ☐ No ☐

If yes, specify
……………………………………………………………………………...........

……………………………………………………………………………………

5	Have you ever had ear drum perforations?	Yes	☐	No	☐
	If yes, when ………………………………………………………………………….				
	which ear is it in	Right	☐	Left	☐
		Both	☐		
	has there been any recent discharge	Yes	☐	No	☐
6	Have you experienced head injury or head surgery	Yes	☐	No	☐

If yes, specify

....
....
....
....
....

7 Describe your general health……..…………………...

……………………………………………………………………………………
…………………………...
....
....
....

8	Are you on any medications?	Yes	☐	No	☐

If yes, specify

……………………………………………………………………………………
………...

9	Do you have common cold, flu or nasal congestion, today?	Yes	☐	No	☐

If yes, specify

....
....

Appendix C. Factors to Convert from dB re 1 μV to dB HL for Artificial Mastoid

A. Factors to Convert from dB re 1 μV to dB HL for Artificial Mastoid S/N 331282

Freq. Hz	RETFL (dB re 1 μN)	Art. Mast. Sens. [1] (dB re 1 μV/μN)	Factor to Convert[2] dB re 1 μV to dB HL
250	67.0	-19.2	47.8
500	58.0	-19.2	38.8
750	48.5	-19.2	29.3
1000	42.5	-19.2	23.3
1500	36.5	-19.2	17.3
2000	31.0	-18.0	13.0
3000	30.0	-18.2	11.8
4000	35.5	-20.2	15.3

B. Factors to Convert from dB re 1 μV to dB HL for Artificial Mastoid S/N 72827

Freq. Hz	RETFL (dB re 1 μN)	Art. Mast. Sens. [1] (dB re 1 μV/μN)	Factor to Convert[2] dB re 1 μV to dB HL
250	67.0	-17.3	49.7
500	58.0	-17.3	40.7
750	48.5	-17.3	31.2
1000	42.5	-16.8	25.7
1500	36.5	-15.8	20.7
2000	31.0	-15.3	15.7
3000	30.0	-15.3	14.7
4000	35.5	-15.3	15.7

C. Factors to Convert from dB re 1 μV to dB HL for Artificial Mastoid S/N 2404338

Freq. Hz	RETFL (dB re 1 μN)	Art. Mast. Sens. [1] (dB re 1 μV/μN)	Factor to Convert[2] dB re 1 μV to dB HL
250	67.0	-23	44
500	58.0	-23	35
750	48.5	-23	25.5
1000	42.5	-22	20.5
1500	36.5	-21	15.5
2000	31.0	-20	11.0
3000	30.0	-20	10.0
4000	35.5	-25	10.5

Notes

These figures for sensitivity are for each particular artificial mastoid. Figures in Table A are for the B&K Type 4930 with S/N 331282. The number comes from the sensitivity of 110 mV/N, which becomes 0.11 μV/μN, thus $20\log_{10}(0.11) = -19.2$. Additional correction factors for each frequency are read from the calibration chart. Figures in table B are for the B& K type 4930 with S/N 728278. The numbers come from the sensitivity of 145 mV/N, which becomes 0.145 μV/μN, thus $20\log_{10}(0.145) = -16.8$, additional correction factors are read from the calibration chart. Figures in table C are for the B& K type 4930 with S/N 2404338. The numbers come from the sensitivity of 82 mV/N, which becomes 0.084 μV/μN, thus $20\log_{10}(0.084) = -21.5$, additional correction factors are read from the calibration chart.

This column is the sum of the RETFL and the mastoid sensitivity, and assumes that the SLM has been set to read out dB re 1 μV

Tolerances are ± 4 dB @ 125 to 4000 Hz; ± 5 dB @ 6000 Hz and above (IEC 60645-1:2001).

Temperature of Mastoid: Target 23±1°C

Appendix D. Verification of transducers: randomisation for HTL

Subject	Session1				Session 2			
1	1	4	3	2	1	3	4	2
2	2	4	3	1	3	2	4	1
3	1	4	2	3	1	2	4	3
4	3	2	4	1	2	4	1	3
5	4	2	3	1	4	3	1	2
6	4	3	2	1	4	3	2	1
7	2	4	3	1	1	2	3	4
8	2	3	1	4	1	4	3	2
9	2	1	4	3	3	4	2	1
10	4	2	3	1	1	2	4	3
11	4	1	2	3	2	4	1	3
12	3	4	2	1	4	1	2	3
13	1	4	3	2	3	4	2	1
14	2	4	3	1	1	4	3	2
15	2	4	1	3	2	4	3	1
16	4	2	3	1	2	4	1	3
17	1	2	3	4	4	2	3	1
18	2	3	4	1	1	2	3	4
19	4	3	2	1	2	3	4	1
20	1	3	4	2	4	3	2	1
21	3	2	4	1	1	4	3	2
22	1	2	4	3	2	4	3	1
23	2	4	1	3	1	4	2	3
24	4	3	1	2	3	2	4	1
25	4	3	2	1	4	2	3	1
26	1	2	3	4	4	3	2	1
27	1	4	3	2	2	4	3	1
28	3	4	2	1	2	3	1	4
29	1	2	4	3	2	1	4	3
30	2	4	1	3	4	2	3	1

1	B71
2	B71
3	BEST
4	BEST

The transducer was assigned to a number according to the Experiment

Appendix E. Test/retest evaluation of the hearing thresholds

Air conduction:

Frequency (Hz)	Experiment 2_ER 3A									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250										
500	2.0	6.6	-7.3	3.7	0.7	0.4	0.9	<0.001	8.8	0.007
1000	2.9	8.6	-9.6	6.3	0.6	0.3	0.8	<0.001	3.5	0.070
2000	2.3	6.5	-7.1	5.5	0.7	0.4	0.9	<0.001	1.4	0.254
3000	2.8	8.1	-9.0	6.4	0.7	0.4	0.9	<0.001	2.3	0.143
4000	2.3	6.8	-7.5	5.4	0.8	0.6	0.9	<0.001	2.3	0.143

Frequency (Hz)	Experiment 3_ER 5A									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.4	9.7	-10.6	8.3	0.5	0.1	0.7	0.004	1.7	0.207
500	3.0	9.1	-10.1	6.4	0.7	0.4	0.8	<0.001	5.9	0.021
1000	2.5	7.0	-7.2	6.8	0.8	0.6	0.9	<0.001	0.1	0.761
2000	3.9	10.8	-10.6	10.9	0.6	0.3	0.8	<0.001	0.0	0.869
3000	4.2	11.6	-10.9	12.2	0.6	0.4	0.8	<0.001	0.3	0.560
4000	4.1	11.4	-11.5	11.1	0.7	0.4	0.8	<0.001	0.0	0.851

Frequency (Hz)	Experiment 4_ER 5A									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.9	10.9	-11.4	10.3	0.5	0.2	0.8	0.003	0.3	0.636
500	2.7	7.4	-7.6	7.3	0.8	0.5	0.9	<0.001	0.0	0.832
1000	3.5	9.8	-8.9	10.5	0.6	0.3	0.8	<0.001	0.6	0.441
2000	4.1	11.4	-10.6	12.1	0.6	0.3	0.8	<0.001	0.4	0.532
3000	2.9	8.1	-7.7	8.4	0.8	0.5	0.9	<0.001	0.2	0.659
4000	3.9	10.8	-10.1	11.4	0.5	0.2	0.8	0.003	0.4	0.558

Experiment 1:

Frequency (Hz)	Experiment 1_B71A									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.4	11.0	-12.3	6.3	0.6	0.2	0.8	0.002	7.19	0.015
500	4.7	13.0	-13.3	12.7	0.6	0.2	0.8	0.002	0.24	0.629
1000	2.8	7.8	-8.1	7.6	0.5	0.1	0.8	0.012	0.11	0.74
2000	3.9	10.9	-11.1	10.7	0.6	0.2	0.8	<0.001	0.03	0.874
3000	2.8	7.9	-8.7	6.7	0.8	0.6	0.9	<0.001	0.70	0.412
4000	2.3	6.3	-6.5	6.2	0.9	0.8	1.0	<0.001	0.04	0.839

Frequency (Hz)	Experiment 1_BEST									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.1	8.7	-9.0	8.3	0.6	0.3	0.8	<0.001	0.06	0.803
500	3.0	8.3	-8.1	8.6	0.7	0.4	0.9	<0.001	0.14	0.715
1000	2.9	10.1	-5.1	11.1	0.5	0.0	0.8	<0.001	10.18	0.005
2000	2.8	7.8	-7.1	8.4	0.8	0.5	0.9	<0.001	0.54	0.471
3000	2.4	6.9	-7.5	6.0	0.8	0.6	0.9	<0.001	0.54	0.472
4000	3.0	8.2	-8.3	8.0	0.8	0.6	0.9	<0.001	0.00	0.957

Frequency (Hz)	Experiment 1_BEST_LFR1									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.1	8.7	-8.3	9.1	0.7	0.3	0.9	<0.001	0.00	0.958
500	2.6	7.3	-6.9	7.7	0.7	0.4	0.9	<0.001	0.13	0.72
1000	2.6	7.4	-6.7	8.0	0.7	0.3	0.9	<0.001	0.30	0.59
2000	2.6	7.2	-7.4	7.2	0.8	0.7	0.9	<0.001	0.02	0.905
3000	3.0	8.4	-7.9	9.0	0.7	0.4	0.9	<0.001	0.27	0.61
4000	3.7	10.2	-10.4	10.1	0.7	0.4	0.9	<0.001	0.07	0.8

Frequency (Hz)	Experiment 1_BEST_LFR2									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.6	10.3	-11.3	9.0	0.4	-0.1	0.7	0.047	0.91	0.353
500	3.9	10.9	-10.3	11.5	0.5	0.1	0.8	0.007	0.11	0.749
1000	3.2	9.0	-7.6	9.9	0.6	0.2	0.8	0.004	0.91	0.352
2000	4.2	12.0	-13.4	9.8	0.6	0.2	0.8	0.002	1.86	0.188
3000	2.6	7.1	-6.8	7.5	0.8	0.6	0.9	<0.001	0.31	0.584
4000	3.5	9.9	-10.9	8.5	0.7	0.5	0.9	<0.001	0.76	0.395

Experiment 2:

Frequency (Hz)	Experiment 2_B71B									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
500	3.8	10.6	-10.4	10.8	0.8	0.5	0.9	<0.001	0.04	0.846
1000	3.3	9.2	-9.2	9.2	0.8	0.5	1.0	<0.001	0.00	0.982
2000	3.8	10.5	-11.0	10.0	0.7	0.4	0.9	<0.001	0.17	0.681
3000	2.9	8.7	-9.8	6.6	0.8	0.6	0.9	<0.001	3.20	0.088
4000	4.8	13.3	-13.5	13.3	0.6	0.3	0.8	<0.001	0.01	0.938
Frequency (Hz)	Experiment 2_BEST									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
500	4.3	11.9	-12.6	11.0	0.7	0.3	0.8	<0.001	0.38	0.542
1000	4.6	12.8	-12.8	13.0	0.6	0.3	0.8	<0.001	0.00	0.949
2000	3.8	10.4	-10.8	10.1	0.7	0.4	0.8	<0.001	0.09	0.767
3000	2.6	7.3	-7.3	7.3	0.9	0.7	0.9	<0.001	0.00	0.977
4000	3.6	9.9	-9.3	10.4	0.8	0.7	0.9	<0.001	0.24	0.631

Experiment 3:

Frequency (Hz)	Experiment 3_B71A									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.3	9.3	-9.7	8.6	0.6	0.377-	0.8	<0.001	0.04	0.81
500	5.3	14.8	-13.7	15.5	0.6	0.4	0.8	<0.001	0.16	0.69
1000	2.9	8.2	-8.4	7.9	0.7	0.5	0.9	<0.001	0.20	0.66
2000	3.8	10.6	-11.0	10.1	0.5	0.2	0.7	<0.001	1.26	0.03
3000	3.5	9.8	-10.3	9.2	0.8	0.7	0.9	<0.001	0.10	0.75
4000	4.0	11.3	-11.8	10.6	0.8	0.6	0.9	<0.001	2.00	0.17

Frequency (Hz)	Experiment 3_B71B									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.8	10.6	-10.4	10.8	0.7	0.5	0.9	<0.001	0.44	0.51
500	4.5	12.6	-12.9	12.0	0.5	0.2	0.7	<0.001	0.44	0.51
1000	4.9	13.7	-14.2	13.0	0.8	0.7	0.9	<0.001	0.09	0.76
2000	5.1	14.4	-15.5	12.6	0.8	0.7	0.9	<0.001	0.23	0.64
3000	3.2	9.0	-9.2	8.6	0.8	0.6	0.9	<0.001	0.35	0.56
4000	3.6	10.5	-11.4	8.8	0.7	0.5	0.9	<0.001	0.33	0.57

Frequency (Hz)	Experiment 3_BEST									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	4.1	11.4	-11.6	11.2	0.6	0.4	0.8	<0.001	0.04	0.852
500	4.9	13.9	-15.0	12.3	0.5	0.2	0.7	<0.001	1.16	0.29
1000	4.3	11.9	-12.3	11.3	0.7	0.5	0.9	<0.001	0.18	0.647
2000	6.0	16.6	-15.9	17.1	0.5	0.2	0.7	<0.001	0.14	0.715
3000	5.6	15.9	-17.2	13.8	0.5	0.1	0.7	<0.001	1.33	0.258
4000	3.5	9.7	-9.6	9.7	0.8	0.6	0.9	<0.001	0.01	0.941

Frequency (Hz)	Experiment 3_BEST_LFR1									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	4.7	13.3	-12.3	14.0	0.5	0.2	0.742	<0.001	0.50	0.484
500	4.9	13.6	-14.1	12.8	0.5	0.2	0.750	<0.001	0.26	0.617
1000	3.5	9.9	-9.1	10.5	0.9	0.7	0.930	<0.001	0.59	0.449
2000	4.3	12.1	-11.2	12.8	0.7	0.5	0.848	<0.001	0.52	0.479
3000	3.8	10.7	-9.6	11.4	0.8	0.5	0.872	<0.001	0.91	0.3
4000	3.4	9.5	-10.0	8.7	0.9	0.7	0.930	<0.001	0.59	0.449

Experiment 4:

Frequency (Hz)	Experiment 4_B71C									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	5.5	15.4	-16.4	14.0	0.4	0.0	0.7	0.024	0.29	0.596
500	5.6	15.8	-16.9	14.4	0.6	0.3	0.8	<0.001	0.84	0.368
1000	5.9	15.0	-15.1	17.4	0.7	0.4	0.8	<0.001	0.57	0.458
2000	4.2	13.2	-12.0	11.2	0.7	0.5	0.9	<0.001	0.11	0.741
3000	4.9	14.2	-14.4	12.8	0.7	0.4	0.8	<0.001	0.18	0.678
4000	3.4	11.0	-9.7	9.0	0.8	0.6	0.9	<0.001	0.07	0.801

Frequency (Hz)	Experiment 4_B71D									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	5.3	13.5	-16.1	13.4	0.5	0.2	0.8	0.004	1.36	0.255
500	4.1	10.1	-11.5	11.1	0.8	0.6	0.9	<0.001	0.01	0.939
1000	4.5	14.2	-14.6	10.2	0.8	0.5	0.9	<0.001	2.14	0.156
2000	3.3	9.2	-10.2	8.2	0.8	0.7	0.9	<0.001	1.50	0.233
3000	3.8	10.1	-12.3	8.7	0.8	0.7	0.9	<0.001	3.46	0.075
4000	4.9	12.4	-12.1	14.8	0.7	0.5	0.9	<0.001	1.07	0.311

Frequency (Hz)	Experiment 4_BEST_LFR1									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	5.8	15.8	-17.5	14.9	0.4	0.0	0.7	0.017	0.38	0.545
500	3.8	9.8	-9.8	11.4	0.8	0.7	0.9	<0.001	0.78	0.385
1000	5.0	13.7	-15.5	12.3	0.6	0.3	0.8	<0.001	1.39	0.251
2000	4.1	10.2	-11.5	11.5	0.8	0.6	0.9	<0.001	0.00	1.000
3000	3.9	11.1	-11.5	9.9	0.8	0.5	0.9	<0.001	0.20	0.656
4000	3.0	8.3	-7.7	8.8	0.8	0.6	0.9	<0.001	0.70	0.412

Frequency (Hz)	Experiment 4_BEST_LFR2									
	Precision	Repeatability	Limits of agreement		Intraclass correlation				ANOVA	
			Lower	Upper	ICC	CI		p	F	p
250	3.5	9.7	-11.5	7.7	0.7	0.5	0.9	<0.001	4.24	0.051
500	4.8	12.7	-14.9	11.9	0.7	0.5	0.9	<0.001	0.79	0.383
1000	5.1	14.2	-13.3	14.9	0.6	0.3	0.8	<0.001	0.22	0.943
2000	4.6	14.0	-14.1	11.4	0.7	0.5	0.9	<0.001	0.89	0.355
3000	4.1	11.1	-11.3	11.3	0.8	0.6	0.9	<0.001	0.00	0.972
4000	3.9	10.3	-11.2	10.5	0.7	0.5	0.9	<0.001	0.21	0.654

Appendix F. Percentage of differences in hearing thresholds between test-retest in 1 dB intervals

Air conduction		±1	±2	±3	±4	±5	±6	±7	±8	±9	≥10dB
	250										
	500	32	41	50	73	95	100	100	100	100	0
	1000	18	41	55	64	73	82	91	95	100	0
	2000	32	50	68	77	86	100	100	100	100	0
	3000	27	59	73	77	86	95	95	95	95	5
E2	4000	27	55	68	77	82	91	95	100	100	0
	250	33	53	73	80	80	83	87	87	90	3
	500	27	60	63	70	73	90	90	97	97	3
	1000	33	60	73	77	87	93	97	97	100	0
	2000	37	67	77	80	93	93	93	97	97	3
	3000	37	63	73	87	87	87	87	87	87	13
E3	4000	27	50	73	83	87	87	90	90	93	7
	250	25	33	46	58	67	67	79	83	92	8
	500	25	50	63	75	92	92	96	96	100	0
	1000	21	42	46	58	75	75	92	92	92	8
	2000	29	50	50	63	75	88	92	92	92	8
	3000	21	38	50	71	88	92	96	96	100	0
E4	4000	38	54	67	71	75	79	83	92	96	4
Total		29	51	63	73	82	88	92	94	96	4

B71A		±1	±2	±3	±4	±5	±6	±7	±8	±9	≥10dB
	250	5	25	45	60	65	75	80	95	95	5
	500	25	50	60	60	60	65	65	75	80	15
	1000	45	55	55	65	80	90	95	100	100	0
	2000	25	35	40	60	70	75	85	85	85	5
	3000	35	60	65	80	85	90	95	95	95	5
E1	4000	35	55	75	85	95	95	95	100	100	0
	250	27	40	60	70	77	83	90	90	90	10
	500	13	27	47	57	60	67	77	83	87	13
	1000	27	37	57	73	83	87	93	97	100	0
	2000	10	27	47	67	83	90	93	93	93	7
	3000	17	47	63	83	87	87	90	93	97	3
E3	4000	23	37	57	70	77	83	90	90	93	7
Total		24	41	56	69	77	82	87	91	93	6

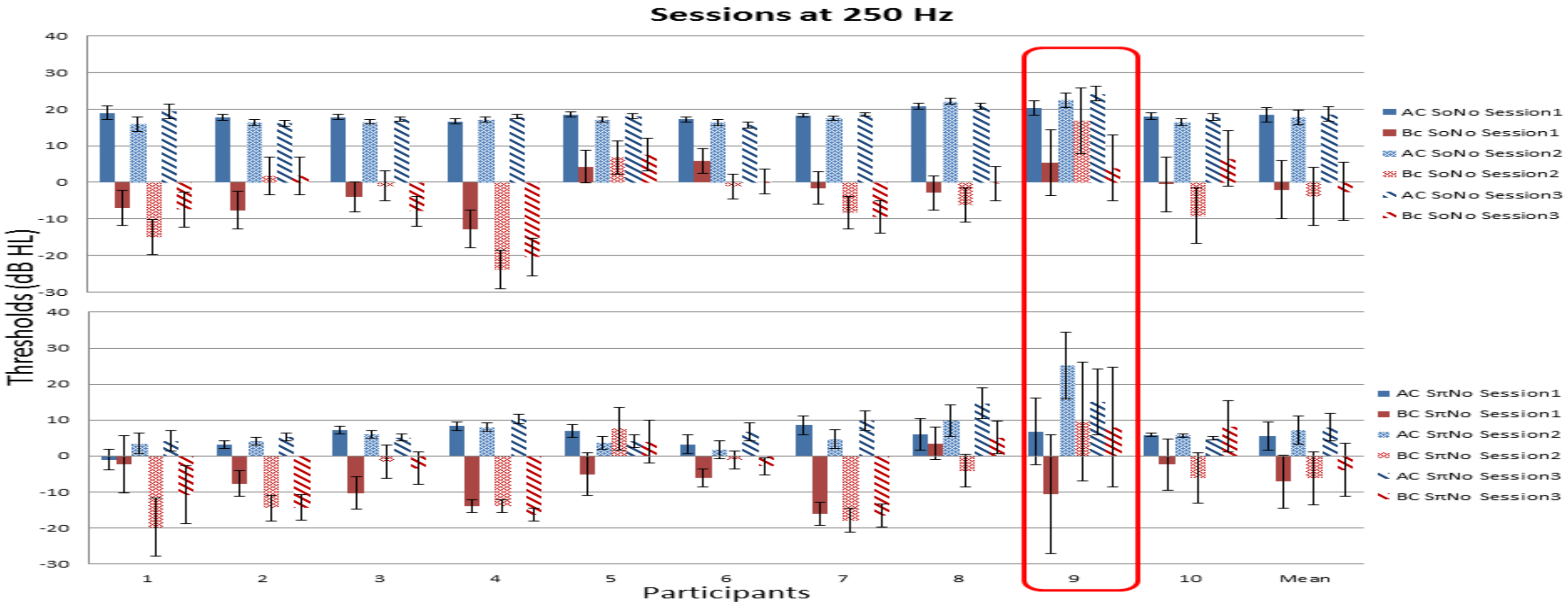
B71C and B71D		±1	±2	±3	±4	±5	±6	±7	±8	±9	≥10dB
	250	17	33	42	54	63	63	75	79	88	13
	500	13	25	33	46	67	75	75	75	79	21
	1000	13	25	42	58	63	75	79	83	83	17
	2000	21	25	33	42	67	79	88	88	92	8
	3000	25	33	54	54	75	79	79	79	79	21
B71C	4000	33	46	54	67	71	71	79	88	88	13
	250	25	33	50	67	71	75	75	79	83	17
	500	13	29	50	71	79	79	79	83	92	8
	1000	25	33	38	46	58	67	75	79	79	21
	2000	25	38	50	67	88	92	92	92	92	8
	3000	29	46	54	67	79	79	88	96	96	4
B71D	4000	21	29	50	58	71	79	83	96	96	4
Total		22	33	46	58	71	76	81	85	87	13

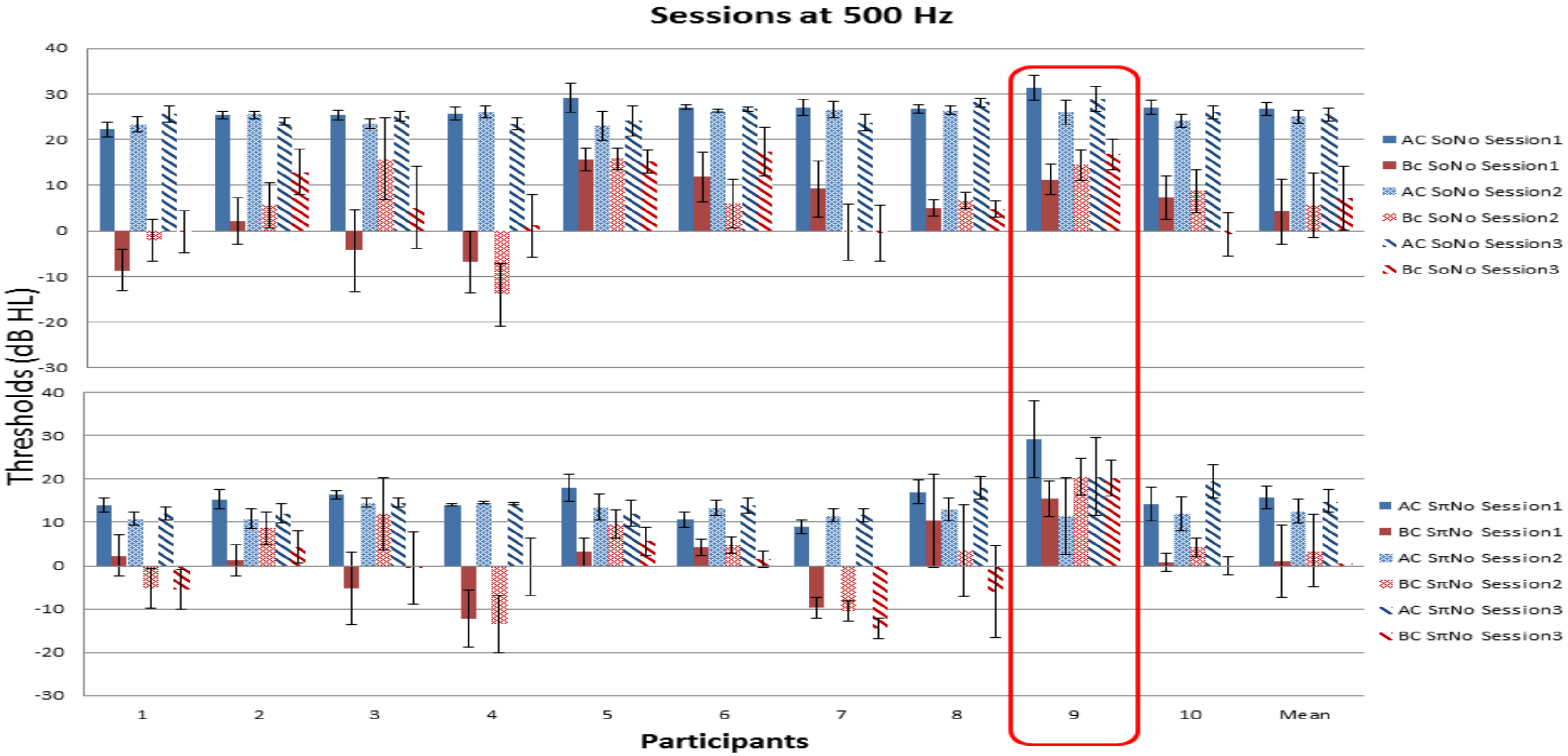
BEST original		±1	±2	±3	±4	±5	±6	±7	±8	±9	≥10dB
	250	40	65	70	85	90	90	90	90	90	10
	500	40	50	60	70	75	90	95	95	95	5
	1000	35	45	60	60	70	70	75	85	100	0
	2000	35	55	60	80	85	90	95	95	95	5
	3000	25	55	65	85	90	95	95	100	100	0
E1	4000	40	45	60	85	90	90	95	95	95	5
	250										
	500	23	32	41	50	55	64	73	77	91	5
	1000	18	23	41	45	64	68	77	86	86	14
	2000	23	41	50	64	73	77	77	86	91	9
	3000	27	45	59	59	82	95	100	100	100	0
E2	4000	23	45	50	59	77	82	82	91	91	9
	250	13	23	37	50	60	73	83	83	87	13
	500	27	43	50	60	67	67	87	87	90	10
	1000	27	43	50	63	77	80	83	87	87	13
	2000	20	30	40	53	67	73	77	77	77	23
	3000	30	43	50	60	67	73	77	80	90	10
E3	4000	20	43	57	73	87	90	93	93	97	3
Total		27	43	53	65	75	80	86	89	92	8

BEST LFR1		±1	±2	±3	±4	±5	±6	±7	±8	±9	≥10dB
	250	20	35	65	70	80	80	85	100	100	0
	500	30	70	70	75	85	90	95	95	100	0
	1000	45	55	60	80	85	90	95	95	100	0
	2000	20	50	70	80	90	95	95	95	100	0
	3000	25	45	60	75	80	90	90	95	95	5
E1	4000	15	35	55	60	65	75	80	90	95	5
	250	30	37	50	57	77	80	80	83	83	17
	500	13	27	47	57	67	73	77	77	87	13
	1000	40	43	60	60	70	73	80	90	97	3
	2000	30	50	57	67	70	83	87	90	90	10
	3000	50	57	63	80	87	90	90	90	93	7
E3	4000	23	43	53	63	63	83	93	93	97	3
	250	21	29	46	63	63	71	75	75	79	21
	500	50	54	58	67	83	88	92	92	96	4
	1000	21	33	50	63	63	63	67	79	88	13
	2000	8	29	46	58	71	71	79	92	96	4
	3000	29	42	42	54	67	71	71	83	88	13
E4	4000	25	33	58	71	83	88	92	96	96	4
Total		28	43	56	67	75	81	85	89	93	7

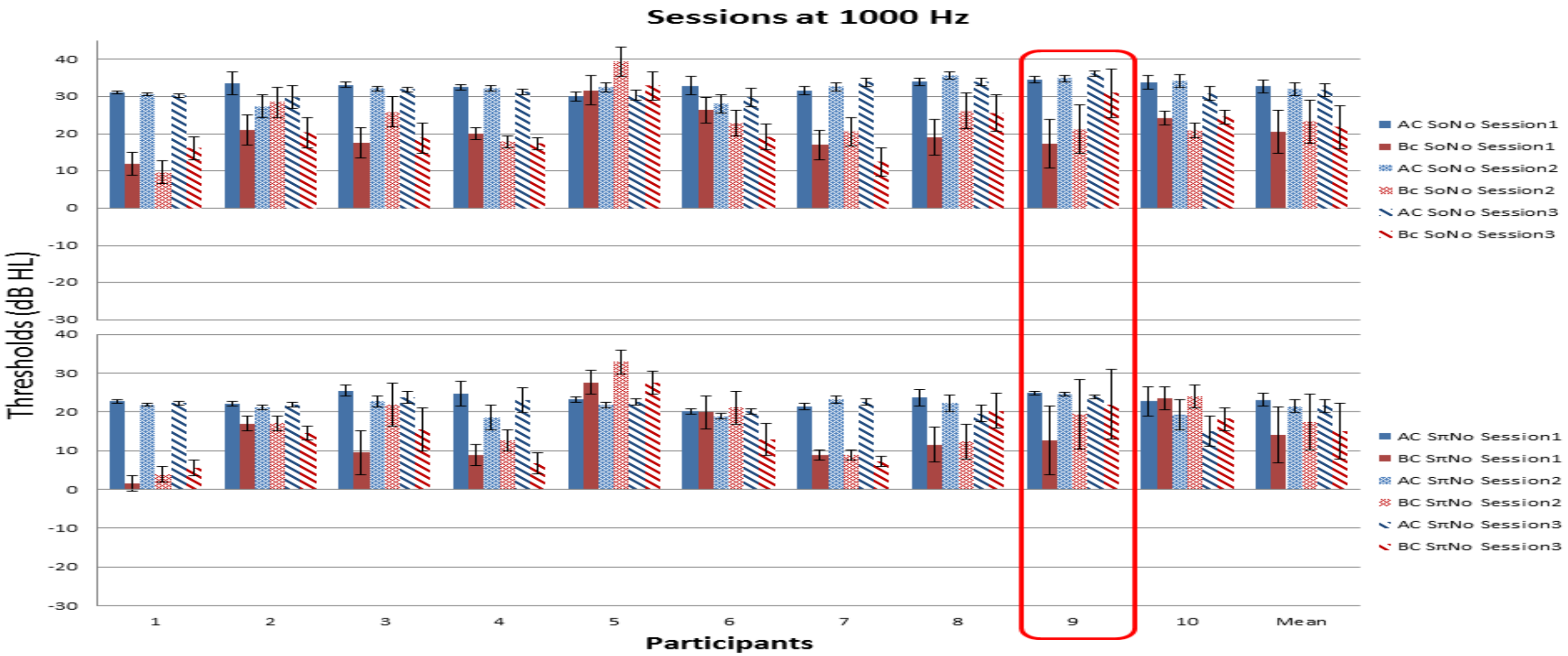
BEST LFR2		±1	±2	±3	±4	±5	±6	±7	±8	±9	≥10dB
	250	20	45	50	50	65	85	85	85	90	10
	500	20	40	60	75	80	80	85	90	90	10
	1000	10	15	45	60	80	90	95	95	100	0
	2000	15	35	55	70	80	85	95	95	95	5
	3000	45	50	65	75	85	95	95	100	100	0
E1	4000	25	50	55	55	70	75	90	90	95	5
	250	25	38	42	71	75	75	88	88	92	8
	500	33	38	54	58	71	71	83	83	88	13
	1000	17	33	42	54	63	63	67	75	79	21
	2000	17	33	46	58	75	79	79	83	83	17
	3000	17	33	50	63	75	83	83	88	88	13
E4	4000	29	42	58	75	88	92	92	92	96	4
Total		23	38	52	64	75	81	86	89	91	9

Appendix H. Individual responses in preliminary investigation (Error bars show SD for each individual)

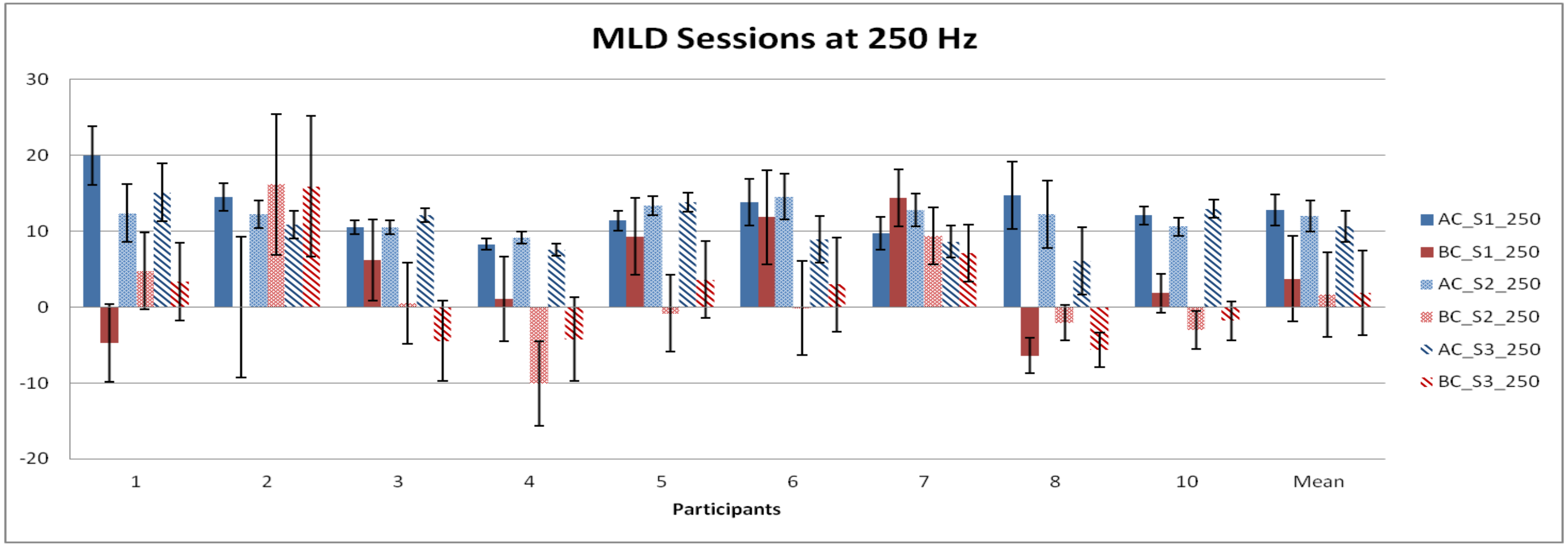




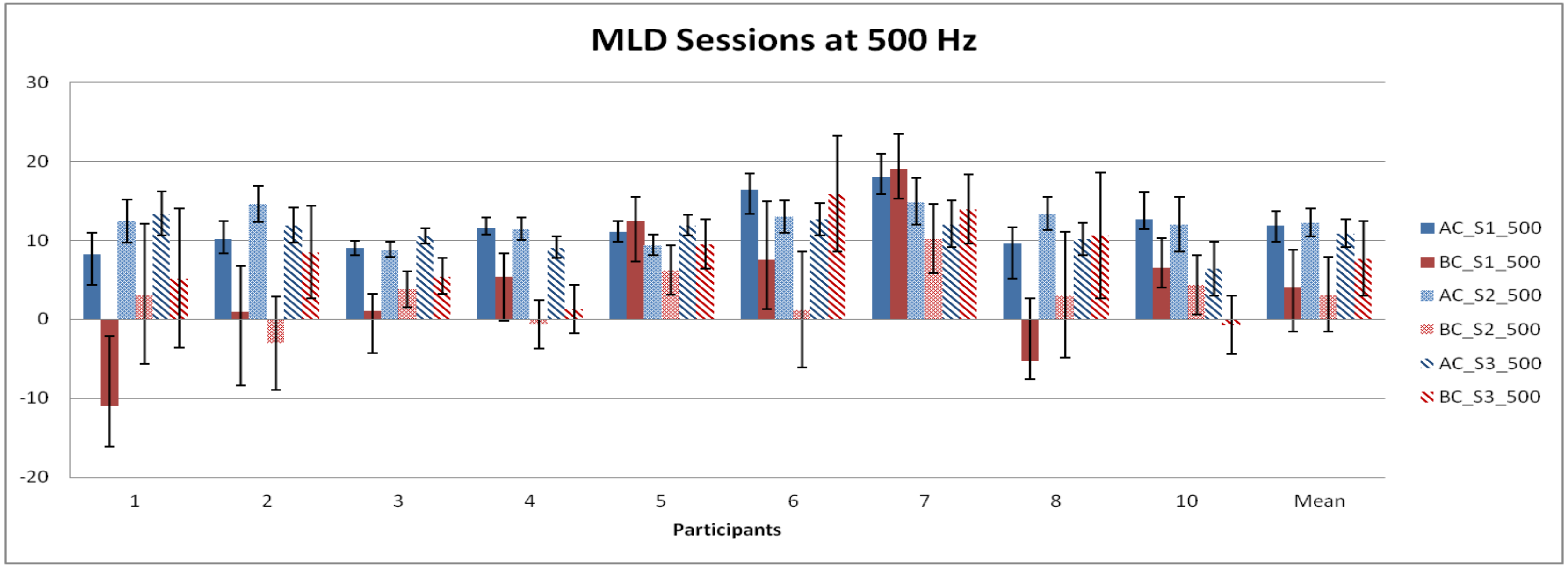
Sessions at 500 Hz
Thresholds (dB HL)
Participants
1
2
3
4
5
6
7
8
9
10
Mean
AC SoNo Session1
Bc SoNo Session1
AC SoNo Session2
Bc SoNo Session2
AC SoNo Session3
Bc SoNo Session3
AC SπNo Session1
BC SπNo Session1
AC SπNo Session2
BC SπNo Session2
AC SπNo Session3
BC SπNo Session3


Sessions at 1000 Hz
Thresholds (dB HL)
40
30
20
10
0
-10
-20
-30
AC SoNo Session1
Bc SoNo Session1
AC SoNo Session2
Bc SoNo Session2
AC SoNo Session3
Bc SoNo Session3
AC SπNo Session1
BC SπNo Session1
AC SπNo Session2
BC SπNo Session2
AC SπNo Session3
BC SπNo Session3
1
2
3
4
5
6
7
8
9
10
Mean
Participants

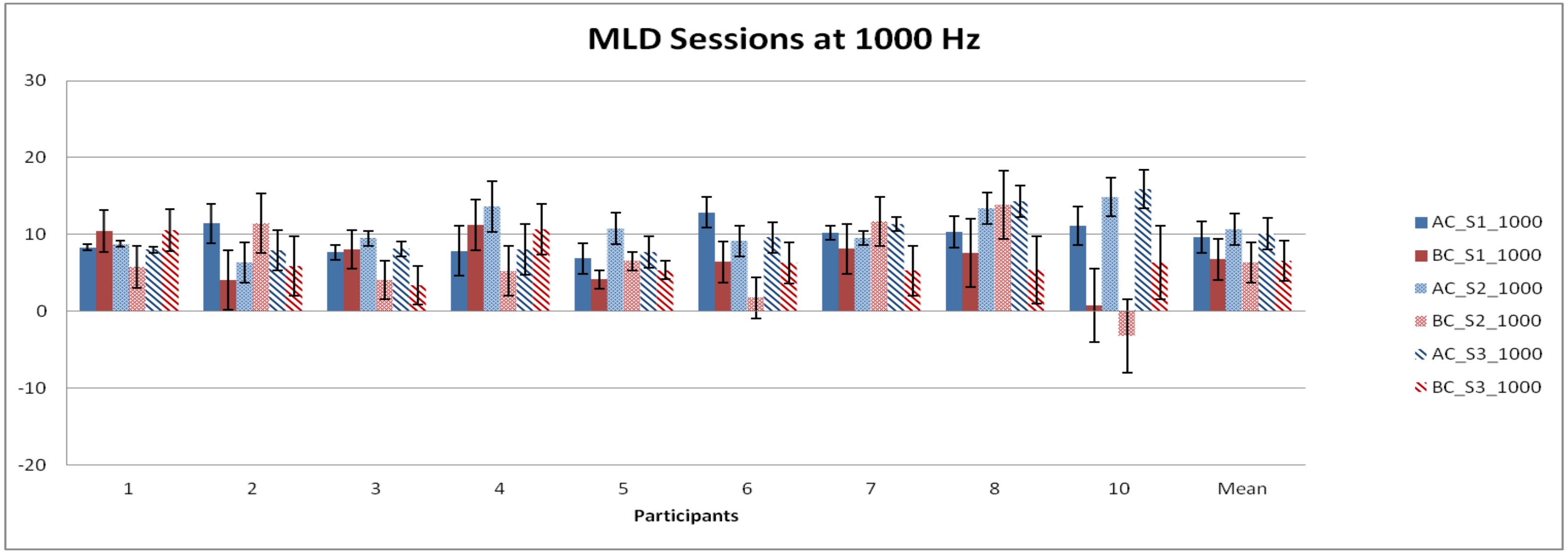
Appendix I. Individual MLD responses in preliminary investigation (Error bars show SD for sessions)



Appendix I. Individual MLD responses in preliminary investigation (Error bars show SD for sessions)



Appendix I. Individual MLD responses in preliminary investigation (Error bars show SD for sessions)



Appendix J. Randomisation of test sessions

S	Session 1			Session 2			Session 3		
1	Screening	Freq 3 (2000)	TA	Freq 1 (500)	Freq 2 (1000)	TA	Freq 1 (500)	Freq 3 (2000)	Freq 2 (1000)
2	Screening	Freq 1 (500)	Freq 3 (2000)	TA	Freq 2 (1000)	Freq 3 (2000)	Freq 1 (500)	TA	Freq 2 (1000)
3	Screening	Freq 2 (1000)	Freq 1 (500)	Freq 3 (2000)	TA	Freq 2 (1000)	TA	Freq 1 (500)	Freq 3 (2000)
4	Screening	Freq 1 (500)	TA	Freq 3 (2000)	Freq 2 (1000)	TA	Freq 2 (1000)	Freq 3 (2000)	Freq 1 (500)
5	Screening	TA	Freq 3 (2000)	Freq 2 (1000)	Freq 1 (500)	Freq 3 (2000)	TA	Freq 2 (1000)	Freq 1 (500)
6	Screening	Freq 1 (500)	Freq 2 (1000)	Freq 3 (2000)	TA	Freq 1 (500)	TA	Freq 3 (2000)	Freq 2 (1000)
7	Screening	Freq 1 (500)	Freq 2 (1000)	TA	Freq 3 (2000)	Freq 3 (2000)	Freq 2 (1000)	TA	Freq 1 (500)
8	Screening	Freq 2 (1000)	TA	Freq 1 (500)	Freq 3 (2000)	Freq 2 (1000)	Freq 1 (500)	TA	Freq 3 (2000)
9	Screening	Freq 3 (2000)	Freq 1 (500)	Freq 2 (1000)	TA	TA	Freq 2 (1000)	Freq 1 (500)	Freq 3 (2000)
10	Screening	Freq 2 (1000)	Freq 1 (500)	Freq 3 (2000)	TA	TA	Freq 1 (500)	Freq 2 (1000)	Freq 3 (2000)
11	Screening	TA	Freq 1 (500)	Freq 2 (1000)	Freq 3 (2000)	Freq 2 (1000)	Freq 1 (500)	Freq 3 (2000)	TA
12	Screening	TA	Freq 2 (1000)	Freq 1 (500)	Freq 3 (2000)	Freq 3 (2000)	Freq 1 (500)	Freq 2 (1000)	TA
13	Screening	Freq 2 (1000)	Freq 1 (500)	TA	Freq 3 (2000)	Freq 2 (1000)	TA	Freq 1 (500)	Freq 3 (2000)
14	Screening	Freq 3 (2000)	Freq 2 (1000)	TA	Freq 1 (500)	Freq 1 (500)	Freq 2 (1000)	TA	Freq 3 (2000)
15	Screening	Freq 1 (500)	TA	Freq 3 (2000)	Freq 2 (1000)	Freq 1 (500)	Freq 2 (1000)	Freq 3 (2000)	TA
16	Screening	Freq 3 (2000)	TA	Freq 2 (1000)	Freq 1 (500)	TA	Freq 3 (2000)	Freq 2 (1000)	Freq 1 (500)
17	Screening	TA	Freq 2 (1000)	Freq 3 (2000)	Freq 1 (500)	Freq 1 (500)	TA	Freq 3 (2000)	Freq 2 (1000)
18	Screening	Freq 2 (1000)	TA	Freq 1 (500)	Freq 3 (2000)	Freq 2 (1000)	Freq 1 (500)	Freq 3 (2000)	TA
19	Screening	Freq 3 (2000)	Freq 1 (500)	TA	Freq 2 (1000)	Freq 1 (500)	Freq 3 (2000)	TA	Freq 2 (1000)
20	Screening	TA	Freq 1 (500)	Freq 3 (2000)	Freq 2 (1000)	Freq 3 (2000)	TA	Freq 1 (500)	Freq 2 (1000)

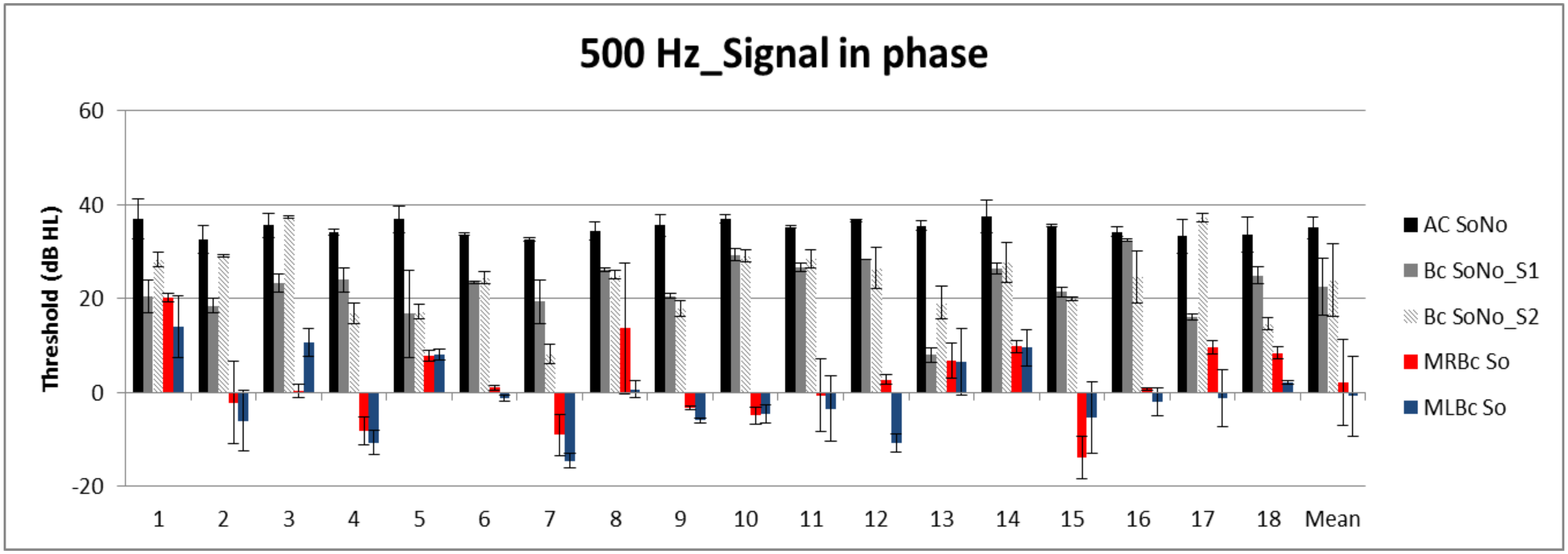
Appendix K. Randomisation of transcranial attenuation

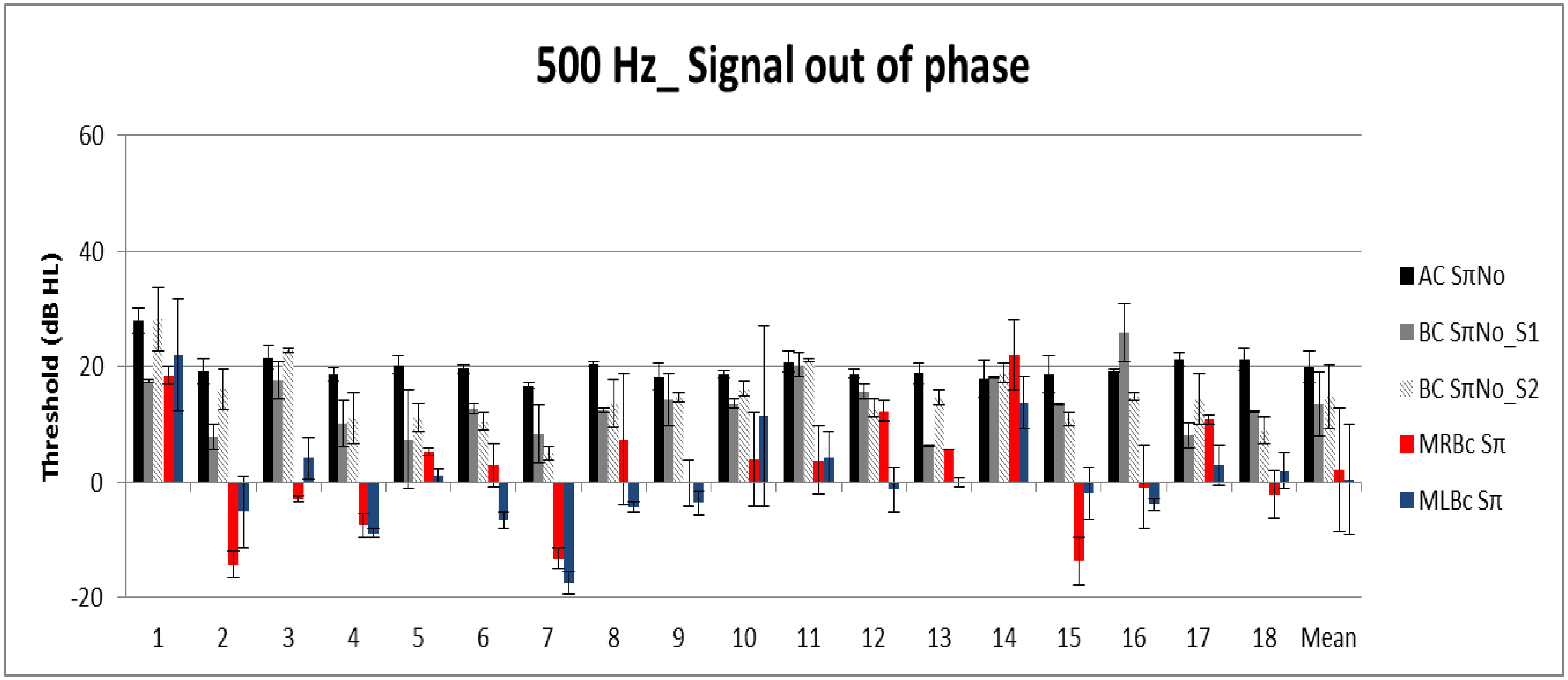
	Session 1				Session 2			
1	Lt contra	Rt contra	Rt ipsi	Lt ipsi	Rt ipsi	Lt ipsi	Rt contra	Lt contra
2	Rt contra	Rt ipsi	Lt contra	Lt ipsi	Rt ipsi	Lt ipsi	Rt contra	Lt contra
3	Rt contra	Lt ipsi	Rt ipsi	Lt contra	Lt contra	Lt ipsi	Rt contra	Rt ipsi
4	Lt contra	Lt ipsi	Rt ipsi	Rt contra	Lt contra	Rt contra	Lt ipsi	Rt ipsi
5	Rt ipsi	Lt contra	Rt contra	Lt ipsi	Rt contra	Lt ipsi	Lt contra	Rt ipsi
6	Rt contra	Lt contra	Rt ipsi	Lt ipsi	Rt ipsi	Lt ipsi	Rt contra	Lt contra
7	Rt contra	Lt ipsi	Rt ipsi	Lt contra	Rt contra	Lt contra	Rt ipsi	Lt ipsi
8	Lt contra	Rt contra	Lt ipsi	Rt ipsi	Rt contra	Lt ipsi	Rt ipsi	Lt contra
9	Lt contra	Lt ipsi	Rt ipsi	Rt contra	Rt contra	Lt contra	Lt ipsi	Rt ipsi
10	Lt contra	Rt ipsi	Lt ipsi	Rt contra	Rt contra	Lt contra	Lt ipsi	Rt ipsi
11	Rt contra	Lt contra	Lt ipsi	Rt ipsi	Lt contra	Rt ipsi	Lt ipsi	Rt contra
12	Rt contra	Lt ipsi	Rt ipsi	Lt contra	Lt contra	Lt ipsi	Rt ipsi	Rt contra
13	Rt contra	Lt contra	Rt ipsi	Lt ipsi	Lt contra	Rt contra	Lt ipsi	Rt ipsi
14	Rt ipsi	Lt ipsi	Rt contra	Lt contra	Rt contra	Lt ipsi	Rt ipsi	Lt contra
15	Rt ipsi	Lt ipsi	Lt contra	Rt contra	Rt ipsi	Lt contra	Rt contra	Lt ipsi
16	Rt ipsi	Lt ipsi	Lt contra	Rt contra	Rt ipsi	Lt contra	Rt contra	Lt ipsi
17	Lt contra	Rt contra	Lt ipsi	Rt ipsi	Lt contra	Lt ipsi	Rt ipsi	Rt contra
18	Lt contra	Lt ipsi	Rt contra	Rt ipsi	Rt contra	Lt ipsi	Rt ipsi	Lt contra
19	Rt ipsi	Lt ipsi	Rt contra	Lt contra	Rt contra	Rt ipsi	Lt contra	Lt ipsi
20	Rt ipsi	Lt ipsi	Rt contra	Lt contra	Lt contra	Rt contra	Rt ipsi	Lt ipsi

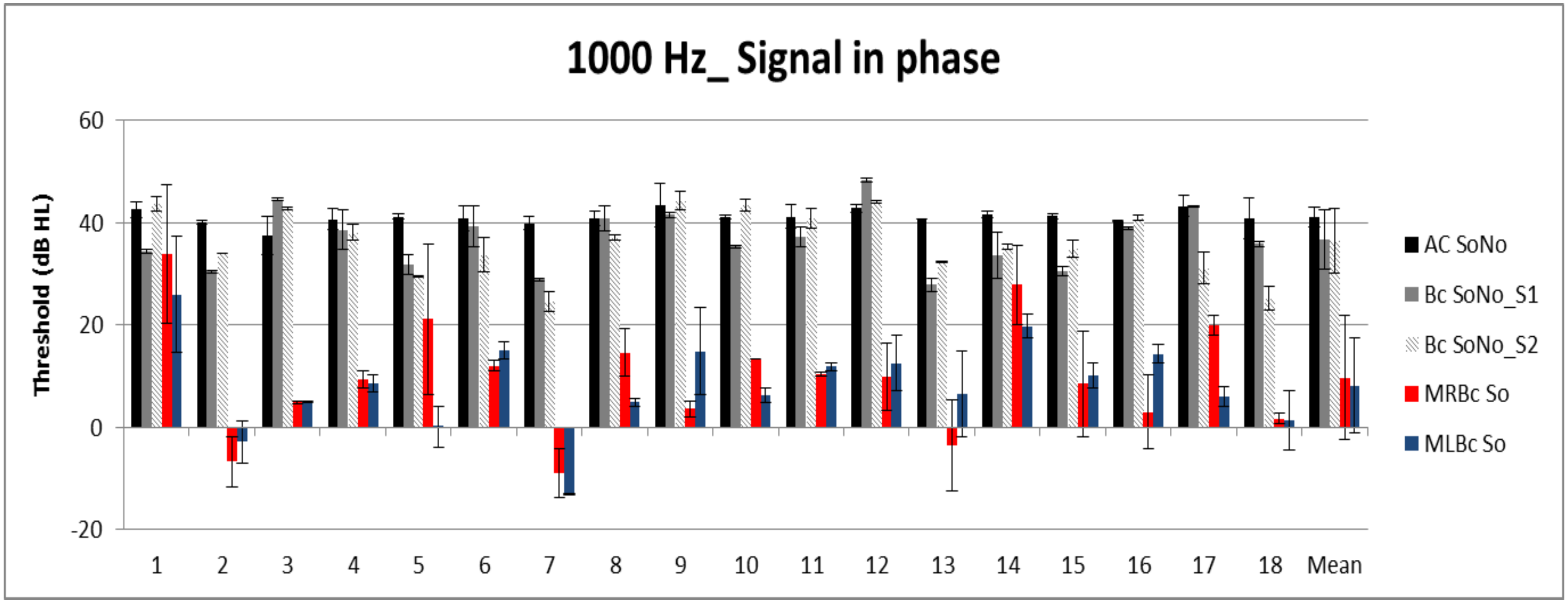
Appendix L. SD of the mean for each participant in various test conditions

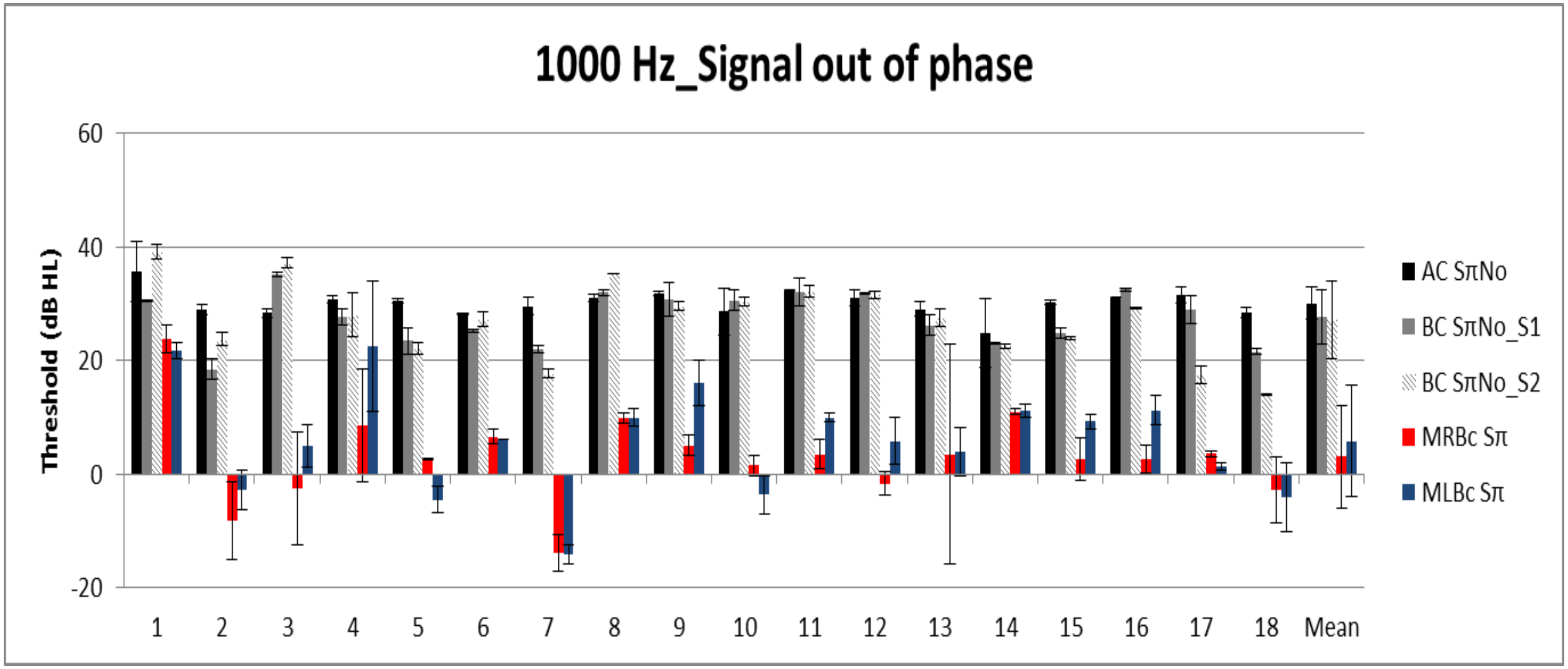
Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
AC SoNo_500	4	3	3	1	3	0	0	2	2	1	0	0	1	3	0	1	4	4
AC SπNo_500	2	2	2	1	2	1	1	0	2	1	2	1	2	3	3	0	1	2
Bc SoNo_S1_500	4	2	2	3	9	0	5	0	0	1	1	0	1	1	1	0	1	2
Bc SoNo_S2_500	2	0	0	2	2	1	2	1	2	1	2	4	4	4	0	6	1	1
Bc SπNo_S1_500	0	2	3	4	9	1	5	0	5	1	2	1	0	0	0	5	2	0
Bc SπNo_S2_500	6	3	0	4	2	2	1	4	1	1	0	2	1	2	1	1	4	2
MRBc So_500	1	9	1	3	1	1	4	14	0	2	8	1	4	1	5	0	1	1
MRBc Sπ_500	1	2	1	2	1	4	2	11	4	8	6	2	0	6	4	7	1	4
MLBc So_500	7	6	3	3	1	1	2	2	0	2	7	2	7	4	8	3	6	0
MLBc Sπ_500	10	6	4	1	1	1	2	1	2	16	4	4	1	4	5	1	4	3
AC SoNo_1000	2	0	4	2	0	3	1	1	4	0	2	1	0	1	0	0	2	4
AC SπNo_1000	5	1	1	1	0	0	1	1	0	4	0	1	1	6	0	0	1	1
Bc SoNo_S1_1000	0	0	0	4	2	4	0	2	1	0	2	0	1	4	1	0	0	0
Bc SoNo_S2_1000	1	0	0	2	0	3	2	1	2	1	2	0	0	0	2	0	3	2
BC SπNo_S1_1000	0	2	0	1	2	0	1	1	3	2	2	0	2	0	1	0	2	1
BC SπNo_S2_1000	1	1	1	4	1	1	1	0	1	1	1	1	2	0	0	0	2	0
MRBc So_1000	14	5	0	2	15	1	5	5	1	0	0	7	9	8	10	7	2	1
MRBc Sπ_1000	2	7	10	10	0	1	3	1	2	2	3	2	19	0	4	2	1	6
MLBc So_1000	11	4	0	2	4	2	0	1	8	1	1	5	8	2	2	2	2	6
MLBc Sπ_1000	2	3	4	12	2	0	2	2	4	3	1	4	4	1	1	3	1	6
AC SoNo_2000	1	2	3	0	2	0	1	0	1	1	0	2	3	0	0	0	2	2
AC SπNo_2000	1	0	6	2	1	0	4	1	1	2	1	1	2	1	1	0	0	1
Bc SoNo_S1_2000	0	0	1	0	1	4	1	2	1	0	1	2	1	2	0	0	2	3
Bc SoNo_S2_2000	0	1	0	0	1	1	0	0	3	1	1	3	2	1	2	4	1	0
BC SπNo_S1_2000	1	1	1	0	1	1	3	3	0	3	2	0	0	3	1	2	0	2
BC SπNo_S2_2000	0	1	1	2	1	0	2	2	0	3	0	1	3	1	1	1	0	1
MRBc So_2000	2	1	6	2	1	0	0	0	2	1	3	9	2	5	3	1	6	1
MRBc Sπ_2000	1	0	0	12	0	0	2	5	1	0	8	3	1	1	2	2	8	2
MLBc So_2000	5	1	6	2	1	1	3	2	0	1	4	2	3	1	2	8	1	2
MLBc Sπ_2000	14	3	1	1	0	1	2	1	0	1	2	0	0	2	0	4	3	2
BC SoNo_2S_500	**5**	**6**	**8**	**5**	**5**	**1**	**7**	**1**	**2**	**1**	**2**	**3**	**7**	**3**	**1**	**6**	**12**	**6**
BC SoNo_2S_1000	**5**	**2**	**1**	**2**	**2**	**4**	**3**	**3**	**2**	**5**	**3**	**2**	**3**	**3**	**3**	**1**	**7**	**6**
BC SoNo_2S_2000	**1**	**2**	**2**	**1**	**1**	**3**	**1**	**2**	**2**	**0**	**2**	**4**	**2**	**2**	**2**	**2**	**1**	**9**
BCSπNo_2S_500	**7**	**5**	**3**	**4**	**6**	**2**	**3**	**2**	**3**	**2**	**1**	**2**	**5**	**1**	**2**	**7**	**5**	**2**
BC SπNo_2S_1000	**5**	**3**	**1**	**2**	**2**	**1**	**2**	**2**	**2**	**1**	**2**	**0**	**2**	**0**	**1**	**2**	**7**	**4**
BC SπNo_2S_2000	**2**	**2**	**2**	**2**	**1**	**2**	**3**	**3**	**1**	**2**	**3**	**2**	**2**	**2**	**3**	**1**	**4**	**7**

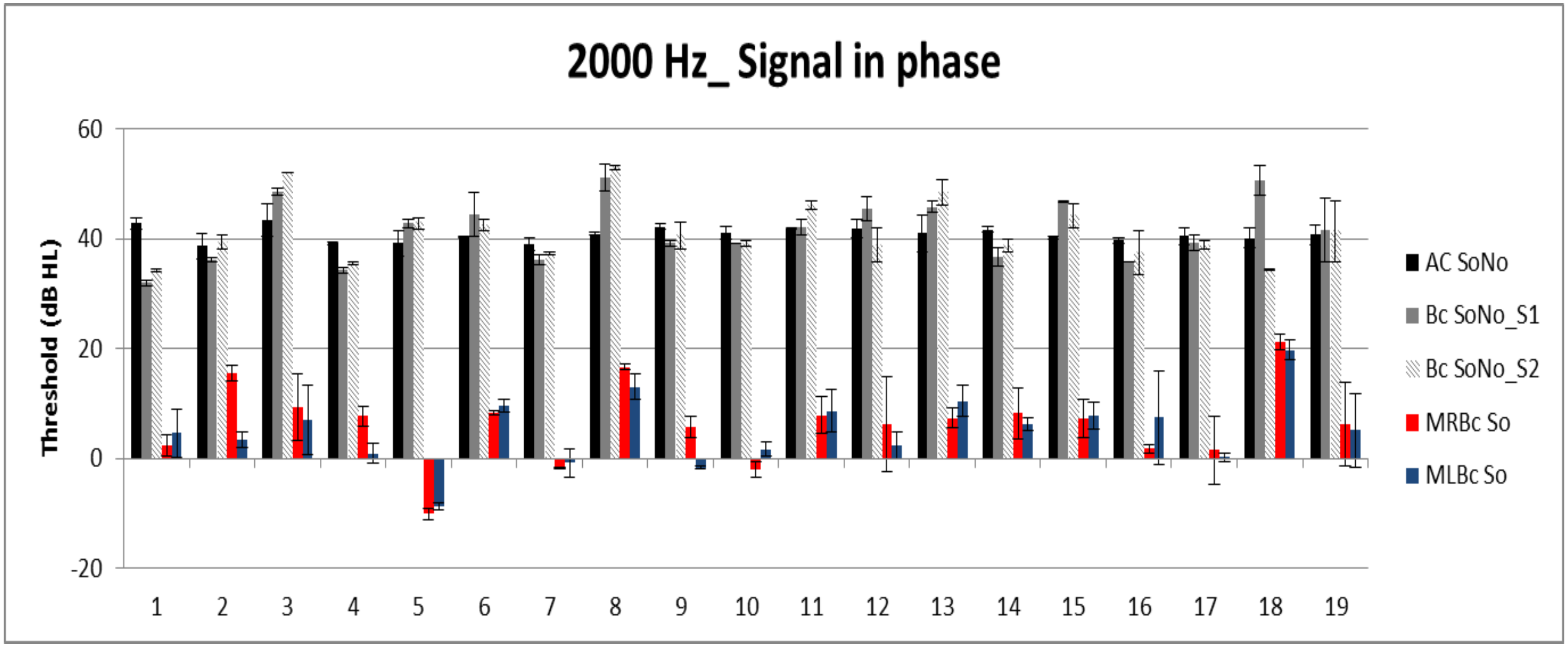
Appendix M. Individual results at the three frequencies, error bars indicate the SD of the mean for each participant




500 Hz_ Signal out of phase
Threshold (dB HL)
60
40
20
0
-20
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Mean
AC SπNo
BC SπNo_S1
BC SπNo_S2
MRBc Sπ
MLBc Sπ


1000 Hz_ Signal in phase
Threshold (dB HL)
60
40
20
0
-20
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Mean
AC SoNo
Bc SoNo_S1
Bc SoNo_S2
MRBc So
MLBc So


1000 Hz_Signal out of phase
Threshold (dB HL)
60
40
20
0
-20
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Mean
AC SπNo
BC SπNo_S1
BC SπNo_S2
MRBc Sπ
MLBc Sπ


2000 Hz_ Signal in phase
Threshold (dB HL)
60
40
20
0
-20
1
2
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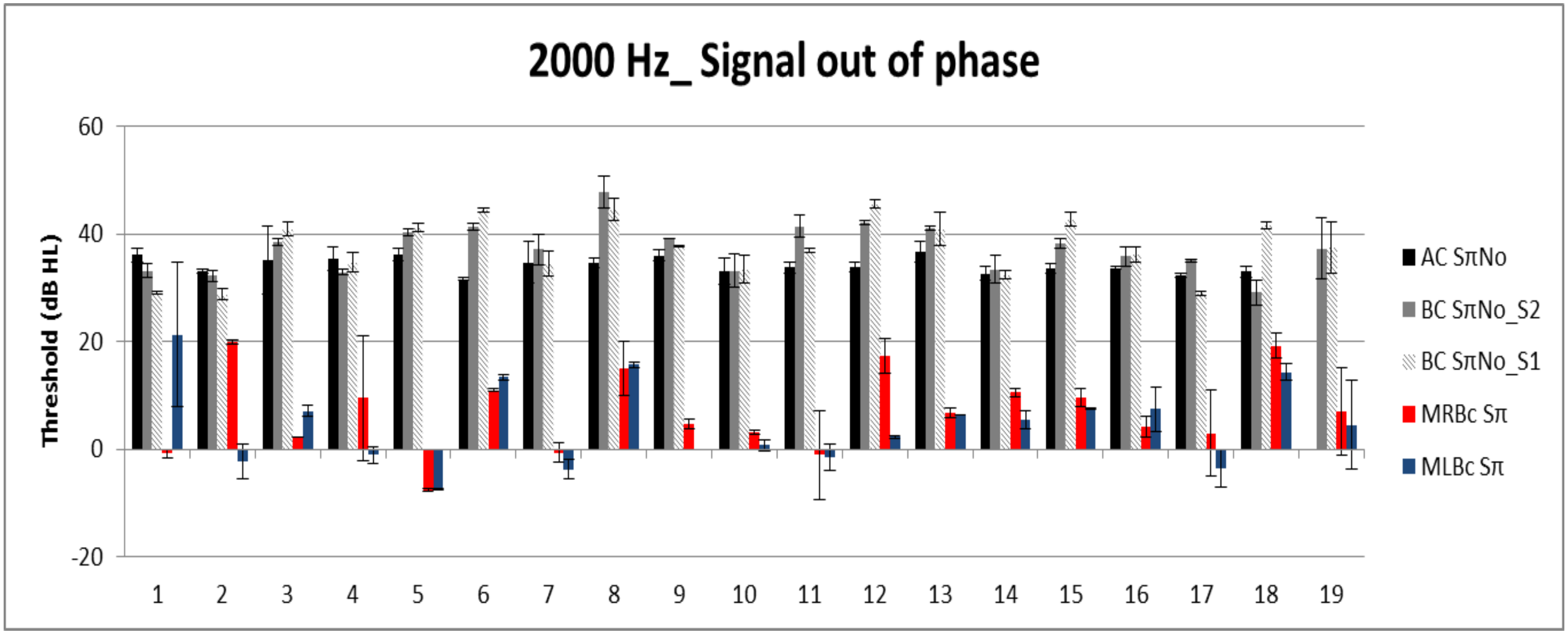
17
18
19
AC SoNo
Bc SoNo_S1
Bc SoNo_S2
MRBc So
MLBc So


2000 Hz_ Signal out of phase
Threshold (dB HL)
60
40
20
0
-20
1
2
3
4
5
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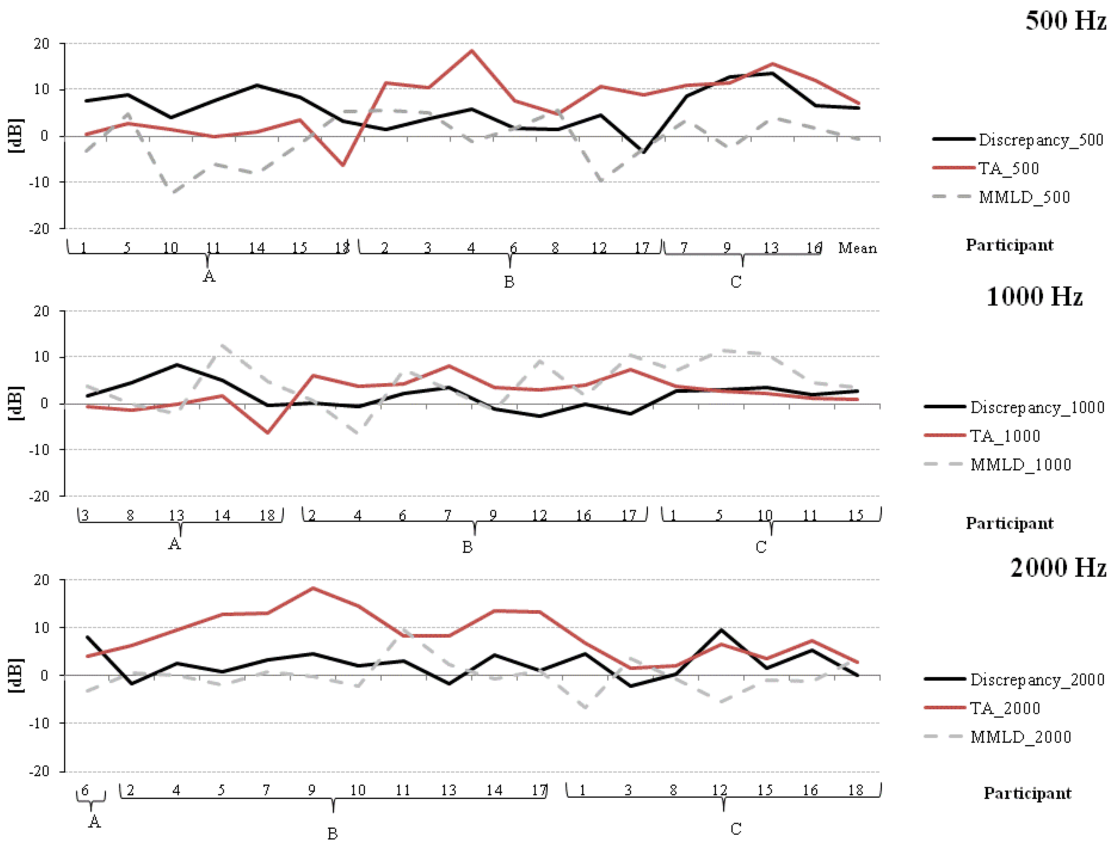
10
11
12
13
14
15
16
17
18
19
AC SπNo
BC SπNo_S2
BC SπNo_S1
MRBc Sπ
MLBc Sπ

Appendix P. The discrepancy between the AC and BC MLD compared to the TA and MTLD for all the participants at the three test frequencies



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