UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Institute of Sound and Vibration Research

Is binaural hearing accessible using bone conduction stimulation?

by

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ABSTRACT

FACULACULTY OF ENGINEERING AND THE ENVIRONMENT

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Doctor of Philosophy

IS BINAURAL HEARING ACCCESSIBLE USING

BONE CONDUCTION STIMULATION

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It may be assumed that people who rely on hearing via bone conduction (BC) are unable to benefit from the advantages of listening with two ears. Subtle differences in sound perceived at each ear enable a listener to enjoy improved hearing in certain situations, compared to listening with one ear only. When listening via BC, the two ears lack independence compared to air conduction (AC). However, a small number of studies provide evidence to the contrary, indicating that some people may have sufficient independence between the ears to enable at least some benefit. The low independence of the ears seen with BC is due to sound vibrations crossing over the skull and stimulating the opposite cochlea. The effect of BC vibrations inter-ear independence is likely to be influenced by differences in skull characteristics between individuals. It may be that some skulls afford sufficiently large inter-ear independence for the individual to benefit from listening with two ears.

A set of three experiments were carried out, culminating in an ambitious experiment that has not, to the author's knowledge been previously reported. The main aim was to investigate inter-subject variation in inter-ear independence. The ability to take advantage of listening with both ears via BC was explored by measuring individual skull characteristics and lateralisation ability, using normal hearing subjects. But first, the behaviour of a recently designed bone vibrator (BV), the balanced electromagnetic separation transducer (BEST), was compared to the B71 with the aim of commenting on the suitably of the BEST for research and clinical use.

Experiment 1 indicated that the BEST is suitable for research and clinical use and was used for Experiments 2 and 3. Experiment 2 showed high inter-subject variations in inter-ear independence and lateralisation ability. This indicates the possibility of sufficient inter-ear independence to allow people to benefit from listening with both ears via BC, although not as strongly as with AC. Experiment 3 repeated Experiment 2 using a refined method and with the addition of a deeper investigation in factors that influence inter-ear independence.

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Declaration of authorship

I, Alison Vaughan, declare that the thesis entitled “Is binaural hearing accessible using bone conduction stimulation?” and the work presented in it is my own.

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
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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 myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself

Signed:……

Date:……

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List of abbreviations

AC	Air conduction
ABRad	Air-borne radiation
AFC	Alternative forced choice
ANOVA	Analysis of variance
BAHA	Bone anchored hearing aid
BC	Bone conduction
BEST	Balanced electromagnetic separation transducer
$BEST^{LFR}$	BEST low frequency reinforced
$BEST^{ORIG}$	BEST original
BV	Bone vibrator
dB HL	Decibels hearing level
dB SPL	Decibels sound pressure level
ECSPL	Ear canal sound pressure level
HTL	Hearing threshold level
IA	Interaural attenuation
ILD	Interaural level difference
IPD	Interaural phase difference
ITD	Interaural time difference
LTE	Left as test ear
NTE	Non-test ear
PC	Phase cancelation
REM	Real ear measurement
RETFL	Reference equivalent threshold force level
RTE	Right as test ear
SD	Standard deviation
TA	Transcranial attenuation
TC	Threshold comparison
TD	Transcranial delay
TE	Test ear

Chapter 1

Introduction

1.1 Introduction and overview

"God gave man two ears but only one mouth so that he might hear twice as much as he speaks" – Epictetus the Stoic. Wise words indeed, but the availability of two working ears has practical as well as moral implications. Our ability, and that of all mammals, to localise a sound source in the horizontal plane is dependent on two ears. Their separation either side of the head produces subtle differences in the sound arriving at each ear when the source if off to one side. Sound sources in front compared to behind and above compared to below can be distinguished with a single ear. But it is the ability to distinguish right from left and the fine detail of the horizontal position that is critical for many of our activities in daily life. The ability to localise sound enables us to follow speech in the presence of background noise and turn to the source when spoken to or react to a danger signal.

People with hearing loss are often unable to hear the features of sounds necessary for localisation. Conventional hearing aids can help to partially restore localisation ability but are not appropriate for all hearing losses. For example some people have deformed ear canals or chronically discharging ears making the use of hearing aids that feed sound into the ear canal not practical. These people typically have problems conducting sound to the cochlea, rather than within the cochlea itself. Hearing via BC can be a useful solution for these people as sound bypasses the site of the hearing loss. Bone anchored hearing aids (BAHA) have been a successful option for nearly 40 years, but do have limitations, especially when fitted to one ear only. It may be that individuals who rely on hearing using BC would largely be denied the benefits of binaural hearing. This is due to sound passing across the skull and stimulating both cochleae, which at least reduces the isolation between the ears. This lack of isolation reduces the subtle differences in sound reaching the cochleae as with AC, thus making the cues required for localisation weaker and therefore localisation more difficult.

However, a small number of studies indicate that some people seem to be able to access features of sound via BC, which is only available with two ears. The ability to perceive speech in a noisy environment is improved when listening via two ears compared to one when using BC as well as AC (Stenfelt & Zeitooni 2013; AlOmari 2014). Also localisation ability has been demonstrated with BC, although not as strong as with AC (van der Pouw et al. 1998; Bosman et al. 2001; Priwin et al. 2004; MacDonald et al. 2006). These findings suggest that some people are able to detect subtle differences between the ears, implying that at least some isolation between the ears is preserved when listening via BC.

One explanation is that the amount of isolation between the ears associated with BC is dependent on the amount of vibration energy lost, i.e. transcranial attenuation (TA) and the time taken i.e. transcranial delay (TD) while the sound crosses the skull. Differences in skull characteristics between individuals may result in some people having sufficiently large TA and TD to enable enough isolation between the ears to benefit from hearing with two ears.

This study set out to explore lateralisation using BC signals. Lateralisation ability was measured using acoustic cues that are known to be used when listening via AC with low and high frequency sounds. Differences in skull characteristic were considered by estimating TA and TD in each subject. Previous studies typically report a large variation in TA between people (Nolan and Lyon 1981) and some early studies suggest that TA increases as frequency increases (Snyder 1973). However, more recently TA has been reported as being less influenced by frequency (Stenfelt 2012). The estimation of TD is far from cohesive, with different methods reporting different values. Transcranial delay is time consuming to estimate and previous studies typically use small sample sizes.

Previous studies report that some individuals are able to use cues within sounds that are only accessible when using two ears. It may be that localisation should not be possible when hearing via BC, this research aims to investigate why some individuals apparently seem to have some localisation ability. It is proposed that inter-subject variation in TA and TD may play a role in explaining differences in lateralisation ability seen in human subjects. Experiment 3, explored

this by estimating TA, TD and lateralisation ability in the same group of normally hearing people. To the author's knowledge this has not previously been attempted.

Before commencing this investigation, a suitable BV was chosen by carrying out a series of studies comparing the behaviour of two types of BV, namely the commonly used B71 and the recently developed balanced electromagnetic separation transducer (BEST). This study was performed in collaboration with another PhD student. The B71 is known to have limitations, in terms of the frequency range and output loudness that can be used, before hearing thresholds become affected. The B71 is known to produce high levels of sound from the casing at frequencies above 2 kHz, which when heard via AC can falsely improve BC thresholds. At frequencies below 1 kHz, B71s are susceptible to harmonic distortion as well as becoming vibrotactile i.e. the listener can feel the BV vibrating against the skin at low output levels. The BEST has been designed specifically to address the problem of harmonic distortion, which has been shown to be successful (Håkansson 2003; AlOmari 2014). However, the amount of sound emitted from the case and thresholds at which the BEST becomes tactile are similar to the B71. The BEST was chosen for use in this research due to lower harmonic distortion and comparable amount of sound radiation and vibrotactile thresholds compared to the BEST.

This research has implications in both research and clinical settings. The BEST produces lower harmonic distortion than the B71 at 250 and 500 Hz, increasing its usefulness at these frequencies. This means that the BEST is able to be driven at lower frequencies and higher output levels, compared to the B71, thus providing more information in the clinical setting. Also over recent years, interest in and use of BC hearing aids has been fuelled by the excellent results produced by the introduction of the bone anchored hearing aid (BAHA). The believed limitation of benefit at least in terms of localisation ability, to be gained by bilateral BAHA has resulted in routine unilateral fitting. If isolation between the ears is sufficiently large to enable differences in sound between the ears to be perceived, then the present unilateral fitting policy for BAHA may be due for reassessment. In recent years, interest in bone conduction communication devices has gained momentum for professional and leisure purposes. The presentation of auditory information using BC prevents the need to block the ears, as with earphones, thus maintaining an awareness of environmental sound. This is desirable for

military, police and security personnel. Bone conduction communication devices have been developed for use with iPods and are suitable for use underwater, while earphones are not.

1.2 Aims

The aim of this research was firstly to explore the behaviour of the BEST in comparison to the B71. The designers of the BEST claim improved performance in terms of harmonic distortion. Behaviour in terms of sound emission from the case and vibrotactile thresholds had not previously been investigated.

A method was developed with the aim of investigating lateralisation ability with BC signals. Auditory cues known to be important for lateralisation with AC were presented via BC, with the aim of investigating differences in the accessibility of these cues using AC and BC.

A subject's TA and TD may play a part in determining lateralisation ability. Transcranial attenuation and delay were estimated with the aim of exploring inter-subject variation. A high amount of TA may provide sufficient isolation between the ears to enable the individual to benefit from hearing with two ears. When TA is high, TD may also play a role in isolation between the ears. Therefore TA and TD were estimated with the aim of exploring the relationship between lateralisation ability and the amount of between ear isolation.

1.3 Contribution to knowledge

Experiment 1, demonstrated that the BEST produces a similar amount of sound from the case when compared to the B71. The lower susceptibility to harmonic distortion revealed by the collaborative study, suggests the BEST would be suitable for use in the clinical setting as well as for research.

This thesis adds weight to previously reported inter-subject variation in TA. Although only one frequency was measured, the result is in agreement with previous studies in terms of mean and inter-subject variation. Transcranial delay is time consuming to measure and not easy to achieve. This study used a relatively large sample size, compared to previous studies and offers

some test-retest data, which is sparse in the existing literature. This study contributes to research by the description of a novel amendment to the method used to estimate TD. The method is dependent on precision which can be difficult to achieve with stimuli presented via BC. The adjustment to the previously reported method makes cancellation easier to detect, which reduces the time taken to achieve and increases the number of subjects able to complete the task.

Lateralisation ability with BC was demonstrated when using two types of cue that are important for localising low and high frequency sounds with AC. When using the low frequency cue, lateralisation ability with BC was typically worse compared to AC. When using the high frequency cue, lateralisation was generally better with BC than with AC. This observation can only be attributed to the frequency used in this research and cannot be considered the case at higher or lower frequencies.

The relationship between TA and lateralisation ability in Experiment 2 suggested that subjects with relatively high TA seem better at lateralisation than those with low TA. The results of Experiment 3 suggest no significant relationship between an individual's TA and TD, between lateralisation performance using stimuli manipulated via ILD and IPD and between either TA or TD and lateralisation performance.

1.4 Thesis overview

Chapter 2: Background information and literature review

This chapter explains the mechanisms and application of hearing via BC. The theory of sound localisation using air conduction is then described before discussing the limitations expected when using BC. Current literature relating to TA, TD and localisation of sound presented via BC is explored. Experimental aims are also set out.

Chapter 3: Experiment 1. Justification of the choice of bone vibrator

This chapter starts by considering types of bone vibrator (BV) available for this research and their relative merits and limitations. Experiment 1 describes a comparison between two types of BV: the commonly used B71 and the balanced electromagnetic separation transducer (BEST). Chapter 3 is mainly concerned with the amount of sound emitted from the case, although this study forms part of a collaborative study in which another PhD student investigated different aspects of the BVs behaviour. Two methods were used. Firstly, emitted sound was measured with each transducer placed on an artificial mastoid. Secondly, sound pressure was measured in human ear canals while each BV was placed on the mastoid. The BEST was shown to produce no more sound than the B71 and differences in other aspects of the BVs behaviour was not significantly different and therefore the BEST was chosen to be used for Experiments 2 and 3.

Chapter 4: Experimental design

This chapter describes the general methods used for Experiments 2 and 3. The experimental set up and equipment used was similar for both. Experiment 2 measured TA and lateralisation ability. The method used to estimate lateralisation in Experiment 2 was altered for Experiment 3. Experiment 3 included the estimation of TD in addition to TA and lateralisation. These amendments to the experimental design are described in the relevant section of Chapter 6.

Chapter 5: Experiment 2. Transcranial attenuation and lateralisation

This chapter sets out the experimental rationale, aims and overview for Experiment 2. The main aim of Experiment 2 was to investigate the previously reported inter-subject variation in TA. Also to use lateralisation ability as a way of determining if binaural cues are accessible using BC. A further aim was to investigate whether inter-subject differences in TA could explain the apparent ability to lateralise a sound, seen in some individuals using BC. Transcranial attenuation was estimated using hearing threshold level comparison and the results are reported. Lateralisation ability using AC and BC was used as a measure to investigate the accessibility of binaural cues with AC and BC stimulation. A brief discussion is included for both sections.

Chapters 6 and 7: Experiment 3. Transcranial attenuation and delay

These chapters set out the experimental rationale, aims and overview of Experiment 3. The aim of Experiment 3 was to repeat Experiment 2 using refined methods and with the addition of estimating TD as well as TA in each subject. Lateralisation, TA and TD with BC has previously been reported, but not using the same subjects. Adjustments made to the method for Experiment 3 compared to Experiment 2 are described and reasons given. The method of hearing threshold level comparison was used to measure TA again in Experiment 3 and results reported and discussed. Transcranial delay was estimated using the method of phase cancellation which is described and results reported and discussed. This method also provided another estimate of TA for each individual. Lateralisation performance using AC and BC is reported and discussed. The effect of TA and TD on lateralisation is reported and discussed. The remaining sections make a series of comparisons and discuss the affects. Comparisons are made between lateralisation performance in Experiments 2 and 3 and lateralisation measured using AC and BC. The effect of TA and TD on lateralisation performance are then discussed. The amount of variation and the effect of measurement error on the results are also considered.

Chapter 8: Conclusions and further research

Chapter 8 summarises the conclusions and applicability of the findings and considers areas where further research may be warranted.

1.5 Presentations at auditory research meetings

Aspects of this research have been reported at the following auditory research meetings:

Al Omari H, Vaughan A and Rowan D. Evaluation of two types of transducer for auditory research. Poster presented at the British Society of Audiology Short Papers Meeting on Experimental Studies of Hearing and Deafness; September 17-18, 2009; Southampton, UK.

Vaughan A, Al Omari H and Rowan D. Evaluation of two types of transducer for auditory research. Poster presented at the British Association of Audiology Annual Conference; November 25-27, 2009; Liverpool, UK.

Vaughan A and Rowan D. Application of cross-talk cancellation to bone-conduction hearing devices to improve binaural hearing. Poster presented at SET for BRITAIN, House of Commons; March 8, 2010; London, UK.

Vaughan A, Romeo E and Rowan D. Does skull density affect spatial perception? Poster presented at the British Society of Audiology annual conference; September 8-10, 2010; Manchester, UK.

Vaughan A, Rowan D and Simpson D. Investigating sound localisation using bilateral bone conduction stimulation. Poster presented at the British Society of Audiology annual conference (incorporating the Experimental and Clinical Short Papers meeting); September 5-7, 2012; Nottingham, UK.

Chapter 2

Background information and literature review

2.1 Introduction

This thesis explores whether the cues required for binaural processing are accessible via BC. The ability to judge the source of a sound when listening via BC is used as a measure. This chapter explores the theories and experimental literature that underpins our understanding of hearing via BC, the mechanism and benefits of using both ears when hearing using AC and the expected limitations and challenges associated with listening with two ears via BC.

The ability to localise sound in the horizontal and vertical plane using AC is well understood, while this is not the case with BC. The ability to localise a sound in the horizontal plane, is dependent on the comparison of a different percept of the same sound reaching each cochlea (i.e. binaural processing) (Hafter & Trahiotis 1997). This readily occurs when listening via AC due to the large interaural isolation afforded by having an ear either side of the head. When listening with BC, sound crosses the skull resulting in both cochleae being stimulated (Stenfelt 2012). The complicated pattern of vibration pathways across the skull are expected to at least reduce interaural isolation and therefore hamper the ability to localise a sound.

Congenitally impaired subjects, show a significant improvement in sound localisation when stimulated with binaural compared to monaural input (van der Pouw et al. 1998; Bosman et al. 2001; Priwin et al. 2004). Binaural processing using BC is also demonstrated by the release from masking revealed when measuring binaural masking level difference (Bosman et al. 2001; Priwin et al. 2004; Stenfelt & Zeitooni 2013). Hearing impaired subjects report a subjective improvement in the ability to localise sound using bilateral input (Dutt et al. 2002). Normal hearing subjects have been used to indicate comparable localisation ability using AC and BC (MacDonald et al. 2006). The theory of listening via BC implies that localisation ability should be at least degraded, due to crossed pathways, while the above evidence suggests differently. The question is ‘Why?’

We know that cross pathways degrade interaural isolation but not to what extent. When using BC, an individual's interaural isolation is determined by their TA and TD. Transcranial attenuation varies widely between individuals and seems to increase as frequency increases (Hurley & Berger 1970; Snyder 1971; Nolan & Lyon 1981). Relatively little is known about TD, and there is a lack of agreement between studies. This may be due to methological differences and few subjects being used in each study. We know that interaural isolation is required for localisation ability. In theory, individual differences in TA and TD may explain differences in ability to localise sound, therefore TA and TD are expected to be important, but as yet we don't know the roles they play. It is expected that TA is more important than TD. If high TA means no vibration energy is reaching the cochlea contralateral to the site of stimulation, then TD is immaterial.

This chapter proceeds by describing the mechanism of hearing by BC and its applications. Section 2.2 explains the process and benefits of listening with two ears, before discussing what is known about localisation ability using BC as set out in Section 2.3. Previous studies measuring TA and TD are described in detail in Sections 2.3.2 and 2.3.3. This chapter concludes with a prediction of the effect of cross pathways on localisation with BC.

2.1.1 Hearing via BC

Hearing via BC is a complex, and not completely understood system. The basilar membrane response to a sound presented via BC is the result of a combination of a number of paths whose influence is dependent on frequency (Stenfelt et al. 2002; Stenfelt et al. 2003). At least eight contributory pathways have been proposed, the individual importance of the minor ones being a subject of conflicting ideas. According to Stenfelt & Goode, 2005b the five main contributors are:

1) Sound radiated into the external auditory meatus
2) Inertia of the ossicles
3) Inertia of the cochlear fluids
4) Compression of the cochlear walls
5) Pressure transmission from the cerebrospinal fluid.

Other routes suggested include middle ear cavity compliance, mobility of the oval window, mobility of the round window and the compliance effect of the cochlear aqueduct (Tonndorf 1966) as well as non-osseous routes (Sohmer et al. 2000; Freeman et al. 2000). These studies suggest that BC hearing does not rely solely on conduction by bone. The five routes considered of most significance to BC hearing are depicted in Figure 2.1 and considered further below.

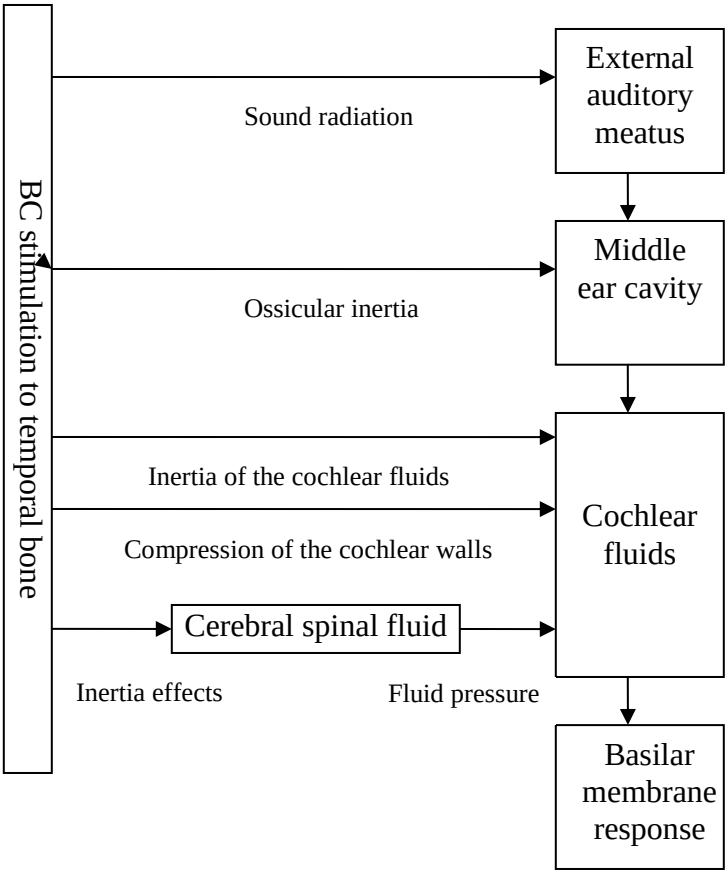


Figure 2.1 Schematic of the main routes that contribute to hearing via BC.

The osseotympanic contribution describes vibrations of the outer ear canal wall which results in vibrations of the tympanic membrane and stimulation via the AC pathway. This route becomes significant when the ear canal is occluded. Sound radiated to the occluded ear canal is the dominant BC component for frequencies from 0.4 to 1.2 kHz (Stenfelt et al. 2003). Ossicular inertia occurs when the ossicles move relative to the skull, being most influential between 1.5 and 3.1 kHz (Stenfelt 2006). Inertia of the cochlear fluids results in a hearing sensation due to movement of the fluid within the cochlea relative to the skull and is the dominant mode at frequencies up to 1 kHz (Stenfelt & Goode 2005). As the skull vibrates, the bone housing the

cochlea is compressed and expanded, which results in movement of the fluid within the cochlea. Compression of the cochlear walls has most influence at frequencies above 4 kHz (Stenfelt & Goode 2005). Once sound energy reaches the cochlea, the response of the basilar membrane and perception within the brain seems to be the same whether the original stimulation was via AC or BC (Zwislocki 1953; Boezeman et al. 1984). These studies presented an AC and BC sound concurrently, equal in amplitude, but 180^{o} out of phase and found that they cancelled. This was demonstrated at frequencies from 1 to 15 kHz.

The sensitivity of hearing by BC is dependent on the site of stimulation, being between 8 and 14 dB more sensitive when stimulating at the mastoid than at the forehead, especially at low frequencies (Weston et al. 1967; Dirks et al. 1968; Haughton & Pardoe 1981). Until recently, the accepted explanation was that mastoid stimulation ensures the inertial component of hearing is at its most sensitive, as the direction of stimulation is parallel to that of the ossicular chain. Forehead placement results in the direction of stimulation being perpendicular to the direction of the ossicles making them unresponsive to the stimulation. However, recent studies using cadavers indicate that stapes footplate motion is similar irrespective of the direction of stimulation (Stenfelt et al. 2000). These studies indicate that the ossicles do not move in a fixed direction, but are able to rotate and also suggest that the skull moves in all three directions wherever the skull is stimulated. The difference in sensitivity may be explained by the greater distance to the cochlea from the forehead than the mastoid and thicker skin and muscle layer found at the forehead compared to the mastoid.

The structure of the skull is complicated, making a full understanding of bone vibration transmission difficult. Variations in bone structure within different parts of the skull result in differences in wave propagation. The cranial vault is made of two sheets of dense bone with fluid between and is attached to skin and soft tissue on the outside and brain matter and cerebrospinal fluid on the inside. All of these structures influence wave transmission (Stenfelt & Goode 2005). Studies have suggested that wave transmission in the cranial vault occurs in the form of plate waves which comprise longitudinal and transverse components (Zwislocki 1953; Franke 1956; Tonndorf & Jahn 1981). A feature of plate waves is dispersion (i.e. velocity changes with frequency). The thick bone characteristic of the skull base, results in a

longitudinal mode of wave propagation that is almost independent of frequency. Wave transmission has been shown to be higher (approximately 400 m/s) at the skull base than at the cranial vault (approximately 250 m/s at 2 kHz and 300 m/s at 10 kHz), indicating different modes of wave transmission at different parts of the skull (Stenfelt & Goode 2005).

The pattern of vibration of the skull depends on frequency. At frequencies up to approximately 600 Hz, wavelength is larger than the dimension of the head so the skull vibrates as a whole in the direction of the stimulation. The shorter wavelengths associated with higher frequencies result in the back of the head, assuming forehead stimulation, starting to lag behind the vibration of the front, due to differing inertia in various sections of the skull. The lead-lag behaviour of the skull creates standing waves within the bones of the skull, which starts to move in a number of parts that vibrate in opposite directions, resulting in a compressional mode of vibration (Tonndorf 1966).

The resonant frequencies of the skull have been investigated, using dry and wet skulls (Franke 1956; Stenfelt et al. 2000) and living humans (Håkansson et al. 1994). There is wide variation between studies and between individuals, with the first skull resonance being reported to be between 0.5 to 1.6 kHz. Using living humans, the consensus appears to be that the first resonant frequency occurs at approximately 1 kHz (Håkansson et al. 1994). Bone thickness, stiffness and skull size are probably the main influences on where the first skull resonance occurs. Importantly, as the resonant frequencies are highly damped, the influence on hearing via BC should be minimal. However, antiresonances have been shown to produce a considerable reduction in sound transmission. This may be due to sound propagation following different paths through the skull that have different phase responses which leads to cancellation of the stimulus (Håkansson et al. 1994).

In summary, it can be seen that hearing by BC is far more multifaceted than AC. Stimulation via BC results in wave propagation to the cochleae via various routes, each likely to be affected in different ways due to the type of bone they are travelling through. The stimulus frequency also affects the way the skull behaves in response to the stimulation. Although not fully

understood, hearing via BC has well established applications which are described in the following section.

2.1.2 Application of BC

In clinical audiology, the threshold of hearing using BC stimulation is routinely measured and compared to the threshold of hearing using AC stimulation in order to ascertain broadly where in the auditory system a hearing loss originates. Disease or damage occurring in the outer or middle ear will influence the AC pathway to a greater extent than the BC pathway. As a result, the threshold of hearing using BC would be expected to be better than that using AC, and an air-bone gap would be apparent on the audiogram. Such a hearing loss is known as conductive hearing loss and a hearing loss occurring due to a lesion in the cochlea or auditory nerve is known as sensorineural hearing loss. A mixed hearing loss occurs when an individual has lesions of both conductive and sensorineural origin.

Interest in communicating by BC has grown in the last 10 years, and not just to help the hearing impaired. Evidence suggests that the development of the BAHA has improved the quality of life of many people (Lloyd et al. 2007; Tringali et al. 2008; Snik et al. 2008), but other applications of BC technology is growing. There are situations when it is desirable to communicate via a bone conduction communication device (MacDonald et al. 2006) and such devices are becoming commercially available. How successful bone conduction communication devices could be in terms of binaural hearing is uncertain. The following section explores some of the applications of hearing via BC in more depth.

2.1.3 BC hearing aids

Some individuals are unable to benefit from amplification provided by conventional AC hearing aids. Narrow or absent external ear canal (aural atresia), deformed or absent pinna (microtia) or a chronically discharging ear can create a problem in getting sound to the tympanic membrane (Dillon 2001). Benefit can often be found using a bone-conduction hearing aid. Until recently bone conduction hearing aids consisted of a BV pressed against the head using a steel spring which tended to be of poor sound quality and uncomfortable. In 1977, the BAHA was developed which has largely overcome these problems. Bone-anchored hearing

aids comprise a percutaneous titanium implant embedded in the temporal bone approximately 55 mm behind the ear, as shown in Figure 2.2. A BC transducer with amplifier attaches to the implant by way of a bayonet coupling.

Figure 2.2 BAHA abutment (left) and with sound processor attached (right).
(Picture credit http://topnews.in/health/files/baha-098.jpg)

Over time the abutment osseointegrates with the bone, creating an effective coupling for the BAHA (Hakansson et al. 1985). Sound energy is transmitted directly to the cochlea via vibrations of the skull, therefore bypassing the outer and middle ear. On average, individuals performance is significantly improved with a BAHA compared to a conventional bone conduction hearing aid (Mylanus et al. 1994). This maybe explained by the damping affect of the skin and subcutaneous tissue layers in the mastoid region that have been shown to attenuate acoustical vibrations by between 10 and 20 dB (Hakansson et al. 1984). However, the thickness of the skin of the mastoid has been shown to not vary enough to have a significant effect on thresholds obtained transcutaneously versus percutaneously (Mylanus et al. 1994).

The BAHA was originally intended for the treatment of those with conductive or mixed hearing loss. The severity of the conductive loss is not important. The degree of any sensorineural component limits the candidacy for a BAHA. Bone-anchored hearing aids are capable of providing stimulation for individuals with BC thresholds (average 0.5 to 3 kHz) of up to 45 dB HL for the head-worn aid and 60 dB HL (Mylanus et al. 1994) for the body-worn aid. For an

individual with no sensorineural component, the maximum output of the BAHA can compensate for a loss of 60 to 70 dB HL (Stenfelt & Goode 2005).

When using AC hearing aids to treat a conductive loss, the high level of amplification required can lead to problems with acoustic feedback and poor sound quality (Hakansson et al. 1985). The majority of patients with conductive or mixed hearing loss report a preference for the BAHA rather than their previous BC or AC hearing aid (Mylanus et al. 1998; McDermott et al. 2002; Hol et al. 2005). Mylanus et al. 1998 used 34 patients with bilateral conductive or mixed hearing loss to compare speech recognition in noise performance with bilateral AC hearing aids and unilateral BAHA and found a small but significant improvement with the BAHA. Whilst the patients did not express a preference regarding speech recognition in noise, a questionnaire revealed that the majority preferred the BAHA due to reduced incidence of ear infections, improved understanding of speech in quiet, improved sound quality and reduction in acoustic feedback.

A group of patients were used in a two part study with the aim of investigating the long term outcomes of using a BAHA after previously using AC hearing aids. In the initial study, subject's performance using analogue AC hearing aids compared to BAHA was compared by measuring free-field aided thresholds and speech recognition in quiet and noise. Tests using the AC hearing aids were completed before the BAHA was fitted. Tests using the BAHA were carried out 4 to 6 weeks after fitting. Results reveal an improvement in aided thresholds using the BAHA at high frequencies (> 4 kHz) compared to the AC aids. The speech in quiet revealed no difference while the speech in noise test showed a small but significant improvement with the BAHA. The amount of improvement was related to the size of the air-bone gap: the greater the conductive loss, the better the performance with the BAHA. When the air-bone gap reached 25 – 30 dB, speech perception was better with the BAHA. Overall, results indicated that most individuals preferred the BAHA (Mylanus et al. 1998). The same subjects were invited to repeat these tests seven years later. All subjects were still using the BAHA and the majority (89%) preferred the BAHA, citing speech recognition in quiet, sound quality and comfort as more advantageous compared to the AC aids (Hol et al. 2005). These studies are interesting because the tests were carried out at a time when subjects were fully acclimatised to

each hearing device. Studies often make comparisons after the fitting of the BAHA, the subject therefore being more acclimatised to the BAHA than the AC hearing aid. The subject could no longer be expected to perform at their best with the initial device.

More recently this study has been partly replicated using subjects who previously used a unilateral BAHA. Aided thresholds and speech recognition scores were measured using the most recent version of BAHA (BAHA Intenso). Subjects were then fitted with an up to date powerful digital behind the ear hearing aid with feedback cancellation, and after an acclimatisation period of 4 weeks, aided thresholds and speech recognition scores were again measured. Results were similar to those reported by Mylanus et al. (1998), however the point at which the BAHA became more favourable had shifted to between 30 and 35 dB as opposed to 25 to 30 dB.

To summarise, studies carried out using analogue behind the ear hearing aids indicate that listeners prefer BAHA over behind the ear hearing aids in terms of reduced incidence of infection, understanding speech in quiet, improved speech quality and fewer problems caused by acoustic feedback. Also a small, but significant improvement in the ability to recognise speech in noise is seen when using BAHA, when the air-bone gap is greater than 25 - 30 dB. However, studies using up to date digital behind the ear hearing aids, imply that behind the ear hearing aids are preferable as long as the air bone gap is less than approximately 45 dB.

Bone-anchored hearing aids can also benefit those with unilateral profound sensori-neural hearing loss (Wazen et al. 2001; Wazen et al. 2005; Hol et al. 2004). The main difference in benefit for conductive hearing loss and sensorineural hearing loss would be expected to be in terms of binaural hearing. In the case of a conductive hearing loss, both cochlea still function, so if sufficient amplification can be provided, some degree of binaural processing has been shown to be restored (Snik et al. 2002). However, with a profound sensori-neural hearing loss, only one cochlea is functioning fully. A BAHA implanted on the deaf side, picks up stimuli and transmits to the healthy cochlea via BC as depicted in Figure 2.3A. The BAHA effectively transmits sound from the hearing impaired side, therefore removing the ‘head shadow’, which would otherwise occur on the deaf side of the head. Attempts have been made to reduce the

head shadow by using a contralateral routing of sound aid, which consists of a microphone that sits on the pinna of the poor hearing ear. A wire carries sound around the head to a receiver that sits on the pinna on the good hearing side as depicted in Figure 2.3 B.

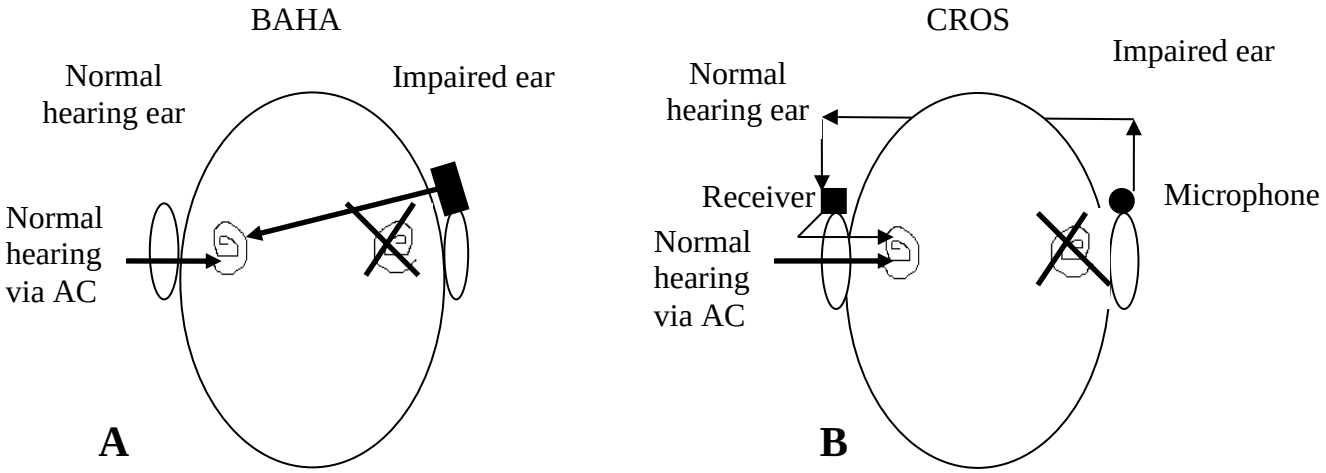


Figure 2.3 Options to reduce the head shadow typical of unilateral deafness, using a bone anchored hearing aid (BAHA) in diagram (A) and a contralateral routing of sound aid in diagram (B).

However, a BAHA has been shown to be effective at removing the head shadow and can give greater benefit than the contralateral routing of sound (Niparko et al. 2003; Bosman et al. 2003; Wazen et al. 2003; Hol et al. 2004). Importantly, the fitting of a BAHA contralateral to a normal working cochlea, does not appear to interfere with the function of the normal ear, through bone-conduction (Wazen et al. 2001).

Localisation and lateralisation ability has been shown to be poor in individuals with unilateral sensorineural hearing loss, when both unaided and fitted with a BAHA to the impaired side (Hol et al. 2004; Wazen et al. 2005). The ability to localise a sound relies on a slightly different version of the signal being perceived in each ear and is explained in detail in Section 2.2, but in this population sound is only ever perceived by one cochlea. The fitting of a BAHA results in improved speech perception in noise when the speech is presented from the front with the noise to the impaired ear, but not when the noise is presented from the front and the signal to the poor ear (Wazen et al. 2005). The perception of speech in noise requires two working cochleae, but

in this case the improvement can be explained by the improvement in signal to noise ratio at the hearing ear, rather than having two working cochleae. However, the fitting of a BAHA to the poor ear of a conductive hearing loss, is beneficial in terms of localisation and speech recognition in noise (Hol et al. 2005), although Wazen et al. (2001), dispute this reporting that speech recognition with the BAHA is comparable to the patient's best score in the unaided condition. In the case of a conductive hearing loss , hearing threshold levels are reported to be improved after BAHA fitting, reflecting the advantage gained by bilateral input compared to unilateral input i.e. binaural summation (Wazen et al. 2001).

The improvement in our understanding of hearing via BC and the success of BAHA, has led to the development of bone conduction communication device. Receiving auditory information via BC has a number of applications as discussed below.

2.1.4 BC communication devices.

The presentation of auditory information via a bone conduction communication device avoids blocking the ears, thus allowing detection of ambient sounds which can be desirable in certain situations e.g. to enable military, police or security personal. Although useful at least in theory, it seems we have some way to go before bone conduction communication devices deliver as high a quality in terms of sound, volume and comfort compared to headphones. One study implies that useful binaural hearing can be achieved via BC (MacDonald et al. 2006), while others doubt it (Stenfelt & Goode 2005a; Stenfelt 2005). Skin attenuates sound, especially high frequencies, and the lack of interaural isolation associated with BC makes the use of BC questionable when using high-fidelity applications.

So far, this chapter has concentrated on the mechanism of hearing by BC and its application. The focus of this thesis is on binaural processing when listening via BC. Before considering this, the next section considers our knowledge of the binaural hearing using AC stimulation.

2.2 Listening with two ears

The use of two ears (i.e. binaural hearing) has long been recognised as important for sound localisation and for understanding speech in noise (Hafter & Trahiotis 1997). This section explores and discusses the experiments that provide the evidence that underpins our knowledge of binaural hearing and perception, i.e. the reason we have two ears and how we perceive one world through two ears. Firstly, terminology used in this area is explained, followed by an overview of spatial perception.

2.2.1 Terminology

A ‘monotic’ or ‘unilateral’ stimulus is one that is presented to one ear only, while ‘bilateral’ stimulation refers to both ears receiving stimulation concurrently. In the case of bilateral presentation, the ears can receive identical signals, known as ‘diotic’ stimulation or dissimilar signals called ‘dichotic’ stimulation. This terminology describes the presentation of stimulation to the ears only, with nothing being implied regarding how the auditory system receives and processes the sound signals. Monaural hearing/processing describes functions of the auditory system for which stimulation of one ear only is required. Binaural hearing/processing refers to functions underlying the effects of listening with two ears rather than just one.

Two ears are connected through the head by an imaginary line known as the interaural axis. The interaural axis extends in a circular fashion around the head forming the horizontal plane. Assuming zero degrees refers to a point on the horizontal plane directly in front of the listener’s nose, azimuth refers to the angle between zero degrees and the sound source. Another imaginary line creates the sagittal plane, by passing through the head, perpendicular to the interaural axis, effectively splitting the head into right and left sides. The distance between the horizontal plane and a sound source is known as elevation. When a sound is presented at zero azimuth and elevation in a sound field, it would be expected that a normally hearing listener would perceive the source of the sound as being directly to the front. Moreover they would be expected to report that the sound is heard outside of the head i.e. ‘externalised’. When a diotic stimulus is presented via headphones or insert earphones, a listener would be expected to report hearing a sound at a position midway along the interaural axis, inside the head i.e. internalised.

Generally, ‘localisation’ refers to sounds that are heard outside the head, typically during experiments in a sound field and ‘lateralisation’ refers to sounds that are heard within the head, typically in experiments when stimuli are presented via headphones or insert earphones. It should be noted that it is possible to manipulate stimuli to produce the perception of externalised sound under headphones/inset earphones and internalised sound using a sound field (Plenge 1974).

2.2.2 Advantage of binaural hearing

Compared to monaural, binaural hearing affords the listener considerable advantages in terms of increased amplitude of sound (binaural summation), sound localisation and binaural unmasking, enabling improved speech recognition in noise (Hafter & Trahiotis 1997). In some situations, normal hearing subjects are able to access advantageous information contained within a sound when using binaural but not monaural hearing. It is important to note that advantage can be gained by the bilateral fitting of hearing aids, even if binaural hearing is not occurring. The threshold of hearing is improved when using two ears compared to one ear due to the perception of extra loudness i.e. binaural summation (Marks 1978). However, binaural processing is required for sound localisation and speech discrimination in noise. Binaural processing has been studied by measuring individual’s ability to localise sound and binaural masking level difference, both of which are discussed below. The following section describes the anatomy of binaural hearing. Sections 2.2.4 to 2.2.10 offer an overview of aspects of localisation applicable to hearing via AC.

2.2.3 Anatomy of the afferent auditory pathway

This section describes how information received at each ear is collated within the auditory system. The afferent auditory pathway consists of an intricate system of millions of nerve fibres that form neural pathways to convey acoustic information from the cochleae to the auditory processing centres in the brain. The following is a simplified overview of the central auditory nervous system. Figure 2.4, amended from Gelfand 2004, features the major nuclei only, ensuring the relay stations of importance to binaural hearing are included.

On stimulation, the inner hair cells generate an action potential which causes neural impulses to travel along the auditory nerve to synapse with the homolateral cochlear nucleus within the brainstem. Neurons leave the CN in parallel, some continue ipsilaterally along the afferent pathway, but most synapse with the nuclei of the contralateral superior olivary complex. The superior olivary complex receives information from both cochleae and is considered the first level at which binaural processing occurs. Both superior olivary complexs use the bilateral input to extract information regarding ITD and ILD. Binaural information is conveyed to the inferior colliculus, either through or bypassing the lateral lemniscus. Monaural information that does not decussate (cross to the contralateral side) bypasses the superior olivary complex and synapses with the contralateral inferior colliculus by way of the lateral lemniscus. Monaural and binaural pathways converge in the inferior colliculus where binaural information is assimilated, making it another important relay station for the extraction of binaural information. Information regarding binaural hearing is conveyed from the inferior colliculus to the superior colliculus which receives multi-sensory input. Information is transmitted onwards to the medial geniculate body before arriving at the auditory cortex.

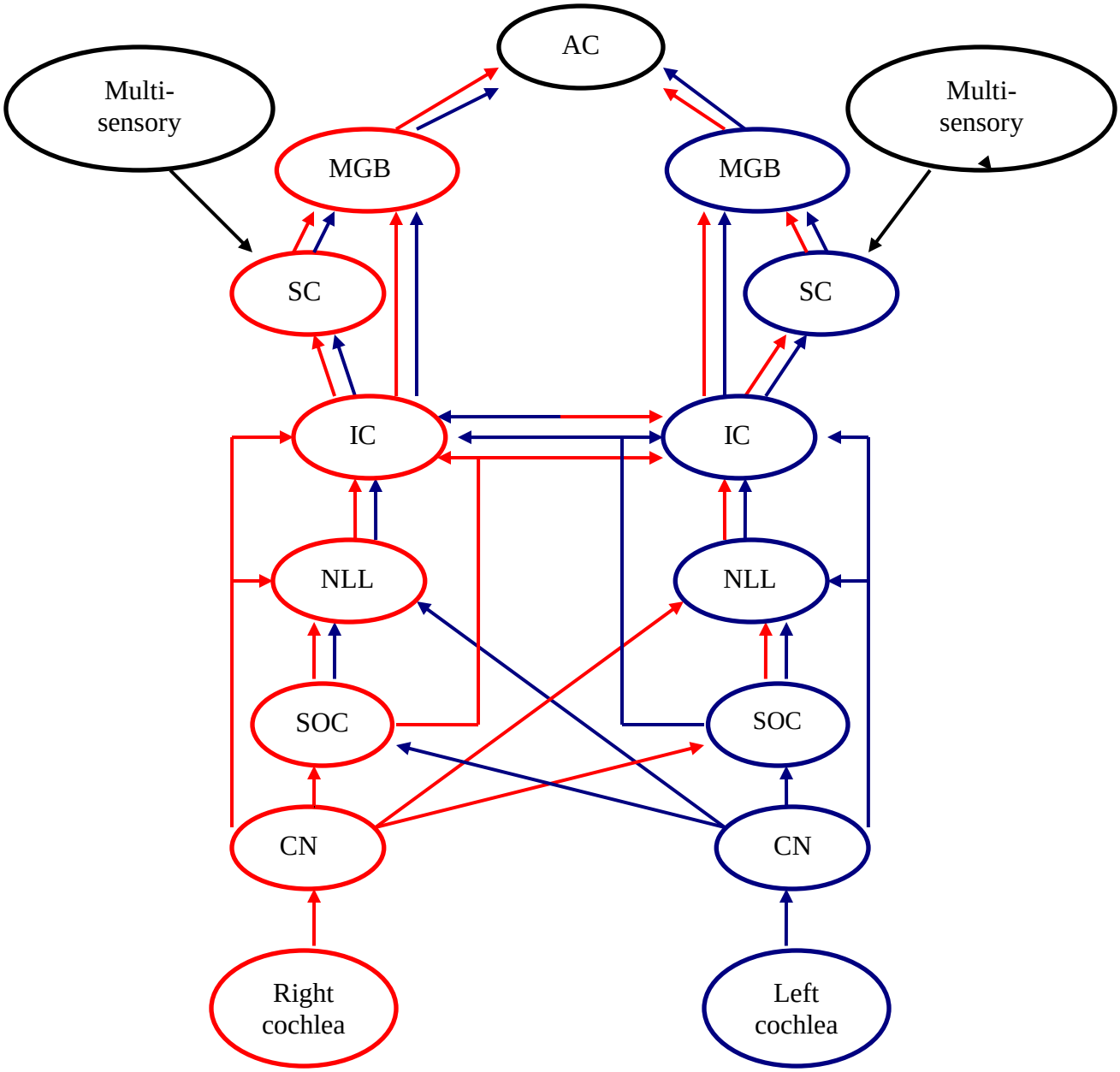


Figure 2.4 Schematic showing the important afferent pathways for binaural hearing. (CN - Cochlear nucleus, SOC - superior olivary complex, NLL - nucleus of the lateral lemniscus, IC - inferior colliculus, SC - superior colliculus, MGB - medial geniculate body).

When a hair cell is stimulated, an action potential is released along its corresponding nerve fibre, resulting in a neural spike travelling to the cochlear nucleus via the auditory nerve. Neural spike rate is related to the velocity of basilar membrane motion. Individual neurons are

characterised by an ‘all or nothing’ pattern of firing, meaning that the amplitude of the stimulus does not affect neural discharge. However, amplitude does have an impact on the number of nerve fibres firing in response to stimulation. Nerve fibres are not sensitive to all frequencies, but are responsive to a narrow range of frequencies. The characteristic frequency is the frequency to which the nerve fibre is maximally sensitive. The characteristic frequency is directly representative of the place on the basilar membrane that the nerve fibre innervates. The characteristic frequency becomes lower the closer to the apex of the basilar membrane, known as ‘cochleotopicity’. The temporal pattern of stimulation is reflected in the displacement of the basilar membrane. The basilar membrane moves up and down in synchrony with the temporal characteristics of the stimulus, the peak of displacement corresponding to the characteristic frequency of the stimulus. This is known as ‘phase-locking’ and occurs for pure tones of less than approximately 4 kHz (Moore 2004).

This section explored anatomy that enables binaural processing. The following sections consider the benefit of binaural processing in for localisation and speech understanding in the presence of competing noise.

2.2.4 Localisation

The ability to localise sound is beneficial in many listening situations and is maximised when listening via binaural stimulation. The human brain is able to localise a sound, with varying accuracy, arriving from anywhere in the three-dimensional space around them, as well as judge the distance of a sound source. The comparison of sound arriving at each cochlea enables localisation of a sound in the horizontal plane. Binaural cues are most important for localisation in the horizontal plane, while monaural cues created by the pinna, head and torso predominate for localisation in the vertical plane (Belendiuk & Butler 1977). Distance perception is more complex, using a combination of loudness, experience and the relationship between direct and reverberant sound energy (Hafter & Trahiotis 1997). Experience also influences the ability to localise a sound (Javer & Schwarz 1995).

2.2.5 Localisation in the horizontal plane

Having two normally functioning ears set a distance apart, affords humans the ability to judge the direction of a sound source in the horizontal plane. A sound arriving from anywhere on the sagittal plane (i.e. zero azimuth) arrives at both tympanic membranes with near identical time and sound pressure level. However, when a sound does not originate from the sagittal plane, the ear nearest will be stimulated sooner than the ear furthest from the sound source. This delay is known as the interaural time difference (ITD) and is depicted in Figure 2.5.

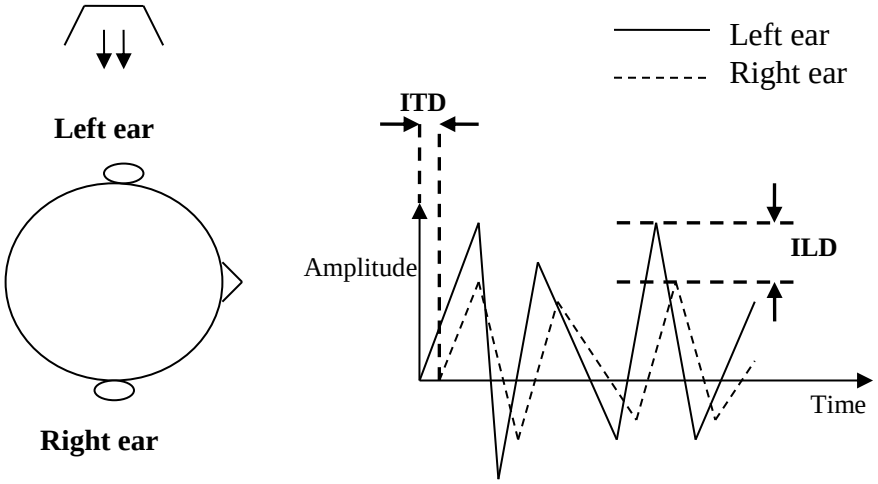


Figure 2.5 Schematic illustrating interaural time difference (ITD) and interaural level difference (ILD) with a sound source nearest the left ear.

Interaural time cues can be apparent at the onset/offset as well as in the ongoing portion of the stimulus. Ongoing ITD based cues are important for frequencies up to between 700 and 800 Hz. At higher frequencies, phase ambiguities can occur as half the period of the tone is equal to or greater than the maximum ITD produced by the head (Bernstein & Trahiotis 1985). Phase locking of the auditory nerve fibres starts to break down at approximately 4 to 5 kHz (Moore 2004).

Interaural time differences are maximal at an azimuth of ± 90^{o} being approx between 600 and 800 μs, depending on the size of the skull (Kuhn 1977). When using complex sounds, ITD may provide cues for localisation at higher frequencies due to information extracted from the

onset, offset and envelope of the stimulus (Middlebrooks & Green 1991; Bernstein & Trahiotis 2002). A sound can be split into two parts: the temporal fine structure, which is conveyed by frequency modulations and the envelope, which can be conveyed by amplitude modulations. When both cues are available, fine structure dominates for localisation (Bernstein & Trahiotis 2002).

Interaural level difference (ILD) is the second important cue for localisation in the horizontal plane and is also depicted on Figure 2.5. Sound approaching from one side of the head will reach the far ear at a lower sound pressure level than the near ear, relative to the sound source, due to the acoustic shadow created by the head. The difference in sound pressure arriving at the ears is referred to as the ILD. Interaural level difference is a more robust cue at higher frequencies, rising from approximately 5 dB at frequencies below 500 Hz to approximately 25 dB at 4 kHz (Kuhn 1977). Localisation based on ILD cues becomes difficult at frequencies below 500 Hz as the wavelength of the sound becomes relatively longer than the width of the head and weakens the acoustic shadow effect of the head. Interaural level difference is also dependent on azimuth, increasing from 0 dB at 0^{o} and 180^{o}, to a maximum of approx. 20 dB at $\pm 90^{o}$ (Feddersen et al. 1957).

Localisation ability depends on the type of stimuli used. Localisation accuracy improves with increasing bandwidth, meaning broadband stimuli are easier to localise than narrowband or pure tones (Middlebrooks & Green 1991). Signals with a wide bandwidth contain more cues for sound localisation i.e. ITD and ILD. However, the periodic characteristic of pure tones leads to phase ambiguity as frequency increases (Wightman & Kistler 1997). Localisation of pure tones can be improved by using rapid onsets that provides ITDs in the arrival of the envelope which also facilitates the use of the precedence effect (Rakerd & Hartmann 1985).

2.2.6 Localisation in the vertical plane

On arrival at the tympanic membrane, sound will have been influenced by the pinna, head and torso, altering its spectrum compared to that at source. Frequencies in the region of between 4 and 8 kHz are most important for the judgement of elevation, resolving front-back confusion and monaural localisation (Hebrank & Wright 1974; Musicant & Butler 1985; Middlebrooks &

Green 1991). The short wavelength associated with high frequency signals, create strong pinna reflections which are useful for elevation judgement. Cues found in frequencies below approximately 3 kHz, associated with head diffraction and reflection of the torso have been shown to have an influence on vertical localisation (Algazi et al. 2001; Gardner 1973).

2.2.7 Binaural masking level difference

Binaural masking level difference refers to the differences in masked threshold for hearing a signal in the presence of noise when the noise and signal are presented in certain ways. When a noise and signal are presented bilaterally, simultaneously and identical in level and phase, the threshold of hearing the signal will be higher than when either the noise or the signal are presented in some way dichotically. An overview of these conditions is shown in Table 2.1. For clarity, shorthand is used to depict the relationship between signal and ears where 'S' and 'N' refer to signal and noise, 'm' indicates a monotic stimulus and 'o' indicates a diotic stimulus. Therefore SmNm indicates the signal and noise is presented to one ear only while SoNo indicates identical signal and noise is presented to both ears. The symbols 'π' and 'τ' depict a reverse in phase and time delay respectively.

Table 2.1 Masking level differences for different conditions

Input	Shorthand	MLD
Identical signal and noise presented simultaneously to both ears	SoNo	0 dB
Signal presented to one ear Identical noise presented simultaneously to both ears	SmNo	9 dB
Identical signal presented to both ears. Noise presented bilaterally, one reversed in phase relative to the other	SoNπ	13 dB
Signal presented bilaterally, one reversed in phase relative to the other. Identical noise presented simultaneously to both ears	SπNo	15 dB
Identical signal presented to both ears. Noise presented bilaterally one side delayed relative to the other.	SoNτ	3-10 dB

In the SoNo condition, binaural masking level difference is 0 dB and the signal is not audible due to the noise. When the signal is presented monaurally (SmNo), it becomes audible due to a

binaural masking level difference of 9 dB, compared to the SoNo condition. The binaural advantage is increased to 13 dB when the signal and noise are presented bilaterally with the noise reversed in phase between the ears. The binaural masking level difference has been shown to be maximal at 15 dB when the noise and signal are presented bilaterally with the signal reversed in phase between the ears (Green & Henning 1969; Colburn & Durlach 1965; Jeffress et al. 1952).

Binaural masking level difference holds for tones (Licklider 1948) and speech (Hirsh 1948). The size of the binaural masking level difference is dependent on a number of factors, with the binaural masking level difference increasing as the spectrum of the noise increases and when the noise is presented diotically (Hirsh 1948; Blodgett et al. 1962; Dolan & Robinson 1967). The largest binaural masking level difference have been show to occur when either the signal or the noise are antiphasic (Hirsh 1948; Jeffress et al. 1952; Colburn & Durlach 1965). The size of the binaural masking level difference is dependent on the frequency of the stimulus, being greatest at low frequencies. At low frequencies, the firing patterns of auditory nerve fibres are phase-locked to the stimulus so the relatively large binaural masking level differences seen with antiphasic conditions may be linked to phase locking in the neural coding of the stimuli (Green & Henning 1969).

This phenomenon is a useful way to study binaural processing by demonstrating that binaural hearing offers some ‘release from masking’ i.e. it improves our ability to overcome the detrimental effects of room reverberation and may be related to our ability to follow a conversation in the presence of multiple speakers i.e. the ‘cocktail party effect’. Furthermore, release from masking indicates an intact brainstem auditory pathway (Strouse et al. 1998).

A measurable binaural masking level difference demonstrates the brain’s ability to make sense of a number of different sounds arriving simultaneously at the cochleae and combine them to the listeners benefit. A similar phenomenon is seen when different sounds arrive sequentially at each cochlea. This is known as the precedence effect and is described below.

2.2.8 Precedence effect

The precedence effect describes the way that humans localise a sound source in an enclosed environment, when direct and reflected waves are providing conflicting directional cues (see Litovsky et al. 1999 for review). In a reverberant environment, sound bounces off walls and surfaces and propagates in multiple directions. The eardrums are therefore subjected to a clutter of information that the auditory system is able to organise, enabling listeners to identify and localise individual sounds accurately. Although the precedence effect only occurs naturally in a reverberant environment, difficulties in controlling the stimuli mean that most studies have used headphones.

Under headphones, various ITD or ILD configurations are used to create the illusion of sounds originating from either side of the listener. When two equally loud, spatially separated sounds are presented with a short delay between them (i.e. simulating a direct and reflected sound), a listener will perceive one sound only, known as 'summing localisation'. At delays of less than 5-10 ms using clicks (Freyman et al. 1991) and approximately 40-50 ms for speech (Lochner & Burger 1958), listeners report the perception of one fused image. As the delay increases, the fused image becomes audible as two separate sounds. The temporal boundary at which one fused sound becomes audible as two separate sounds, known as the 'echo threshold', varies depending on stimulus type and duration, subject instructions and extent of spatial separation (Zurek 1980). The consensus of opinion is that echo threshold occurs at approximately 10 ms for clicks (Freyman et al. 1991), 5-22 ms for noise (Schubert & Wernick 1969) and 30-50 ms for speech (Lochner & Burger 1958). Comparison with early studies, carried out in a free field implies that echo thresholds are shorter for headphones than for stimuli presented in a free field (see Blauert (1997) for review),

Further important aspects of fusion have been reported. There appears to be considerable inter-subject variation in the delay during which individuals experience fusion (Clifton & Freyman 1989; Freyman et al. 1991; Clifton et al. 1994). Also the extent of spatial separation of the contributory sounds has a strong effect on echo threshold (Litovsky et al. 1999). Historically, it was thought that the precedence effect relies on binaural hearing, but some aspects of

precedence, including fusion, have been shown to occur at similar delays with monaural and binaural stimulation (Blauert 1977).

Another important aspect of the precedence effect is known as 'localisation dominance', which refers to the auditory system's capacity for the initial sound to dominate the judgement of the origin of a sound (Litovsky et al. 1999). Two identical sounds presented simultaneously at 45^{o} either side of a listener, will be perceived as a fused image with an origin directly to the front. A delay in the presentation of one of the stimuli by between 1 and 2 ms, (i.e. less than the echo threshold), results in the fused image appearing to originate from the direction of the first presentation. This phenomenon is known as the "law of the first wavefront" and has been demonstrated using headphone stimulation (Leakey et al. 1958; Zurek 1980; Shinn-cunningham et al. 1993). If the amplitude of the delayed sound is increased, the fused image moves back to centre. This implies a trade off in localisation dominance between delay and relative amplitude of the contributory sounds.

Stenfelt (2005) refers to the precedence effect as it may apply to cross-hearing. The main cue for sound localisation of non-stationary complex sounds (i.e. speech) is interaural differences in time of arrival. He points out that the first sound to arrive determines the perceived localisation, even if it is not dominant in intensity (i.e. the precedence effect). He goes on to suggest that ITD is probably a major cue in determining the direction (at least lateralisation) of a sound source for individuals fitted with bilateral BAHAs. Stenfelt reports that the inter-cochlear time delay for BC transmission at frequencies above 800 Hz is approximately 0.2 ms. He suggests that this time difference may be enough for the auditory system to resolve interaural cues and localise a sound using BC stimulation.

The precedence effect is an area that as yet has not been formally investigated with BC stimulation. However, it may be important for localisation ability when listening via BC. The next section considers the brain's ability to adapt to differences in sensory input, important for BAHA users who have been deprived of binaural input since birth.

2.2.9 Plasticity and adaption

The developing brain is highly responsive to information from the environment and able to change in response to it, a capability known as 'plasticity' (Illing et al. 2000; Knudsen 1983).

Although stability is required for reliable performance, it seems that the mature human brain maintains the ability to change in response to a change in sensory input loss (Neuman 1996).

Plasticity can be demonstrated in terms of auditory deprivation and acclimatisation. An individual with symmetrical hearing loss (impaired hearing threshold levels and speech recognition scores) fitted with a unilateral hearing device, may see a worsening in the ability of the unaided ear to recognise speech (Silman & Gelfand 1984). It appears that auditory deprivation is more complex than lack of stimulation as symmetrically hearing impaired individuals who do not wear hearing aids, do not seem to suffer auditory deprivation (Gelfand et al. 1987).

Recovery of the auditory deprived ear does not always occur, although can be dramatic (Neuman 1996). Improvement can only happen following bilateral amplification and can take many months or even years to occur. One explanation for the wide variation in outcome after bilateral fitting is that many individuals choose to not use the second aid as they have become used to unilateral amplification and prefer this to the combined sound provided by bilateral aids. They therefore do not persevere with an aid in the auditory deprived ear rendering it without the stimulation required for recovery to occur.

Due to ethical considerations, few studies have been carried out to investigate the effects of early bilateral deprivation on binaural processing later in life. Patients with congenital hearing loss caused by atresia or middle ear deformity have been used to study binaural abilities in individuals who have been deprived of binaural cues since birth. Following bilateral implantation of BAHAs, some patients have shown scores within the normal range on binaural hearing tests, suggesting that the human auditory system may be capable of at least some binaural processing after extended deprivation (van der Pouw et al. 1998). Bosman et al. (2001) used six patients with congenital aural atresia to show that prolonged periods of monaural hearing due to unilateral fitting, do not preclude binaural hearing with bilateral fitting at some later stage. This view was upheld by Schmerber et al. (2005), although they suggest that while the mature auditory brainstem has a potential to employ binaural cues later in life, it is to a restricted degree.

Another phenomenon that suggests there is plasticity in the auditory system is known as ‘acclimatisation’. The brain becomes used to the available stimuli, so when that stimuli changes in some way (i.e. the fitting of hearing aids to overcome a high-frequency hearing loss), the listener will need time to get used to the new sound, which can take many months. A period of acclimatisation is apparent in patients who are fitted with bilateral BAHAs (Dutt et al. 2002). This study recruited subjects who had had their bilateral BAHAs fitted for at least a year. They studied patient satisfaction following the implantation of a second BAHA (i.e. sequential) and found that individuals who had used the second BAHA for less than two years seemed to perceive no difference when using one or two in some situations. Patients reported a gradual process of perceptual acclimatisation when using their BAHAs over time.

Hearing aids usually alter cues for localisation. Localisation performance tested using an unfamiliar fitting configuration, results in a marked deterioration in a listener’s localisation ability. However, listeners often adapt quickly to such changes, starting within a few hours and lasting a few days, sometimes a few weeks (Byrne et al. 1996; Florentine 1976). When one ear is occluded, ILD cues are disrupted and horizontal plane localisation ability reduces substantially. Over several days, the brain gets used to the sound being softer in one ear and effectively recalibrates itself, allowing the listener to use ILD to localise sounds. Interestingly, when the occlusion is removed, the brain takes several days to readjust back to normal localisation ability (Florentine 1976). A similar response has been shown by distorting ITD cues. Bilateral hearing aids with an ITD of 171 or 684 μs were fitted to normally-hearing subjects. All subjects were able to correctly locate the origin of a sound prior to the introduction of a delay, but responses became prejudiced to one ear when the delay was activated. After several days of wearing the delayed devices, the bias started to reduce (Javer & Schwarz 1995). These studies demonstrate that the brain is able to adapt to changes in the cues used for sound localisation in the horizontal plane.

Studies investigating the ability of the auditory neural system to process binaural stimulation when binaural stimulation has been absent from birth, is contradictory using animals and scarce using humans. A critical period beyond which the neural pathways necessary for binaural

processing cannot be developed has been suggested (Moore 1986). Binaural processing has been studied in patients with congenital unilateral conductive hearing loss who were deprived of binaural input until at least six years of age. After surgery, several patients performed binaural hearing tests as well as normal hearing people (Wilmington et al. 1994). This suggests that the human auditory system is able to process binaural information even after long term binaural deprivation.

The ability of the auditory system to adapt to bilateral input and therefore enable a listener the benefits of binaural processing is really important when considering bilateral implantations of BAHAs. Hearing impairment also has an influence on localisation ability. The fitting of bilateral BAHA requires the auditory system to adapt to an increase in amplitude and well as bilateral input. The effect of hearing loss on localisation ability is considered next.

2.2.10 The influence of hearing loss on localisation.

Localisation ability is affected by hearing loss. Large individual differences in type and degree of hearing loss, frequency region, age, etiology and duration of impairment all influence how localisation is affected.

Studies using hearing impaired subjects suggest that binaural hearing ability is usually most adversely affected in the case of conductive hearing loss (Jongkees & Veer 1957; Nordlund 1964; Häusler et al. 1983; Noble et al. 1994). In the unaided ear, as the degree of conductive loss increases, the proportion of sound that stimulates the cochlea via BC increases relative to AC. The resultant crosstalk degrades interaural differences, and reduces the listener's ability to access localisation cues (Häusler et al. 1983; Zurek 1986). Furthermore, phase differences between AC and BC pathways can alter IPDs considerably, when the AC and BC signals reach the cochlea, even if BC is still weaker than AC (Noble et al. 1994).

Air conduction hearing aids can provide a considerable improvement in localisation ability in the horizontal plane for individuals with conductive hearing loss The reason for this may be due to the increase in dominance of audibility via AC, therefore restoring ILD and ITD cues (Byrne et al. 1996).

Sections 2.2 explored the anatomy and physiology of binaural hearing using AC stimulation, before the effect of brain plasticity on localisation ability. The influence of hearing loss on localisation was then introduced, which has important implications for this study. Although normal hearing subjects were used for this study, the population that ultimately this research would benefit is primarily those with a conductive hearing loss, which is often congenital. The following section considers the influences and limitations associated with binaural hearing when listening via BC. Previous research that used lateralisation as a measure of binaural input is then critiqued.

2.3 Binaural hearing using BC stimulation

Having considered the advantages of being able to access cues that enable binaural hearing, this section considers the limitations and possibilities of successful binaural hearing using bone conduction. Factors that may affect the amount of cross-hearing that occurs when using BC stimulation are explored.

2.3.1 Cross-hearing

Cross-hearing, also known as ‘shadow hearing’ or ‘shadow responses’, occurs when a sound presented monaurally is perceived by both the near and far cochlea (i.e. the ipsilateral and contralateral ear). It is conventional to call the ear receiving the stimulation the ‘test ear’ (TE) and the opposite ear the ‘non-test’ ear (NTE). For a sound to be heard in the NTE, it must be possible for sound energy to be transmitted across the skull. The amount of energy lost during transmission is known as ‘interaural attenuation’ (IA). The amount of IA depends on the physical characteristics of the skull as well as the means of presentation of the stimulus (Zwislocki 1953). When stimulating via AC, sound energy is transmitted to the skull, via the transducer vibrating against the skull. Sound energy is then propagated to the NTE via the BC hearing route. When presenting AC tones via supra aural earphones interaural attenuation is between approximately 40 and 80 dB (Zwislocki 1953). Therefore, a sound presented to the TE will need to be at least 40 dB higher than sensation level, to also stimulate the NTE. Insert earphones provide the greatest IA, which may be as much as 100 dB at frequencies between 250 and 500 Hz and 80 dB at frequencies between 2000 and 4000 Hz for deeply inserted

earphones (Zwislocki 1953). Minimum IA for inserts is approximately 55 dB (Sklare & Denenberg 1987). Insert earphones provide less IA when inserted to a shallow depth than a deep depth as the amount of IA is directly related to the contact area of the transducer against the skull (Henry & Letowski 2007). An AC stimulus can therefore be presented to the TE at a higher level using insert earphones than supraaural earphones without cross-hearing occurring.

When stimulating via BC, the term 'transcranial attenuation' (TA) is used instead of IA. When using BC stimulation TA is much reduced compared to AC meaning cross-hearing occurs more readily with BC than AC stimulation. For forehead placement TA is essentially zero, whereas for mastoid placement, some studies have suggested that TA depends on frequency, being approximately 0 dB for a pure tone of 250 Hz, increasing to approximately 15 dB for a tone of 4000 Hz (Stenfelt et al. 2000; Snyder 1971). Furthermore, variability between subjects appears to be greater for BC than AC stimulation (Studebaker 1962).

A sound presented via AC will reach the contralateral cochlea with an external ILD/ITD represented by the dashed line. However, when sound is presented via BC, the ILD/ITD will still exist, but may be degraded due to cross-hearing of the sound arriving at the ipsilateral ear, represented by the dotted line in Figure 2.6. The delayed sound reaching the contralateral cochlea will also cross back to the ipsilateral side, represented by the dot/dash line. Theoretically cross-hearing would be expected to adversely influence localisation ability as interaural differences created by external ILD/ITD will be degraded, at least to some extent, by the crossed pathways. Degraded interaural differences would be expected to result in the listener having a reduced access to binaural cues necessary for localisation.

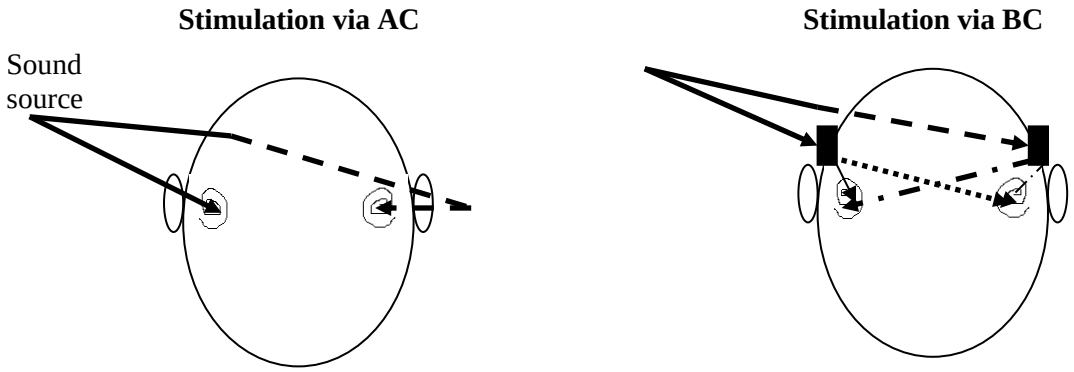


Figure 2.6 Interaural differences with AC and BC stimulation

The amount of sound that reaches the contralateral cochlea is dependent on the TA afforded by the individual's skull. The next section discusses current literature concerning TA in detail.

2.3.2 Transcranial attenuation

Transcranial attenuation refers to the difference in hearing sensitivity of one cochlea when the skull is stimulated at similar positions on the ipsilateral compared to the contralateral side of the head, and is dependent on frequency, position of stimulation, the propagation properties of an individual's skull and the transducer used (Stenfelt 2012). The human head is a complex structure containing skin, soft tissue, bone, cartilage, the brain and cerebrospinal fluid all potentially having an impact on vibratory energy travelling to the cochlea (Stenfelt et al. 2000; Stenfelt & Goode 2005). Transcranial attenuation is important for creating interaural differences, which enables a listener to take advantage of the benefits of binaural hearing. Cross-hearing via BC is therefore likely to be a problem for those individuals who rely on hearing through BC devices, as they are expected to have reduced access to binaural cues, especially if their TA is low. Studies investigating TA have been carried out using acoustic (Stenfelt et al. 2000; Stenfelt & Goode 2005) and psychoacoustic methods (Hurley & Berger 1970; Snyder 1971; Nolan & Lyon 1981; Stenfelt 2012). Acoustic methods using dry skulls and intact cadaver heads have the advantage of being objective and vibration can be measured close to the cochlea, but may not be a faithful representation of the vibratory behaviour of living heads. Psychoacoustic methods are more realistic in terms of perception of vibrated sound but they are susceptible to the variability associated with subjective BC studies.

Although the amount of TA seems to depend on the method of measurement, evidence suggests that TA increases with frequency (Snyder 1971; Stenfelt et al. 2000; Stenfelt & Goode 2005), although some studies suggest a weaker link (Hurley & Berger 1970; Nolan & Lyon 1981).

Two recent acoustic studies have used cadaver heads to investigate TA. Stenfelt et al. (2000) used one dry skull containing damping material and Stenfelt & Goode (2005) used six intact human male heads. Both studies used accelerometers attached near the cochlea to measure vibration, in three directions from six (Stenfelt et al. 2000) and twenty-seven stimulation sites (Stenfelt & Goode 2005). Table 2.2 gives an overview of these studies.

Table 2.2 Overview of acoustic studies investigating TA.

Author and method	Conclusions	Critique
Stenfelt et al. (2000) • Dry skull with damping • Vibrations measured with accelerometers in 3 directions • TA estimated using 6 stimulation sites • Used BAHA	• Tendency for TA to be higher at higher frequencies • Greater contralateral response seen < 1000 Hz. • TA of between 5 and 10 dB seen > 2000 Hz. • Stimulation close to the cochlea increases directivity	• N = 1 • Although containing damping material, dry bone has different vibratory characteristics to wet bone • Lack of realism re: stimulation/direction of response.
Stenfelt & Goode (2005) • Intact cadaver heads • Vibrations measured with accelerometers in 3 directions • TA estimated using 27 stimulation sites • Used BAHA (same model as above)	• Greater contralateral response < 500 Hz. • TA of between 10 and 20 dB > 3000 Hz	• N = 6 • Lack of realism re: stimulation/direction of response • Unknown effect of head not being attached to body

Both studies report that TA is generally negative for frequencies below about 0.5 to 1 kHz, thereafter increasing as frequency increases. For a negative TA to occur, the response is larger in the contralateral than the ipsilateral ear. This occurs when the stimulation arrives at the ipsilateral cochlea either before or at a higher level compared to the contralateral cochlea (Tonndorf 1966). This is most likely due to anti-resonances in the transfer function from the point of stimulation to the nearest cochlea, caused by cancellation effects due to patterns of

vibration and multiple transmission pathways of BC sound. Anti-resonance characteristics vary widely between subjects (Håkansson et al. 1994; Stenfelt & Goode 2005), although usually occur at frequencies below 1 kHz (Stenfelt et al. 2000). Stenfelt & Goode (2005) report that at low frequencies vibration measured at the ipsilateral cochlea is generally between -5 and 0 dB less than that measured at the contralateral cochlea. Transcranial attenuation then increases to a maximum of between 10 and 20 dB at higher frequencies. Stenfelt et al. (2000) found approximately 0 dB at frequencies below 1 kHz rising to between 5 and 10 dB at frequencies up to 10 kHz. The lower level reported by the earlier study could be explained by the use of a dry skull. Although it was filled with damping material the bone would remain relatively dry. Sound transmission through the less damped dry skull would be faster and therefore TA would be expected to be less than an intact wet skull (Stenfelt & Goode 2005). Although this observation is not surprising, one drawback of the Stenfelt et al. (2000) study is that just one skull was used, thus preventing variation between skulls to be investigated. Data from the later study is the mean of six heads, thus allowing for some variation between subjects. Furthermore, the low level of TA at frequencies below 1 kHz reported by these studies could be explained by the observation that the skull moves as a rigid mass at low frequencies meaning the sensation level at each cochlea would be expected to be similar.

Acoustic studies define TA as the difference between vibrations measured at or near the contralateral compared to ipsilateral cochlea. Psychoacoustic studies define TA as the difference in perceived hearing level in the contralateral cochlea relative to the ipsilateral cochlea. Transcranial attenuation reported in the literature for acoustic and psychoacoustic studies differs. The results of the vibration measurements are more strongly frequency dependent than the BC threshold measurements. It could be assumed that there is a strong link between vibrations measured near the cochlea and the perception of BC sound within the cochlea. Furthermore, very few studies have been undertaken using cadavers, so maybe the true picture is yet to emerge.

Transcranial attenuation has been investigated using psychoacoustic methods using living human subjects. Some studies have used unilaterally deaf subjects (Hurley & Berger 1970; Snyder 1971; Nolan & Lyon 1981; Vanniasegaram et al. 1994; Stenfelt 2012) while others

have used normally hearing subjects and prevented the non-test ear perceiving the stimulus by presenting narrow-band masking noise to the non-test ear (Nolan & Lyon 1981; Reinfeldt et al. 2007). Table 2.3 summarises a number of psychoacoustical studies that measured TA using living subjects.

Table 2.3 Overview of psychoacoustical studies investigating TA. (Table amended from Stenfelt 2012)

	TA (dB) as a function of frequency (Hz) Mean, range and SD (stated in dB), except Vanniasegaram et al. which shows approximate confidence limits and Stenfelt shows median						Critique
Author and method	250	500	1000	2000	3000	4000	
Hurley & Berger 1970 Unilaterally deaf		5	4		2		B70A
Snyder 1973 Unilaterally deaf	8 -15 to 20 6	8 -10 to 25 7.1	7 -5 to 25 6.6	11 -5 to 35 8.1		13 -5 to 40 8.1	N = 106 B70A
Nolan & Lyon 1981 Group A Unilaterally deaf	8 0 to 25 6.5	9 0 to 25 8.2	11 0 to 20 7	13 0 to 30 9.6	10 5 to 25 5.5	16 0 to 30 9.8	N = 15 B71
Nolan & Lyon 1981 Group B Normal hearing	9 0 to 20 6.3	11 -5 to 35 10.5	7 -5 to 20 5.3	13 0 to 30 8.3	11 0 to 25 5.8	8 -10 to 40 9.6	N = 35 B71

Vanniasegaram et al. 1994 Unilateral sensorineural hearing loss. Interaural difference of at least 80 dB 0.5 – 4 kHz Used PTA (not-masked BC)		6 3.4-8.9	7 5.4-9.1	11 8.2-13.8		17 14.7-19.1	N = 32 B71 Children (7-16 years). Differences in skull size, density and elasticity compared to adults.
Reinfeldt et al. 2007 Normally hearing Hearing threshold level	0	-1	0	3		10	N = 20 (same subjects as below) BEST
Reinfeldt et al. 2007 Normally hearing Ear canal sound pressure level	3	7	0	6		15	N = 20 (same subjects as above) BEST
Stenfelt 2012 Unilateral Sensorineural hearing loss. Stimulation at mastoid and BAHA site	4.5 -16 to22 ±7.9	2.0 -16 to28 ±9.1	1.5 -5 to 13 ±4.9	4.0 -11 to 22 ±8.3	9.5 -2 to 22 ±6.6	7.0 -7 to 31 ±9.4	N = 28 B71

The experimental set up for most of these studies is similar and depicted in Figure 2.7. The hearing threshold level (HTL) of the test ear was measured with the BV placed on the mastoid nearest to the TE. The BV was then swapped to the side of the NTE and threshold of the TE was re-measured. The NTE was prevented from perceiving sound due to either deafness in that ear or masking noise presented to that ear. Transcranial attenuation is calculated to be the difference in HTL measured in condition 'A' compared to condition 'B' i.e. TA = HTL A – HTL B.

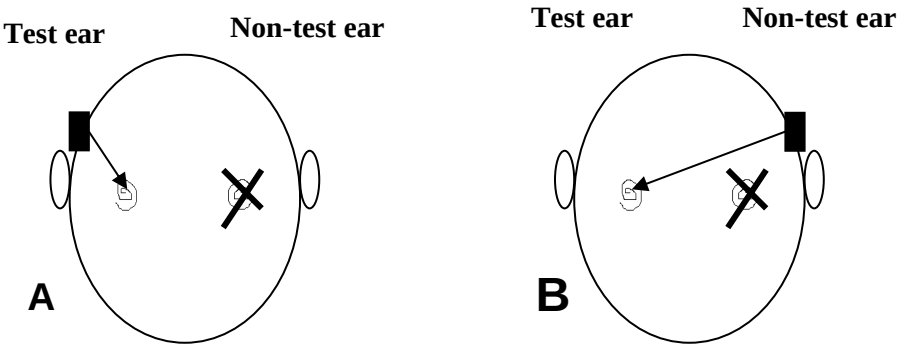


Figure 2.7 Method of measuring TA comparing hearing thresholds in the same cochlea.

A number of studies have used behavioural BC thresholds to estimate TA. Although agreement between studies is limited, the general consensus does seem to indicate that TA increases as frequency increases. Therefore, although psychoacoustic studies have shown variable results, they are broadly in agreement with data from acoustic studies.

From 1970 onwards different models of BV have been used i.e. B70-A, B71 and BEST, making direct comparisons difficult. However, Nolan & Lyon (1981) and Snyder (1973) used a sample size of 15 and 106 and the B70-A and B71 respectively and report a similar average TA of 10 dB in the frequency range 0.25 to 4 kHz. However, using a similar method Hurley & Berger (1970) report that TA decreases gradually as frequency increases. A study using thirty-two children (7 – 16 years) with hearing asymmetry of at least 80 dB (0.5 – 4 kHz), report increasing TA as frequency increases, (Vanniasegaram et al. 1994). No significant difference was found in the distance between the mastoids or in attenuation between different age groups of children used for this study. However, bone density and elasticity changes with age made comparisons between studies using children and adults potentially confusing and drawing

conclusions difficult. Furthermore, although TA was statistically significant at all frequencies, with greater significance at high frequencies, if normal variability in BC HTL is taken into account (Hart & Naunton 1961) a significant difference was seen at 4 kHz only. Conversely, no statistically significant difference has been reported for BC HTL in the frequency range 1 to 16 kHz (Frank & Ragland 1987). The test re-test reliability of TA measurement was investigated by Nolan & Lyon (1981). A subset of subjects were retested two weeks after the initial testing, revealing a high test retest reliability.

Stenfelt (2012) reports results of a recent study that compared TA with the transducer (B71) on the mastoid and the site of a BAHA, in 28 unilaterally deaf subjects at 31 frequencies between 0.25 and 8 kHz. Median TA was found to be between 3 and 5 dB at frequencies below 0.5 kHz, approximately 0 dB at 0.5 to 1.8 kHz, 10 dB at 3 to 5 kHz and 4 dB at 8 kHz. Furthermore, median TA was shown to be between 2 and 3 dB less when stimulation was at the BAHA site compared to the mastoid. This is in agreement with previous studies that report that TA was maximal when the skull was stimulated nearest to the cochlea (Stenfelt et al. 2000). Similar results have been obtained using wet, intact skulls (Stenfelt & Goode 2005).

Transcranial attenuation has also been measured by comparing sound pressure measured in the contralateral relative to the ipsilateral ear canal (Reinfeldt et al. 2007). This study was motivated by the finding that TA estimated by comparing vibration level at the ipsilateral and contralateral cochlea is more strongly frequency dependent than estimating TA using behaviour thresholds. It would be reasonable to assume that there would be a strong link between vibrations at the cochlea and the perceived HTL. However, this is impossible to test so (Reinfeldt et al. 2007) compared TA measured by behavioural thresholds, using the BEST and TA measured by ear canal sound pressure level (ECSPL), following BC stimulation, in the same twenty people. Transcranial attenuation was found to be frequency dependent for both methods and similar at frequencies above 800 Hz, being approximately 0 dB at frequencies below 1 kHz, rising to approximately 15 dB at 8 kHz. The reason for the discrepancy at lower frequencies is reported as unclear. This implies that for higher frequencies, BC hearing levels can be estimated from ear canal sound pressure level. Furthermore, this study implies that the level of vibration measured at the cochlea of cadavers can be related to BC HTL, at least for the

stimulation sites studied. The authors report that the lowest standard deviations were found around 1 kHz, with the HTL measurements revealing slightly lower values than those for ECSPL measurements.
The studies for which variation is stated, report large inter-subject variability suggesting that TA may not be frequency dependent. Nolan & Lyon point out that the overall range in mean TA as a function of frequency was 4.5 dB which is less than the 5 dB limit accepted in audiological testing. However, the large standard deviation indicates wide variability within subjects within the group. This may reflect the effect of differences associated with different models of BV, effects of transducer placement, difference in the static force of the BVor variability in the transmission properties of each skull. A similar trend was seen in both the monaurally deaf and normally hearing subjects, implying that TA is similar when measured by both methods.

It is clear that the picture regarding TA is not clear. The wide variation encountered when measuring using BVs, coupled with studies using different methods and transducers and the subjective impact of using human subjects makes coming to a definitive opinion difficult. However, considering all available data, TA that increases with frequency seems to be a reasonable conclusion, at least in some people.

While TA seems to be an important aspect of binaural hearing with BC, the role of TD is largely unknown. When TA is large, TD is expected to play no role as sound is dissipated before it reaches the far cochlea. However, TD is expected to play a role when TA is low. In this case, differences in both loudness and time of arrival have the potential to be influential. The following section critiques published literature regarding TD.

2.3.3 Transcranial delay

Transcranial delay refers to the time difference that occurs between the times of arrival at each cochlea when a stimulus is presented at a single point on the skull. Although TD is small, some studies have found TD to be sufficiently large to potentially have important implications for binaural hearing via BC. As with TA, TD has been investigated by acoustic and psychoacoustic methods. The acoustic studies are outlined in Table 2.4**.**

Table 2.4 Overview of acoustic studies investigating TD.

Author and method	Conclusion	Critique
Stenfelt et al., 2000 One damped, dry skull. Stimulated using BAHA attachment. Stimulation at 6 sites Measured phase response at petrous part of temporal bone in 3 directions.	Contralateral phase response flat at frequencies below approx. 1.5 kHz. Contralateral phase response increased with increase in frequency above 1.5 kHz.	N = 1 Although containing damping material, dry bone differs in vibratory characteristics to wet bone Lack of realism re stimulation/direction of response.
Stenfelt 2005b Fresh cadaver heads Stimulated at ipsi and cont BAHA sites Measured response using triaxial accelerometer	Time delay between cochleae is approximately 200 μs.	N = 5
Stenfelt & Goode 2005b Used intact cadaver heads Stimulation via mini bone vibrator attached to an abutment that was coupled directly to bone. Measured phase response at cochlear promontory in 3 directions.	Phase differences virtually non-existent below 0.5 kHz. Phase difference increases above 1.2 kHz.	N = 6 Although intact, severed heads may differ in vibratory characteristics to when attached to the body wet bone Lack of realism re stimulation/direction of response.

Transcranial delay has been estimated by measuring the phase response at the cochlea relative to that of the original stimuli, in the frequency range 0.1 to 10 kHz (Stenfelt et al. 2000). Three accelerometers where attached to the petrous part of the temporal bone, which was thought to be the closest point to the cochlea that could be drilled without causing deformity to the temporal bone. Phase responses were measured in three directions medial, posterior and cranial on each side of the head. Stimuli were presented via a BAHA attached at six different positions on the skull, including the BAHA site (55 mm behind the opening of the ear canal) and the site of an audiometric BV. For both sites, the phase response is flat at frequencies below approximately 1.5 kHz, before increasing as frequency increases, implying that the contralateral response occurs later than the ipsilateral response. Subsequent work by Stenfelt & Goode (2005) using a similar method and the same BAHA transducer, with six cadaver heads found virtually non-existent phase differences at frequencies less than 0.5 kHz. They suggest this is due to the skull vibrating as a whole at low frequencies. In agreement with their previous work, they found phase differences between ipsi- and contralateral mastoids at frequencies above 1.2 kHz, again indicating a time delay at these frequencies. Furthermore, this study demonstrates the complexity of sound transmission through the skull by reporting a phase velocity of 400 ms^{-1} measured at the skull base but only between 250 and 300 ms^{-1} measured at the cranial vault. This finding is likely to reflect differences in wave propagations in different parts of the skull. This could be due to the thicker bone and longitudinal wave transmission seen at the base of the skull, whereas the cranial bones may vibrate with a mixture of modes (Stenfelt & Goode 2005). This study also found that the greatest difference in both phase and intensity between the cochleae occurs when the skull is stimulated close to the cochlea.

Psychoacoustic studies have also been used to investigate TD in human subjects. Due to the inability of humans to perceive time differences of such small magnitude, indirect methods have been developed. An overview is show in Table 2.5.

Table 2.5 Overview of psychoacoustic studies investigating TD.

Author and method	Conclusion	Critique
Békésy 1948 Time difference between two pick-up points	Speed of sound through skull of 570 ms^{-1}.	N = 1 Imprecise method used
Zwislocki 1953 Phase cancellation AC stimulation	260 ms^{-1} for frequencies > 0.25 kHz.	N = 1 Speed calculation based on distance between the ears of 30 cm (i.e. around the skull). Cochlea to cochlea distance 14.5 cm.
Franke 1956 Time differences between two pick-up points	80 ms^{-1} for f < 500 Hz 300 ms^{-1} for f > 1000 Hz	N = 2
Tonndorf and Jahn 1981 Phase cancellation B72	330 ms^{-1} for frequencies > 2 kHz.	N = 1
Boezeman et al., 1984 Phase cancelation Normally hearing subjects. Non- test ear not masked Used B71	AC quicker than BC. BC stimulation on frontal bone time lag of 2 ms at 0.5 kHz and 0.8 ms at 2 and 4 kHz. BC stimulation on mastoid time lag 1.5 ms at 0.5 kHz and zero at 2 kHz.	N = 10

The first attempt to measure the speed of sound through a living skull was carried out by von Békésy (1948). One vibration pick-up was positioned on the forehead and one on the back of the skull. The subject clicked his teeth and the times of arrival of the vibration at the two pick-ups were compared. Békésy reports a speed of sound through the skull of 570 ms^{-1}.
An earlier experiment carried out by Békésy in 1932 was the first to demonstrate that two sounds presented to the same cochlea at the same level and of opposite phase, will cancel each other out. This so called 'cancellation method' has been used to investigate TD, by presenting bilateral sounds, while the threshold of the non-test ear is raised by masking noise. Phase cancelation refers to the attenuation that occurs when two pure tones of the same frequency and opposing polarity are combined. The attenuation can be total when the signals are of equal amplitude (Kapteyn et al. 1983). The listener alters the phase and intensity of one signal relative to the other to cancel the sensation. The phase shift required to cancel the signal is used as a measure of the difference in travel time from input site to each cochlea. Studies using this method suggest an increase in the speed of sound transmission as frequency increases and stimulation-site dependent TDs for BC (Zwislocki 1953; Tonndorf & Jahn 1981; Boezeman et al. 1984).

Zwislocki (1953) and Tonndorf & Jahn (1981) used a similar method to show that phase difference decreases as frequency increases between 500 and 750 Hz, which is consistent with findings from TA studies. Thereafter, they report a generally linear increase of phase difference (i.e. TD) as frequency increases. Similarities are evident between data presented by Zwislocki (1953), Franke (1956) and Tonndorf & Jahn (1981). Higher transmission velocities are reported by Békésy (1948), which may be explained by use of a dry skull. Living and intact skulls have higher damping characteristics, slowing the transmission of sound vibrations. Therefore sound transmission would be expected to be faster across a dry skull.

When reviewing results of acoustic and psychoacoustic methods used to measure TA and TD, certain factors should be considered**.** Objective acoustic studies using cadavers are important and valuable, but results are not directly comparable with psychoacoustic studies. Living skulls would be expected to have different BC sound propagation characteristics, due to differences in mass loading and damping properties (Stenfelt et al. 2000). Also, measurements using cadavers

predict the effect of stimulation by measurements made at a site near the cochlea, which may differ from the subjectively perceived effect of BC by the living cochlea. The total sound level perceived by the living cochlea is likely to be a combination of amplitude and phase information arriving from a number of directions, especially at high frequencies, whereas acoustic studies are unable to replicate the directional sensitivity of the cochlea with sufficient accuracy (Stenfelt & Goode 2005). However, it has been shown that vibrations of the skull are largest by approximately 5 to 10 dB, in the direction of stimulation at frequencies up to 0.5 kHz (Stenfelt et al. 2000; Stenfelt & Goode 2005). This effect gradually reduces for higher frequencies.

The use of cadavers has the advantage of being relatively simple and not subject to variation seen with the subjective nature of BC testing. The vibratory characteristics of the living human skull are complex, due to the variation in viscosity of its constituent parts. The use of a cadaver allows some variables to be controlled i.e. by the removal of the brain and fluid allowing the vibratory characteristics of the bone to be investigated separately. Furthermore, the skin can be removed allowing the transducer to be attached directly to the bone of the skull, thus avoiding the damping effect of the skin (Stenfelt et al. 2000; Stenfelt & Goode 2005). Data from such studies can be useful when considering the use of BAHAs as the abutment is implanted in the bone. Transcranial differences are important when considering bilateral BAHA as it indicates the amount of sound that is likely to reach the contralateral cochlea (Tjellström et al. 2001). However, the use of cadavers has enabled studies to be carried out that are not possible using living subjects, e.g. vibratory response measurements near the cochlea and the effect of the skin on hearing via BC.

The age of the skull should be considered when drawing comparisons between acoustic and psychoacoustic studies. Bone density reduces with age and skulls used for acoustic studies tend to be older than subjects recruited for psychoacoustical studies. Vibration energy travels faster the denser the medium, implying that TD may be less in young compared to old skulls.
As is the case with TA, it is not possible to directly compare data collected using cadavers with live humans, but both methods have their merits. Acoustic methods allow objective measurements to be made at the cochlea and precise patterns of vibration to be studied.

Furthermore influences of individual variation (e.g. skull thickness) can be investigated. However, psychoacoustic methods benefit from using a living, intact skull. Human perception is an important part of the hearing process and although, subjective, adds validity to experimental data.

The advantages of binaural hearing and the limitations expected when listening via BC have been considered. The next chapter details the evidence that suggests the auditory system is able to access at least some binaural cues.

2.3.4 Spatial perception using BC

Localisation ability using BC is of particular interest to this study as a way to investigate whether individuals who rely on hearing through BC are able to benefit from binaural hearing. The reduction in interaural differences compared to AC sound that theoretically occurs when stimulating via BC implies that useful spatial hearing will be limited due to the inability to access important cues. Furthermore, cues generated by the pinna and torso will be redundant as BVs are usually placed behind the pinna. It could be expected that BC users may have some ability to perceive distance as loudness and experience are available to them, but perception of the relationship between direct and reflected sound may be degraded due to cross-hearing. Table 2.6 shows the auditory cue that is used to carry out some listening tasks and indicates which auditory cues are available for individuals reliant on BC hearing.

Table 2.6 Important auditory cues for spatial hearing.

Mode	Auditory cue	Importance	Available in BC hearing
Binaural	Interaural time difference	Localisation in horizontal plane	Assumed to be limited
	Interaural level difference	Localisation in vertical plane	Assumed to be limited
Monaural	Pinna and ear canal effects	Localisation in vertical plane Resolution of front-back confusion	No (assuming microphone is behind the pinna)
	Diffraction and reflection of sound due to interaction with the head, shoulders and torso.	Localisation in vertical plane	No (assuming microphone is behind the pinna)
Operational	Head movements	Resolution of localisation confusion	Yes
	Auditory memory/experience	Localisation in horizontal and vertical plane Distance judgement Needed in the absence of physical reference. Apparent with ITD/ILD Relating ITD to sound source	Yes
	Loudness Direct/reverberant sound energy	Distance judgement Important for distance judgement	Yes Unclear

Studies investigating localisation ability using bilateral BC are scarce. Most of the few that have been carried out have used a small sample size. Ideally subjects would be used that are fitted with bilateral BAHAs, but as the benefit of bilateral BAHA is unclear, such people are in short supply. Table 2.7 outlines the main points of previous studies.

Table 2.7 Key points of previous studies investigating bilateral stimulation using BC

Study	Subjects	Method	Test conditions	Conclusion	Critique
van der Pouw et al. 1998 Assessed directional hearing and speech recognition in quiet and noise	N = 4 All congenital bilateral atresia. Probably symmetrical conductive hearing loss. Used unilateral BC HA since < 1 year (deprived of binaural speech cues). Bilateral BAHA (at least 2 years' experience)	Sound field - seven loudspeakers in semi-circle 1 m. narrowband noise bursts centred at 0.5 and 2 kHz of 1 sec duration at 60 dBA. Head turning not allowed. Correct = ± 1 loudspeaker (i.e. 30^{o}).	1) Unilateral BAHA on side of initial implant. 2) Bilateral BAHA	Significant improvement in sound localisation with bilateral BAHA compared to unilateral bone conduction hearing aid. Results imply that the auditory system can adapt in to binaural inputs even after childhood.	Small sample size BC HL People accustomed to bilateral making unilateral worse? Correct response within 60^{o}
Bosman et al. 2001 Assessed directional hearing, speech recognition in quiet and noise and binaural masking level difference.	N = 25 Mixture of congenital bilateral atresia and recurrent discharge. Symmetrical BC HTL (≤15 dB) Bilateral BAHA (at least 3 months)	Sound field – 7/9 loudspeakers in semi-circle 1 m. 1/3 octave narrowband noise bursts centred at 0.5 and 2 kHz of 1 sec duration at 65 dBA. Correct = ± 1 loudspeaker (i.e. 30^{o}).	1) Unilateral BAHA on side of initial implant. 2) Bilateral BAHA	Significant improvement seen with bilateral BAHA compared to unilateral BAHA. Binaural masking level difference results indicate binaural processing.	N= 25
Priwin et al. 2004 Assessed HTL, directional hearing and binaural masking level difference.	N = 12 (3 congenital aural atresia, 9 mixed loss). Symmetrical HL. Bilateral BAHA > 1 year	Sound field – 12 loudspeakers 30^{o} spacing. 1 m. 1/3 octave narrowband noise centred at 0.5	1) Unilateral BAHA on best side. 2) Unilateral BAHA on shadow side 3) Bilateral BAHA	Significant improvement with bilateral compared to unilateral BAHA Benefit due to binaural hearing not	N=12

		and 2 kHz. 65 dB HL for 1 sec.		just bilateral stimulation.	
MacDonald et al. 2006 Compared localisation ability using AC and BC	N = 4 Normal hearing. Localisation using Gaussian noise spatialised using individualised head related transfer function.	8 speaker locations simulated through head related transfer functions. 2.5 m. Train of 8 250 ms noise bursts with 300 ms intervals. 75 dBA (BC loudness matched to AC individually). BC stimulation at the condoyle.	Bilateral BC stimulation at the mandibula	Performance using BC similar to AC	Small sample size Used masking noise to prevent perception of air-borne radiation but subjects were wearing headphones. Headphones on for BC – occlusion effect 75 dBA loudness matched to BC – vibrotactile Possibly all high interaural isolation
Dutt et al. 2002 Assessed patient satisfaction with bilateral BAHA using questionnaire	N = 11 Bilateral BAHA > 1 yr.	Postal questionnaires		Reports subjective satisfaction re localisation of sounds using bilateral BAHA	Subjective Small sample size

Studies using bilateral BAHAs indicate that stimulation via bilateral BC results in improved hearing thresholds, spatial and direction perception as well as better speech perception in quiet and noise compared to unilateral (Bosman et al. 2001; van der Pouw et al. 1998; Priwin et al. 2004). However, these results need to be interpreted with caution as approximately 50% of subjects in each study had AC hearing threshold levels that may have been low enough to perceive the localisation stimuli. However, if subjects were localising with AC, no difference would be expected to be seen between bilateral and unilateral conditions. It could also be argued that the perception of AC as well as BC stimuli may result in worse localisation ability than BC alone due to the confusion of level and phase information from both AC and BC arriving at each cochlea concurrently. Although this implies some binaural hearing effects, performance is reduced compared to bilateral AC stimulation. This conclusion is substantiated in studies using subjects with conductive hearing impairment. Conductive hearing loss leads to the perception of high levels of BC sound compared to AC sound relative to normal hearing individuals. If BC vibrations reach normally hearing cochleae, at a level comparable to the AC sound, the cochleae are no longer acoustically isolated. Interaural differences are therefore disrupted by cross-hearing created by the BC sound. People with conductive loss seem to be at least partially deprived of the benefits of binaural hearing (Zurek 1986). A point of particular interest revealed by the van der Pouw study is that all subjects improved their localisation performance using ILD and 75 % improved using ITD.

An investigation into the usefulness of unilateral BAHA, using cadaver heads, concludes that an individual will benefit from the implantation of a BAHA on the side of the poor hearing ear as long as they have a high degree of TA. Conversely a low TA will reduce interaural isolation rendering the BAHA of limited use for spatial perception (Stenfelt 2005).

A further study using normal subjects, investigated spatial perception using bilateral BC, by applying individually measured head related transfer functions to the stimuli that was then presented via headphones and BVs placed at the condoyle and localisation ability with AC and BC stimulation was compared. Results imply that BC performance is comparable to that with AC (MacDonald et al. 2006). While this study does show evidence of localisation ability with

BC, the use of head related transfer function provides information to the listener not normally accessible via BC due to the site of stimulation.

Recently simulation studies of spatial hearing using BC have been undertaken at ISVR (Romeo 2010; Hamid 2012) by presenting a simulation of binaural hearing using BC stimulation via insert earphones. The stimuli were first subjected to head related transfer functions related to a known position in space. A cross-talk simulation was then used to manipulate levels of TA (100, 20, 10, 5, 0 dB) and TD (0.2, 0.7 ms). Using broadband noise, mean localisation error started to deteriorate gradually between a TA of 20 dB and 10 dB, increasing rapidly when TA was less than 10 dB. This is interesting as TAs of approximately 10–15 dB seem to be apparent in some people, at least in the higher frequency range. This implies that the interaural attenuation of 40 dB seen with AC is more than required and successful spatial perception is possible with the lower levels of TA found in some individuals with BC stimulation. TD was manipulated using a TA of 0 dB. Spatial perception using TD of 0.2 and 0.7 ms was found to be better than the case of TA of 0 dB, with the 0.7 ms condition showing improved performance than 0.2 ms condition. This implies that TD does provide at least some interaural isolation.

While these studies are encouraging, it is important to consider what is being assessed. Benefit could be gained by the combined input from two amplifiers, whereas this study is interested in binaural hearing, i.e. access to binaural cues in order to take advantage of bilateral input. Binaural masking level difference is sensitive to proving the existence of binaural processing. Some binaural masking level difference conditions could be explained by in-phase signal addition (i.e. signal in phase, noise anti-phasic) but it cannot account for the binaural masking level difference effect seen when the signals are anti-phasic and the noise in phase, as this implies a cancellation of cross heard signals (Bosman et al. 2001).

Evidence presented by MacDonald et al. (2006) implies that localisation with BC stimulation is as good as localisation with AC. Subjects heard spatial information containing individualised head related transfer functions, not available to the BAHA users in the other three studies.

Subjects in the MacDonald study only had cross-talk to interfere with localisation capability, whereas the BAHA people had no access to head related transfer function cues and cross-talk.

As previously discussed, humans are sensitive to ITD when using low frequency stimulation and ILD when using high frequency stimulation. Rowan & Gray (2008) hypothesize that IPDs are converted to ILDs when using bilateral BC stimulation due to acoustic interference arising from cross-talk. Normal hearing subjects localised 3 and 6 kHz pure tones, as a function of IPD, presented via bilateral B71s placed on the mastoids. Five out of the seven subjects showed some ability to lateralise although humans are insensitive to IPD at the frequencies tested. It is suggested that the transcranial transmission seen with BC effectively convert external IPD to internal ILD. It is argued that inter-subject variation in transcranial transmission explains the lack of lateralisation ability seen in two subjects. The authors suggest that although external IPD within the fine structure of a high frequency pure tone is not accessible using AC, it seems that it may be with BC.

In summary, cross-talk would be expected to interfere with cues that enable a listener to take advantage of binaural hearing. However, localisation ability has been reported in subjects fitted with bilateral BAHA as well as with normal hearing subjects listening through BVs. Furthermore, binaural masking level difference experiments using bilateral BC stimulation provide further evidence that binaural processing occurs. It seems that both TA and TD can have a desirable influence on localisation ability, effectively reducing the detrimental effect of cross-talk. The following section explores the effect of cross talk by using a model that considers the effect of varying levels of TA and TD on localisation ability.

2.4 Modeling the effect of cross-talk on hearing via bone conduction

Listening via BC consists of a complex pattern of pathways that convey vibration energy from the skull surface to each cochlea. The picture is further complicated by the lack of interaural isolation due to sound readily crossing the skull and stimulating the contralateral as well as the ipsilateral cochlea. Modeling has been used to explore and predict the effect of crosstalk on binaural hearing ability, mostly notably Zurek (1986).
This section uses the Zurek model as a base to explore the influence of cross-talk on the amplitude, phase, ITD and ILD of bilateral BC compared to AC using sinusoidal stimuli.

Due to the complex nature of hearing by BC, this model is a simplified version of what is likely to be occurring in reality. Sound perception using BC stimulation at each cochlea is influenced by:

- Symmetry of the skull
- Transmission properties of an individual's skull (i.e. TA, TD, resonance characteristics)
- Symmetry of the transmission pathways through the skull
- Location of the sound source (external ILD and ITD)
- Location of the bone vibrator
- Frequency of the sound source
- Sensitivity of each cochlea
- Subjective perception

For this reason Zurek makes some assumptions:

- In the case of normal hearing, all BC conducted sounds are negligible in comparison to more dominant AC conducted sound.
- In the case of normal hearing, the cochleae are acoustically isolated
- Assuming symmetrical ipsilateral AC pathways, external ILD and ITD are preserved at the cochleae, creating equal intercochlear level and time differences.

- In the case of conductive loss, the ipsilateral AC pathway in partially blocked, and the BC pathway is unaffected.
- In the case of conductive loss, sensitivity to intercochlear phase and level differences is equal to normal subjects.

These assumptions can be based on the theory that when considering each cochlea separately following bilateral stimulation, vibrated energy arrives at each cochlea along only two pathways (i.e. direct and crossed), each associated with time delay and level difference. Assuming symmetry of skull transmission, cochlea sensitivity, TA and TD the effect of the combination of these two pathways will be expected to be equal in each cochlea.

The mechanism of hearing via BC is very complicated. The use of a model is a helpful way to explore and predict the influence of cross pathways on binaural hearing. It is useful to gradually build up the layers of what we know and attempt to predict what we are not sure about before testing our predictions via experimentation. However, modeling BC does have limitations due to the assumptions made. Perfect skull symmetry and cochlea sensitivity is unlikely and TA and TD may not be equal for right to left and left to right pathways for any given individual. We know that BC stimulation consists of a number of pathways with largely unknown effects on TA and TD. We also don't know whether sensitivity to intercochlear phase and level difference is equal in normal hearing and conductively impaired subjects. While the model is a useful way to help understand what research implies and make predictions for future research, the limitations must be considered.

Figure 2.8 shows that in normal hearing subjects, BC pathways (dashed lines) are not important due to the higher sensitivity of the brain to the AC pathways (solid lines). External ILD and ITD are maintained at the cochlea level due to interaural isolation. Cross-talk is not an issue as the BC pathways are effectively redundant.

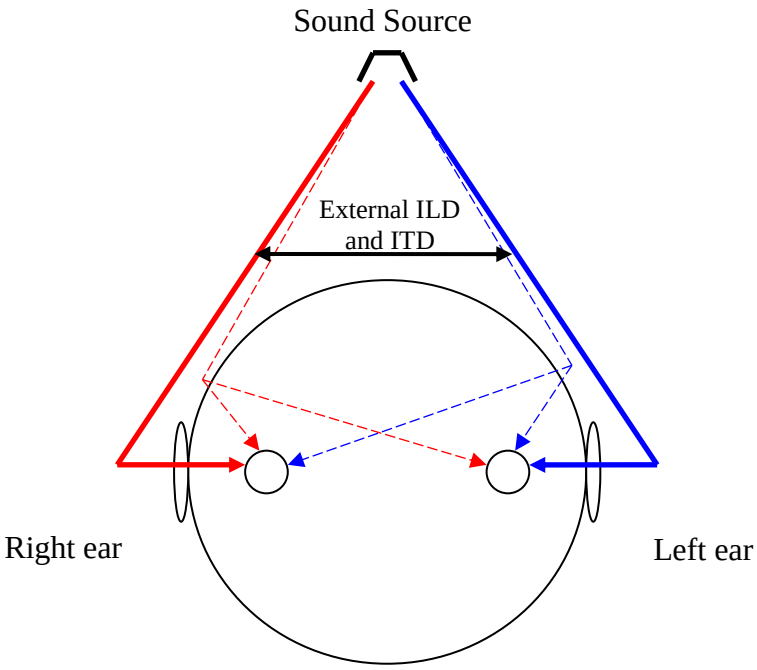


Figure 2.8 In the case of normal hearing, cross-talk has no effect on interaural differences due to sufficiently large interaural isolation. External interaural level difference (ILD) and interaural time difference (ITD) are preserved at the cochleae.

Figure 2.9 considers the case of listening via BC only, when the BC pathways become relatively more dominant and AC perception less dominant. Therefore, interaural isolation is expected to be reduced compared to normal hearing. As a result external ILD and ITD are degraded leading to reduction in the ability to benefit from binaural hearing. The ability to access cues for binaural hearing is assumed to depend on an individual's TA and TD.

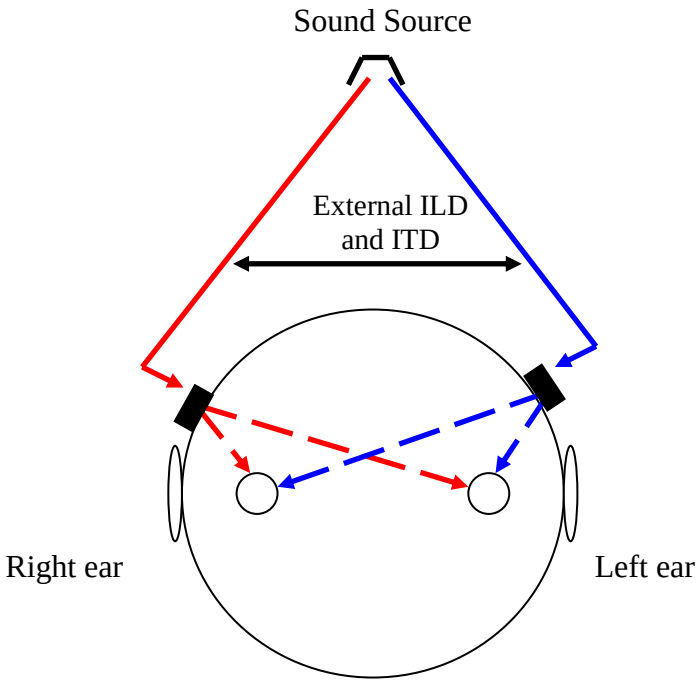


Figure 2.9 When listening via BC only, cross-talk is expected to at least reduce external interaural level difference (ILD) and interaural time difference (ITD) at the cochleae.

Individuals who often benefit from BC stimulation are those with a conductive hearing loss and Section 2.2.9 tells us that a conductive hearing loss is known to degrade binaural hearing ability (Häusler et al. 1983; Noble et al. 1994). Zurek suggests the hypothesis that this degradation is due to the abnormally high influence of BC relative to AC sound and is illustrated in Figure 2.10. In the case of a conductive loss, sound energy perceived via the AC pathways is attenuated due to the pathology, leaving the BC pathways to become more dominant than in normal hearing people. External ILD and ITD are likely to be at least degraded due to cross-talk. The resulting reduction in interaural isolation would be expected to lead to a decrease an individual's ability to access cues required for successful binaural hearing.

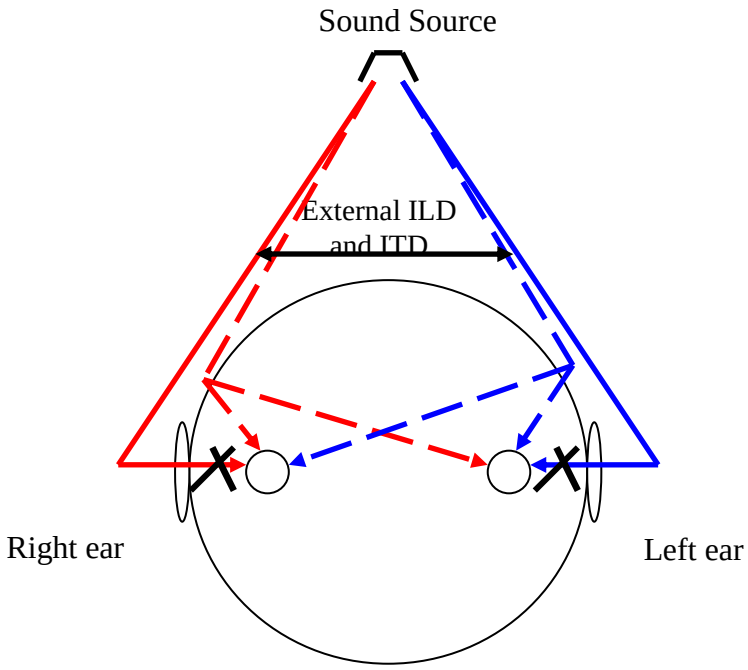


Figure 2.10 In the case of a conductive loss, the relative dominance of AC is lost, resulting in cross pathways degrading external interaural level difference (ILD) and interaural time difference (ITD).

While Zurek's model, offers an explanation of the effect of crosstalk on binaural hearing ability, the focus of this thesis is to consider the influence that an individual's TA and TD are likely have on how much interaural isolation is lost to crosstalk. The prediction of the effect of TA is relatively straight forward, but TD not so. An individual's TD is likely to not just have a delaying effect on the crossed pathway. The relative phase of the two signals on arrival is expected to have a reinforcing or cancelling effect on the sound level perceived in the cochlea. Of course similar would be expected to be happening in the second cochlea as well, making the understanding of the effect of TD somewhat difficult to untangle.

So far the combined sound from the direct and crossed pathways at each cochlea has been considered. However, binaural hearing relies on the comparison of sound at each at cochlea. Table 2.8 explores the effect that differing levels of TA and TD might be expected to have on binaural performance. A listener relying on hearing by bilateral BAHA is assumed, with negligible AC input.

Table 2.8 Predicted effect of varying levels of TA and TD on localisation ability

Condition	Effect of cross pathway	In cochlea/perception	Localisation ability
TA = 0 TD = 0	No energy lost No time delay	Contralateral cochlea stimulated with same stimulus as ipsilateral, for both ears. No interaural isolation	Expected to be poor as external ILD and ITD nullified due to crossed pathways.
TA = 0 TD = Large	No energy lost Large time delay	Cross signal arrives in contralateral ear with time delay, but no level reduction.	Ability depends on effect of time delay and effect of phase interaction of sounds. External ILD nullified External ITD maintained
TA = Large TD = 0	All energy lost No time delay	No cross-talk perceived in contralateral cochlea Interaural isolation maintained	Similar to AC as no contralateral perception due to large TA. TD has no influence.
TA = Large TD = Large	All energy lost Large time delay	No cross-talk perceived in contralateral cochlea Interaural isolation maintained	Similar to AC as no contralateral perception due to large TA. TD has no influence.
TA = 0 TD = Medium	No energy lost Some time delay	Arrives at contra at same level as ipsi but with some delay. Some interaural isolation	Ability depends on effect of delay and phase interaction.
TA = Medium TD = 0	Some energy lost No time delay	Arrives at contra with no delay but reduced level. Level difference only. Some interaural isolation	Depends on effect of level difference
TA = Medium TD = Medium	Some energy lost Some time delay	Arrives at contra with reduced level and time delay Some interaural isolation	Depends on effect of level difference and effect of time delay and phase interaction.

2.5 Experimental aims and contribution to knowledge

Since the introduction of the BAHA approximately 35 years ago, most recipients have been fitted unilaterally. The rationale being that sound will be perceived in both cochleae following stimulation at a single site on the skull. Interaural isolation needs to be present for a listener to enjoy the benefits of binaural hearing, which is reduced when listening via BC compared to AC. However, interaural isolation afforded the listener via AC is more than enough, and at least some subjects may have sufficiently large TA and TD when listening via BC to facilitate at least some ability to access cues for successful localisation. A small body of literature suggests that some people may be able to use cues associated with binaural hearing, but little is known about the specific cues being accessed. MacDonald (2006) summarises by saying "Although the vibrations from the transducers are likely to interfere with one another, the TA and TD may be sufficient to allow the listener to segregate the overlapping auditory inputs into separate percepts". Dutt et al. (2002) is in agreement suggesting that "Bilateral amplification may be successful in restoring binaural hearing depending on the hearing configuration and the integrity of the peripheral auditory system".

Much research has been carried out to investigate human's localisation ability using AC, whereas research using BC is sparse. Whilst there is evidence that lateralisation ability is possible with BC, no studies present any details regarding TA or TD of the subjects used. Furthermore, reported TA and TD generally lack agreement in the present published literature.

The main aims of this research are to fill gaps in knowledge by answering the following questions:

1. By how much does TA vary between subjects?
2. By how much does TD vary between subjects?
3. Are normal hearing subjects able to access binaural cues when listening via BC?
4. Does an individual's TA and TD influence their lateralisation ability?

Transcranial attenuation, transcranial delay and lateralisation ability using BC have all been estimated before. However, no study has attempted to measure all three on each participant. An

investigation looking at the effect that TA and TD have on the ability to access ILD and ITD cues, will contribute to our knowledge of binaural hearing using BC stimulation.

2.6 Application of this research

This study contributes to research, by measuring three parameters which may lead to further understanding of potential benefit of bilateral BAHA fitting. This information would be useful to clinical BAHA specialists/ear nose and throat surgeons and parties considering cost/benefit of routine bilateral fitting.

The BV presently in clinical use is limited in terms of frequency and level at which it gives reliable indications of a subject's BC hearing thresholds. If the BEST is shown to be capable of being driven at higher levels than the B71 before the output becomes distorted, vibration is felt against the skin and audible sound is emitted from the casing, the possibly of them superseding the B71 in clinical settings may be considered. A collaborative experiment was carried out which compared the behaviour of the BEST to the B71. Low frequency distortion and the sensation of vibration was investigated by a colleague (Al Omari, 2014). The tendency of BVs to produce audible sound at high frequencies, made up part of the research reported in this thesis. Chapter 3 describes Experiment 1 which investigated whether the BEST produces less audible sound compared to the B71. The aim was to enable an informed choice to be made as to which would be least susceptible to limitations and therefore create least problems when considering the experimental design of Experiments 2 and 3.

Chapter 3

Experiment 1: Justification of the choice of bone vibrator

3.1 Introduction

Bone vibrators are known to have limitations at low (see section 3.2.1) and high (see section 3.2.2) frequencies which may create problems with experimental design or contribute to measurement error. Two models of BV were available for use, namely the well-known B71 and the more recently designed Balanced Electromagnetic Separation Transducer (BEST). The designer of the BEST claims lower total harmonic distortion and greater sensitivity at low frequencies compared to the B71 (Håkansson 2003). At 3 kHz and above, the casing if the B71 produces audible sound, hereafter referred to as air-borne radiation (ABRad), which has been shown to falsely improve BC HTLs, due to the listener being able to perceive AC via sound waves as well as BC via vibration energy (Lightfoot 1979). Bone vibrators with a large mass produce higher amounts of ABRad than those with a smaller mass (Lightfoot 1979; Shipton et al. 1980; Bell et al. 1980). The BEST is housed in a smaller case that the B71 which leads to the question:

Does the BEST produce less ABRad than the B71?

This is an important consideration as ABRad could be problematic during Experiments 2 and 3, if it occurs at the frequencies tested, by stimulating the test ear via AC when the test stimuli is to be via BC only.

3.2 Bone vibrators

Until recently, three BVs have been developed for clinical purposes, namely the B70A, B71 and the B72. These BVs all have known limitations in terms of frequency and maximum loudness at which they give reliable indications of an individual's BC HTL. Although all have a cuboidal body and flat circular contact area of 175 mm^2, as required for clinical use (BS EN ISO 389 – 3:1999) they differ in size, weight and frequency response. Recent progress in the

design of BVs has led to the development of the BEST, which has a similar shaped case compared to the B71, but is smaller, as illustrated in figure 3.1.

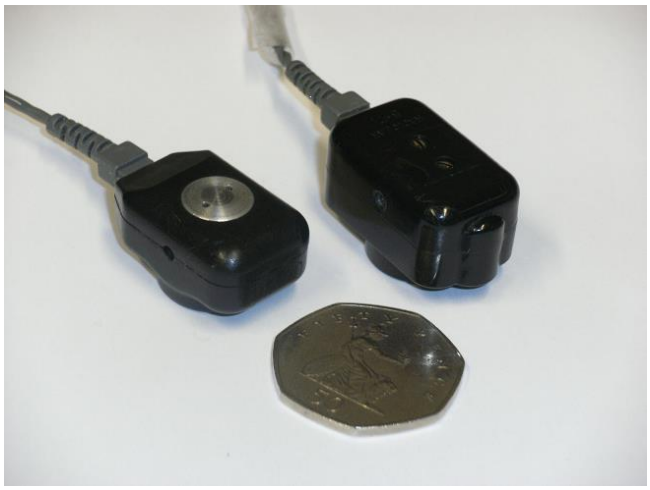


Figure 3.1 Comparison of the size and shape of the cases of the BEST (left) and B71 (right) showed next to a 50p piece.

The BEST was designed principally to improve BV performance at low frequencies. Since the introduction of the BEST, a low-frequency reinforced version has been developed, which is capable of greater sensitivity at low frequencies compared to the original version (Håkansson 2003; AlOmari 2014). The low frequency reinforced version is housed in the same case as the original so is not expected to differ in terms of amount of ABRad produced. The original BEST will hereafter be referred to as the $BEST^{ORIG}$ and the low frequency reinforced as the $BEST^{LFR}$. The following sections explore the low and high frequency behaviour of BVs.

3.2.1 Low frequency limitations of bone vibrators

The B71 tends to produce sufficient total harmonic distortion to limit its usefulness at frequencies below 0.5 kHz (Lightfoot 2000). The B72 was developed to address this problem, by increasing its mass and therefore lowering the resonant frequency. This seems to have been achieved as the B72 has been shown to be capable of producing 60 dB HL at 0.25 kHz while the B71 and B70A are capable of only 25 dB HL before the onset of gross distortion (Lightfoot 2000). However, the larger case of the B72 has proved difficult to place on the mastoid and the

B71 has remained preferable for clinical use. The BEST was been developed in another attempt to address the problem of low frequency distortion and the designers propose significant improvement in total harmonic distortion when comparing a prototype of the BEST with the B71 (Håkansson, 2003). Håkansson demonstrated lower total harmonic distortion with the BEST (3.3%) compared to the B71 (61%) at 40 dB HL when using 250 Hz. This suggests the ability to measure reliable BC thresholds at frequencies as low as 250 Hz and at hearing levels not previously accessible. While these results are encouraging, they are reported by the designer of the BEST. However, an independent comparison revealed similar findings (AlOmari et al. 2010; AlOmari 2014). Acoustic measurements of total harmonic distortion were performed using three BESTs and three B71s and revealed a stark difference in total harmonic distortion of 4% for BESTs compared to 30% for B71s at 250 Hz and 40 dB HL, as reported by Håkansson.

Bone vibrators are also known to become vibrotactile (i.e. sensations felt against the skin, rather than just being heard) at output levels as low as 25 dB HL at frequencies below 500 Hz (Boothroyd and Cawkwell 1970). Boothroyd and Cawkwell reported the B71 to become vibrotactile above 25 dB HL output at 250 Hz, 55 dB at 500 Hz and 70 dB at 1 kHz. A study comparing three examples of B71 and three examples of BEST and using 20 normally hearing subjects revealed similar vibrotactile thresholds at 250 Hz of approximately 35 dB (AlOmari 2014).

3.2.2 High frequency limitations of bone vibrators

Bone vibrators have a tendency to produce ABRad when driven at frequencies above 2 kHz (Lightfoot 1979; Shipton et al. 1980; Bell et al. 1980). The B70A, B71 and B72 are manufactured with the vibratory parts attached to the back of the inside of the casing. When used at frequencies above 2 kHz, the whole casing vibrates, making the BV liable to produce audible levels of ABRad. If ABRad is able to enter the external ear canal, it could reach the cochlea via the normal AC pathway. The listener then perceives sound via the AC route of hearing as well as vibration through the skull, potentially resulting in falsely improved BC thresholds when using normally hearing subjects.

Several methods have been used to investigate the importance of ABRad with BC thresholds. In one method, ABRad is measured with the BV mounted on an artificial mastoid. This is a useful way to compare ABRad emitted from different models of BV, allowing differences in output characteristics of BVs to be assessed. The relationship between ABRad and stimulus level is approximately linear, at least for outputs of between 0 and 50 dB HL at frequencies between 0.5 and 4 kHz (Bell et al. 1980; Shipton et al. 1980). Furthermore, the B71 produces approximately 9 dB more ABRad at 4 kHz from the large surface parallel to the head, compared to the smaller end surface (Shipton et al. 1980), due to the difference in surface area. While measuring ABRad is easy and useful using an artificial mastoid, head and pinna effects are not taken into account, making it inappropriate to draw conclusions of the effect of ABRad on humans.

A number of methods use human subjects to investigate ABRad:

1. Measuring sound pressure level at the entrance to the ear canal
This method places a microphone at the entrance to the ear canal and measures sound pressure while the BV is driven on the skull. This method measures sound pressure level that is influenced by the subject's head related transfer function from the site of the BV to the microphone (Lightfoot 1979; Shipton et al. 1980).

2. Measuring sound pressure level in the ear canal.
A probe microphone is placed near the tympanic membrane and ECSPL is measured. Sound pressure measured in this way includes ABRad emitted by the BV that is altered by the subject's head related transfer function as in the first method as well as the acoustical characteristics of the subject's ear canal. Furthermore, sound arriving in the ear canal via vibrations of the walls of the canal contributes to the ECSPL measured.

3. Comparing occluded and unoccluded BC hearing threshold level.
This method compares BC HTL measured with the ear canal unoccluded and occluded. If ABRad did not have an influence, unoccluded and occluded BC HTL would be similar. However, if BC thresholds are being affected by ABRad, the unoccluded HTL would be

expected to be lower than the occluded HTL, the difference being an indication of ABRad. Whilst ABRad is the likely cause of enhanced BC HTL at or above 2 kHz, at frequencies of 1 kHz and below, enhanced BC HTL can be due to the occlusion effect. The occlusion effect occurs when sound created by vibrations of the walls of the ear canal is unable to escape from the ear canal and reaches the tympanic membrane and is perceived via the AC route of hearing. However, the occlusion effect occurs at frequencies up to approximately 1 kHz (Berger & Kerivan 1983) while ABRad occurs at frequencies above 2 kHz (Lightfoot 1979; Shipton et al. 1980; Bell et al. 1980). Bell et al. (1980) concludes that the occlusion effect created by plugging the ear is not significant at the frequencies when ABRad is expected to occur when using the B71.

The artificial mastoid method has been used to measure ABRad using examples of B70A, B71 and B72 (Bell et al. 1980; Shipton et al. 1980). While Bell used one example of each BV, Shipton used three, enabling a mean value to be calculated. Also, Shipton repeated each measurement five times removing and replacing each BV between each measurement, while Bell does not indicate repeat measurements were made. Air-borne radiation was shown to be higher than vibration output at 4 kHz for all three models of BV with the B72 emitting 25 dB above BC output (Bell et al. 1980). In order to make a comparison between ABRad and vibrator output, dB SPL was converted to dB HL using the binaural minimum audible field values and binaural/monaural difference values as described by Lightfoot (1979). Shipton also report ABRad to be higher than vibration output at 4 kHz for the B72 and B71, although they report the B70A to not produce sufficient ABRad to falsely improve BC thresholds. Again the B72 emitted the highest ABRad. The Shipton study used dB SPL to measure ABRad then estimated the equivalent dB HL and made an adjustment for the difference in distance from sound source to measurement point. Using the artificial mastoid, the distance was 190 mm and for human subjects, the distance from mastoid to entrance to the ear canal was 45 mm. However, no adjustment was made for the disturbance of the sound field due to body, head or pinna effects.

Lightfoot (1979) measured ABRad at the entrance to the external auditory meatus, using just one subject and one example of B70A, B71 and B72. A microphone was placed in the concha,

approximately 30 mm from the BV (placed on the mastoid) and moved until the position of maximum output was found. Audiometric frequencies from 0.25 to 4 kHz where used. Air-borne radiation measured in dB SPL was compared to vibrator output, measured in dB HL, by converting dB SPL to dB HL using the minimum audible field and data on the binaural/monaural difference as presented by Shaw et al. 1947. Results indicate the amount of ABRad from the B71 and B72 to be sufficient to potentially create false air-bone gaps at 3 and 4 kHz and the B70A at 4 kHz, as shown in Table 3.1.

Table 3.1 Acoustic output from BVs measured at the concha in terms of dB HL (derived) as reported by Lightfoot (1979).

	3 kHz	4kHz
B70A	-15 dB HL	4 dB HL
B71	2 dB HL	6 dB HL
B72	7 dB HL	24 dB HL

Shipton et al. (1980) strapped a microphone to the cheek of four subjects positioning it so the protective grid sat at the anti-tragus. Five repeat measurements were made removing and refitting the BV on the mastoid between each measurement. Shipton et al. also converted measured dB SPL to dB HL including a correction for diffraction effects and report ABRad as shown in Table 3.2.

Table 3.2 Acoustic output from BVs measured at the concha in terms of dB HL (derived) as reported by Shipton (1980).

	3 kHz	4kHz
B70A	-2 dB HL	3 dB HL
B71	1 dB HL	6 dB HL
B72	9 dB HL	12 dB HL

Differences in ABRad reported by Shipton and Lightfoot can be explained by the use of different correction factors for the adjustment from binaural to monaural threshold. Also Lightfoot did not correct for diffraction. Also of note is that Shipton used warble tones to

minimise acoustical problems associated with pure tones when measured in a free field. However, despite these differences, Shipton et al. and Lightfoot report a similar finding that the B70A is least likely to create problematic ABRad and the B72 is most likely to at 3 and 4 kHz.

Air-borne radiation has also been measured by placing a probe microphone into the ear canal. Fagelson & Martin (1994) used 16 subjects and one example of B71 to investigate ECSPL at 0.5, 1, 2 and 4 kHz. Harkrider & Martin (1998) used 50 subjects, one B71 and 2 and 4 kHz. Fagelson & Martin inserted the probe tube as far as the osseocartilaginous junction, while Harkrider & Martin inserted an ear plug to a depth where the lateral surface of the ear plug was at the osseocartilaginous junction. This was done to reduce sound pressure in the ear canal produced by vibrations of the ear canal walls. The end of the probe tube was placed close to the ear plug. Fagelson & Martin report significantly higher ECSPL with mastoid compared to forehead stimulation at 2 and 4 kHz as shown in Table 3.3. The BV was placed on the right mastoid and ECSPL measured in the right ear canal.

Table 3.3 Mean ECSPL reported by Fagelson and Martin (1994)

	Mastoid	Forehead
2 kHz	70.14 dB SPL	55.51 dB SPL
4 kHz	72.33 dB SPL	59.98 dB SPL

They conclude that ABRad would be less problematic if BC audiometry was carried out using forehead placement rather than mastoid. Harkrider & Martin conclude that that a clinically significant (> 10 dB) false air-bone gap, is likely at 4 kHz and agree with Fagelson & Martin in suggesting the use of forehead placement to prevent this.

Human subjects have been used to compare ABRad by comparing BC HTL with the ear canal unoccluded and occluded. The B72 has been shown to produce the highest ABRad and the B70A the lowest at 4 kHz (Bell et al. 1980; Frank & Holmes 1981). Both studies used 10 subjects and reveal a difference of 12 dB using the B72, 3 dB for the B71 and no change for the B70A (Bell et al. 1980) and 7 dB using the B72, 1 dB for the B71 and B70A (Frank & Holmes 1981).

Experiment 1 measured ABRad using an artificial mastoid and ECSPL using human subjects. Measurements made using the artificial mastoid served as an objective comparison of sound emitted by the B71 and BEST. Human subjects were also used to compare the behaviour of the two models of BV, using forehead and mastoid placement. The method of ECSPL was chosen as being most clinically representative of the effect of ABRad because directivity of ABRad, diffraction effects of the body and head and acoustical shadows caused by the pinnae are considered.

The measurement of ABRad was carried out as part of a comparison study investigating behavioural differences of the B71 and the BEST. Initially, it was unclear which frequencies would be included in Experiments 2 and 3, but ABRad is known to have the potential to falsely improve BC HTL at frequencies at or above 3 kHz using the B71. Experiments 2 and 3 rely on the accurate measurement of BC HTL, making it important to be aware of the likelihood of ABRad falsely improving BC HTL. The expectation was that the BEST would not produce more ABRad than the B71, due to the smaller mass of the BEST (Lightfoot, 1979), potentially less. The decision as to which model of BV to use during Experiments 2 and 3 was based on previous literature (Håkansson, 2003, Al Omari 2014) and the result of Experiment 1. Experiment 1 investigated ABRad and is presented in this chapter.

3.3 Experiment 1a

3.3.1 Experimental aim

This experiment set out to test the hypothesis that the BEST produces less ABRad than the B71. The motivation was to ascertain which BV is least liable to cause experimental design problems and create measurement error, when used for Experiments 2 and 3. At 3 and 4 kHz the B71 has the potential to produce enough ABRad to falsely improve BC HTL. Even if the BEST is found to produce less ABRad than the B71 it could still be enough to have a detrimental effect in Experiments 2 and 3. The large case characteristic of the B72 has been found to emit higher levels of ABRad compared to the B70A and B71 (Shipton et al. 1980; Bell et al. 1980). Therefore, it is proposed that the smaller casing of the BEST compared to the B71,

and resultant reduction in mass, may result in a reduction of ABRad when compared to the B71.

Experiment 1 employed two methods. Firstly ABRad was measured with each BV placed on an artificial mastoid. This method served as an objective way to compare ABRad emitted from each BV. Secondly, ECSPL was measured in normally hearing subjects, thus taking the effects of the head and pinna into consideration.

3.3.2 Method 1: ABRad measured using an artificial mastoid

An artificial mastoid (Brüel & Kjaer type 4930) was set up in a sound treated room. A sound level meter (Brüel & Kjaer 2260 investigator) was mounted on a tripod and placed with the microphone 76 mm from the side of each BV with the BV placed on the artificial mastoid. This distance was chosen to enable comparison with measurements using humans as it approximates the combined distance from BV, when placed on the mastoid, to tragus of 45 mm (Shipton et al. 1980; Bell et al. 1980) and tragus to tympanic membrane of 31 mm (Gelfand 2004). Three examples of B71 were chosen at random from the stock at ISVR and the three available examples of BEST were used. 'BEST-1' is a different model to BEST-2 and 3. BEST-1 (i.e. $BEST^{ORIG}$) is the original model, while BEST-2 and 3 are "low frequency reinforced" models ($BEST^{LFR}$). Higher output levels can be reached without the output becoming distorted using the $BEST^{LFR}$ compared to the $BEST^{ORIG}$ (AlOmari 2014). Each BV was placed on the artificial mastoid in turn and driven at 1, 2, 3 and 4 kHz with an output of 60 dB HL. These parameters were used as previous studies have shown ABRad to be maximal at frequencies above 2 kHz and most easily measured at relatively high output levels (Lightfoot 1979; Shipton et al. 1980). Air-borne radiation was measured six times using each BV, three from each side, moving and replacing it between every measurement. ABRad was measured from the long side of the BV as this face is nearest the opening of the ear canal, so minimising differences when comparing ABRad results using the artificial mastoid and human subjects. Air-borne radiation was measured at the right and left sides, because each BV was to be placed on the right and left mastoid, thus placing a different side of the BV to the right and left ear. This procedure was repeated for each frequency and the experiment repeated on three different days: two days in a row, then again after one month.

Calibration was carried out according to BS EN ISO 389-3:1999. Whilst recording ABRad as described, a second sound level meter (Brüel & Kjaer type 2231) was connected to the artificial mastoid enabling constant monitoring to ensure a consistent output of the BV. Sound pressure level was variable by approximately ± 1 dB, which was found to be due to different placements of the BV on the artificial mastoid. In the case of a discrepancy greater than ± 1 dB, the BV was repositioned on the artificial mastoid until a consistent sound pressure level was achieved.

3.3.3 Results: ABRad using an artificial mastoid

Air-borne radiation was measured using three B71s and three BESTs. In turn, each BV was placed on an artificial mastoid and driven at 1, 2, 3 and 4 kHz with an output of 60 dB HL. Air-borne radiation emitted from the right long side and the left long side of the BV was measured three times using each BV on three different days. Figure 3.2 compares mean sound pressure level measured from the right and left side of each BV (i.e. mean calculated from a total of nine measurements) at each frequency.

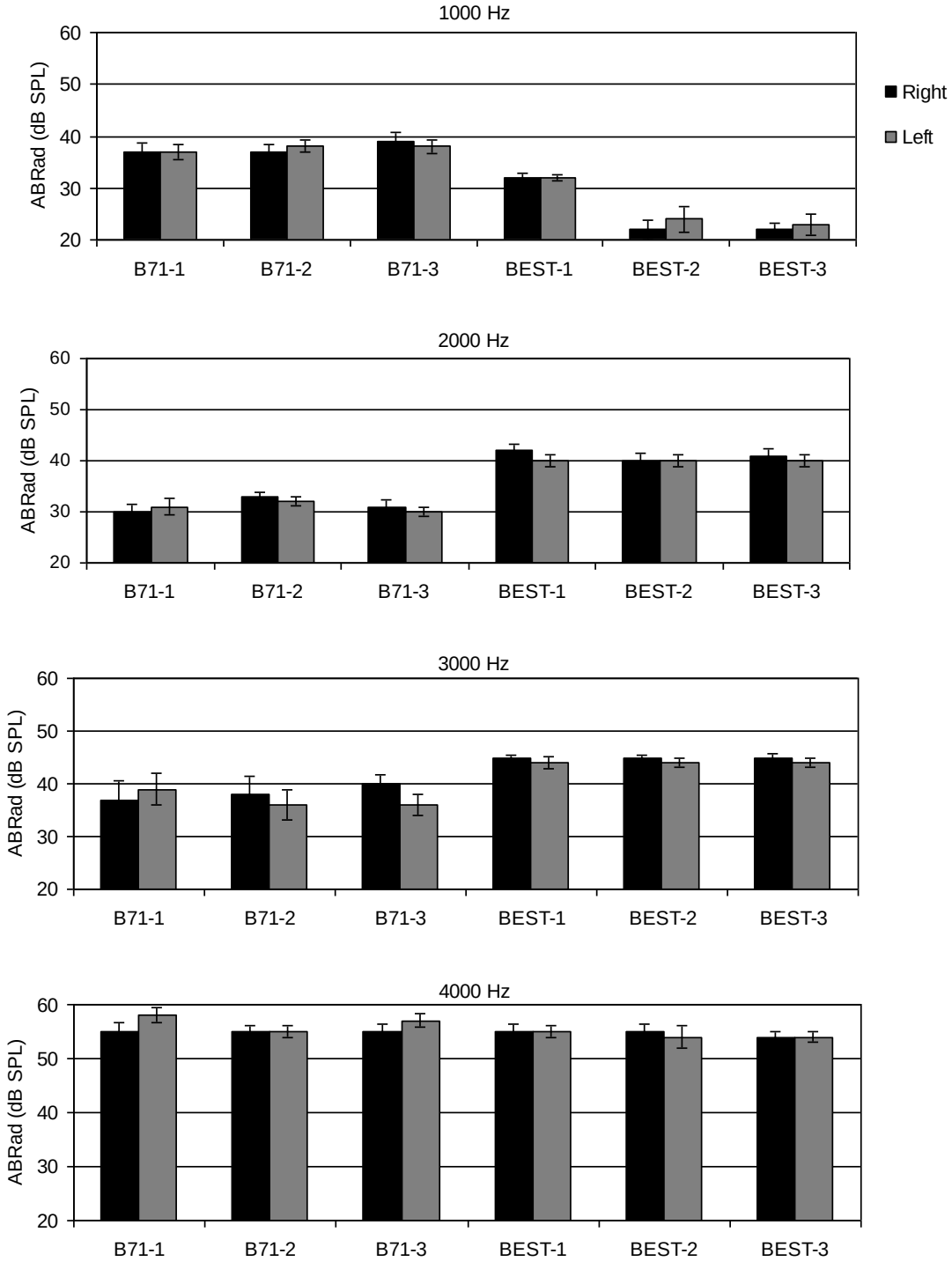


Figure 3.2 Mean air-borne radiation emitted from right (black) and left (grey) long side, using three B71 and BEST for each frequency. (Error bars represent ±1 SD).

Figure 3.2 reveals a similar amount of ABRad emitted from the right and left side of each BV for all frequencies tested. Overall mean difference between ABRad emitted from the right and left side for all frequencies was 1 dB with an overall mean standard deviation (SD) of 1 dB. The largest difference between right and left was 4 dB, occurring for the B71-3 using 3 kHz. Standard deviation was low, indicating a low level of measurement error. This was expected as the equipment set up was unchanged within each session and care was taken to ensure consistency between sessions (i.e. the sound level meter as placed on a tripod and the distance from microphone to BV carefully measured). Furthermore, each BV was carefully placed centrally on the artificial mastoid and positioned as similarly to the others as possible.

Shapiro-Wilk tests of normality indicated no gross deviation from normality, so paired sample *t*-tests were used to explore the differences between ABRad emitted from right and left sides. A Bonferroni correction was applied to each analysis to reflect the use of 6 *t*-tests (0.05/6 = 0.008). Statistical significance was reached in four cases, as shown in Table 3.4.

Table 3.4 Details significant *t*-test results for mean difference in sound emitted from the right and left sides as depicted in Figure 3.2.

Frequency	Bone vibrator	*T*	*df*	Two-tailed *p*
2	BEST-1	3.538	8	0.008
3	B71-3	4.637	8	0.002
3	BEST-2	3.702	8	0.006
4	B71-1	-8.824	8	< 0.001

A result of statistical significance was not expected in this case and is difficult to explain. All four instances occur using a different BV at different frequencies and the BEST and B71 are equally represented. As one BV is not consistently producing differing amounts of sound from each side, it seems reasonable to assume random error.

Air-borne radiation emitted by each example of B71 and BEST from the right and left side was pooled and the mean determined for each BV (i.e. 18 measurements). This information is

shown in Figure 3.3, where an upward trend with increasing frequency can clearly be seen for the B71s and the BESTs. Interestingly a higher level of ABRad was measured at 1 kHz than was expected, most prominently with the B71s and BEST-1.

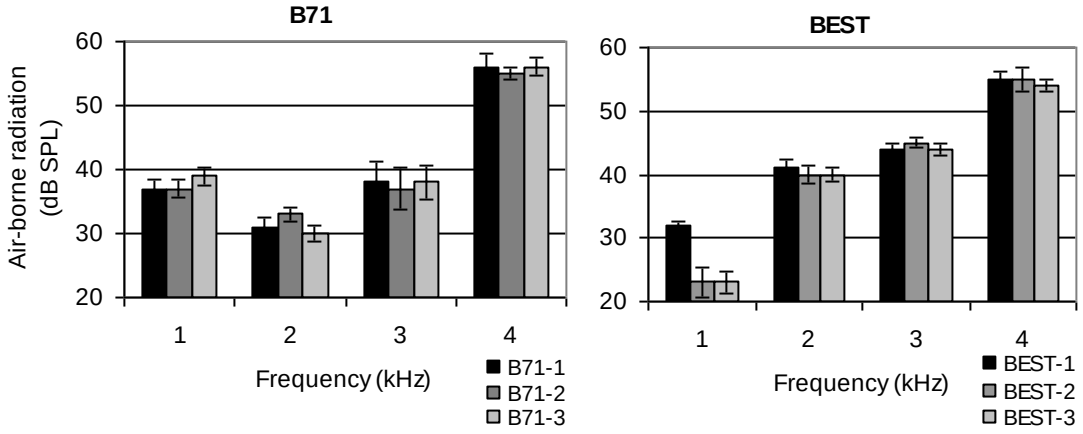


Figure 3.3 Mean air-borne radiation measured using B71 and BEST mounted on an artificial mastoid. (Error bars represent ±1 SD)

The difference between examples of each BV at each frequency is greater than 2 to 3 dB at 1 kHz only for the BEST. A probable explanation for this is that the BEST-1 is the original model and BEST-2 and 3 are "low frequency reinforced". The behaviour of BEST-1 is more comparable to that of the B71s, than the other 2 BESTs, implying that it does behave differently at low frequencies compared to the low frequency reinforced BESTs. Standard deviation is shown in Figure 3.3 as an indication of measurement error. Overall mean SD for the B71, across all frequencies is 2 dB compared to 1 dB for the BEST, implying the output of the B71s is more variable than the BEST.

Eight one way independent Analysis of Variances (ANOVA) were used to statistically analyse ABRad emitted by the B71s and BESTs (i.e. one ANOVA for each frequency for both BVs). The test of homogeneity of variances was significant for the BEST at 1 kHz (p = .003) and 4 kHz (p = .015) and for B71 at 4 kHz (p = .031). The strongest significance was seen at 1 kHz which would be expected due to the higher level of ABRad emitted by BEST-1 compared to BEST-2 and 3. In order to control the familywise error, a Bonferroni correction was applied to

the level of significance for each test. To ensure the cumulative Type 1 error remained below a significance level of 0.05, a significance criterion of 0.016 was used (i.e. 0.05/3 comparisons).

Using B71, a one-way ANOVA showed an overall significant difference in ABRad at 1 kHz ($F_{2,51} = 5.06$, $p = 0.010$), 2 kHz ($F_{2,51} = 21.60$, $p = < 0.001$) and 4 kHz ($F_{2,51} = 4.66$, $p = 0.014$) and using the BEST at 1 kHz ($F_{2,51} = 174.04$, $p = < 0.001$). Difference in ABRad between BVs did not reach statistical significance at 3 kHz using the B71 ($F_{2,51} = 0.290$, $p = 0.750$) and the BEST at 2 kHz ($F_{2,51} = 2.10$, $p = 0.133$), 3 kHz ($F_{2,51} = 0.42$, $p = 0.656$) and 4 kHz ($F_{2,51} = 4.08$, $p = 0.023$). Pairwise comparison *post hoc* tests, appropriate for homogeneity of variance were used. When variances were equal, Tukey HSD was used and when unequal Games-Howell was used and is shown in Table 3.5.

Table 3.5 Summary of post hoc results for bone vibrator pairings that show statistical significance.

1 kHz		*P*	Post hoc test used
B71-1	B71-3	0.012	Tukey HSD
BEST-1	BEST-2	< 0.001	Games-Howell
BEST-1	BEST-3	< 0.001	Games-Howell
2 kHz			
B71-1	B71-2	< 0.001	Tukey HSD
B71-2	B71-3	< 0.001	Tukey HSD
4 kHz			
B71-2	B71-3	0.011	Games-Howell
BEST-2	BEST-3	0.005	Games-Howell

Although the difference in ABRad reaches statistical significance for the above BV pairings, statistical significance shown at most frequencies can be attributed to the small standard error of the means, characteristic of this data. The greatest difference was at 1 kHz using the BESTs, most probably due to BEST-1 showing different behaviour to BEST-2 and 3. Although other statistical significance was found, in reality the difference in ABRad is not likely to be detrimental during Experiments 2 and 3.

Figure 3.3 compared three examples of each model of BV at each frequency tested. The overall mean for the three examples of B71 and BEST are compared at each frequency in Figure 3.4. Again a clear upward trend in ABRad with increasing frequency can be seen.

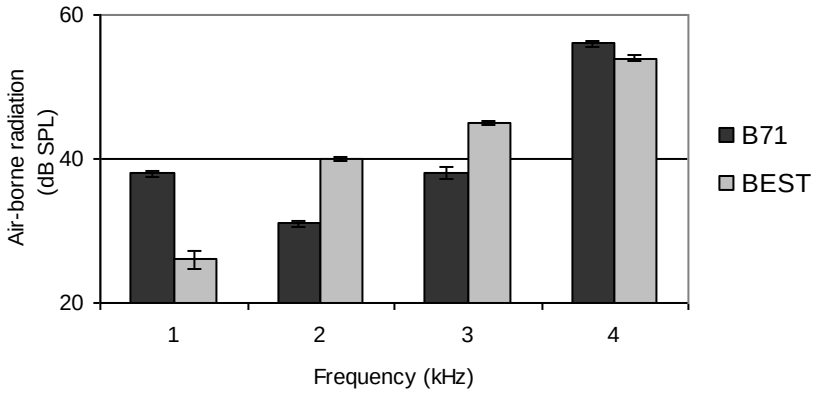


Figure 3.4 Mean air-borne radiation comparing bone vibrators at each frequency. (Error bars represent 95% confidence interval)

Variation in ABRad is represented by confidence intervals in Figure 3.4. Confidence intervals indicate the range of values within which the population mean falls. The small confidence intervals shown at each frequency implies that the sample means are close to the mean of the population of B71 and BEST. The largest confidence interval is associated with the BEST at 1 kHz, which can be explained by referring back to Figure 3.3. BEST-1, the original model, produced significantly higher ABRad than the low frequency reinforced models (BEST-2 and 3) at 1 kHz. Therefore the mean value shown in Figure 3.4 for BEST at 1 kHz contains higher differences in ABRad than the means at other frequencies, resulting in larger confidence intervals. Furthermore, confidence intervals indicate a significant difference in ABRad produced by the BVs at each frequency.

Figure 3.4 shows the BEST produces more ABRad than the B71s at 2 and 3 kHz, and less at 1 and 4 kHz. Unrelated *t*-tests were used to explore the significance of these relationships. Levene's test for equality of variance tells us that the variances are equal at 2, 3 and 4 kHz, but not at 1 kHz. Therefore, significance appropriate to equal variances not assumed was used at 1

kHz. A Bonferroni correction was applied to reflect the use of four *t*-tests, meaning a significance criterion of 0.0125 (0.05/4 = 0.0125). Table 3.6 shows statistical significant

Table 3.6 Summary of statistical significance of mean ABRad emitted by B71 and BEST at each frequency tested.

Frequency	**BV**	**Mean dB SPL**	**SD dB**	***t***	***df***	**Two-tailed *p***
1 kHz	B71	38	1..53	3.80	4	<0.001 *
	BEST	26	4.74			
2 kHz	B71	31	1.76	-9.55	4	<0.001 *
	BEST	40	1.37			
3 kHz	B71	38	3.09	-14.14	4	<0.001 *
	BEST	45	0.86			
4 kHz	B71	56	1.65	2.12	4	<0.001 *
	BEST	54	1.45			

3.3.4 Discussion: ABRad measured using an artificial mastoid

Air-borne radiation was measured with the BVs mounted on an artificial mastoid, a method previously used by Shipton et al. (1980). Shipton used a stimulus of 40 dB and distance of 190 mm, whereas the current study used a stimulus of 60 dB and distance of 76 mm. To facilitate comparison, ABRad reported by Shipton has been adjusted as shown in Table 3.7.

Table 3.7 Adjustment of air-borne radiation reported by Shipton et al. 1980 to facilitate comparison with the current study.

Shipton et al. 1980	B71			
Frequency (kHz)	1	2	3	4
Output 40 dB HL at 190 mm	19	18	27	30
Linear so increase by 20 dB	39	38	47	50
Add 6 dB as approx. ½ distance	45	44	53	56
Adjusted air-borne radiation (output of 60 dB HL at 76 mm)	45	44	53	56

Airborne radiation has been shown to be linearly related to stimulus level (Bell et al. 1980; Shipton et al. 1980). Bell et al. studied the relationship between ABRad and stimulus level using the B71 placed on an artificial mastoid using output levels ranging from 45 to 75 dB HL at 1 kHz and 25 to 85 dB HL at 4 kHz. Airborne radiation was found to be linearly related over these ranges and at these frequencies. Linearity is also demonstrated by Shipton et al. who used one B71 and a range of input levels of 0 to 50 dB HL at frequencies between 0.25 and 4 kHz. At 0 dB HL, deviations from linearity of 1 dB were seen, while at higher levels linearity deviations were less than 0.2 dB. An increase of 6 dB was imposed due to the distance of measurement being approximately half, resulting in a twofold change in sound pressure (Speaks 1992).

Although approximate, cautious comparison of the data is interesting. Mean ABRad measured using B71 and BEST shows an upward trend from 2 to 4 kHz, which is in agreement with data presented by Shipton et al. (1980), who used B71 and is shown in Figure 3.5.

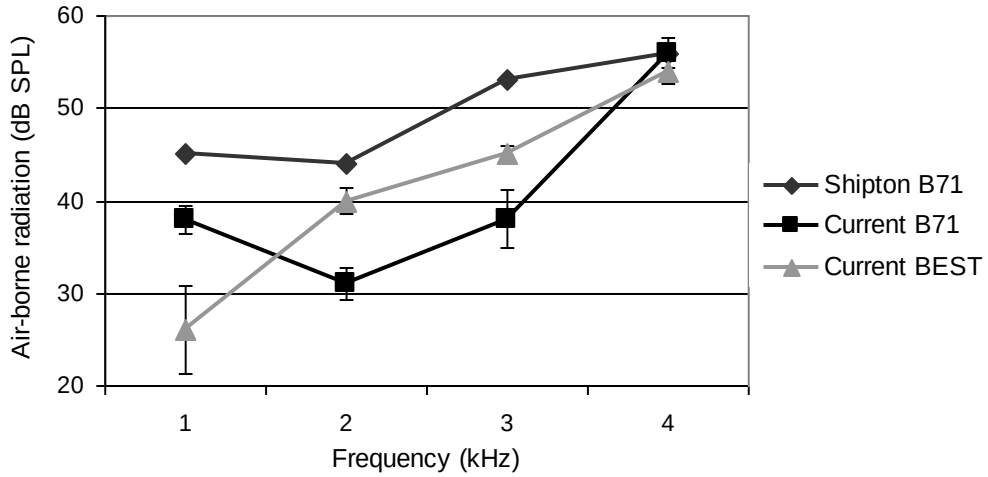


Figure 3.5 Comparison of mean air-borne radiation (ABRad) measured using an artificial mastoid in the current study and Shipton et al. (1980). Current ABRad using both BVs has been adjusted for ease of comparison as explained in Table 3.3. (Error bars represent ± 1 SD. SD for the Shipton study was not available).

Air-borne radiation is shown to be higher at 1 kHz than at 2 kHz for the B71 both in the current study and Shipton. Shipton reports higher ABRad at 250 Hz and 500 Hz compared to 1 and 2 kHz. This may be explained by audible harmonics contributing to ABRad at frequencies higher than the fundamental, which is characteristic of the B71 (Håkansson 2003). The BEST, especially the BEST^{LFR}, have been shown to produce less total harmonic distortion than the B71 (Håkansson 2003: AlOmari 2014). This is clearly illustrated by the relatively low level of ABRad emitted by the BEST compared to the B71 at 1 kHz, shown in Figure 3.5 and previously in Figure 3.4.

Differences in ABRad between studies are seen at all frequencies except at 4 kHz. A difference of up to 15 dB SPL is seen between B71 used in the Shipton and current study. Shipton used three examples of B71 and made five repetitions for each frequency, removing and replacing the BV between each measurement. Similarly, the current study used three examples of each model of BV and made three repeats on three different occasions, again repositioning the BV between measurements. Although great care was taken to position each BV in the same place, differences in placement may account for variation seen between studies. Another contributory factor in the difference between studies is that Shipton used warble tones, while the current study used pure tones. Shipton opted for warble tones to reduce the possibility of standing

waves associated with pure tones, detrimentally adding to measurement error. The current study used a semi anechoic room and pure tones. Differences in the acoustic set up of these studies is unclear. Although both studies attempted to control conditions by using warble tones (Shipton) and a semi anechoic room (current study), it may be argued that a reverberant room may be more realistic when measuring total noise emitted. Another reason for the difference seen between B71 in the Shipton and current study is the adjustment made to the Shipton results as explained in Table 3.7, which may inflict a degree of error on the Shipton data.

Measuring ABRad with BVs placed on an artificial mastoid is a straight-forward, objective method to compare ABRad from different BVs. It also enabled the comparison of ABRad emitted from each side of the BVs. This was important as during Experiment 2, each BV was placed on the right and left mastoid in turn, thus exposing a different long side of the BV to the ear canal. Results showed that a difference in ABRad emitted from the two sides was not significantly different and not creating measurement bias between the ears. While an initial comparison has been made, the use of an artificial mastoid does not take into consideration the disturbance of the sound field due to source diffraction, head and pinna reflections or acoustic properties of the ear canal. Human subjects were used during Experiments 2 and 3, so ABRad produced by B71s and BEST was measured using humans allowing further comparisons between BVs to be made.

3.4 Experiment 1b

3.4.1 Method 2: ECSPL measured using human subjects

Air-borne radiation was also measured using 13 normal hearing subjects, all recruited from the University of Southampton student population. Subjects were screened using a health questionnaire followed by otoscopy and tympanometry to ensure it was safe to insert a real ear measurement (REM) tube and that middle ear function was within normal limits. The questionnaire can be found in Appendix A. Hearing sensitivity was not considered relevant so was not assessed. ISVR safety and ethics approval was granted before commencing this experiment.

Subjects were seated in a sound-treated room. Portable REM modules were hung from each ear and connected directly to their paired sound level meter. A REM tube was inserted into each ear canal to a depth of approximately 27 mm, to reduce the chance of the ECSPL being influenced by standing waves (Dirks and Kincaid 1987: BSA procedures 2007). The setup is depicted in Figure 3.6. Once inserted, the REM tubes remained in place for the duration of the experiment. They were not taped in place, but care was taken not to move them when swapping BVs and regular visual checks ensured they did not come dislodged.

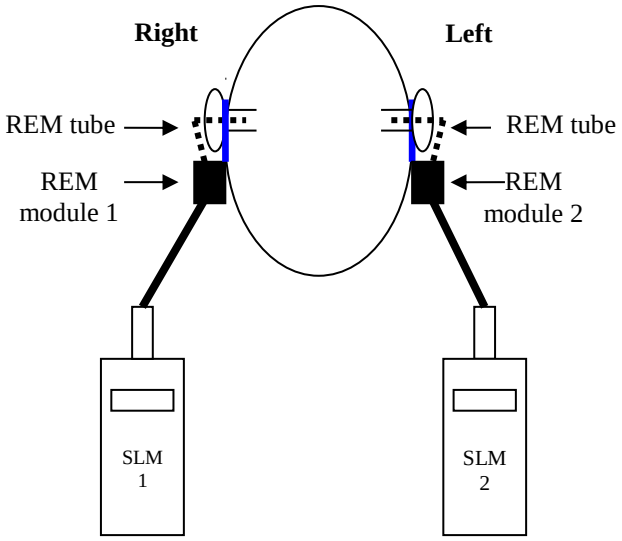


Figure 3.6 Schematic of experimental setup. SLM 1 refers to sound level meter 1 and SLM 2 refers to sound level meter 2.

In turn, all six BVs were placed on the right mastoid. Pure tones of 1, 2, 3 and 4 kHz were presented at 60 dB HL and the ECSPL in ipsi- and contralateral ear canals was measured. This procedure was repeated with each BV placed on the forehead. The forehead placement was included to add validity to measurements made using the mastoid. Although a subject's skull and pinnae are unlikely to be perfectly symmetrical, ECSPL measured in right and left ear canals, with stimulation at the forehead, is expected to be approximately equal. If ECSPL measured in the right and left ears, using forehead placement were not similar, concerns were raised as to the validity of the ECSPL measured. A higher output force level, dependent on frequency, was used for the forehead placement compared to the mastoid placement as set out

in standard BS EN ISO 389-3:1999. The same three BEST and B71 devices as used on the artificial mastoid were used. Each BV was used at each frequency and both stimulation sites twice on the same day, removing and replacing the BV between measurements.

All BVs were calibrated twice before testing, according to BS EN ISO 389-3:1999. Two sound level meters were used to calibrate the REM modules, the recorded output of both was compared to ensure they recorded similar sound pressure level. They were found to measure within 0.5 dB SPL of each other when stimulated by a 1 kHz pure tone produced by a pistonphone. Each REM module was paired with a sound level meter for the duration of testing. For calibration, each REM module was connected to its allocated sound level meter, the other sound level meter being used as the reference. The REM tube was loosely taped along the preamplifier of the reference sound level meter, with the end of the REM tube level with the end of the microphone. Care was taken to ensure the tube was not constricted. A pure tone stimulus of 1, 2, 3 and 4 kHz was presented in turn and the reading from the sound level meter sound level meter connected to the REM module was compared to the reading on the reference sound level meter. This procedure was repeated for the second REM module. Both REM modules were found to be variable (REM module 1 varied by approximately ± 3 dB and REM module 2 by approximately ± 4 dB), so they were calibrated prior to each testing session. Six REM tubes were individually calibrated using the method described above, and found to vary by less than 1.6 dB. A variation of this magnitude was not deemed sufficiently large to warrant calibration of each REM tube used, so individual REM tube calibration was not carried out.

The same steel spring headband was used for all BVs. For mastoid placement, the headband produced a nominal static force of 5.5 ± 0.2 N for the B71 and 5.2 ± 0.2 N for the BEST, across a distance of 145 mm. For forehead placement, nominal static force was 5.5 ± 0.2 N across a distance of 190 mm for the B71 and 5.1 ± 0.2 N for the BEST. The slightly lower nominal force with the BEST is due to its slimmer casing. This difference is within tolerance for a headband according to BS EN 60645-1:2001.

3.4.2 Results: ECSPL measured using human subjects

Three examples of both B71 and BEST BVs were placed in turn on the mastoid and forehead of 13 human subjects, and ECSPL was measured in each ear canal using pure tones at 1, 2, 3 and 4 kHz and an output of 60 dB HL. Data was analysed to reveal any differences in ECSPL that is evident between ipsi- and contralateral ear canals for mastoid placement and right and left ear canal for forehead placement, with particular interest in mean difference between B71 and BEST. Ear canal sound pressure level was measured twice using each BV, therefore a total of six measurements were made for each model of BV in each condition for each subject.

Mean ECSPL and SD were calculated for each model of BV for each test condition. Figure 3.7 summarises the mean ECSPL for placement site, ear and frequency, measured using the B71 and the BEST.

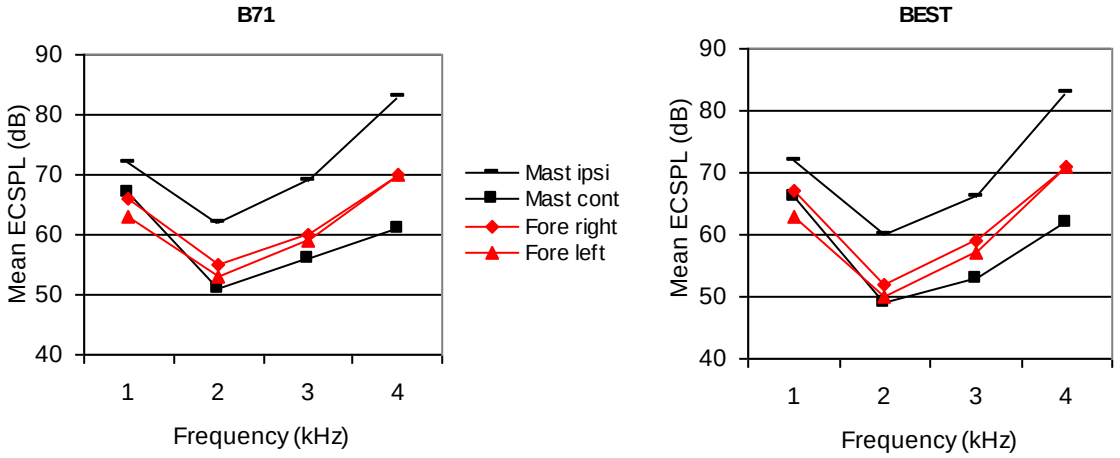


Figure 3.7 Mean ear canal sound pressure level (ECSPL) measured in both ears using mastoid and forehead placement using two models of BV, as a function of frequency. (SD was typically 4 to 5 dB, but error bars are omitted due to confusing overlapping).

Figure 3.7 reveals an upward trend in ABRad with increasing frequency from 2 to 4 kHz, although is strongest in the ipsilateral ear for mastoid placement (black line dash). Ear canal sound pressure level is higher for 1 kHz than at 2 and 3 kHz using both placement sites and BVs. Also of note is that the difference in mean ECSPL measured in the ipsi- compared to the contralateral ear canal widens as frequency increases. Furthermore, when using mastoid placement a higher level of mean ECSPL was measured in the ipsilateral ear canal compared to

the contralateral ear canal, at all frequencies (black lines). This was expected due to the shorter distance from stimulation site to measurement probe for the ipsi- compared to the contralateral placement.

Using forehead placement, ECSPL is similar in right and left ear canal, due to the approximate symmetry of skull and pinnae. The red lines in Figure 3.7 refer to mean ECSPL measured in the right and left ear canals. The pattern of increase in ABRad as frequency increases between 2 and 4 kHz is clear as is the similarity of mean ECSPL measured in right and left ear canals, for both B71 and BEST. Interestingly 2 to 3 dB less mean ECSPL is measured in the left ear than the right at 1, 2 and 3 kHz for both BVs.

The difference in ECSPL measured in the ipsi- and contralateral ears using the B71 at each frequency was analysed using unrelated *t*-tests. Shapiro-Wilk tests revealed no deviation from a normal distribution for both BVs at all frequencies and mastoid and forehead placement. A Bonferroni correction was applied giving a significance criterion of 0.0125 (0.05/4 = 0.0125).

Using mastoid placement and both the B71 and BEST, the difference in mean ECSPL measured in ipsi- and contralateral ears was statistically significant at all frequencies tested, as indicated by an asterix in Table 3.8.

Table 3.8 Overview of statistical analysis relevant to mean ABRad measured using mastoid placement for B71 and BEST.

Mastoid	**Ipsilateral**		**Contralateral**					
	Mean dB SPL	SD dB	Mean dB SPL	SD dB	*t*	*df*	Two-tailed *p*	*r*
B71 1 kHz	72	3.47	66.85	5.14	2.86	24	0.009 *	0.50
B71 2 kHz	62	4.13	51.31	4.23	6.47	24	<0.001 *	0.80
B71 3 kHz	69	5.41	56.15	5.18	6.34	24	<0.001 *	0.79
B71 4 kHz	83	4.83	61.54	2.82	13.98	24	<0.001 *	0.94
BEST 1 kHz	72	3.21	66.23	4.53	3.65	24	0.001 *	0.59
BEST 2 kHz	60	3.40	48.54	3.31	8.77	24	<0.001 *	0.87
BEST 3 kHz	66	3.50	53.00	4.90	7.83	24	<0.001 *	0.85
BEST 4 kHz	83	4.02	61.54	4.20	13.17	24	<0.001 *	0.94

The difference in mean ECSPL measured in the right and left ear using the B71 for forehead placement reached statistical significance at 1 kHz only, using the B71 or the BEST as indicated by an asterix in Table 3.9.

Table 3.9 Overview of statistical analysis relevant to mean ABRad measured using forehead placement for B71 and BEST

Forehead	Right		Left					
	Mean dB SPL	SD dB	Mean dB SPL	SD dB	*t*	*df*	Two-tailed *p*	*r*
B71 1 kHz	66	3.59	63	2.80	2.25	24	0.034 *	0.4
B71 2 kHz	55	4.60	53	5.68	0.91	24	0.371	0.2
B71 3 kHz	61	4.16	58	3.76	1.34	24	0.194	0.3
B71 4 kHz	70	4.28	70	4.45	0.36	24	0.720	0.1
BEST 1 kHz	67	5.61	63	4.07	2.24	24	0.035 *	0.5
BEST 2 kHz	52	4.40	51	4.84	0.763	24	0.453	0.2
BEST 3 kHz	58	5.78	57	4.77	0.555	24	0.584	0.1
BEST 4 kHz	71	2.16	71	3.59	0.397	24	0.696	0.1

Mean ECSPL for the three examples of B71 and BEST was calculated for each subject from which overall means and confidence intervals were derived. A comparison of mean ECSPL measured with BESTs and B71s using mastoid and forehead placement, at each frequency tested, is presented in Figure 3.8.

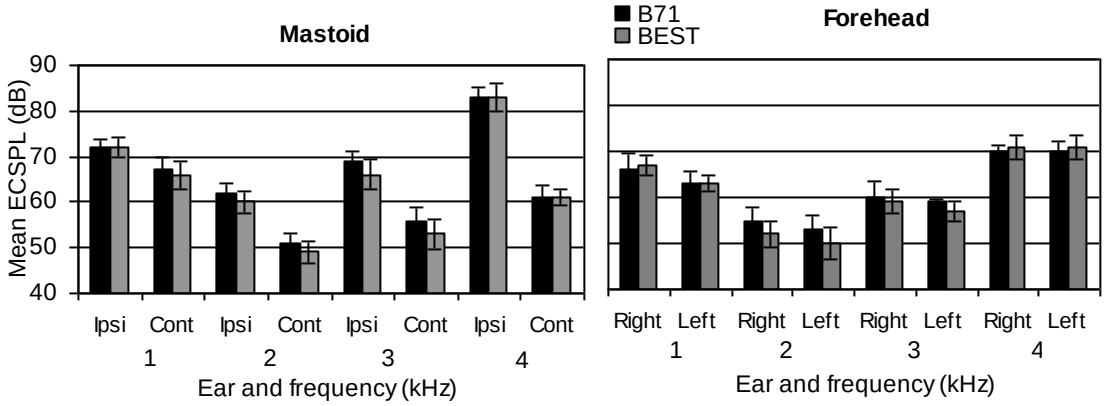


Figure 3.8 Comparison of mean ear canal sound pressure level (ECSPL) measured using BEST and B71 using mastoid and forehead placement. (Error bars represent 95 % confidence interval).

Figure 3.8 reveals a similar mean ECSPL for BEST and B71 in each ear, at all frequencies. A three-way ANOVA was performed with ECSPL as the dependent variable, and three independent variables (model of BV, ear and frequency), for mastoid and forehead placement. Levene's test revealed a non-significant result indicating the assumption of equal variances is met for mastoid and forehead placement. A summary of ANOVA for mastoid placement is shown in Table 3.10.

Table 3.10 Analysis of variance summary table for ECSPL using mastoid placement.

Source of variation	Degrees of freedom	*F*	*P* value	Observed Power
BV	1	6.42	0.012 *	0.71
Ear	1	476.28	< 0.001 *	1
Frequency	3	171.36	< 0.001 *	1
BV*Ear	1	0.03	Not sig	0.05
BV *Frequency	3	1.67	Not sig	0.43
Ear*Frequency	3	32.63	< 0.001 *	1
BV*Ear*Frequency	3	0.08	Not sig	0.07

Table 3.10 reveals a significant effect of ECSPL measured using the B71 compared to the BEST, measured in the ipsilateral compared to the contralateral ear and ECSPL measured at each frequency. Unrelated *t*-tests were used to investigate the differences between BVs and frequencies. Shapiro-Wilk revealed no deviation from a normal distribution in each condition. A Bonferroni correction was applied resulting in a significance criterion of 0.006 (0.05/8 = 0.006). Unrelated *t*-tests showed that mean ECSPL measured using the B71 and BEST, did not differ significantly at any frequency, measured in all ears, as shown in Table 3.11.

Table 3.11 Unrelated *t*-test for mean ear canal sound pressure level (ECSPL) using B71 and BEST

		Mean ECSPL	SD dB	*t*	*Df*	Two-tailed *p*
1 kHz Ipsilateral	B71	72	3			
	BEST	72	3	-0.59	24	.954
1 kHz Contralateral	B71	67	5			
	BEST	66	5	.324	24	.749
2 kHz Ipsilateral	B71	62	4			
	BEST	60	3	1.244	24	.226
2 kHz Contralateral	B71	51	4			
	BEST	49	3	1.859	24	.075
3 kHz Ipsilateral	B71	69	5			
	BEST	66	3	1.809	24	.083
3 kHz Contralateral	B71	56	5			
	BEST	53	5	1.595	24	.124
4 kHz Ipsilateral	B71	83	5			
	BEST	83	4	.265	24	.794
4 kHz Contralateral	B71	62	3			
	BEST	62	4	.000	24	1.00

A three-way ANOVA was also performed to investigate statistical significance of mean ECSPL measured using forehead placement in the right and left ears, using B71 and BEST at each frequency tested. The results are shown in Table 3.12.

Table 3.12 Analysis of variance summary table for forehead placement

Source of variation	Degrees of freedom	*F*	*P* value	Observed power
BV	1	1.92	Not sig	0.28
Ear	1	8.85	< 0.05	0.84
Frequency	3	150.55	< 0.001	1
BV*Ear	1	.000	Not sig	0.05
BV*Frequency	3	1.99	Not sig	0.51
Ear*Frequency	3	1.05	Not sig	0.28
BV*Ear*Frequency	3	0.18	Not sig	0.08

A caveat is present when interpreting this data as the BEST was calibrated using the same reference equivalent threshold force levels (RETFLs) as the B71 (ISO 389-3:1999), as no RETFLs exist specifically for the BEST. The RETFLs are defined as "the vibratory force levels produced by a 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 ontologically normal person" (ISO 389-3, 1999). See AlOmari (2014) for an evaluation of the origin of the RETFLs stated in ISO 389-3, 1999. Recent results suggest that the RETFLs require adjustment for use with the BESTs especially at 2 and 3 kHz (AlOmari 2014). This is in agreement with Frank et al. (1988) who recommend that RETFLS should be transducer specific.

A number of studies have previously investigated ABRad, with Fagelson & Martin (1994) and Harkrider & Martin (1998) using a similar method to the current study. Similarity of methods between these two previous studies and the current study makes comparison of reported ECSPL appropriate and is shown in Figure 3.9. Figure 3.9 compares studies using mastoid placement while Figure 3.10 shows a comparison using forehead placement. Harkrider & Martin did not measure ECPSL at 1 kHz and used mastoid placement only, so this data is omitted from Figures 3.9 and 3.10.

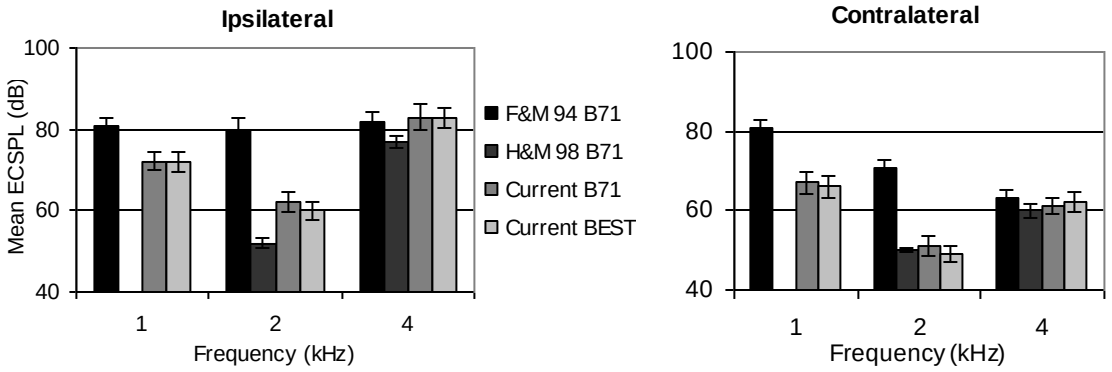


Figure 3.9 Comparison of mean ear canal sound pressure level (ECSPL) measured in the ipsilateral and contralateral ear using mastoid placement as reported by the current and previous studies. F&M 94 and H&M 98 refer to Fagelson & Martin (1994) and Harkrider & Martin (1998) respectively. (Error bars represent 95% confidence interval).

A difference in mean ECSPL between studies is evident in both ipsi- and contralateral ear canals. Confidence intervals were used to investigate the significance of the difference between means and are shown in Table 3.13 for the ipsilateral ear.

Table 3.13 Lower and upper boundaries of confidence intervals for studies shown in Figure 3.9 using ipsilateral ear.

Ipsilateral 1 kHz	Mean	SD	Lower and upper confidence interval
Fagelson & Martin	81	3	79.53 - 82.47
Current B71	72	4	69.83 - 74.17
Current BEST	72	4	69.83 - 74.17
Ipsilateral 2 kHz			
Fagelson & Martin	80	5	77.55 - 82.45
Harkrider & Martin	52	4	50.88 - 53.12
Current B71	62	5	59.27 - 64.73
Current BEST	60	4	57.83 - 60.17
Ipsilateral 4 kHz			
Fagelson & Martin	82	5	79.55 - 84.45
Harkrider & Martin	77	5	75.61 - 78.39
Current B71	83	6	79.74 - 86.26
Current BEST	83	5	80.28 - 85.72

The lower and upper boundaries of the confidence interval indicates any overlap. At 1 kHz lower and upper boundaries of confidence interval overlap for the B71 and BEST in the current study, but the current study does not overlap with Fagelson & Martin. This indicates a significant difference between mean ECSPL reported by Fagelson & Martin and the current study. As 95% confidence intervals have been used, there is a possibility that one of the confidence intervals does not contain the population mean, but this is unlikely as this is expected to happen only 5% of the time (Field 2005). At 2 kHz, a significant difference in mean ECPSL is indicated between studies, except the current using B71 and BEST. At 4 kHz, ECSPL reported by Harkrider & Martin is likely to be significantly different ECSPL reported by Fagelson & Martin and the both BVs used in the current study.

Table 3.14 Lower and upper boundaries of confidence intervals for studies shown in Figure 3.9 using contralateral ear.

Contralateral 1 kHz	Mean	SD	Lower and upper confidence interval
Fagelson & Martin	81	3	79.53 - 82.47
Current B71	67	5	65.61 - 68.39
Current BEST	66	5	63.28 - 68.72
Contralateral 2 kHz			
Fagelson & Martin	71	3	69.53 - 72.47
Harkrider & Martin	50	2	49.44 - 50.56
Current B71	51	4	48.82 - 53.18
Current BEST	49	4	46.82 - 51.18
Contralateral 4 kHz			
Fagelson & Martin	63	4	61.04 – 64.96
Harkrider & Martin	60	6	58.34 – 61.66
Current B71	61	4	58.82 – 63.18
Current BEST	62	5	59.29 – 64.71

Using confidence intervals to indicate significant differences between mean ECSPL measured in the contralateral ears as reported by different studies, a significant difference is seen between

Fagelson & Martin and the current study at 1 kHz, between Fagelson & Martin and the other three studies at 2 kHz and no significant difference between all studies at 4 kHz.

This pattern is repeated for forehead placement, with studies in broad agreement apart from Fagelson & Martin, the data of which is again relatively high at 1 and 2 kHz, as depicted in Figure 3.10.

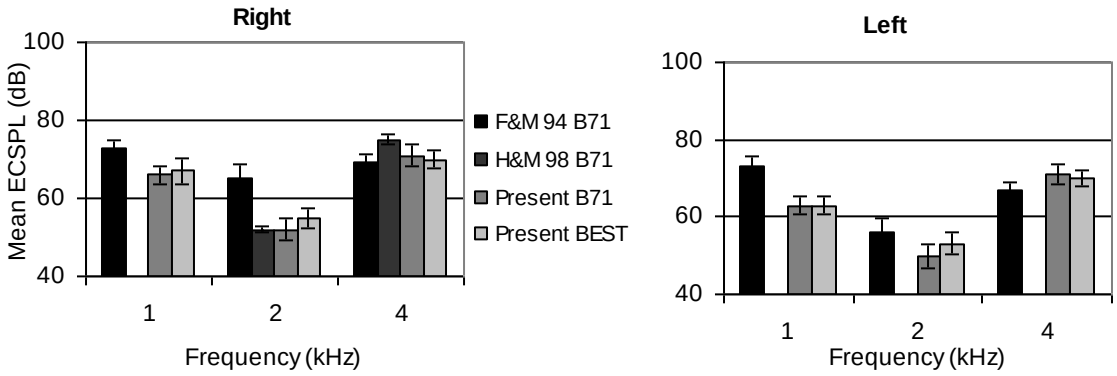


Figure 3.10 Comparison of mean ear canal sound pressure level (ECSPL) measured in the right and left ear canal using forehead placement. (Error bars represent 95% confidence interval).

A similar amount of ECSPL was measured in the right and left ear, which would be expected assuming central placement of the BV and symmetry of the skull. This is shown in each study apart from Fagelson & Martin at 2 kHz.

Again confidences are used to indicate significant differences in mean ECPSL using forehead placement and shown in Table 3.15 for the right ear and 3.16 for the left ear.

Table 3.15 Lower and upper boundaries of confidence intervals for studies shown in Figure 3.10 using forehead placement and the right ear.

Right 1 kHz	Mean	SD	Lower and upper confidence interval
Fagelson & Martin	73	4	71.04 – 74.96
Current B71	66	4	63.82 – 68.18
Current BEST	67	6	63.74 – 70.26
Right 2 kHz			
Fagelson & Martin	65	7	61.57 – 68.43
Harkrider & Martin	52	2	50.92 – 53.08
Current B71	52	5	49.29 – 54.71
Current BEST	55	5	52.29 – 57.71
Right 4 kHz			
Fagelson & Martin	69	5	66.55 – 71.45
Harkrider & Martin	75	4	73.89 – 76.11
Current B71	71	5	68.29 – 73.71
Current BEST	70	4	67.83 – 72.17

Measured in the right ear at 1 and 2 kHz mean ECSPL reported by Fagelson & Martin is significantly different to that reported by the other studies. At 4 kHz, mean ECSPL reported by Harkrider & Martin is likely to be significantly different from that reported by Fagelson & Martin and the present study using B71 and BEST.

Table 3.16 Lower and upper boundaries of confidence intervals for studies shown in Figure 3.9 using forehead placement and the left ear.

Left 1 kHz	Mean	SD	Lower and upper confidence interval
Fagelson & Martin	73	6	70.06 – 75.94
Current B71	63	4	60.83 – 65.17
Current BEST	63	5	60.29 – 65.71
Left 2 kHz			
Fagelson & Martin	56	8	52.08 – 59.92
Current B71	56	6	46.74 – 53.26
Current BEST	53	3	51.37 – 54.63
Left 4 kHz			
Fagelson & Martin	67	67	65.04 – 68.96
Current B71	71	71	68.29 – 73.71
Current BEST	70	70	67.83 – 72.17

When using forehead placement, the only likely significant difference between mean ECSPL is at 1 kHz. Fagelson & Martin report a 10 dB higher ECSPL than the current study.

A number of reasons could explain the difference in ECSPL reported by different studies. Possible reasons are addressed in the discussion.

3.4.3 Comparison of ABRad measured using an artificial mastoid and ECSPL measured using human subjects.

A noticeable difference is evident between ABRad measured using an artificial mastoid and ECSPL measured in the ipsilateral ear using human subjects. Figure 3.11 shows mean ECSPL to be higher than ABRad measured using an artificial mastoid. Ear canal sound pressure level includes sound emitted from the BV which is subject to the effects of ear canal resonance and could also be increased by sound arriving in the ear canal via vibrations of the walls of the ear canal.

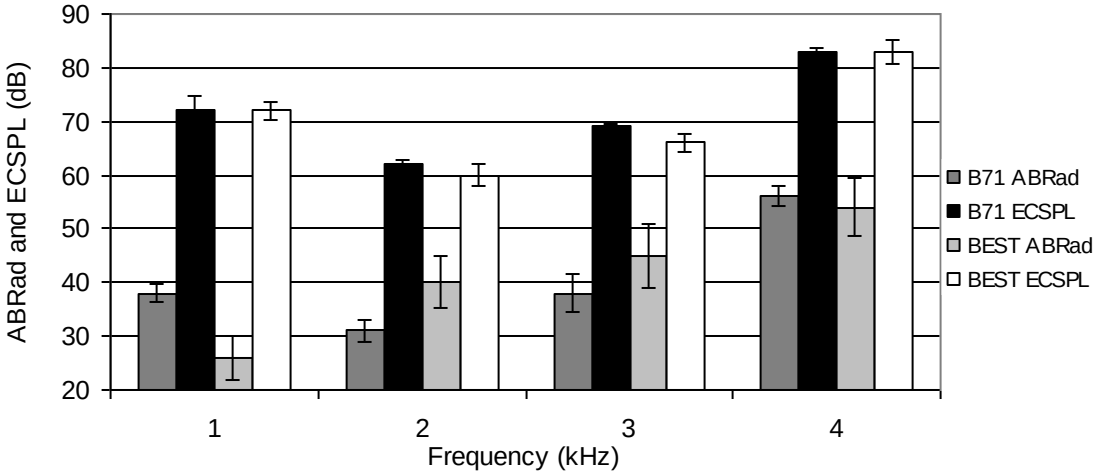


Figure 3.11 Comparison of mean ABRad measured using an artificial mastoid and ECSPL using human subjects, using B71 and BEST. (B71 ABRad refers to ABRad measured using B71, B71 ECSPL refers to ECSPL measured using B71, BEST ABRad refers to ABRad measured using B71 and BEST ECSPL refers to ECSPL measured using BEST) (Error bars represent 95% confidence interval).

Comparing lower and upper boundaries of CIs (see Table 3.17), mean ABRad measuring using an artificial mastoid, compared to mean ECSPL measured using human subjects, at each frequency, reaches statistical significance. This is the case when using B71 and BEST. This implies that the two methods do not produce comparable amounts of ABRad, as the implication is that, for example, B71 ABRad and B71 ECSPL come from different populations, although they were the same BVs. A difference in result is expected between ECSPL measured using humans and ABRad measured using an artificial mastoid because they are measuring different things. When using an artificial mastoid, measured ABRad consists of sound emitted from the side of the BV. When using human ears, measured ECSPL consists of sound emitted from the BV and sound reaching the ear canal via vibrations of the ear canal wall, both of which are subject to the resonant frequencies of the subject's ear canal. Measuring ECSPL using human ears is more realistic as it reflects the sound pressure level that actually reaches the tympanic membrane.

Table 3.17 Lower and upper boundaries of confidence intervals for air-borne radiation (ABRad) and ear canal sound pressure level (ECSPL), as shown in Figure 3.11.

	Mean	SD	Lower and upper confidence interval
1 kHz			
B71 ABRad	38	2	35.34 - 40.66
B71 ECSPL	72	5	69.29 - 74.71
BEST ABRad	26	4	21.47 – 30.53
BEST ECSPL	72	3	70.37 - 73.63
2 kHz			
B71 ABRad	31	2	28.73 – 33.27
B71 ECSPL	62	1	61.46 - 62.54
BEST ABRad	40	4	35.47 - 44.53
BEST ECSPL	60	3	58.37 - 61.63
3 kHz			
B71 ABRad	38	3	34.6 - 41.4
B71 ECSPL	69	1	68.46 - 69.54
BEST ABRad	45	5	39.34 – 50.66
BEST ECSPL	66	3	64.37 - 67.63
4 kHz			
B71 ABRad	56	2	53.74 – 58.26
B71 ECSPL	83	1	82.46 - 83.54
BEST ABRad	54	5	48.34 - 59.66
BEST ECSPL	83	4	80.83 - 85.17

In summary, Figure 3.11 reveals a higher amount of ECSPL than ABRad at all frequencies, although no significant difference is apparent between mean ECSPL measured using B71 and BEST at all frequencies tested. This is an important finding because TA is to be measured using human heads in Experiments 2 and 3. This finding implies that the BEST produces a similar amount of ABRad when measured using human heads compared to the B71, meaning that there no advantage in using the BEST over the B71 for Experiments 2 and 3, at least in terms of ABRad.

3.4.4 Discussion: ECSPL measured using humans

The measurement of ECSPL was used to compare the behaviour of B71 and BEST. No significant difference was found in mean ECSPL measured using B71 compared to the BEST in ipsilateral, contralateral, right and left ears at all frequencies tested. This implies that although the casing of the BEST is smaller compared to the B71, the BEST produces a similar amount of ABRad than the B71.

Referring to Figure 3.7, using mastoid placement, a significant difference in mean ECSPL is seen when comparing ipsilateral to contralateral placement for each frequency, using both types of BV. Difference in mean ECSPL measured in right and left ears using forehead placement did not reach statistical significance. When placed on the forehead, if the right side of the BV was producing more ABRad than the left, a correspondingly higher amount of ECSPL would be expected to be measured in the right ear than the left. The equality shown in Figure 3.7, adds credence to the observation that mean ABRad measured at the right and left side of each BV, on the artificial mastoid, is not significant. Equality of ABRad produced by each side is important for Experiment 2, because one BV was used to estimate HTL in each ear. When the BV was swapped from right to left mastoid, a different side was closest to the test ear. If one side produced more ABRad than the other, the possibility of ABRad creating falsely improved HTL would be greater when the BV is placed on one mastoid compared to the other.

Figure 3.9 depicts differences in ECSPL reported by Fagelson & Martin (1994), Harkrider & Martin (1998) and the current study. There are a number of factors that may account for the differences. Sound pressure measured near the tympanic membrane is comprised of sound radiated from the transducer entering the ear canal as well as sound radiated into the ear canal via vibrations of the ear canal wall. The combined sound pressure arriving from these two routes is then subject to alteration due to the acoustic properties of the subject ear canal, which is highly variable between subjects. The shape and size of the ear canal determines the acoustic characteristics of the ear canal and therefore how sound will be influenced as it travels along it. Peak resonant frequency of the ear canal varies between 2100 and 4800 Hz (Valente & Goebel 1991). Sound energy measured at the tympanic membrane can be 15 to 20 dB higher than at the entrance to the ear canal due to its resonance properties. The frequency of the peak depends on

the resonant characteristics of the subject's ear canal. Therefore, inter-subject variation in the anatomy of the ear canal has a significant effect on the ECSPL measured, especially in the range of 2 to 4 kHz and may explain some of the variation between studies.

In an attempt to measure sound arriving in the ear canal via ABRad only, Harkrider & Martin (1998) inserted an ear plug in the ear canal beyond the osseo-tympanic junction expecting this to prevent sound energy entering the ear canal via vibrations of the ear canal wall. The probe tube was placed with the tip close to the foam plug. However, the osseo-tympanic route of sound energy to the ear canal is mainly via the cartilaginous portion of the ear canal, which is the outer 1/3 of the ear canal (Stenfelt & Goode 2005), thus behind the plug. Such a placing of the plug is likely to affect the resonant properties of the ear canal due to effectively shortening its length. Results presented by Harkrider & Martin, reveal approximately 10 dB lower ABRad at 2 kHz than the other studies for the mastoid placement and were among the lowest for the forehead placement. No measurements were made at 3 kHz and similar results were reported at 4 kHz to the other studies. For the current study, no action was taken regarding the contribution of vibrations of the ear canal to BC threshold. The ear canal has minimal influence on BC hearing for a normal open ear canal as sound is free to pass out of the ear canal (Stenfelt et al. 2003; Tonndorf 1966). However, when comparing ECSPL between two types of BV, the vibrated component is an important component of the ECSPL measured. Further inter-individual differences could be accounted for by differences in head diffraction and body baffle effects (Valente & Goebel 1991).

The proximity of the probe tube to the tympanic membrane is important to reduce the detrimental effects of standing waves (Dirks & Kincaid 1987). The current study used an insertion depth of 28 mm, and Fagelson & Martin (1994) used "a site at or beyond the osseo-cartilaginous junction" as a landmark for comparable placement between subjects. Although care has been taken to ensure consistency of placement from the opening of the ear canal, the distance from the tip of the tube to the tympanic membrane is the important distance and is likely to be variable due to differences in length of the ear canal.

Fagelson & Martin (1994) used one portable test box, moving the probe microphone from ear to ear during testing. Unless extreme care was taken, variation in the position of the probe tube may have contributed to inter-subject variation. Also these studies used different output levels. Fagelson & Martin used 50 dB HL, Harkrider & Martin 65 dB HL while the current study used 60 dB HL. Sound emitted from BVs is linear with increasing output levels (Bell et al. 1980), so for comparison purposes, data was adjusted as if the output was 60 dB HL in all studies (see Table 3.7). Standard deviations are those stated in the studies related to the original output level. There is reasonable agreement between studies apart from Fagelson & Martin who measured higher levels of ECSPL at 1 and 2 kHz than the other studies.

A number of studies have attempted to quantify ABRad using human subjects (Shipton et al. 1980; Frank & Holmes 1981; Fagelson & Martin 1994; Harkrider & Martin 1998). Although the BEST was found to produce a similar amount of ECSPL than the B71, both types of BV can produce ABRad, especially at 3 kHz and above. It is important to consider whether the ABRad that the BVs have been shown to produce is at an acceptably low level to not falsely improve BC HTL in Experiments 2 and 3. Shipton et al. (1980) quantified ABRad by measuring ABRad at the entrance to the ear canal and conclude that when using the B71, ABRad is unlikely to falsely improve BC HTL at frequencies below 3 kHz. Harkrider & Martin (1998) concur, reporting that excessive acoustic radiation from the B71 appears to be significant at 4 kHz only. These findings imply that as long as frequencies of 2 kHz or less are used in Experiments 2 and 3, ABRad is unlikely to influence BC HTL measured with the BEST, as the BEST appears to produce a similar amount of ABRad than the B71.

The main aim of Experiment 1 was to ascertain whether to use the B71 or BEST for Experiments 2 and 3. This was achieved by comparing ABRad from the casing of B71 and BEST (Experiment 1). A colleague investigated vibrotactile thresholds and total harmonic distortion (AlOmari 2014). The BEST was found to have similar vibrotactile thresholds to the B71s in both normal hearing and deaf participants at 250 Hz. At 500 Hz, vibrotactile thresholds estimated with deaf subjects were significantly different. Total harmonic distortion was reported as significantly lower for the BEST compared to the B71 at 250 Hz.

3.5 Experiment 1: Conclusions

- Although there are some statistically significant differences between ABRad emitted by the B71 and BEST, the difference is typically 3 dB or less at 1, 2, 3 and 4 kHz.
- Excessive acoustic radiation from the B71 and BEST seems to be likely to improve BC HTL at frequencies of 3 kHz and above.

In summary, the psychoacoustic behaviour of the BEST was similar to the B71. The BEST was designed to produce less total harmonic distortion than the B71, which it does at 250 Hz, while the limitations shown by the B71 at 3 kHz and above are still apparent in the BEST. The BEST proved to be stable and consistent over time, having been used in a number of studies over the last three years. Test-retest variability is low over time with no indication of performance fluctuation. It is therefore concluded that the BESTs can be expected to be suitable and reliable for use in Experiments 2 and 3.

Chapter 4

General methods

4.1 Introduction

This research was carried out to investigate the role of TA and TD in binaural hearing using bone conducted stimulation. A stimulus presented via BC to one site on the skull can be perceived by both cochleae due to crossed pathways associated with BC stimulation. This is due to limited TA which would be expected to at least degrade binaural cues by reducing interaural isolation (Zurek 1986). A number of studies suggest that some subjects are able to access cues for binaural hearing, although not as well as with AC (Priwin et al. 2004; van der Pouw et al. 1998). It is reasonable to suggest that the amount of interaural isolation is determined by the TA and TD afforded by an subject's skull. This set of experiments sought to assess the role played by TA and TD in lateralisation ability with BC stimulation. Previous studies have investigated TA, TD and lateralisation ability with BC separately, but no published research has been found that estimated all three parameters in each subject. The current experiments have done just that.

4.2 Overview of experiments

Experiment 1, as described in Chapter 3, was undertaken to ascertain the most appropriate BV to use during Experiments 2 and 3. The B71 has well known limitations in terms of vibrotactile threshold, harmonic distortion and air-borne radiation (Boothroyd & Cawkwell 1970; Håkansson 2003; Lightfoot 1979). The BEST was chosen to use for Experiments 2 and 3 as described in section 3.5.

Experiment 2 required subjects to complete two tasks. Threshold comparison was used to estimate TA and lateralisation was used as a measure of ability to access binaural cues via BC. Subjects used a sliding scale to indicate the perceived position of a stimulus presented via AC and BC. Transcranial attenuation was included mainly to investigate between subject differences. However, previous literature reports large between subject variability of TA (Nolan & Lyon 1981; Stenfelt 2012) so a further aim was to strengthen agreement between the

results so far reported. Experiment 2 also served to ensure the smooth running of Experiment 3. Experiment 3 was expected to be demanding on subjects, in terms of concentration required and the time limit of physical comfort of wearing bilateral BVs. Experiment 2 was used to ensure methods were easy to understand with minimal training and provide reliable results in a reasonably short time. Some changes in methodological detail were made between Experiments 2 and 3 and are described in Section 6.4.1.

Experiment 3 was conducted to study the role of TA and TD in lateralisation ability with BC stimulation. Transcranial attenuation was measured using two methods, threshold comparison, as used in Experiment 2 and a measure of TA was derived from the result of the estimation of TD. Transcranial delay was measured using phase cancellation and lateralisation ability was estimated using an acoustical pointer to indicate perceived position of AC and BC stimuli. An overview of Experiments 1, 2 and 3 is shown in Figure 4.1.

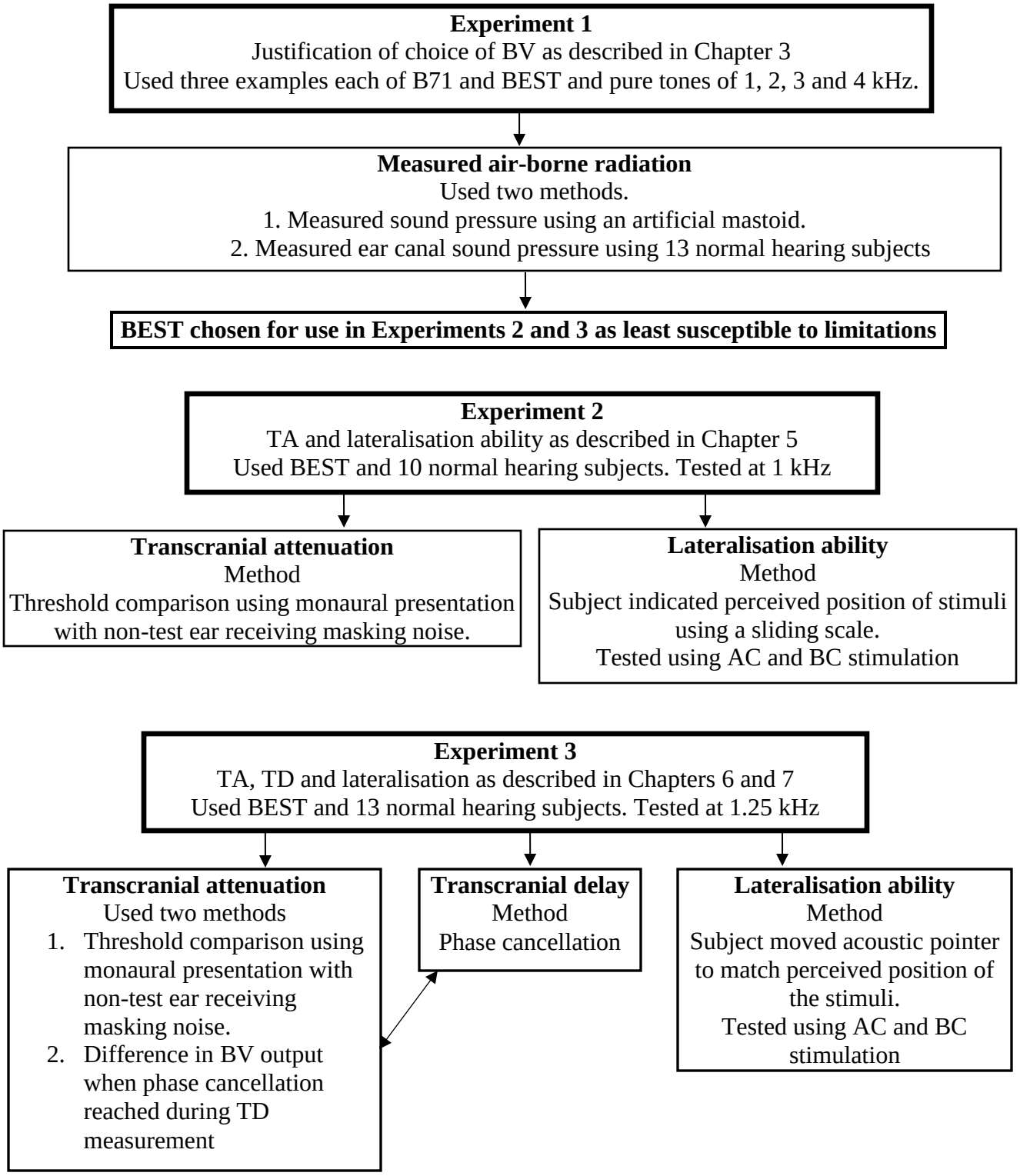


Figure 4.1 Overview of Experiments 1, 2 and 3 which investigated the accessibility of binaural cues using stimulation via BC.

This chapter describes the common methods used for Experiments 2 and 3. Institute of Sound and Vibration Research Human Experimentation Safety and Ethics Committee approval (1258) was granted before carrying out these experiments using healthy, normal hearing, adult volunteers.

4.2.1 Equipment

Subjects were seated in a double-walled sound-treated booth. A tripod-mounted sound level meter (Brüel & Kjær 2260 Investigator) was used to ensure an ambient noise level of consistently less than 30 dB (A). Experiment 2, was conducted with the tester seated in an ancillary room in which the laptop, sound card and audiometers were set up, while the subject sat alone in the sound treated room. This was to control ambient noise levels and is depicted in Figure 4.2. The tester was able to observe the subject through a window for the duration of each testing session.

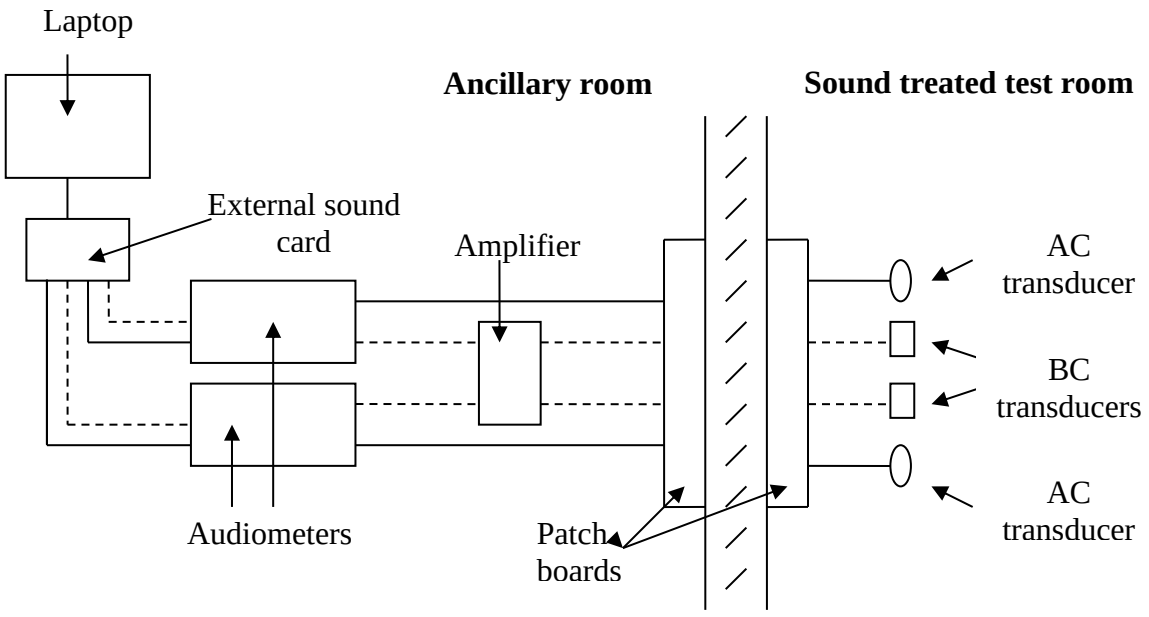


Figure 4.2 Schematic of experimental set up used for Experiment 2. Each subject sat in a sound treated test room, while the experiment was controlled from an ancillary room.

All tasks carried out during Experiments 2 and 3 were run by custom-written MATLAB code (The Math Works Inc.). Stimuli were generated using MATLAB and passed through a stereo

soundcard (Creative, Extigy) to two clinical audiometers (Kamplex, KC50). Air-conducted stimuli were presented via insert earphones (E.A.Rtone 5A). Bone-conducted stimuli were presented using a pair of BESTs attached to clinical headbands. Care was taken to ensure isolation of each BV headband by inserting a piece of high density foam between the subject's hair and the uppermost headband, making sure the foam was only in contact with one headband. This prevented the headbands touching and preventing any stimulus interference via the headbands.

4.2.2 Subjects

Subjects were recruited via blanket email within the population of the University of Southampton. All were either under- or postgraduate students between the ages of 18 and 45 years and participated on a voluntary basis. They comprised a mix of subjects with and without experience of psychoacoustic and BC experiments. All subjects were screened to ensure only subjects with healthy, normally functioning ears were used. An ear related health questionnaire (Appendix A) was used to identify any previous or current ear or hearing problems. Otoscopy was carried out to ensure the absence of excessive wax and damage or disease of the external auditory meatus. Pure tone audiometry (British Society of Audiology, 2004) was used to ensure that AC and BC hearing thresholds levels were better than 20 dB HL and symmetrical (a difference of no more than 10 dB between the ears). A 'type A' tympanogram was used as evidence of normal middle ear function. Subjects not meeting the above criteria were excluded. Screening was carried out at the start of the first testing session. At the start of subsequent testing sessions, all subjects informally reported no ear related problems or exposure to loud noise in the preceding 24 hours.

All subjects were required to complete all elements of each experiment. Each subject attended at least 3 sessions lasting a total of approximately 3 hours for Experiment 2 and up to 4 hours for Experiment 3. In Experiment 3, some subjects found phase cancellation difficult to achieve and needed to return for another session in order to complete this task. Subjects who were used for piloting were not used for the main experiments. Written and verbal instructions were provided for each task of Experiments 2 and 3 and can be found in Appendix B.

4.2.3 Stimuli

Consideration was given to the most appropriate stimulus to use and how many and which frequencies to test. This process was complicated by the need to use a stimulus that was appropriate for each part of Experiments 2 and 3. Previously, pure tones have been used to estimate TA (Snyder 1971; Nolan & Lyon 1981; Vanniasegaram et al. 1994; Stenfelt 2012). It was decided to use pure tones to facilitate comparison. More recently TA has been estimated using frequency modulated tones with a frequency deviation of 8% (Stenfelt & Zeitooni 2013). The rationale for the use of frequency modulated tones is to avoid extreme responses that may occur when using pure tones due to antiresonances in the skull (Stenfelt & Goode 2005). Piloting prior to Experiment 2 showed results similar to those reported in the literature available at that time so pure tones were used. Furthermore, pure tones would need to be used for phase cancellation in Experiment 3 and have been used in previous studies of phase cancellation (Tonndorf & Jahn 1981; Boezeman et al. 1984).

Pure tones were also used during the lateralisation task during Experiment 2. Previous research investigating lateralisation ability using BC used 1/3 octave narrowband noise centred over the test frequency (van der Pouw et al. 1998; Bosman et al. 2001; Priwin et al. 2004) and gaussian noise (MacDonald et al. 2006). During Experiment 2, the results for some subject's indicated that they found the task more difficult than would be expected especially with AC stimulation. For this reason, narrowband noise was used in Experiment 3.

Experiment 3 consisted of three tasks: the estimation of TA and TD and lateralisation of stimuli via AC and BC. This experiment was expected to be demanding on subjects in terms of time commitment and fatigue, so one frequency only was tested. A 1 kHz pure tone was chosen as this frequency minimises experimental difficulties associated with the limitations of BVs (i.e. total harmonic distortion, vibrotactile thresholds and ABRad). Furthermore, with transmission via BC, ITDs are still likely to be accessible as discussed in Section 2.2.5.

During Experiments 2 and 3, narrowband noise was presented to the non-test ear via an insert earphone. Blocking the ear canal carries the risk of increasing sound pressure level in the ear canal resulting in an increase in sound intensity perceived by the listener. This effect is known

as occlusion and may lead to the masking noise being insufficient to completely mask the NTE. The occlusion effect is particularly evident at frequencies up to 1 kHz when using insert earphones (Berger & Kerivan 1983). A deep insertion of the insert earphone has been shown to reduce the occlusion effect, especially when inserted in the ear canal far enough to reach the end of the cartilaginous section (Dean & Martin 2000). The possible influence on BC thresholds of placing an insert into the non-test ear canal was investigated. During piloting, BC hearing threshold levels at 1 kHz were estimated with and without the test ear plugged. No difference was found in threshold levels, meaning that masking noise would not be expected to be raised by the occlusion effect. Care was taken to ensure the insert earphones were consistently inserted deeply in the ear canal.

4.2.4 Calibration

Calibration of equipment was carried out before, during and after data collection to ensure the output of the transducers was consistently at the required intensity. The following calibrations were conducted:

1. Air conducted pure tones using insert ear phones were calibrated according to ISO 389-2:1997, using an occluded ear simulator (IEC 711) connected to a Brüel & Kjær 2260 investigator sound level meter.
2. Bone conducted pure tones using a pair of BESTs were calibrated according to ISO 389-3:1999 using a Braer & Kjaer artificial mastoid (type 4930). Stimuli were found to be variable by ±1 dB so were calibrated every two to three days during testing. Standard RETFLS, developed for use with B71s were used, as RETFLS specific to the BEST are not available.
3. Narrowband masking noise using insert earphones were calibrated according to ISO 389-4:1999 using an occluded ear simulator (IEC 711, 1981) and sound level meter (Brüel & Kjær 2260 investigator).
4. The tension exerted by the BV headbands was measured to ensure they produced a nominal static force according to BS EN 60645-1:2001. Section 10.3 of this standard states that the headband shall hold the vibrator on the mastoid with a nominal static force of 5.4 ± 0.5 N. Static force for both BESTs was measured before, mid-way and

after both Experiments 2 and 3 with a similar average force of 5.2 ± 0.2 N for each headband..

5. Relative output of AC and BC transducers in terms of phase was important for the lateralisation tasks. The phase output of the insert earphones and BVs were compared using an oscilloscope (HAMEG Instruments. 35 MHz analog oscilloscope Type HM303-6). A reference tone was produced via MATLAB and the output in terms of phase of each insert (using an occluded ear simulator) and BV (placed on an artificial mastoid), were compared to the phase of the reference tone. This procedure was repeated on five different occasions. The difference in phase of the output between right and left AC and the reference and was typically zero (mode 0^o, median 0^o, mean 3^o, range 0-10^o). The same was carried out using the BVs consistently revealing a phase difference of zero. It was therefore deemed unnecessary to adjust either pair of transducers in terms of phase.

Extensive checks were carried out to ensure the equipment was working reliably. The experimenter completed listening checks for all tasks before each session of data collection.

All MATLAB code was checked as follows:

- **Transcranial attenuation.** The program was run with the BV on an artificial mastoid. The output of the BV was noted using a sound level meter. Step size and reversal criterion were confirmed.
- **Masking noise.** Masking noise was shown to be loud enough by presenting the tone, at the initial starting level, in the presence of bilateral narrowband noise. The subject confirmed they were unable to perceive the tone. The removal of one insert confirmed the presence of the tone. Cross masking (i.e. masking noise loud enough to raise the HTL in the test-ear) was found to not be occurring by reducing the level of the noise to 25 dB and the threshold of hearing was unaffected.
- **Lateralisation ILD**. The program was run with each BV on an artificial mastoid. The output of the BV was noted using a sound level meter. The level difference altered in the expected step sizes.

- **Lateralisation ITD**. The program was run with the BV on an artificial mastoid. The output of the BV was noted using an oscilloscope. Phase differences were confirmed as expected.
- **Harmonics.** BESTs have been shown to be less susceptible to produce harmonics than B71s. Harmonics were measured using an artificial mastoid and sound level meter and found to be less than the RETFL so deemed to be not audible.

4.3 The estimation of TA

This section describes the procedure used to estimate TA during Experiments 2 and 3. A three-alternative forced choice (3AFC) task combined with an adaptive staircase procedure was used.

4.3.1 TA experimental overview

During Experiments 2 and 3, TA was measured using the method of threshold comparison as previously used by Nolan & Lyon (1981) and Stenfelt & Zeitooni (2013). One ear was assigned as the test ear. Bone conduction HTL of the test ear was estimated with a BV placed on the mastoid behind the test ear. The non-test ear was prevented from perceiving the tone by way of 1/3 octave narrowband noise presented via AC to the non-test ear. The BV was then swapped to the mastoid behind the non-test ear and the threshold of hearing of the test ear was again estimated in the presence of masking noise to the non-test ear. This is depicted in Diagrams 1 and 2 of Figure 4.3.

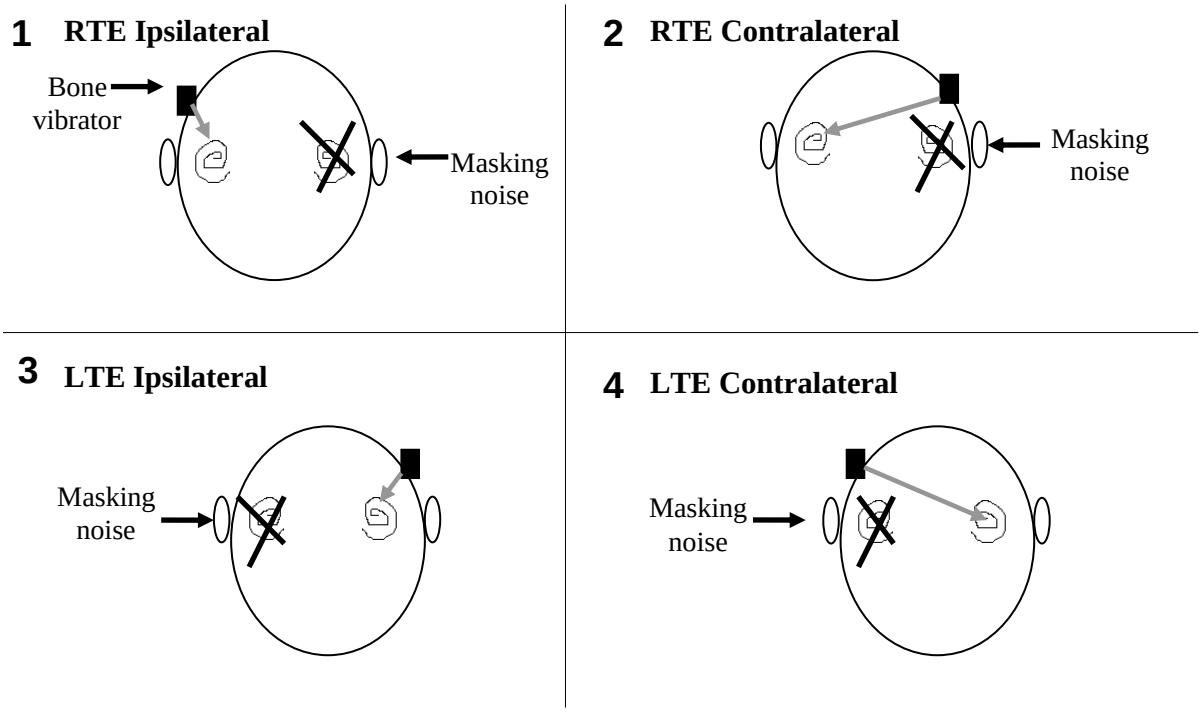


Figure 4.3 Experimental procedure for estimating TA. RTE refers to the right as the test ear. LTE refers to the left as the test ear. Ipsilateral indicates the stimulus is presented on the same side as the test ear. Contralateral indicates the stimulus was presented on the opposite side to the test ear.

The threshold of hearing with the transducer on the contralateral compared to the ipsilateral mastoid was used to estimate TA. This procedure was then repeated to determine TA using the other ear as test ear as shown in Diagrams 3 and 4 of Figure 4.3.

After explanation, each subject completed one practice run of threshold measurement in one condition, in order to become familiar with the task. Thereafter, three threshold measurements were conducted in each condition and the mean threshold for each condition calculated. Transcranial attenuation for the right ear was calculated by subtracting mean HTL measured in the condition depicted in Diagram 2 of Figure 4.3 from mean HTL as depicted in Diagram 1 of Figure 4.3. This was repeated for the left as test ear.

The method described above has been used by most previous investigations into TA (Snyder 1971; Nolan & Lyon 1981; Stenfelt 2012). An alternative way of calculating TA was

considered when planning this experiment. Using normally hearing subjects with symmetrical cochlear sensitivity, the BV remains on one mastoid. Instead of moving the BV, the masking noise is presented to one ear and HTL measured, then presented to the other ear and HTL is again measured, as shown in Diagrams 4 and 1 of Figure 4.3. The difference in HTL measured using each cochlea is then considered to be due to TA. The same is repeated to calculate TA in the opposite direction. This method has the advantage of avoiding variation in HTL created by moving the BV, but assumes equal cochlear sensitivity. The method chosen, entailed moving the BV but differences in hearing sensitivity between cochleae was not important. For Experiment 3, a way was found to eliminate variability in BC HTL due to moving the BV between mastoids and is described in Section 6.4.1.

4.3.2 The task

Three bands of narrowband noise were presented to the non-test ear via AC to ensure only the test ear perceived the tone as illustrated in Figure 4.4. The tone was presented to the test ear to coincide with one of the bands of noise. The band of noise containing the tone was randomly chosen by the MATLAB program. The subject was required to use predetermined keys on a standard QWERTY keyboard to indicate which band of noise contained the tone. There was no limit on the response time. The next trial commenced once the subject had indicated their response.

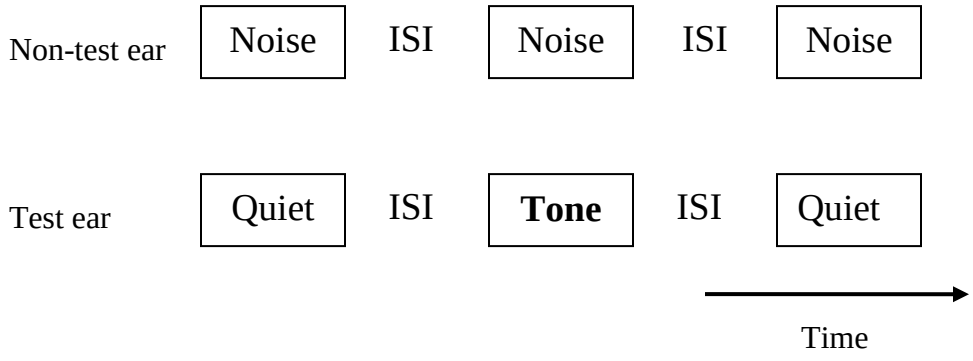


Figure 4.4 Pictorial representation of the experimental protocol. In this example if the subject detected the tone they would press the key representative of the second noise band for a correct response. ISI refers to inter stimulus interval.

The noise bands were set at 45 dB EML, which was motivated by the 45 dB HL used by Nolan & Lyon (1980). Effective masking was used for the current study as it considers differences in HTL, ensuring masking level is the same for all subjects. Checks were carried out to ensure the masking noise was set at the appropriate level as described in Section 4.2.3. Tones were presented with a duration of 0.4 s. This stimulus duration was chosen as there is no apparent effect on threshold above 0.2 to 3 s (Plomp & Bouman 1959). During piloting, subjects reported a duration of 0.4 s made the task easier than a duration of 0.3 s. Masking noise was set at 0.6 s as it needed to be longer than the tone duration and onset and offset ramps were set at 0.02 s, slow enough to prevent an audible click. Each of the three presentations was separated by a silent inter-stimulus interval (ISI) of 0.4 s. Detecting a tone near threshold requires a high level of concentration and visual cues were found to be distracting during piloting so were not provided during testing. A trial typically lasted approximately 5 s.

4.3.3 Adaptive procedure

Tones were presented using a 3AFC task combined with a two-down, one up adaptive staircase procedure. A 3AFC procedure was chosen as it has been shown to be a more time efficient method of reaching a reliable threshold measurement than a 2AFC (Kollmeier et al. 1988). Although a 2AFC task is often used, a 3AFC task was chosen for these experiments as the probability of a correct response through guessing is reduced with 3AFC (Leek 2001) compared to 2AFC. Less variability in threshold measurements has been shown, as the number of intervals increase from 2 to 3, but less so from 3 to 4 (Schlauch & Rose 1990).

An adaptive procedure is one in which the stimulus level presented depends on the subject's response to the previous stimulus. An up-down staircase procedure calls for a reduction in stimulus level when a subject hears the stimulus and an increase in stimulus level when the subject is not able to hear the stimulus (Leek 2001). Adaptive methods are routinely used to measure AC and BC discrimination thresholds, both in research and clinical settings. Adaptive methods are a popular option as they have the ability to target a predetermined response level on the psychometric function. A simple one up-down procedure results in the stimulus altering after every response, an equal probability of the stimulus moving in either direction and the 50% performance level being targeted. To target a higher performance level, the criteria for

downward movement is two or more positive responses, while the upward movements typically remains at one negative response. A two-down, one up procedure targets the 70.7% performance level on the psychometric function (Leek 2001) and was used for this research.

Figure 4.5 shows an example of one block of 40 trials used to make one threshold estimate. Crosses represent 'correct' responses and circles indicate 'incorrect' responses.

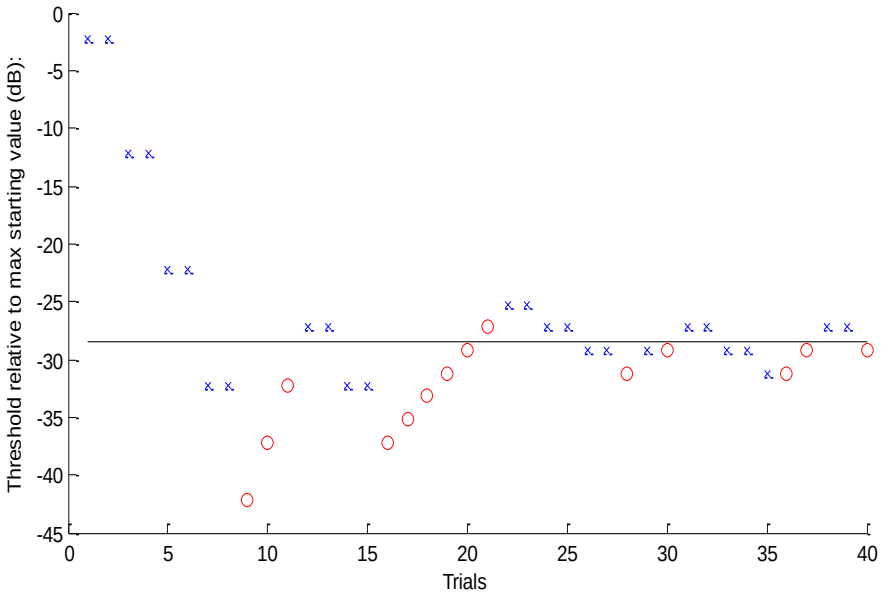


Figure 4.5 Example of the output graph for one block of trials to determine threshold.

Details of the adaptive procedure were:

- **Response scoring**. A 'correct' response occurred when the subject chose the band of noise in which the tone was presented. An 'incorrect' response was when the subject chose a band of noise that did not contain the tone.
- **Decision rule**. The amplitude of the tone decreased after two correct responses and increased after one incorrect response. In theory, this rule targets the 71% correct response level (Levitt 1971). The threshold at which the staircase direction changes is known as a 'reversal'.

- **Initial starting level**. Initial tones were presented using a maximum starting level of 40 dB HL. The trial by trial starting level was randomly varied by the application of jitter set at 10 dB. This prevented subjects making a threshold judgement based on the starting level.
- **Step size**. The step size is the amount of dB the tone altered on consecutive trials. The first trial used a step size of 10 dB which focused in on the threshold quickly before a smaller step size of 5 dB was introduced. The next two used 5 dB and thereafter 2 dB.
- **Termination rule**. Staircases were terminated after six reversals at the smallest step size, or after 40 trials.
- **Calculation of threshold**. Data from the reversals with a step size of 10 dB and 5 dB and the first trial with a step size of 2 dB were discarded. Threshold, relative to the starting value, was estimated as the average of the remaining 5 reversals. The example shown in Figure 4.5 gave an average measurement from the final 5 reversals as -28 dB. Given a starting level of 40 dB, threshold value is calculated to be 12 dB HL (i.e. 40 - 28 = 12).

4.4 Experimental overview: Lateralisation

Lateralisation ability was used in Experiments 2 and 3 as a measure of the accessibility of binaural cues via BC stimulation. While the ability to lateralise sound using AC has been studied extensively (Häusler et al. 1983; Bernstein & Trahiotis 1985; Yost 1981) the ability using BC has attracted less interest. The reason for this may at least partly be due to the well-known lack of interaural isolation associated with hearing via BC (Zwislocki 1953). This research set out to further investigate lateralisation ability using BC.

A number of methods have been used to study localisation with BC. Most commonly loudspeakers have been used to create a phantom sound source in a sound/free field which the subject localises (van der Pouw et al. 1998; Bosman et al. 2001; Priwin et al. 2004). Spatial perception has been studied by applying head related transfer functions to stimuli presented via bilateral BVs and the perceived origin of the sound indicated by the subject (MacDonald et al. 2006). Stenfelt & Zeitooni (2013) studied binaural hearing ability using BC by measuring spatial release from masking, binaural intelligibility level difference and binaural masking level difference. Rowan & Gray (2008) investigated the lateralisation of high-frequency pure tones

via BC by manipulating IPD. Another method, previously used to study localisation with AC, was adapted for the current research. The subject hears a stimulus which has some combination of ITD and ILD and uses a pointer to indicate the perceived position of the sound (Bernstein & Trahiotis 1985).

Lateralisation ability using AC and BC was measured by presenting binaural stimuli which combined to create a tone at a predetermined position on the horizontal plane. The position of the stimulus was influenced by altering ILD and IPD cues. Subjects were required to adjust a slider on a screen to indicate where they perceived the origin of the tone to be. This method is similar to that used by Yost (1981). The slider, as seen by the subject, is depicted in Figure 4.6. Imagining the long rectangle to be the interaural axis running between left and right ears, the subject positioned the grey marker where they perceived the tone to be.

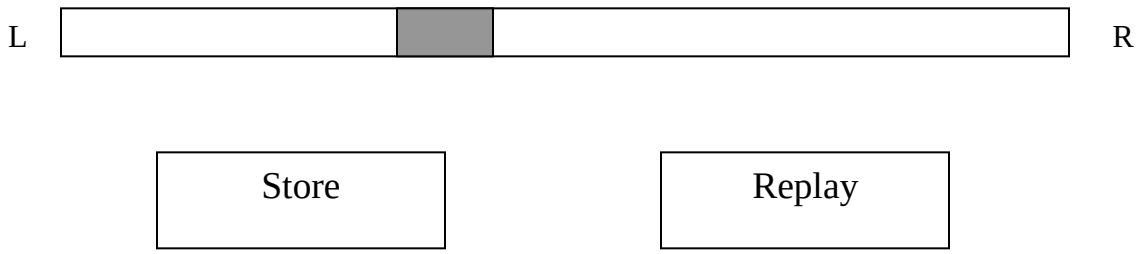


Figure 4.6 Illustration of slider used by each subject to indicate the perceived position of the tone on the interaural axis between left and right ears.

No time limit was set between presentations and subjects could use 'Replay' to hear the tone again. Once satisfied with the position they used 'store' to confirm their decision and the next tone was presented. The initial position of the slider was placed at random places different for each presentation.

A laptop computer used a custom written MATLAB program to present pure tones of 1 kHz, of five ILD (0, ± 10, ± 15 dB) and five IPD (0, ± 45^{o}, ± 90^{o}) via two clinical audiometers. These values were based on data presented by Yost (1981) who reports that values of ILD of 0, 10 and 15 dB place the image at approximately the midline, halfway to the ear and at the ear respectively. ITD values were based on data reported by Kunov & Abel (1981) who report that

for a pure tone of 1 kHz, interaural stimulus delays ranging from 0 to 1000 µs correspond to phase shifts of 0 to 360^{o}. As the period of a 1 kHz tone is 1000 µs, an ITD of ± 250 and ± 125 µs corresponds to ± 90^{o} and ± 45^{o} respectively.

During piloting, subjects were fitted with bilateral insert earphones (for AC) and bilateral BESTs (for BC) concurrently. It soon became apparent that subjects were experiencing unacceptable amounts of discomfort from wearing bilateral insert earphones and bilateral BVs concurrently. Therefore lateralisation ability was measured using AC and BC stimulation separately, i.e. AC ILD and AC ITD were measured separately to BC ILD and BC ITD. This meant that for AC stimulation, the subject wore insert earphones only. Both sets of transducer were still required for BC stimulation, as BVs were required to present the tone and inserts presented the masking noise, but were only required to be worn for half the time. Masking was presented to ensure subjects were unable to perceive harmonics produced by the BV. Conditions were denoted ‘AC ILD’, ‘BC ILD’, ‘AC ITD’ and ‘BC ITD’. Each condition was repeated 20 times.

Although subjects with asymmetry of greater than 10 dB were not recruited, prior to each testing session symmetry was checked by presenting a tone of 1 kHz at 50 dB HL to both ears concurrently via AC. Each subject was asked to report whether the tone was perceived centrally in the head. All subjects reported central perception, indicating symmetry of cochlea sensitivity. However, during piloting bilateral BVs were fitted and subjects were presented with diotic stimuli and asked if the stimuli produced a centralised image. If not, the amplitude of the BVs was altered until each subject perceived the tone to be positioned centrally. However, when several subjects carried out the lateralisation task, the perceived position of the zero azimuth stimuli was skewed to one side. For this reason, the BVs were placed to be visually symmetrical, but were not checked for a centralised image for the main data collection during Experiment 2. This method of fine-tuning was also used by Rowan & Gray (2008). They report difficulty in achieving a centralised image via BC with two subjects, who perceived the images to be lateralised to the opposite mastoid relative to the site of stimulation. During Experiment 3, the BVs were carefully positioned and checked for perceived centralisation of the image. If this was not met, the quieter BV was repositioned until the stimuli was perceived as central.

During Experiment 2, the output intensity of the two inserts was the same and the two BVs produced an equal force level. Stimuli were presented at 50 dB HL for AC and BC, with a duration of 0.4 s and on- and offset ramps of 0.02 s. During BC testing, bands of narrow band noise centred over 2 and 3 kHz were presented bilaterally via insert earphones to be sure harmonics were not perceived. Digital stimuli were produced using a sampling rate of 22050 Hz and 16-bit amplitude resolution.

In order to become familiar with the task, each subject completed one block of lateralisation AC using 10 presentations (ILD 0, ± 10, ± 15 dB and IPD 0, ± 45^{o}, ± 90^{o}) during which informal feedback was given.

4.5 Order of testing

The order of the four tasks required for Experiment 2, TA RTE, TA LTE, lateralisation AC and lateralisation BC were randomised between subjects. When estimating TA, BC HTL is measured twice i.e. with the BV placed on the ipsi- and contralateral mastoid. The order in which the BV was placed on the mastoids was also randomised. Most subjects completed the tasks in 3 sessions, although 3 required a fourth session due to unforeseen limits on subject's time on a particular day. Details can be found in Appendix C.

4.6 Experimental considerations specific to BC

Although the mechanism of hearing via BC is not yet fully understood, it is known to be complex. Experimental procedure and results can be hampered by equipment limitations (harmonic distortion, air-borne radiation and low vibrotactile threshold), subject comfort (pressure exerted by BV), placement effects (contributing to test-retest variability) and the subjective nature of the tasks (motivation, fatigue). Before carrying out this research, careful consideration was given to controlling issues related to the use of BVs and human subjects in order to separate variation due to measurement error from variation due to genuine differences between individuals.

Bone vibrators are known to be limited in terms of frequency and level. At frequencies below 0.5 kHz and even at low intensity levels, they are prone to producing high levels of harmonic distortion which may influence results when using pure tones (Håkansson 2003). Also at frequencies below 1 kHz and relatively low output levels, BVs have a tendency to move against the skin causing the listener to feel and respond to a 'vibrotactile' sensation before perceiving the vibration as sound (Boothroyd & Cawkwell 1970). At frequencies of 3 kHz and above BVs tend to produce an audible sound which if not controlled, can be heard via the AC route of hearing in normal hearing subjects. In this case, the listener perceives the sound presented via BC as well as the air-borne sound, resulting in a falsely improved hearing threshold level (Lightfoot 1979; Shipton et al. 1980; Bell et al. 1980). These issues were discussed in detail in Section 3.2. A frequency of 1 kHz was chosen for this research in an attempt to minimise problems arising due to the above characteristics of BVs.

Care was also taken when placing the BVs on the subjects. The shape of the mastoid varies between people, some having more pointed mastoids making placement and BV stability difficult. Evidence is mixed regarding the test-retest variability in perceived loudness of BC stimulation. Dempsey & Levitt (1990), report that a change in position of the BV has little effect on loudness, but does result in changes in the phase of the stimulus. Conversely a difference in threshold of up to 10 dB has been reported after a small change of position at the mastoid, which was not the case at the forehead (Weston et al. 1967). For this reason forehead stimulation would be advantageous, but binaural input was required for the current experiments and would not be achievable with forehead stimulation. When measuring TA during Experiment 2, two BVs were used, one to stimulate the right mastoid and one to stimulate the left mastoid. These were worn individually and placed carefully to ensure maximum contact area and stability.

For Experiment 3, both BVs were placed on the skull and subject comfort was confirmed. A pure tone was presented via each BV in turn and if one sounded quieter it was repositioned on the mastoid until the listener reported them as being subjectively equal in loudness. Once the BVs were loudness matched, they remained in place for the measurement of threshold comparison and phase cancellation. This prevented variation in perceived loudness that occurs

through repositioning the BVs and afforded consistency of BV placement for each measurement of TA and TD. This was important as the amount of TA measured was used to adjust the output levels of the BVs for phase cancellation. Adjusting for TA prior to attempting phase cancellation made finding cancellation quicker. Ideally, the BVs would have been left on for the lateralisation tasks as well, but were found to become too uncomfortable. Each time the BVs were placed on the skull, they were subjectively loudness matched, to minimise placement effects.

4.7 Some comments on the use of normal hearing subjects

Ideally research exploring localisation ability using BC stimulation would be carried out using individuals who would benefit from this research, i.e. those with hearing impairment treated by bilateral BAHA. However, recruitment of such subjects is difficult so normal hearing subjects were used with advantages and disadvantages as outlined in Table 4.2.

Table 4.2 Advantages and disadvantages of using normal hearing subjects in BC studies.

Advantage	Disadvantage
Good availability of subjects	Multiple pathways for BV to simulate cochlea which may not be available to patients
Pathology does not influence results	Pathology may influence results which may differ when using normal or hearing impaired subjects.
Lack of digital processing of transducer (i.e. no compression and directional microphones) does not influence results	Position of BV not at BAHA site
Subjects are accustomed to processing binaural auditory input	Clinical BV is different to a BAHA Subjects are not used to hearing through BVs. Adequate precautions need to be taken to ensure subjects are unable to use AC cues

Studies using subjects fitted with bilateral BAHAs indicate that some degree of lateralisation is possible with bilateral BC stimulation (van der Pouw et al. 1998; Priwin et al. 2004; Stenfelt 2005a). MacDonald et al. (2006) used normal hearing subjects and reported that lateralisation ability using BC is comparable to that using AC. Lateralisation ability using BC has also been shown in five out of seven normal hearing subjects at high frequencies (Rowan & Gray 2008). There are several possible explanations. Firstly the transducer used with normal hearing subjects is a clinical BV that does not have acoustic features (i.e. compression and directional microphones) that are available in a BAHA and may influence the results. Directional microphones may enhance BAHA user's ability to access binaural cues. Although experiments could be carried out with such features disabled, BAHA users would be used to listening with them active.

The use of normal hearing subjects allows the tester to screen for people with symmetrical hearing loss, which is advantageous at the present stage in our knowledge of binaural hearing with BC. An asymmetry in cochlear sensitivity can at least temporarily disrupt an individual's

ability to localise sound using AC stimulation by creating a difference in loudness perception between cochleae. When attempting to understand binaural hearing via BC, confidence that inter-subject differences in lateralisation ability are due to differences in TA and/or TD rather than a difference in cochlea sensitivity is important at the present stage in our understanding. It must be remembered that a normal hearing person's ability to lateralise with bilateral BC stimulation may differ from that of a hearing impaired person due to differences in stimulation at the cochlea. Binaural hearing ability has been shown to be most adversely affected when a conductive hearing loss is present (Noble et al. 1994). As the degree of conductive loss increases (i.e. as the air-bone gap increases) sound stimulation reaching the cochlea via BC increases relative to AC. The resultant crossed pathways degrade interaural isolation and therefore reduce the subject's ability to access binaural cues (Häusler et al. 1983; Zurek 1986). Furthermore, interaural phase differences between AC and BC pathways can be altered considerably when AC and BC signals reach the cochlea even when the BC signal is weaker than the AC signal (Noble et al. 1994).

As understanding of this area is still limited, it seems reasonable to suggest that the use of transducers without digital sound processing and subjects devoid of the complications that may influence lateralisation is appropriate at this time. Once more light is shed on lateralisation ability using BC with normally hearing subjects, understanding results using those with hearing impairment could be expected to be facilitated. However, the considerable limitations of the current approach need to be taken into account when aiming to generalise conclusions to BAHA users.

4.8 Statistics

Statistical analyses were undertaken using SPSS (IBM SPSS Statistics v 20). Initially, the criterion for significance level was 0.05, although a Bonferroni correction was used to correct this as appropriate for the specific analyses. The aims of Experiment 2 and 3 were:

- To explore between subject variation in TA. Statistical tests were used to ascertain whether variability was due to differences in TA or simply chance. Transcranial attenuation is calculated from two BC HTL measurements which are known to be subjective and variable. If estimates of HTL and TA do not differ from a normal distribution parametric tests would be

used. In this case paired samples *t*-tests would be used for the analysis of TA data in Experiments 2 and 3. In the event of deviation from a normal distribution, non-parametric tests would be used.

- Transcranial attenuation was estimated in two ways during Experiment 3 (see Section 6.3). To investigate whether any variation was due to difference in method or due to chance, a repeated measure ANOVA was planned.
- Lateralisation ability was used to investigate accessibility of binaural cues using BC. A relationship between lateralisation ability using AC and BC was investigated. Regression was expected to be used to investigate lateralisation data.
- The importance of ITD and IPD in lateralisation using BC stimulation was explored using regression, ANOVA and *t*-tests.

The raw data from all experiments are presented in Appendix E.

Chapter 5

Experiment 2: TA and lateralisation

5.1 Introduction

Experiment 1 set out to determine the BV most appropriate to use for Experiments 2 and 3. Although the B71 and BEST were shown to produce similar amounts of ABRad and have similar vibrotactile characteristics, the BEST was chosen due to its capacity to produce less total harmonic distortion at all frequencies (Håkansson 2003; AlOmari et al. 2010). This is advantageous as it minimises the amount of masking required to ensure the subject perceives only the test stimuli.

This chapter describes Experiment 2 which consists of two parts; the estimation of TA using BC and lateralisation performance using AC and BC stimulation. The main aim is to explore whether a subject's TA influences their lateralisation performance using BC stimulation. Lateralisation using AC was included as a comparison to using BC to investigate whether a subject showing poor lateralisation ability with BC is also poor with AC, and vice versa. If this is the case, a central influence may be suggested. Each subject completed all three elements, which have been described separately for clarity.

5.2 Experimental rationale

Transcranial attenuation of bone-conducted sound has been defined as 'the difference in sensitivity between an ipsilaterally transmitted and contralaterally transmitted BC sound when the stimulation is at a similar position at the two sides of the cranium' (Stenfelt 2012). In theory, larger TA leads to larger interaural isolation, whether using AC or BC stimulation. Previous literature shows that interaural isolation is greater with AC than BC, by reporting the level of TA to be less with BC than AC (Snyder 1971; Nolan & Lyon 1981). For clinical purposes, TA with AC is accepted to be between 40 and 80 dB (Munro & Contractor 2010) compared to 0 to 15 dB for BC (Studebaker 1967). Therefore interaural isolation, which is important for spatial perception, is much reduced for BC compared to AC. For many years

unilateral fitting of BAHAs has been accepted as appropriate as one stimulus presented to the skull is perceived by both cochleae due to the crossed pathway. However, recent research using bilateral BAHA wearers shows at least some lateralisation ability, implying that some subjects can access binaural cues with BC (Bosman et al. 2001; van der Pouw et al. 1998; Priwin et al. 2004). Individual differences in lateralisation ability may be linked to individual differences in TA. Experiment 2 investigated variation in TA and lateralisation ability between subjects. Lateralisation ability was used as a measure to investigate whether binaural cues are accessible via BC.

The main aims of Experiment 2 were to determine:

1. If there is inter-subject variation in the ability to lateralise a 1 kHz tone using BC stimulation.
2. When using the same subjects, is there inter-subject variation in TA.
3. If so, whether the inter-subject variation in TA is related to inter-subject variation in the ability to access ITD and ILD as in Aim 1.
4. To evaluate experimental methods and become aware of issues associated with psychoacoustic experimentation using BC stimulation and human subjects.

5.3 Experimental overview

Experiment 2 was comprised of two parts, the estimation of TA and lateralisation ability using AC and BC, as depicted in Figure 5.1. Ten normally hearing subjects were recruited and completed both parts.

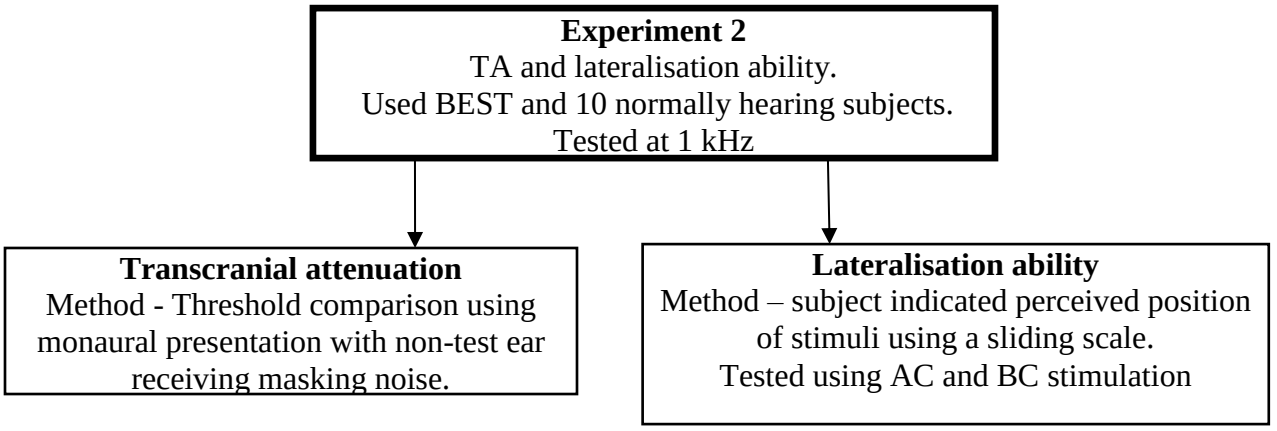


Figure 5.1 Schematic illustration of the organisation of Experiment 2.

Transcranial attenuation was calculated by comparison of BC hearing threshold levels measured with the BV placed on the mastoid of the test ear and then placed on the mastoid of the non-test ear, as shown in Figure 4.3. The non-test ear was prevented from hearing the tone due to masking noise presented via AC. Subjects heard three bands of narrowband noise presented to the non-test ear while the tone was presented to the test ear to coincide with one of the noise bands. The task was to indicate which band of noise contained the tone by pressing one of three keys on a standard QWERTY keyboard.

Lateralisation ability was estimated using AC and BC. Tones were presented bilaterally using varying ILD and ITDs to create the perception of a tone that originated at a predetermined position along the interaural axis. Subjects used a sliding scale, which represented the interaural axis, to indicate the perceived origin of the tone between right and left ears. Procedural details can be found in Section 4.4.

5.3.1 Results: TA

Hearing threshold level was measured in ipsi- and contralateral ears for the right as test ear (RTE) (i.e. TA measured from left to right ear) and left as test ear (LTE) (i.e. TA measured from right to left ear) three times in each testing session, on three days, generating a total of nine HTL estimates. At the end of each session, mean HTL was estimated for ipsi- and contralateral ears for RTE and LTE and compared to ascertain TA for that session. The TA measured in each session was then used to calculate mean TA for each subject. For clarity, an example is shown in Table 5.1.

Table 5.1 Example of how mean transcranial attenuation (TA) was calculated using hearing threshold level (HTL) with right as test ear (RTE) and left as test ear (LTE).

Session 1	**Ipsilateral ear**		**Contralateral ear**		**Session TA (Contra – ipsi)**
	HTL (dB HL)	**Mean HTL (dB HL)**	**HTL (dB HL)**	**Mean HTL (dB HL)**	
RTE	1 2 1	1	12 13 11	12	11
LTE	0 1 -3	-1	6 11 11	9	10
Session 2					
RTE	2 3 5	3	6 6 6	6	3
LTE	-2 -3 -2	-2	10 11 9	10	12
Session 3					
RTE	-3 1 -5	-2	8 6 7	7	9
LTE	1 3 3	2	8 11 13	11	9
					Mean TA
	TA RTE	11	3	9	8
	TA LTE	10	12	9	10

Transcranial attenuation is derived from HTL measurements which are known to be influenced by a number of factors, including subject motivation, fatigue and BV placement effects. Transcranial attenuation was calculated by subtracting HTL measured in the contralateral from HTL measured in the ipsilateral ear, where the ipsilateral ear is the test ear. For each subject, both right and left ears were assigned as test ear in turn. Hearing threshold level was measured using the right as test ear (RTE) and left as test ear (LTE) three times each, on three different occasions. Figure 5.2 shows each measured HTL (i.e. nine estimates) for contralateral (black diamonds) and ipsilateral (red triangles) ears with LTE for each subject. The heavy red and black lines represent mean HTL for contralateral and ipsilateral ears respectively. The thin red and black lines represent ± 1 SD.

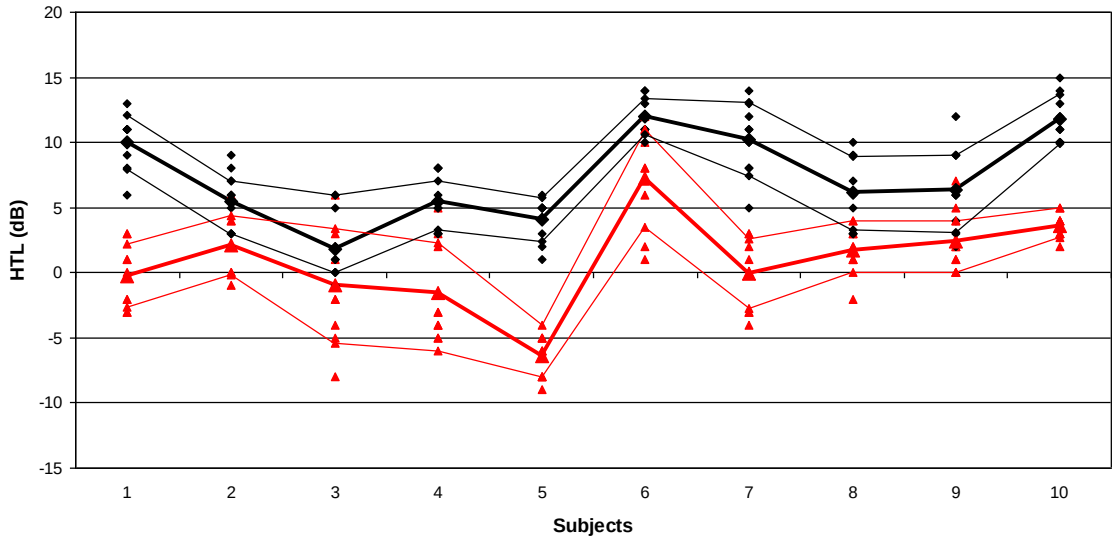


Figure 5.2 Variation in hearing threshold level (HTL) for contralateral (black diamonds) and ipsilateral (red triangles) ears when the left is the test ear for each subject.

Figure 5.3 shows variation in HTL when the right is the test ear.

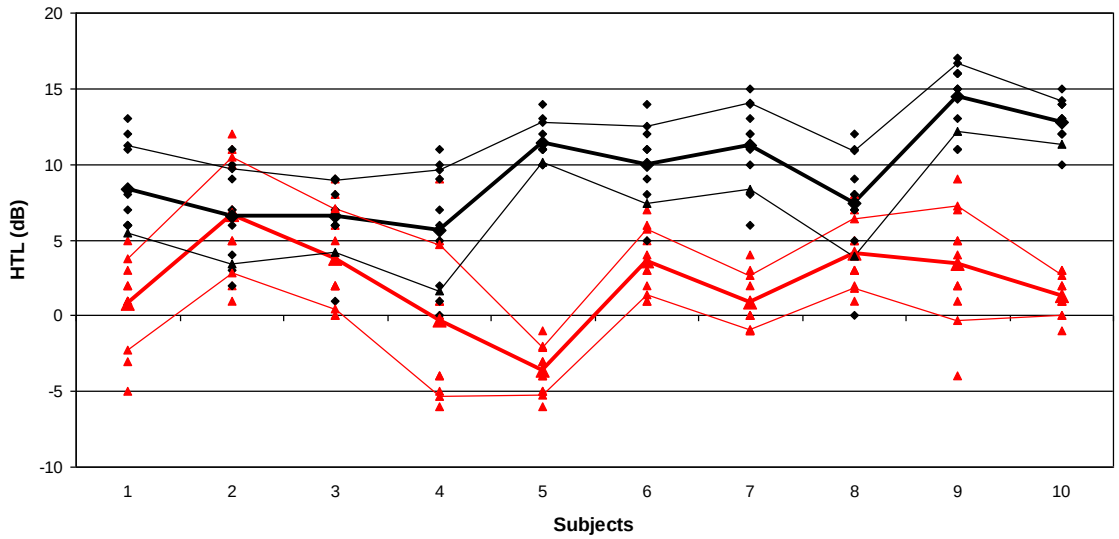


Figure 5.3 Variation in hearing threshold level (HTL) for contralateral (black diamonds) and ipsilateral (red triangles) ears when the right is the test ear for each subject.

Figures 5.2 and 5.3 show the range and mean HTL measured for each subject using both ears during the three sessions. Standard deviation varies between 1 and 5 dB with a mean of 1 dB and SE of 0.2 dB. Frank & Ragland (1987) found no significant difference in repeat BC HTLs for frequencies between 1 and 16 kHz. However, Hart & Naunton (1961) reported variation of 5 dB at 1 kHz with the BV placed on the mastoid.

Standard deviation from BC threshold test-retest has been shown to be between 3.2 and 4.8 dB in the frequency range 0.25 to 4 kHz (Laukli & Fjermedal 1990). In that study, HTL was measured twice on the same day and not on consecutive days as in Stenfelt (2012). Stenfelt used a step size of 1 dB compared to 5dB used by Laukli & Fjermedal.

Mean TA for each subject is shown in Figure 5.4. These results reveal a wide range of TA between subjects, with a minimum of 0 dB and a maximum of 15 dB. Standard deviation varies between 1 and 5 dB with a mean of 3 dB. Most subjects had a similar TA in each ear, with Subjects 5 and 9 showing the largest asymmetry.

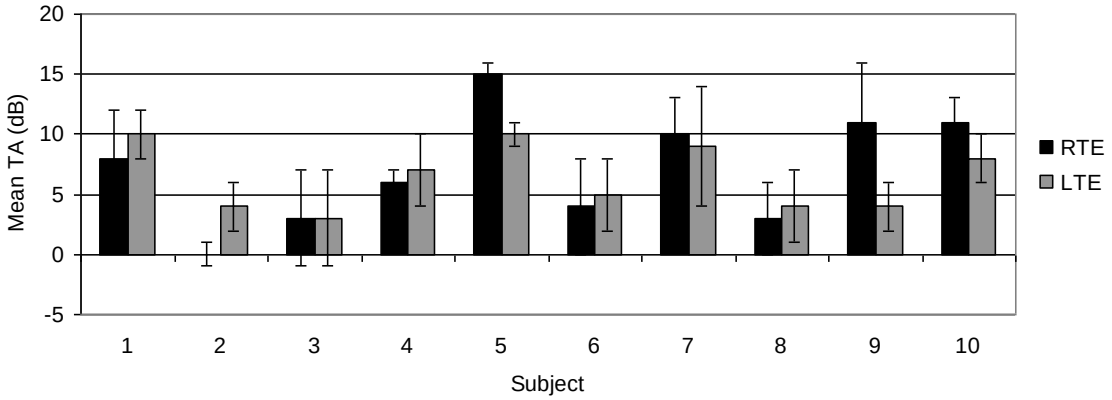


Figure 5.4 Mean transcranial attenuation (TA) estimated on three different days, for right as test ear (RTE) and left as test ear (LTE) for each subject. (Error bars represent ± 1 SD)

Difference in TA between RTE and LTE for each subject was investigated to ascertain whether the difference could be attributed to chance measurement differences. Mean TA for each subject was found to be normally distributed for six subjects and deviated from normality for four, therefore non-parametric analysis was carried out. Paired-samples Wilcoxin Signed Rank Tests were used. A Bonferroni correction gave a criterion probability of 0.005 (0.05/10) and statistical significance was not reached for any subject. This implies the differences between mean RTE TA and mean LTE TA for each subject could be due to chance measurement error.

For the current experiment, Shapiro-Wilks tests revealed that overall mean TA (for all subjects combined) for RTE and LTE are normally distributed so parametric analysis was carried out. A paired sample *t*-test showed no statistically significant difference between mean TA with RTE (M 7 dB, SD ± 5 dB) compared to LTE (M 7 dB, SD ± 3 dB) ear ($t = 0.47$, $df = 9$, two tailed $p = 0.653$). A significant positive correlation was found between mean TA measured with RTE and LTE ($r = 0.83$, $df = 9$, $p = 0.003$). This implies that the TA measured in one ear may be predicted by the TA measured in the other.

Overall mean TA was calculated using TA of all ten subjects for RTE and LTE combined (M = 7 dB, SD = 4 dB) and is in agreement with previous research using psychoacoustic methods. Snyder (1971) reported a mean of 7 dB (SD ± 6.6 dB) and Nolan & Lyon (1981) reported a mean of 7 dB (SD ± 5.3 dB).

Test-retest reliability across the three sessions was investigated by calculating Cronbach's Alpha and is shown in Table 5.2. Cronbach's alpha is an internal consistency estimate of the reliability of test scores. As the intercorrelations among test items increase, Cronbach's Alpha score will also increase. A value of between 0.7 and 0.8 is usually considered an acceptable value of Cronbach's Alpha (Field 2005).

Table 5.2 Test-retest reliability for transcranial attenuation (TA), estimated with the right as test ear (RTE) and left as test ear (LTE) measured in three sessions.

Subject	RTE 1	RTE 2	RTE 3	LTE 1	LTE 2	LTE 3
1	11	3	9	10	12	9
2	0	-1	1	5	1	5
3	5	4	-1	1	6	3
4	7	6	5	8	9	4
5	14	15	16	11	11	9
6	3	11	6	6	1	7
7	12	7	12	14	12	5
8	5	0	5	1	4	7
9	5	12	15	2	6	3
10	10	13	12	10	8	7
Range	0-14	-1-15	-1-16	1-14	1-12	3-9
	Cronbach's Alpha RTE		**0.84**	**Cronbach's Alpha LTE**		**0.73**

Test-retest data reported by previous studies is meager. Nolan & Lyon (1981) estimated TA on two occasions using 10 normally hearing subjects. They report a reliability coefficient of 0.93 at 1 kHz which implies that test-retest reliability is good.

5.3.2 Discussion: TA

The reported value of TA at 1000 Hz is variable in the present literature. One aim of estimating TA in Experiment 2 was to contribute to present knowledge and reassess the value of TA at 1000 Hz. Also, TA was estimated using this method as a pilot for use in Experiment 3, to judge whether TA could be estimated quickly and reliably. Transcranial delay was estimated during Experiment 3 using phase cancellation. Phase cancellation can be difficult to achieve without an accurate value of TA.

The method used in Experiment 2 is similar to that used by previous studies investigating TA, for example, Nolan & Lyon (Group A), (1981). Experiment 2 revealed a mean value of TA and standard deviation that is in agreement with previous estimates of 7 dB as reported by Snyder (1971) and Nolan & Lyon (1981). Experiment 2 also showed a similar inter-subject variation of mean TA, in the order of 20 to 30 dB as shown in Table 2.3 and further discussed in Section 6.4.5.

Mean TA and SD found in Experiment 2 is similar to previous studies using normal hearing and unilateral deaf subjects. This method was easy to understand with limited training and so was used again to estimate TA in Experiment 3.

5.3.3 Results: Lateralisation ability

Lateralisation ability was estimated using stimuli manipulated by varying ILDs and IPDs to present a pure tone at a predetermined position along the interaural axis. This was carried out using AC and BC stimulation. Each subject lateralised five positions using ILD and IPD, 20 times in two blocks of 10. Each block of 10 was completed on different days. Individual plots using AC and BC for ILD and IPD are shown in Appendix D. Mean perceived position was calculated for each subject and the overall mean, consisting of the mean of the subject means, and SD of the means, using stimuli manipulated using ILD and IPD for all subjects are plotted for AC and BC in Figures 5.5 and 5.6. Referring to Figure 5.5, a lateral position of 0.00 relates to an ILD of -15 dB and 1.0 relates to an ILD of +15 dB. In Figure 5.6, 0.00 relates to an IPD of -90º and 1.00 relates to an IPD of 90º. For a stimulus of 1000 Hz, an IPD of ±90º equates to a time shift of ± 0.25 ms.

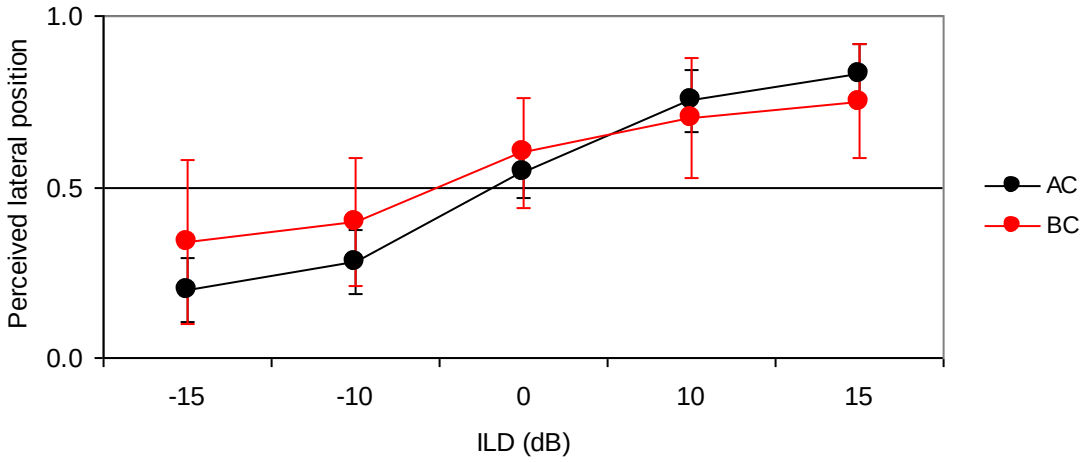


Figure 5.5 Mean perceived lateral position, using interaural level difference (ILD) for AC and BC stimulation. A stimulus perceived to the subject's left is represented by 0.0, centrally by 0.5 and to the right by 1.0. (Error bars represent ± 1 SD).

Figure 5.5 shows that for ILD, the BC tone was perceived as being more toward the front, whereas for AC the stimuli tended to be perceived to come from a wider range of angles. For IPD, shown in Figure 5.6, AC and BC stimuli were perceived as coming from a similar lateral position, with BC showing greater laterality than AC in some cases. This is clearly seen by comparing the relative traces for AC and BC stimulation in Figure 5.6.

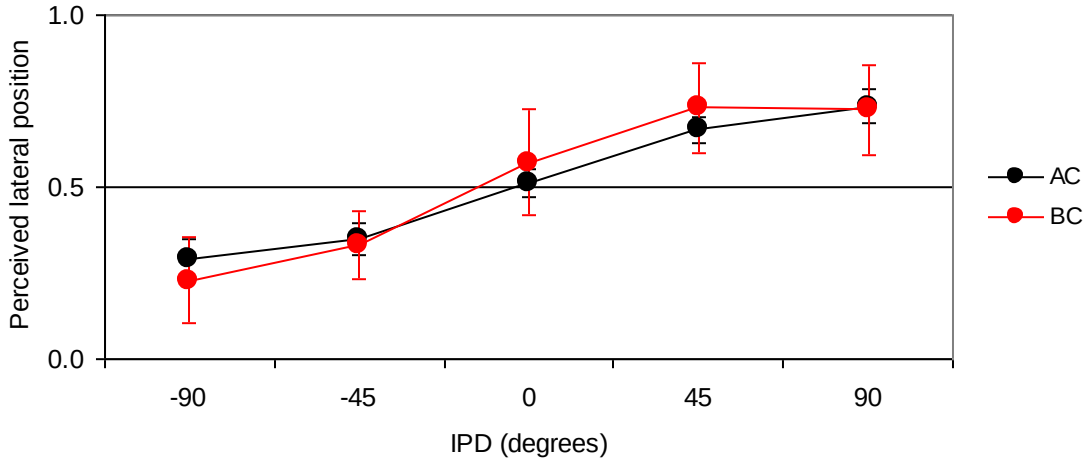


Figure 5.6 Mean perceived lateral position using interaural phase difference (IPD) for AC and BC stimulation. A lateral position of -90o is indicated by 0.0 and 90o by 1.0 (Error bars represent ± 1 SD).

Variation around the mean, as depicted by standard deviation, is larger for BC than AC when lateralising using both ILD and IPD. This greater variation in perceived position of the stimulus implies that subjects were less able to accurately identify the origin of the sound when listening via BC compared to AC.

5.3.4 Discussion: Lateralisation

Experiment 2 investigated the ability of normal hearing subjects to access binaural cues when listening via bilateral BC stimulation. Subjects were asked to indicate the perceived position of the origin of a 1 kHz pure tone that was manipulated to produce a sound at predefined positions on the interaural axis running between right and left ears through the skull, a method previously described by Yost (1981). The main aim was to explore lateralisation ability with BC. Lateralisation performance using AC performance using insert earphones was also measured and used as a comparison to BC performance as well as to act as a check on the experimental design.

5.3.5 Lateralisation with AC

Sinusoids presented bilaterally via AC with an ILD or IPD imposed on them, produce the perception of a fused image situated at a position on the interaural axis determined by the ILD or IPD. When listening via AC, the perceived lateral position of sinusoids presented with ILD and IPD has been shown to be linearly related for ILDs up to ± 15 dB and ± 90^{o} respectively (Yost, 1981). Beyond these limits, lateralisation performance breaks down. These parameters were used for Experiment 2. Figures 5.5 and 5.6 show variation in mean lateralisation ability for ILD and IPD. Yost reports a similar finding and suggests variability may be attributed to the experimental procedure or the diffuse nature of the fused image or a combination of both. Yost (1981) used stimuli of duration varying between 0.02 and 0.5 s and notes that subjects report the short duration image to appear to be like a "point" while the longer duration signals appear more like an "area". Experiment 2 used stimulus durations of 0.4 s which may produce a diffuse stimulus and therefore variable results. This duration was used as a result of feedback from subjects during piloting. Subjects found it more difficult to ascertain the perceived origin of the sound using a shorter duration.

Based on the extent of laterality shown in Figures 5.5 and 5.6, lateralisation performance using AC was better when using ILD than IPD which may be due to several factors. Firstly the wavelength of a 1 kHz pure tone has been shown to create ambiguous IPD cues. Recall the duplex theory of localisation states that sensitivity to phase differences declines with frequency, with an upper limit of between 0.7 and 0.8 kHz (Rayleigh 1907), although more recent studies have reported localisation performance for sinusoids to be poorest for the frequency range of 1.5 to 3 kHz (Sandel et al. 1955), implying that cues for IPD are accessible to 1.5 kHz and ILD above 3 kHz. Furthermore, using pure tones presented via headphones, subjects have shown sensitivity to IPD in the ongoing part of the stimulus for frequencies up to approximately 1 to 1.3 kHz (Zwislocki & Feldman 1956). Although IPD cues within the ongoing part of the stimulus may become ambiguous at frequencies beyond 0.7 to 0.8 kHz, IPD cues have been shown to be detectable from the onset, offset and envelope of the stimulus at higher frequencies (Middlebrooks & Green 1991; Bernstein & Trahiotis 2002).

Secondly, pure tones were used for Experiment 2, which has been shown to be more difficult for the listener to lateralise than bands of noise (Middlebrooks & Green 1991). A stimuli with a broad bandwidth provides the listener with the means to resolve spatial ambiguities due to the availability of a wider range of frequency dependent cues that are absent when using narrow band stimuli.

Thirdly, a number of subjects reported difficulty in transferring the perceived position of the stimulus within their head to the scale on the monitor. It is possible that lateralisation performance error was enhanced due to inaccuracy when recording perceived position on the monitor.

The above factors are likely to have created measurement error due to difficulties carrying out the task. Therefore, the method used was altered before using to measure lateralisation ability during Experiment 3. The task was changed to one where the subject used an 'acoustic pointer' to indicate the perceived position of the tone. Furthermore, the stimulus was changed to a narrowband of noise. Details are fully explained in Section 7.2.

5.3.6 Lateralisation with BC

As the same task was used to measure lateralisation ability using BC as AC, the uncertainties described in the previous section i.e. upper limit for sensitivity to IPD cues, type of stimulus and difficulty of the task, also apply to BC lateralisation.

Transcranial attenuation using BC can be as low as 0 dB (Nolan & Lyon 1981; Stenfelt 2012) making cross talk a very real possibility. A high level of cross talk implies poor lateralisation ability due to lack of interaural isolation. Previous studies are limited in number and varied in method, making comparisons difficult. However, lateralisation ability has been reported with BC and considered as proof that cues for binaural hearing are accessible by some subjects via bilateral BC (van der Pouw et al. 1998; Priwin et al. 2004; MacDonald et al. 2006). This may be explained by variation in TA among subjects.

Figure 5.5 shows mean perceived lateral position as a function of ILD using BC stimulation. When presented with a stimulus via BC manipulated by ILD of ± 15 dB, full lateralisation

ability would be indicated by mean perceived position of the sound to be at ± 15 dB, shown as 0.0 to 1 on Figure 5.5. However, mean perceived stimulus position was the equivalent of approximately 8 dB and -10 dB, making perceived position of the stimulus 7 and 5 dB, respectively, short of the expected position. Figure 5.6 shows the mean perceived lateral position as a function of IPD, using bilateral BC stimulation. When presented with a stimulus manipulated by IPD of ± 90^{o}, shown as 0.0 to 1 on Figure 5.6, the mean perceived position of the sound was the equivalent of -71^{o} when presented with -90^{o} and 63^{o} when presented with 90^{o}. This again reveals perceived lateralisation to be short of the target position. This observation concurs with previous studies that demonstrate lateralisation ability with BC, although less accurate than with AC.

5.3.7 Lateralisation with AC compared to BC

Previous studies comparing lateralisation ability with AC and BC are not in agreement. Some studies show similar results using AC and BC (MacDonald et al. 2006). While others report a weaker performance using BC compared to AC (Stenfelt & Zeitooni 2013). The current study implies that lateralisation with AC is better than with BC, when using stimuli manipulated via ILD and 1 kHz pure tones. This is clearly shown in Figure 5.5 where the target stimuli were perceived to be more towards the front by approximately 50% compared to AC. However, when the stimuli were manipulated via IPD the opposite was revealed and greater laterality was shown using BC than AC. One possible explanation is based on the frequency of the stimulus. A pure tone of 1 kHz is at a frequency that when using AC can lead to ambiguous IPD cues and therefore difficulty in accurate lateralisation (Sandel et al. 1955).

The speed of sound through air is 340 m/s, through the skull is between 2200 and 3100 m/s and through brain matter is between 1532 to 1550 m/s (Henry & Letowski 2007). Therefore, when listening via BC, vibrated sound may travel faster to the cochlea through the skull compared to AC, resulting in a longer wavelength and therefore less ambiguity for IPD cues at 1 kHz.

When lateralising 1 kHz pure tones manipulated via ILD, a wider variation is revealed by standard deviation for BC compared to AC. A paired sample *t*-test showed a significant difference between SD for AC (M = 0.09 dB, SD = 0.007 dB) and BC (M = 0.19 dB, SD = 0.03

dB). Greater mean SD for BC suggests that the perceived position of the stimulus is more variable when listening via BC than AC (t = -8.22, df = 4, two tailed p = 0.001). Standard deviation for IPD again showed wider variation for BC than AC, although to a lesser extent. A paired sample t-test showed a significant difference between SD for AC (M = 0.08 dB, SD = 0.01 dB) and BC (M = 0.13 dB, SD = 0.02 dB) (t = -4.39, df = 4, two tailed p =0.012). This result indicates greater variation in perceived position of the stimulus when listening via BC compared to AC.

5.3.8 The effect of varying levels of TA on lateralisation ability using BC

The advantage of binaural auditory input using AC in respect of loudness summation (Marks 1978) and the ability to localise sound is well documented (Gelfand 2004). It has long been considered that listening via BC severely limits the ability to access binaural cues due to crossed acoustic pathways which adversely affect the ability to localise sound (Zurek 1986). A number of studies have demonstrated that some subjects appear able to localise sounds in the horizontal plane, indicating the accessibility of binaural cues using BC (van der Pouw et al. 1998; Bosman et al. 2001; Priwin et al. 2004; MacDonald et al. 2006). Variation in bone density between subject skulls is expected to result in different amounts of TA. Differences in inter-subject TA may explain inter-subject variation in localisation ability with BC stimulation.

Statistical analysis of the relationship between differing levels of TA and lateralisation ability is difficult, due to different output measures being used. Previous studies have investigated TA (Snyder 1971; Nolan & Lyon 1981; Stenfelt 2012) and lateralisation ability with BC (van der Pouw et al. 1998; Bosman et al. 2001; Priwin et al. 2004), but it seems that no other studies have investigated the effect of different levels of TA on lateralisation ability with each subject. Another issue to consider when investigating the relationship between TA and lateralisation ability is the amount of variation seen with BC stimulation. Mean SD for TA estimates for each subject varied between 1 and 5 dB, with an overall mean SD of 3 dB. Also TA was found to be asymmetric between right and left ears in some people. For example, TA for Subject 9 is 11 dB in the right ear and 4 dB in the left. According to previous studies, 11 dB is a relatively high TA, while 4 dB is low. Standard deviation for the right ear is 5 dB and 2 dB for the left, showing a higher variability in the right ear making the true mean less certain.

As already explained, concerns were raised regarding the method used to measure lateralisation ability using AC because subjects seemed to perceive the stimulus to be in front of them and not as far out to the sides as would be expected. For this reason, further analysis was not carried out and Experiment 2 served as a pilot for Experiment 3.

Chapter 6

Experiment 3: TA and TD

6.1 Introduction

This chapter describes and discusses TA and TD measured in Experiment 3. The main aim of Experiment 3 was to build on the outcome of Experiment 2, which considered the influence of TA on lateralisation ability. Experiment 3 also considers the role of TD as well as TA in lateralisation ability with BC stimulation.

The theoretical rationale for undertaking this work is set out followed by an overview of the experimental design. Methological differences used in Experiment 3 compared to Experiment 2 are explained. Thereafter the chapter is split into two sections:

1. Estimation of transcranial attenuation (Section 6.4)
2. Estimation of transcranial delay (Section 6.5)

Each section contains additional methods followed by results and discussion. Additional methods, results and discussion regarding lateralisation ability can be found in Chapter 7.

6.2 Theoretical rationale

Normal AC hearing affords successful horizontal-plane sound localisation due to the brain's access to acoustical differences (the 'binaural cues') in a stimulus at the two pinnae (Hafter & Trahiotis 1997). Those differences are maintained at the cochleae due to the relatively high interaural isolation in the pathways from pinnae to cochleae.

When listening via BC, the interaural isolation is considerably less (Zwislocki 1953) and might be expected to make horizontal-plane localisation considerably more difficult if not impossible (Zurek 1986). However, there is evidence that some people can access the cues required for binaural hearing via BC and can show some horizontal-plane localisation (van der Pouw et al. 1998; Bosman et al. 2001; Priwin et al. 2004). Inter-subject variation in lateralisation ability may relate to inter-subject differences in interaural isolation due to differences in the transmission properties of the skull. In terms of the Zurek model of cross-talk (Zurek 1986),

inter-subject variation in BC localisation might be due to inter-subject variation in TA and/or TD.

Previous studies have reported marked inter-subject differences in TA and/or TD (Snyder 1971; Nolan & Lyon 1981). However, to the best of the author's knowledge, no studies have been carried out that estimate TA, TD and localisation in the same subjects and to explore any interrelationship in each individual.

Experiment 3 was carried out to address this gap: to provide an initial indication of whether there is a relationship between transcranial transmission and measures of the perception of the binaural cues with BC. As in Experiment 2, psychoacoustical measures were used to do this. Binaural hearing with BC was measured by the lateralisation of ITD and ILD, again investigated separately because the loss of acoustical isolation might affect them differently (Zurek 1986). Due to the difficulties in the interpretation of the lateralisation data from Experiment 2 (attributed to the method used), the desire to improve the measurement error associated with estimates of TA and the introduction of TD estimation, the measurement techniques were refined.

The aims of Experiment 3 were to determine:

1. If there is inter-subject variation in the access to ITD and ILD using BC stimulation.
2. Using the same subjects, if there is inter-subject variation in TA and TD.
3. If so, whether the inter-subject variation with Aim 2 is related to that with Aim 1.
4. Whether the inter-subject variation with Aim 2 might explain that with Aim 1.

6.3 Experiment 3: Structural overview

Experiment 3 consists of three tasks: the estimation of TA (using two different methods), TD and lateralisation ability using AC and BC. Transcranial attenuation was estimated using two methods. Firstly, the method of comparing BC hearing threshold levels (see Section 4.3) as used in Experiment 2 was again used to estimate TA in Experiment 3. This method was employed in previous studies (Nolan & Lyon 1981; Stenfelt 2012) and was found to be easy to understand for the subjects and straight forward to carry out. Next, TD was estimated by using

the method of phase cancellation. During phase cancellation, TA was calculated by the second method, by comparing the difference in BV output level when phase cancellation was achieved (see Section 6.5). For optimal cancellation, both phase and amplitude of the signals from the two BVs need to be matched.

Lateralisation ability was estimated using AC and BC. An acoustic pointer task was employed, where the perceived lateral position of the stimulus (presented via bilateral BC) was indicated by varying the ILD of an acoustic pointer (presented via bilateral AC) to match the perceived position of the target. Further details are explained in Section 7.2. This method has previously been used by Bernstein & Trahiotis (1985). The organisation of Experiment 3 is shown in Figure 6.1. Each subject was required to complete all parts of the experiment.

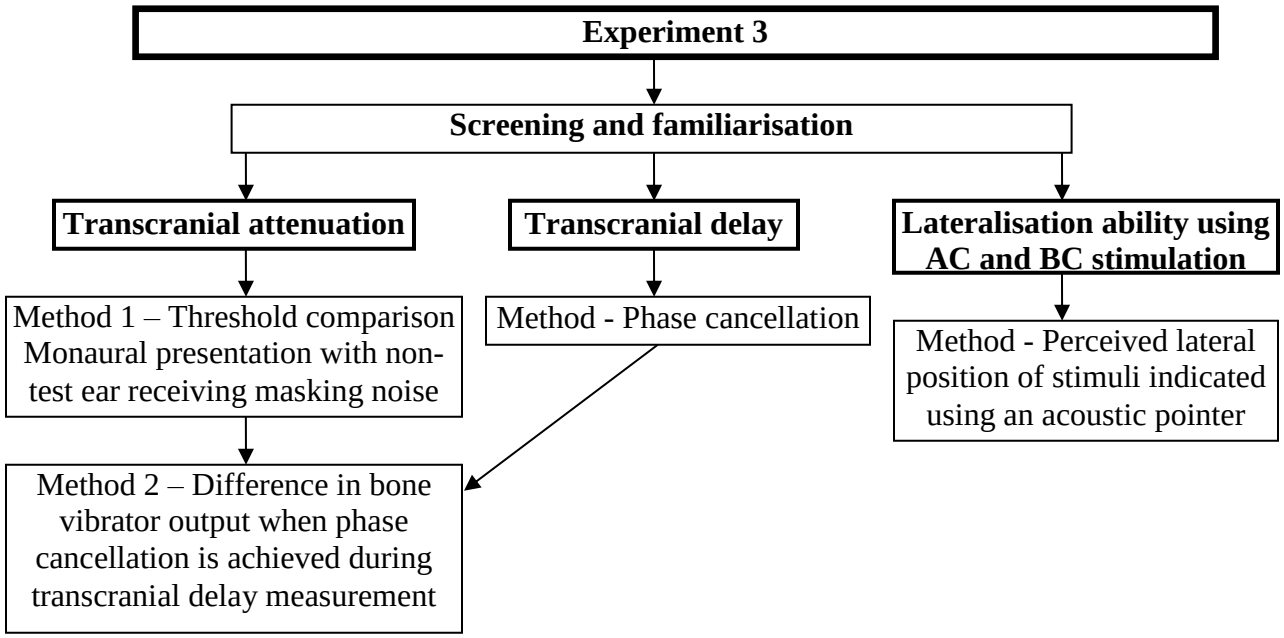


Figure 6.1 Schematic illustration of the organisation of Experiment 3.

A number of changes were made to the methods used to estimate TA and lateralisation ability between Experiments 2 and 3, and details can be found at the start of each relevant section. One difference that is common to all parts of Experiment 3 is the stimulus frequency. In Experiment 2, testing was carried out using a 1 kHz pure tone. This frequency was chosen to reduce difficulties that may occur due to issues with the BVs i.e. to avoid frequencies at which BVs

may become vibrotactile or produces strong air-borne radiation. A 1250 Hz pure tone was chosen for Experiment 3 for two reasons. Firstly to maximise the chance of finding subjects with varying levels of TA as TA has been reported to increase with increasing frequency, with a maximum between 3000 and 5000 Hz (Snyder 1971: Stenfelt et al. 2000: Stenfelt & Goode 2005: Stenfelt 2012). While a higher frequency was advantageous in terms of TA, a low enough stimulus frequency was needed to ensure subjects were still able to access ITDs. One frequency was tested only due to the demanding and time-consuming nature of Experiment 3. Each subject spent at least four hours in total, some more, completing the required tasks. While other frequencies would be interesting to test, the time commitment required of the subjects would have been prohibitive, with detrimental effects on recruitment and probably also data quality. The session content for each subject can be found in Appendix C.

6.4 Estimation of TA

6.4.1 Additional methods: TA

During Experiment 3, TA was measured twice. The first method used was threshold comparison, as used in Experiment 2 and described in Section 4.3. An estimate of TA was also determined when using phase cancellation to measure TD. For clarity, the results of the two methods of TA measurement are shown and compared before the experimental procedure used to measure TD is described in Section 6.5.

When measuring TA in Experiment 2, one BV was used and moved to each mastoid as required. This is likely to result in measurement error due to placement effects (Dempsey & Levitt 1990; Weston et al. 1967). In order to minimise the effect of BV placement, the two $BEST^{LFR}$ BVs were placed in turn on an artificial mastoid (type 4930) and the difference in output amplitude was found to be less than 1 dB. This difference was deemed to be sufficiently low to treat BVs as identical. The BVs were placed on the subject's mastoids concurrently and the BVs were alternatively activated with the same input signal and were adjusted (by repositioning the quieter one) to be subjectively equal in loudness. They were then left in place for the measurement of TA and TD.

An ear was assigned as the test ear. The tone was prevented from being perceived in the non-test ear by the presence of a 1/3 octave narrowband masking noise, presented at 45 dB EML via an insert earphone. The level of masking noise was chosen to be sufficiently loud to prevent perception of the tone in the non-test ear while not being loud enough to cause cross-masking, thereby increasing the threshold of hearing of the test ear. During piloting, the level of masking noise was found to be loud enough when narrowband noise was presented bilaterally at the same time as a monaural tone and the tone was not perceivable. The skull was stimulated using the BV on the side of the test ear using BV ipsilateral and then the side of the non-test ear using BV contralateral. Testing using the right as the test ear is shown in Figure 6.2.

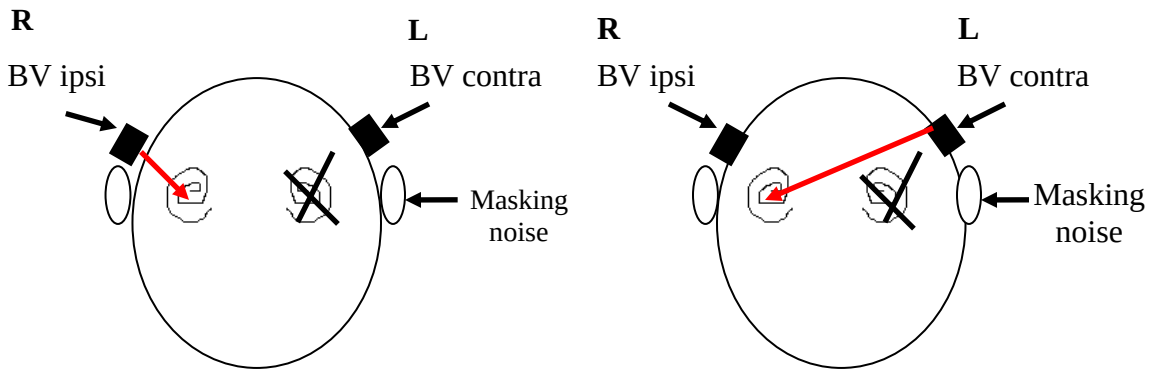


Figure 6.2 During Experiment 3, a BV was placed on each mastoid. An ear was assigned as the 'test ear' and masking noise presented to the 'non-test ear'. This example depicts the right as the test ear.

The order of testing was chosen randomly. Each HTL was estimated at least twice on each ear without altering the position of the BV for all subjects. If the difference between measurements was more than 5 dB a third measurement was taken. In every case the value of the third measurement was between the previous two. For each direction, TA was estimated by subtracting the HTL measured using the BV on the contralateral mastoid from that of the ipsilateral mastoid.

6.4.2 Results: TA

Transcranial attenuation was estimated using both the right as the test ear (RTE) and left as test ear (LTE) in 13 subjects. Results are shown in Figure 6.3. Mean for the RTE is 4 dB (SD = 6) and the left ear is 5 dB (SD = 4). Overall mean TA is 4 dB (SD 5 dB) with a range of -3 to 16 dB.

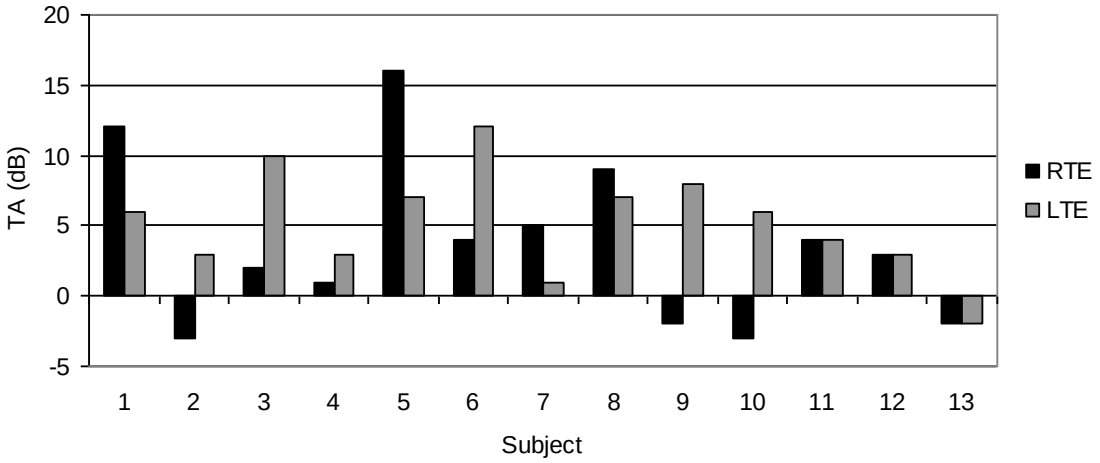


Figure 6.3 Transcranial attenuation at 1250 Hz measured in right (RTE) and left (LTE) ears using threshold comparison. (The absence of error bars is explained in the main text)

Transcranial attenuation was measured repeatedly in seven subjects, and so no error bars are included in Figure 6.3. While a subset of subjects repeated TA estimates, most completed one only. Figure 6.3 shows each subject's first TA measurement. Transcranial attenuation is a measurement derived from at least two BC HTL measurements, therefore measurement uncertainty of TA is linked to measurement uncertainty of each BC HTL measurement. For this reason, care was taken to ensure good repeatability of BC HTL measurement. The mean difference between measurements, taken without moving the BV was 2 dB (SD 2 dB, range 0 to 6 dB) for ipsilateral ears and 2 dB (SD 2 dB, range 0 to 7 dB) for contralateral ears.

Overall mean TA measured using each subject's first measurement of TA, using RTE (M = 4 dB) and LTE (M = 5 dB) is shown in Figure 6.4. Figure 6.4 shows that TA is higher by approximately 1 dB in the left ear, but variability is higher in the right ear.

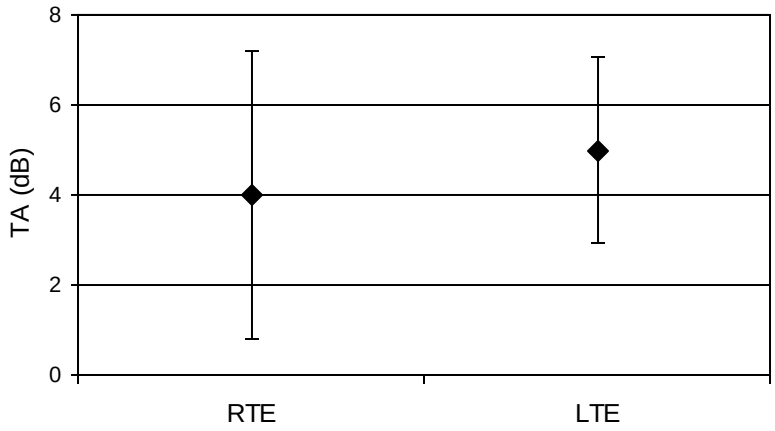


Figure 6.4 Overall mean TA using threshold comparison measured with right as test ear (RTE) and left as test ear (LTE) for all 13 subject's first TA measurement. (Error bars represent 95% confidence interval).

Variation in TA, as depicted in Figure 6.4 by 95% confidence interval, indicates that the mean of TA measured for RTE and LTE both lie within the expected boundaries of the population mean and therefore have a not significant relationship. This implies that the variation in TA measured using the right and left ears is due to chance.

Seven subjects repeated TA on two different days, Subjects 6 and 8 repeating both ears, giving a total of nine ears. Mean TA for Session 1 was 6 dB (SD = 4.24 dB) and for Session 2 was 4 dB (SD = 7.49 dB). This data is shown in Figure 6.5.

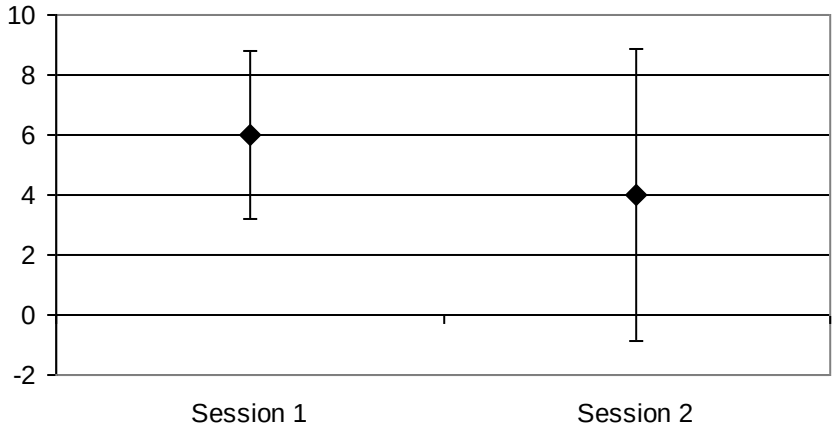


Figure 6.5. Variation of TA measured on two different days. (Error bars represent 95% confidence interval)

The difference in TA between days was typically 2 to 3 dB except Subject 2 whose range of TA values was 12 dB, which is reflected in the larger confidence interval seen for Session 2 compared to Session 1. The 95% confidence interval seen in Figure 6.5 imply that mean TA measured in Session 1 does not deviate significantly from mean TA measured in Session 2.

Transcranial attenuation was estimated using BC HTL comparison during Experiment 2 (N = 10) and Experiment 3 (N = 12). Figure 6.6 compares mean TA estimated during these experiments.

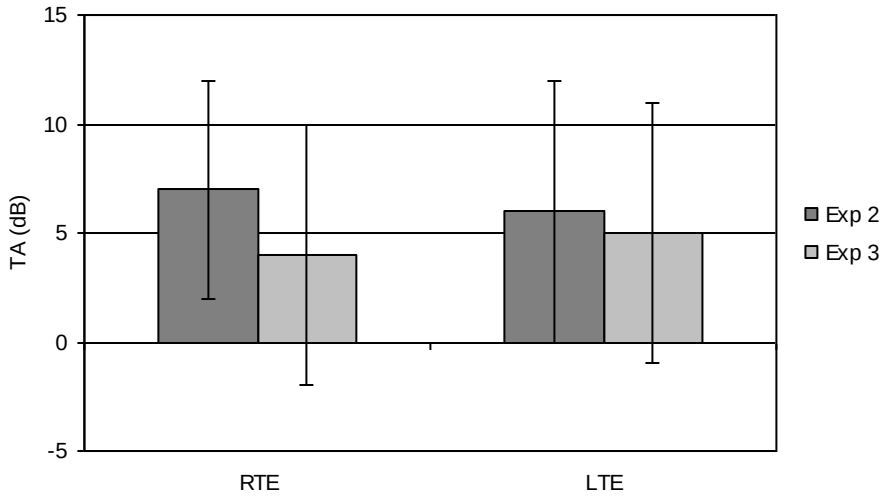


Figure 6.6 TA measured using threshold comparison during Experiments 2 and 3. (Error bars represent ± 1 SD).

For the right as test ear, mean TA is 2 dB higher in Experiment 2 (M = 6 dB) than in Experiment 3 (M = 4 dB). Mean TA for the LTE is also higher in Experiment 2 (M = 6 dB) compared to Experiment 3 (M = 5 dB). Shapiro-Wilks tests suggest mean TA in all four conditions to be normally distributed. An independent samples *t*-test showed that the mean for the RTE, Experiment 2 (M = 6 dB, SD = 5 dB) is not statistically significantly different (t = 1.16, df = 21, two tailed p = 0.26) from mean TA estimated in Experiment 3 (M = 4 dB, SD = 6 dB). The mean for the LTE, Experiment 2 (M = 6 dB, SD = 6 dB) is not statistically significantly different (t = 0.45, df = 21, two tailed p = 0.66) from mean TA estimated in Experiment 3 (M = 5 dB, SD = 6 dB). Difference as shown by SD is typically 6 dB for Experiment 2 and 5 dB for Experiment 3.

6.4.3 Results from phase cancellation: TA

Transcranial delay may play an important part in sound lateralisation with BC, so was included in Experiment 3. The experimental procedure for PC is described in Section 6.5. Before coming to this, the result of TA measured during PC is presented, compared to TA measured using BC HTL and discussed. One subject (Subject 8) was unable to achieve cancellation, so TA was found using PC in only 12 subjects.

Transcranial delay was measured using (PC) immediately after measuring TA, without moving the BVs. This avoided differences in perceived loudness due to BV placement effects. In order to find the point where complete cancellation occurs, it is necessary for the basilar membrane excitation from both BVs to be equal in amplitude in the test cochlea and anti-phasic (i.e. one excitation to be 180^{o} shifted compared to the other). If the basilar membrane response is not equal in amplitude, complete cancellation will not be achieved. An amplitude difference of only 2 dB greatly influences the degree of cancellation achieved and 6 dB makes it very difficult to detect (Kapteyn et al. 1983). When complete cancellation is found, the amplitudes of the two excitations are equal at the basilar membrane and the difference in amplitude output of the BVs can be assumed to be due to TA.

Transcranial attenuation (i.e. difference in BV output when cancellation is achieved) for each subject was determined for both pathways from right to left and left to right. Due to limitations of the duration that BVs could remain comfortably on the skull, difficulties in finding phase cancellation and restriction on the length of test sessions, subjects were asked to find phase cancellation once only.

Transcranial attenuation using PC was estimated using the RTE and the LTE in the 12 subjects. Results are shown in Figure 6.7. Error bars are not included as TA was measured only once. Mean TA for the right ear is 3 dB (SD = 5 dB) and the left ear is 4 dB (SD = 5 dB). Overall mean TA is 3 dB (SD 5 dB) with a range of -5 to 12 dB.

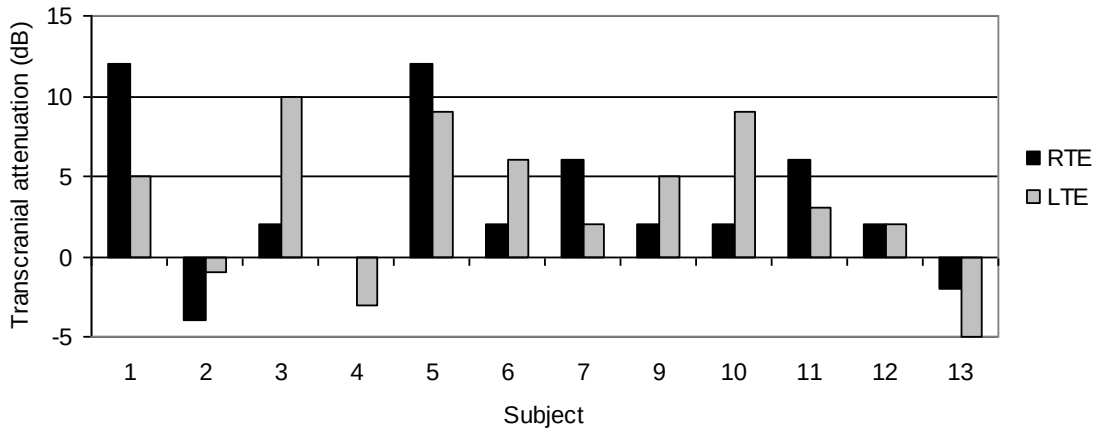


Figure 6.7 Transcranial attenuation measured for right as test ear (RTE) and left as test ear (LTE) during PC. Subject 8 was unable to achieve phase cancellation so has been omitted.

For all subjects, TA is either positive or negative for both ears of the same subject. Some left and right ear asymmetry is evident in the majority of subjects. Mean TA (N = 12) measured using PC with RTE and LTE is shown in Figure 6.8.

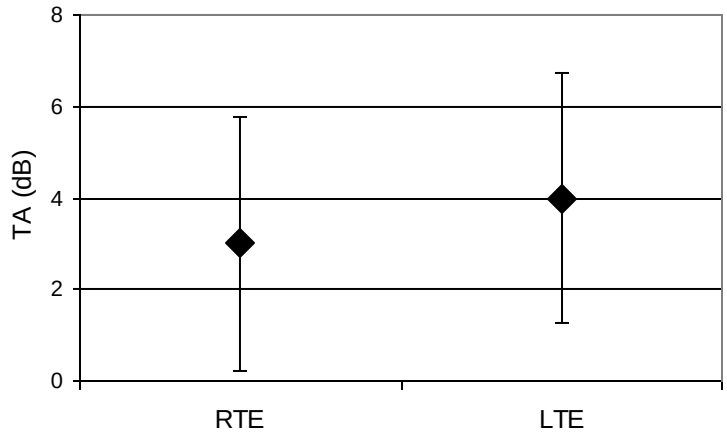


Figure 6.8 Mean TA revealed during PC measured in subject's right (RTE) and left (LTE) ears. (Error bars represent 95% confidence interval)

Figure 6.8 reveals mean TA to be higher in the left ear by 1 dB compared to the right ear and similar variation around the means. The upper and lower boundaries of the confidence intervals indicate that mean TA using the RTE and LTE are not significantly different, suggesting variation is due to chance.

Four subjects (6 ears) repeated PC on different days. Mean TA estimated in Session 1 (M = 3 dB, SD = 6.15 dB) was compared to mean TA for Session 2 (M = 3 dB, SD = 3.50 dB). Data is shown in Figure 6.9.

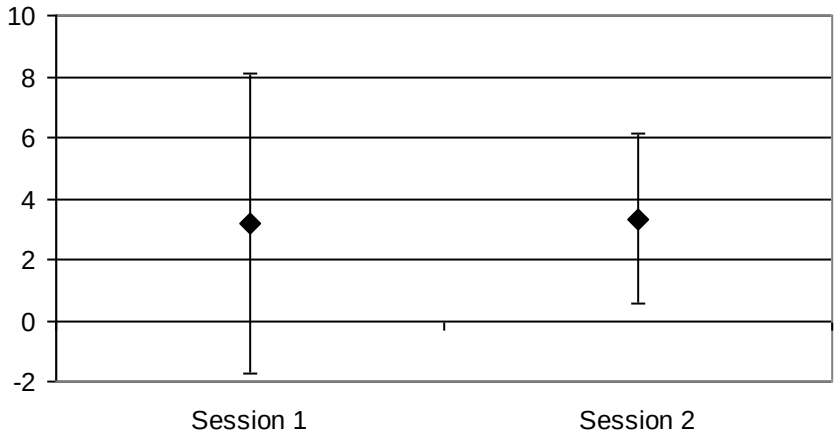


Figure 6.9 Comparison of TA measured using phase cancellation measured on two different days. (Error bars represent 95% confidence interval).

Good repeatability of TA measured in the two sessions is shown, with a highest variation of 6 dB. Inspection of the confidence interval boundaries suggests a not significant relationship between TA measured in Session 1 compared to Session 2.

The main aim of estimating of TA was to investigate inter-subject variation, as reported by previous studies (Snyder 1971; Nolan & Lyon 1981). Figures 6.4 and 6.8 reveal similar inter-subject variation in TA to previous studies, using two methods: threshold comparison and phase cancellation. Within-subject variation was investigated using a small number of subjects, by comparing TA measured on two different days. Again a not significant result was found revealing that variation in TA measured is likely to reflect the influence of removing and

replacing the BVs and subject factors (time of day, mood and alertness). Furthermore, within subject variation in TA is dependent on variation in hearing threshold level. Mean difference in HTL without moving the BV was found to be 2 dB, suggesting good repeatability of HTL measurements. The following section compares TA measured using two methods: threshold comparison and phase cancellation.

6.4.4 Comparison of results: TA measured using two methods

Transcranial attenuation was estimated using a direct and an indirect method. The method of TC is strongly subjective while the estimation of TA via PC is more objective. Although the point of maximal cancellation is a subjective loudness judgement, cancellation will not occur unless the amplitude of the stimuli creates an equal basilar membrane response. This makes a comparison particularly interesting. Figure 6.10 compares TA measured using the right (red dots) and left (blue dots) ears using both methods.

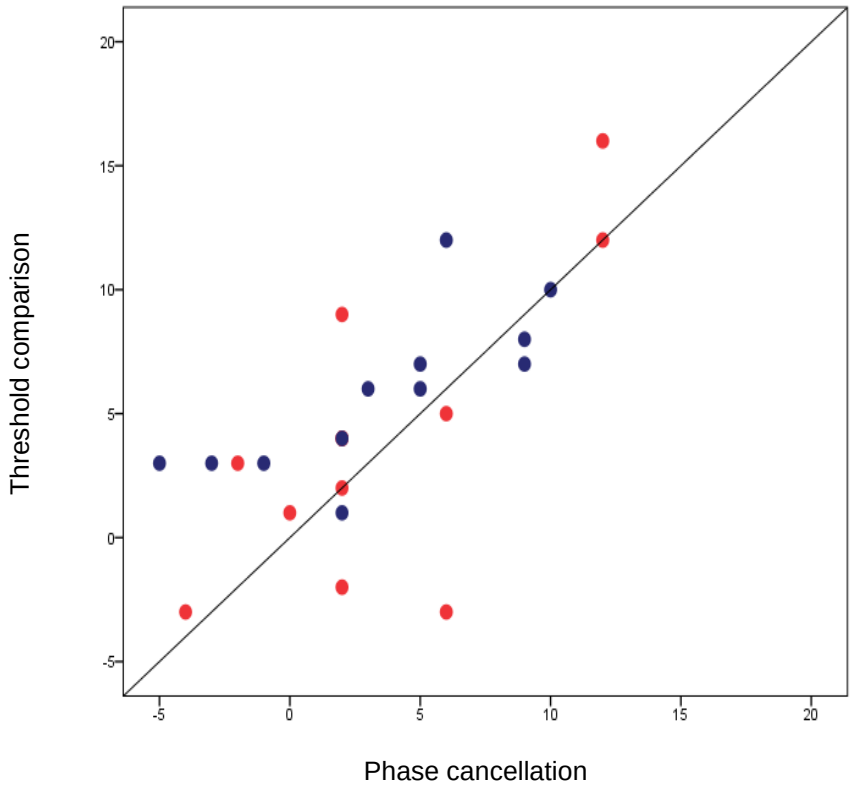


Figure 6.10 Scatterplot showing TA measured using threshold comparison and phase cancellation for individual ears. (Red dots indicate right ears and blue dots indicate left ears).

Approximately half the subject's TA estimates using each method were within 5 dB and Subjects 1, 3, 7 and 12 were within 2 dB. The comparison of TA estimated using TC and PC reveals similar mean and SD as shown in Figure 6.11. Mean values, as shown in Figure 6.11 are derived from each subject's first attempt for TA measured using TC and PC, within the same session, i.e. without replacing the BVs.

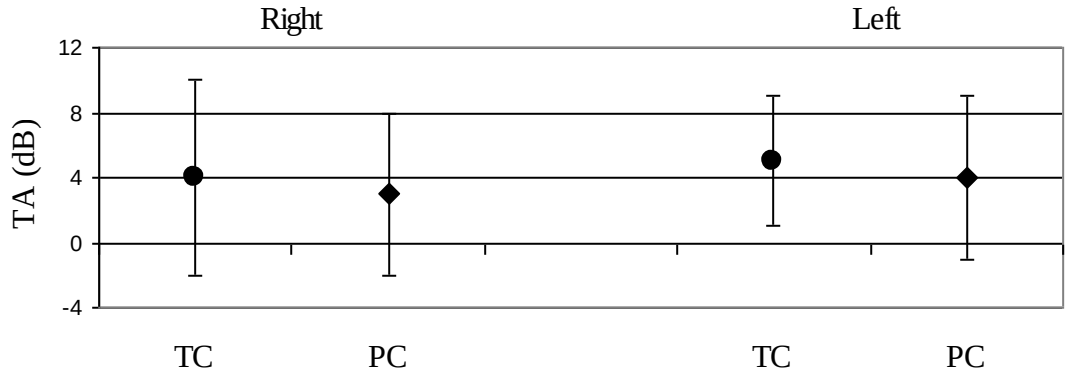


Figure 6.11 Mean TA measured using threshold comparison (TC) and phase cancellation (PC) for right and left ears (Error bars represent ± 1 SD).

Shapiro-Wilk test suggests no deviation from a normal distribution. An independent sample *t*-test showed no significant difference in method of TA measurement for right or left ears. For the right ear, mean TA measured using TC (M = 4 dB, SD = 6 dB) is not significantly different ($t = 0$, $df = 22$, two-tailed $p = 1.0$) than TA measured using PC (M = 3 dB, SD = 5 dB). For the left ear, mean TA measured using TC (M = 5 dB, SD = 4 dB) is not significantly different ($t = 0.664$, $df = 22$, two-tailed $p = 0.513$) than TA measured using PC (M = 4 dB, SD = 5 dB).

Mean TA for the right ear is 1 dB higher when measured using PC (M = 5 dB, SD = 4 dB) compared to using TC (M = 4 dB, SD = 6 dB). Mean TA for the left ear is 1 dB higher when measured using TC (M = 5 dB, SD = 4 dB) compared to using PC (M = 4 dB, SD = 5 dB). When measuring TA using TC, mean TA for the right ear (M = 4 dB, SD 6 dB) is 1 dB higher then the left (M = 5 dB, SD = 4 dB). When measured via PC mean TA for the right ear (M = 5 dB, SD = 4 dB) is 1 dB higher than the left (M = 4 dB, SD = 5 dB)

Overall mean TA measured using PC (M = 3 dB, SD = 5 dB) is less than TC (M = 4, SD = 5 dB), although not to a statistically significant amount. One possible influence could be the level of concentration demanded of the subject was arguably greater for PC, due to the difficulty of this task for subjects. Furthermore, PC was carried out after TA when the subject was possibly getting fatigued and the BVs may have been getting a little uncomfortable, which could have led to weakening concentration. It was not possible to randomise the order of testing TA and TD because the TA estimate was used to adjust one BV to compensate for TA to make the finding of TD quicker (see section 6.5.1).

Variation in TA measured using two methods does not reach statistical significance, indicating differences are due to measurement error, rather than methodological influences. This similarity between methods as well as compared to previous studies provides credence to the validity of the inter-subject variation in TA measured in the current study.

6.4.5 Discussion: TA

The aim of including the estimation of TA in Experiment 3, was to investigate the inter-subject variation in TA reported in previous studies (Snyder 1971; Nolan & Lyon 1981). Transcranial attenuation was also measured in Experiment 2, the result serving as a comparison to Experiment 3 and a measure of experimental consistency. Furthermore, TA was estimated using two methods during Experiment 3.

Thirteen subjects were used to estimate TA with right and left ear as test ear. Transcranial attenuation was calculated from BC HTL using 1250 Hz pure tones while presenting masking noise to the non-test ear via AC. This method is similar to that used by previous studies investigating TA, for example, Nolan & Lyon (1981) (Group A). Other studies used subjects with unilateral hearing loss, meaning that masking noise was not required to prevent the non-test ear perceiving the tone (Hurley & Burger 1970: Snyder 1973: Nolan & Lyon (1981) (Group B): Stenfelt 2012). Table 6.1 compares TA measured during Experiments 2 and 3 to those from previous studies. All previous studies used stimulation at the mastoid and a wider range of frequencies (i.e. 0.25 to 4 kHz). For comparison, only 1 kHz is shown.

Table 6.1 Comparison of TA reported by previous studies and Experiments 2 and 3.

Author	Subjects	BV	Data	1000 Hz	dB
Snyder 1973	120 Unilaterally deaf	B70A	Mean	TA ± SD	7 ± 6.6
				Range	-5 to 25
Hurley & Burger 1970	15 Unilaterally deaf	B70A	Mean	TA ± SD	4.1 ± 2.8
Nolan & Lyon 1981 (Group A)	15 Unilaterally deaf	B71	Mean	TA ± SD	8.5 ± 6.1
				Range	-5 to 20
Nolan & Lyon 1981 (Group B)	35 Normal hearing	B71	Mean	TA ± SD	7.3 ± 5.3
				Range	-5 to 20
Stenfelt 2012	28 Unilaterally deaf	B71	Mean	TA	2.1
				Range	-4 to 14
			Median	TA ± SD	1.5 ± 4.9
Current study Experiment 2	10 Normal hearing	BEST	Mean	TA ± SD	7.0 ± 3.78
				Range	0 to15
Current study Experiment 3 (HTL comparison)	13 Normal hearing	BEST	Mean	TA ± SD	4.19 ± 5.25
				Range	-3 to 16
Current study Experiment 3 Phase cancellation	12 Normal hearing	BEST	Mean	TA ± SD	3.4 ± 4.51
				Range	-4 to 12

Experiments 2 and 3 revealed mean TA in agreement with previous estimates. Stenfelt is the lowest, not being too dissimilar to Hurley & Burger. Nolan & Lyon (Group B) and the current study are the only ones to have used normal hearing subjects and are in agreement in mean TA, SD and range reported. The standard deviations and range of TA of the previous studies, where reported, are similar to the current study except Hurley and Burger which has a lower SD. There are procedural differences that may at least partially explain the difference in results. Three transducers have been used in the above studies (i.e. B70A, B71 and BEST) which differ

in size, weight and frequency response which may affect BC sound transmission as discussed in Chapter 3.

The current and previous studies show a large inter-subject range of TA, in the order of 20 to 30 dB. This can be explained by a number of factors. Individual skull characteristics in terms of bone density and resonant properties are expected to play a part in variability in TA (Stenfelt & Goode 2005). On arrival at the cochlea, vibrations from different BC pathways add constructively or destructively according to their relative phase, a phenomenon not yet fully understood. Inter-subject differences in the resonant property of the skull affects ipsi- and contralateral BC pathways differently in different subjects, (Stenfelt et al. 2000; Stenfelt & Goode 2005; Eeg-Olofsson et al. 2011; Zwislocki 1953; Tonndorf & Jahn 1981), which may explain the asymmetry seen in some subjects. Negative values of TA are reported (i.e. BC HTL is more acute when stimulated at the mastoid of the contralateral compared to ipsilateral ear) (Snyder 1971; Nolan & Lyon 1981; Stenfelt 2012). Negative values of TA can be explained by antiresonances and measurement error (differences in BV placement).

During Experiment 2, TA was estimated from BC HTL estimates using right and left ears of ten subjects. As the calculation of TA is derived from HTL estimates, variation in TA is dependent on variation in HTL estimates. The measurement of pure tone thresholds are known to be subject to measurement error due to test-retest variability. The source of variability is a combination of the subject's decision process (mood, state of arousal, motivation and fatigue), transducer placement and differences in transducer output. The current study strived to minimise the effect of these parameters across subjects and test sessions by keeping sessions short, avoiding testing late in the day and keeping subjects interested by altering the order of testing. During Experiment 2, care was taken to place the BV on the mastoid in a consistent place. Transducer output was calibrated regularly and subjective listening checks carried out prior to each testing session.

During Experiment 2, test-retest variation in TA was assessed on three different days using TC (20 ears tested) and during Experiment 3 on two different days using TC (9 ears tested) and PC (7 ears tested). Mean difference in TA for Experiment 2 is 5 dB, for Experiment 3 using TC is 2 dB and using PC is 0 dB. There are a number of explanations for this finding. Estimates of

TA from Experiment 2 are derived from three BC HTL estimates, whereas those from Experiment 3 comprise two repetitions. It may be expected that a greater number of repetitions, measured on different days may result in wider variation due to placement effects. Another contributing factor may be the positioning of the BVs was more consistent in Experiment 3 due to experience gained during Experiment 2.

Estimates of TA reported in Experiments 2 and 3, using both methods are not significantly different and are in concurrence with previous studies. This suggests wide inter-subject variation in TA is likely to be genuine and may play a role in explaining why some people seem more able to access binaural cues using BC than others. The next section considers transcranial delay.

6.5 Estimation of TD

6.5.1 Method: TD

The measurement of TD was introduced in Experiment 3, as it may play a role in lateralisation ability with BC, especially when TA is low. During Experiment 3, TD was estimated using phase cancellation, a method previously used by others (Zwislocki 1953; Tonndorf & Jahn 1981; Boezeman et al. 1984).

Phase cancellation has been used to investigate interaural isolation Zwislocki (1953), to measure the propagation velocity of BC sound through the skull of a human subject (Tonndorf & Jahn 1981) and has also demonstrated that the basilar membrane response is the same for AC and BC stimulation (Lowy 1942; Kapteyn et al. 1983; Boezeman et al. 1984). The methods of using an AC tone to cancel a BC tone and using a BC tone to cancel a BC tone was investigated during piloting and the BC tone cancelling a BC tone was found to be easier to achieve and was thus used.

The equipment set up used for Experiment 3 was similar to that depicted in Figure 4.2. The only difference was that the audiometers were placed in the test room as the subject used the loudness adjustment to alter the stimulus amplitude. Subjects were seated in a sound treated room, as before. The same pair of BEST^{LFR} BVs used to measure TA, were already placed

concurrently on the subject's skull as TD was estimated straight after TA, without moving the BVs. An insert earphone (E.A.Rtone 5A) was used to present a 50 dB EML masking noise, with duration of 0.4 s and ramp of 0.02 s, to the non-test ear. Stimuli were generated using MATLAB and passed through a stereo soundcard (Creative, Extigy) to two clinical audiometers (Kamplex, KC50). The stimulus was a 1250 Hz pure tone with a duration of 0.3 s and a ramp of 0.02 s and was initially calibrated to produce 40 dB HL to each BV. Each subject's TA was estimated immediately prior to the estimation of TD, and the TA measured was used to facilitate the detection of phase cancellation. Complete phase cancellation will only occur when two conditions are met. Firstly, bilateral stimulation is necessary and the amplitude response of the basilar membrane to each stimulus must be equal in magnitude. Secondly, stimuli must be anti-phasic on arrival at the test cochlea. Pilot work proved that trying to establish both the comparative amplitude and phase difference of the BVs to achieve phase cancellation was very time-consuming and would not be a viable method to use. To facilitate finding the point of phase cancellation the stimuli were initially presented at a loudness that was estimated to produce a similar amplitude response in the cochlea. This was achieved by increasing the output of the BV on the non-test mastoid by the TA just measured to compensate for the change in amplitude created by the TA. The subject then set out to find the point of phase cancellation with a chance of the relative loudness of the BVs being near enough to equal to find cancellation in a short time. Subjects adjusted the phase of one BVs, in step sizes of 10 and 2 dB, until partial phase cancellation was detected, then adjusted the amplitude difference to achieve as near complete phase cancellation as they were able.

During method development, subjects heard two bursts of a pure tone in succession with an inter stimulus interval of 0.4 s, presented bilaterally and differing in phase. This pair of tones was then repeated. If the subject perceived no difference in loudness between the tones, they altered the phase of the right stimulus and again heard the two tones (now with a larger phase difference). The task was to listen for cancellation as indicated by each set of two tones becoming quieter than the previous two, as depicted by the arrow in Figure 6.12.

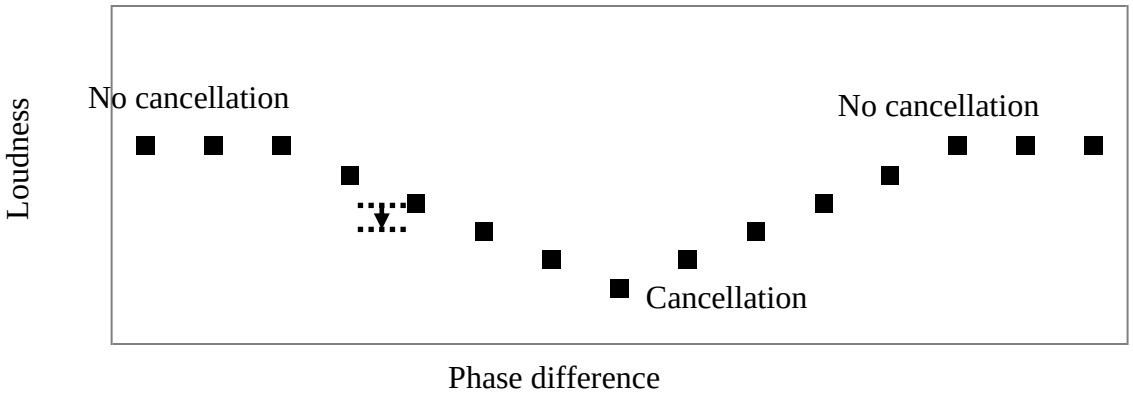


Figure 6.12 Each subject listened for a difference in loudness between two presentations.

However, using this method to detect phase cancellation proved to be difficult and time consuming. The main reason seemed to be due to difficulty in perceiving a difference in the loudness of the tones when the slope of cancellation was shallow. As steepness of cancellation is affected by difference in loudness of the stimuli arriving at the test cochlea, accuracy of TA measurement was crucial to quickly achieving phase cancellation. When the loudness of tone arriving at the test cochlea from each BV was equal, cancellation was quite clear as loudness dropped away steeply as the phase difference between BVs approached 180^{o}. If loudness was dissimilar, the slope of the cancellation was often too shallow for loudness changes to be perceived and cancellation was easily missed.

An innovative solution to this problem was found. Phase cancellation occurs when two stimuli arrive at the same cochlea and their combined effect on the basilar membrane results in neither being perceived. For this reason, phase cancellation can never occur with monaural presentation. The first tone was set as a binaural presentation and the second as monaural, meaning the subject was comparing the loudness of a binaural presentation with a monaural presentation, as shown in Figure 6.13. As the monaural stimulus will never alter in loudness, the difference in loudness of the two tones became large enough to be relatively easy to perceive. Subjects were then able to achieve cancellation more quickly. To the author's knowledge, the method depicted in Figure 6.13 has not previously been documented.

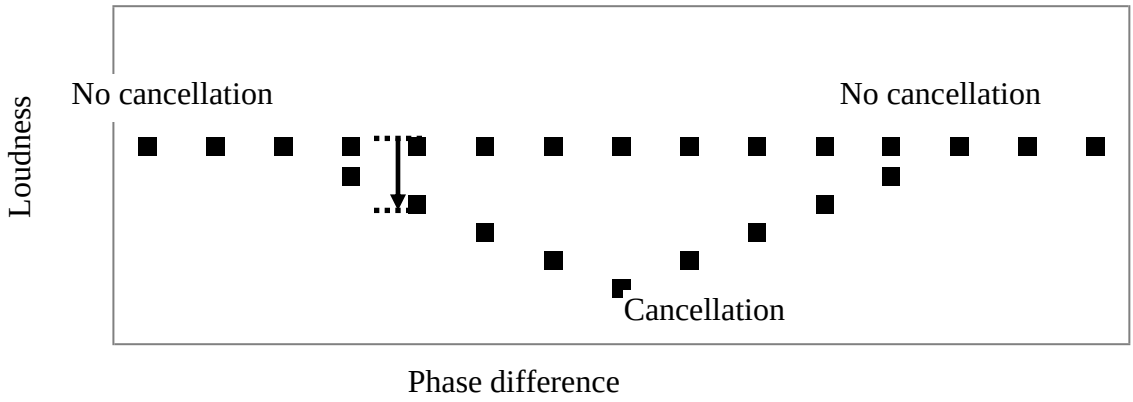


Figure 6.13 Larger difference in loudness compared to Figure 6.12, (depicted by longer arrow than shown in Figure 6.12) heard when comparing monaural and binaural stimuli, making phase cancellation easier to hear.

The starting phase of the right BV was randomised and the subject adjusted the phase of the right BV compared to the left, until a difference in loudness was heard. Initially phase difference was altered using a step size of 5^{o} until a noticeable difference in loudness of the tones was perceived. Thereafter a step size of 1^{o} was used to pinpoint the phase difference at which the tone was quietest and therefore cancellation greatest. During piloting, these step sizes were found to be most efficient at finding the point of cancellation. Too large a step size and cancellation could be missed and too small the experiment would take too long to complete.

Phase cancellation can be difficult to find especially if there is an amplitude difference arriving at the test cochlea. It was important to check subjects were reporting the point when phase cancellation was at its greatest. Once each subject reported cancellation had been found, repeatability was checked by asking them to adjust the right BV until the tone became louder again, then change direction and again report where they perceived cancellation to be. This seemed to be beneficial, with several subjects reporting that they had found a more pronounced point of cancellation by exploring either side in this way.

Additional calibration was carried out prior to Experiment 3. The relative output of the BVs in terms of phase was important for TD estimation. An oscilloscope (model - HAMEG

Instruments. 35 MHz analog oscilloscope Type HM303-6) was used to compare phase output of the BVs. The difference in phase between each BV and a reference tone produced by MATLAB was compared. This was repeated on five different occasions. The difference in phase between the right BV and the reference and the left BV and the reference was zero. It was therefore deemed unnecessary to adjust either BV in terms of phase. An oscilloscope was also used to confirm that the MATLAB code was correctly altering the phase of the right BV. Subjective checks were carried out before each testing session to ensure the equipment was working correctly. No practice was given for phase cancellation, due to the difficulty and time taken to find cancellation in most people.

6.5.2 Transcranial delay: calculation

Transcranial delay can be calculated using PC if the difference in phase of the BVs is known when cancellation is achieved. Figure 6.14 illustrates a phase delay (PD) where stimulus 2 (black line) is delayed compared to stimulus 1 (red line).

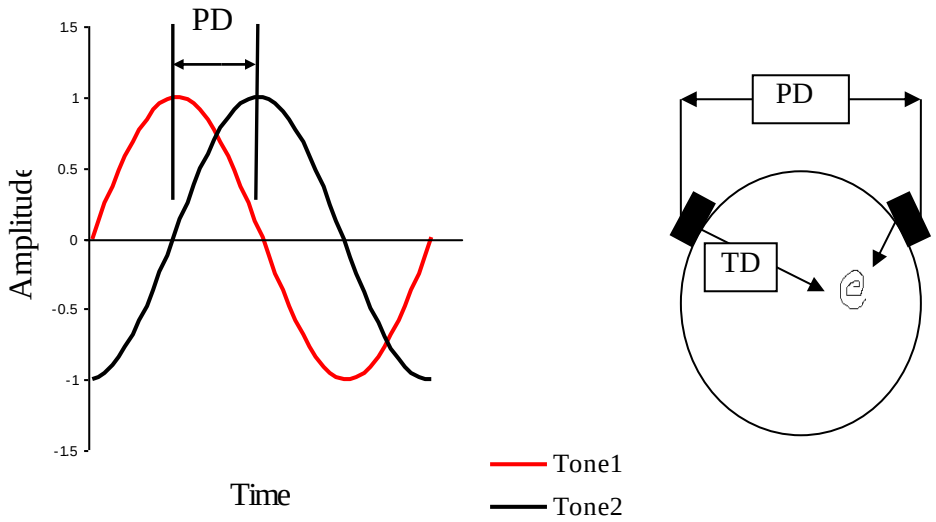


Figure 6.14 Phase delay (PD) recorded when phase cancellation is achieved can be used to calculate transcranial delay (TD). As TD increases, PD required to achieve phase cancellation will also increase and vice versa.

Phase delay in degrees can be used to calculate transcranial delay in microseconds, by calculating the ratio of phase delay in degrees compared to total degrees in a circle. If the time taken for the pure tone to complete one cycle is known, PD can be calculated by using the ratio in degrees multiplied by the time taken to complete one cycle. For example, assuming a pure tone of 1000 Hz and phase delay of 45^o at cancellation is reported, transcranial delay can be calculated as follows:

Phase delay/degrees in a circle x period of the tone

$45^o/360^o = 0.125$

$0.125 \times 1^{e-3} = 1.25^{e-4} = 12.5\mu s.$

Therefore a phase difference of 45^o is equivalent to a time delay of 12.5 μs for a 1000 Hz pure tone.

When searching for the phase difference at which phase cancellation occurs, each subject adjusted the phase of the right BV relative to the left.

A schematic diagram is shown in Figure 6.15 where the two input signals (x_L and x_R) are altered (delayed or attenuated) during transfer through the skull and together produce the signal y at the cochlea. For the case of the left cochlea, we can assume (without loss of generality – see below) that the signal from the right BV is delayed and attenuated (z_Δ), then added (interfering with) that from the left ear, and then their sum is further delayed and attenuated (Z_L), before arriving at the cochlea (y).

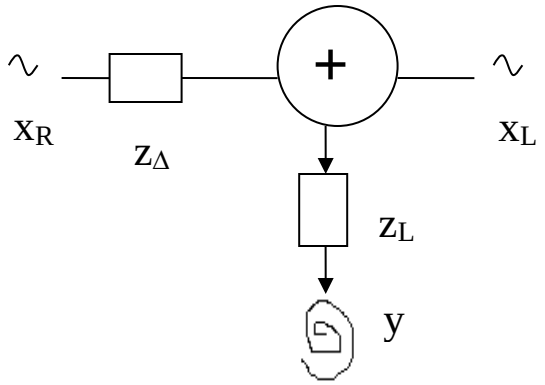


Figure 6.15 Input signals x_R and x_L are altered (delayed and attenuated) by the skull (represented by impedance z_L and z_Δ and combine to produce output 'y' at the test cochlea. (z_Δ is the ratio of impedance between the right and left ear and the cochlea).

This model may be derived by first assuming that the impedances from left to right are given by z_R and z_L, respectively, with summation of BV signals occurring at the cochlea.

$y = x_R z_R + x_L z_L$

This may now be expressed as

$y = x_R(z_R/z_L.z_L) + x_L z_L$

$y = x_R(z_\Delta.z_L) + x_L.z_L$

where $z_\Delta = z_R/z_L$

and hence

$y = (x_R z_\Delta + x_L).z_L$

The last equation is represented by the diagram in Figure 6.14.

For phase cancellation to occur one stimulus needs to arrive at the basilar membrane 180^o out of phase in comparison to the other. Calibration showed that when the input signals to the two BVs are in phase, their outputs are the same, so phase difference reported by the subject when cancellation is found can be assumed to represent TD.

Referring to Figure 6.15, and assuming x_L and x_R are of equal amplitude, phase cancellation can be defined mathematically as follows.

$y = x_R (z_\Delta . z_L) + x_L z_L = (x_R z_\Delta + x_L). z_L$

At cancellation, let ($x_R = x_{RO}$ and $x_L = x_{LO}$)

$0 = x_{RO} (z_\Delta . z_L) + x_{LO} z_L = (x_{RO} z_\Delta + x_{LO}). z_L$

$x_{RO} z_\Delta = -x_{LO} = x_{LO} e^{+j\pi}$

$z_\Delta = x_{LO}/x_{RO} e^{+j\pi}$

$\measuredangle z_\Delta = \measuredangle x_{LO} - \measuredangle x_{RO} \pm 180^o$ where $\measuredangle$ represents the phase angle.

$\measuredangle z_\Delta = \Phi = \pm 180^o$ –PD, where PD is the phase difference (in degrees) between the BV signals from right and left.

For example a subject reported that cancellation occurred with a phase difference of 138^o (i.e. the right bone vibrator was shifted 138^o compared to the left.

$\Phi = 180 - PD$

$\Phi = 180 - 138$

$\Phi = 42^o$

Given a frequency of 1250 Hz, one cycle corresponds to $1/1250 = 8*\text{-}10^{-4}$ s = 800 µs.

A delay of 42^o corresponds to 42/360 = 0.1167 of a cycle, and is hence $0.1167* 8e10^{-4} = 93*10^{-6}$ seconds

TD = 93 µs

This calculation makes two assumptions. Firstly, at cancellation PD always indicates that the right BV is delayed compared to the left. If the right is ahead of the left, a delay has not occurred. While a TA can be negative due to resonant/antiresonant properties of the skull, no evidence has been found to suggest that TD can be affected in the same way. The second assumption is that the phase of the delayed stimuli occurs in the succeeding cycle of the waveform, rather than one or more ahead.

6.5.3 Results: TD

Transcranial delay measured in both ears for 12 subjects. Subject 8 was unable to achieve phase cancellation after trying both ears on two separate occasions. A reduction in loudness of the stimulus was reported, but finding a convincing and repeatable point of phase cancellation was elusive and so is not included in this part of the analysis.

The MATLAB output for phase cancellation, was reported as a phase difference (PD) between the BVs, when a subject achieved phase cancellation. Table 6.2 shows how TD and speed of vibration was calculated from the PD, using the equation above. The velocity of BC vibration was calculated using a distance of 30 cm (Zwislocki 1953).

Table 6.2 Calculation of transcranial delay (TD) and speed of vibration from phase difference (PD) measured for right and left as test ear.

	Right as test ear					Left as test ear				
Subject	PD	180^o - PD	**TD (μs)** /360*800	TD (s)	**Speed (ms)** 0.3/TD (s)	PD	180^o - PD	**TD (μs)** /360*800	TD (s)	**Speed (ms)** 0.3/TD (s)
1	-40	220	**489**	$489*10^{-6}$	**613**	89	91	**202**	$202*10^{-6}$	**1485**
2	-39	219	**487**	$487*10^{-6}$	**616**	-27	207	**460**	$460*10^{-6}$	**652**
3	150	30	**67**	$67*10^{-6}$	**4478**	152	28	**62**	$62*10^{-6}$	**4839**
4	117	63	**140**	$140*10^{-6}$	**2143**	99	81	**180**	$180*10^{-6}$	**1630**
5	128	52	**116**	$116*10^{-6}$	**2586**	-117	297	**660**	$660*10^{-6}$	**455**
6	-80	260	**578**	$578*10^{-6}$	**519**	87	93	**207**	$207*10^{-6}$	**1449**
7	-76	256	**569**	$569*10^{-6}$	**527**	53	127	**282**	$282*10^{-6}$	**1064**
9	17	163	**362**	$362*10^{-6}$	**829**	-90	270	**600**	$600*10^{-6}$	**500**
10	-101	281	**624**	$624*10^{-6}$	**481**	-178	358	**796**	$796*10^{-6}$	**377**
11	-82	262	**582**	$582*10^{-6}$	**515**	85	95	**211**	$211*10^{-6}$	**1422**
12	180	180	**0**	$0*10^{-6}$	**0**	145	35	**78**	$78*10^{-6}$	**3846**
13	-104	284	**631**	$631*10^{-6}$	**475**	24	156	**347**	$347*10^{-6}$	**865**
Range			**0-631**		**0-4478**			**62 - 796**		**377 - 4839**

Speed of sound vibration showed wide variation between subjects, with an overall mean of 1349 ms^{-1} (mean for RTE is 1149 ms^{-1} and mean LTE is 1549 ms^{-1}).The velocity of sound through living bone has previously been reported to be 260 ms^{-1} (Zwislocki 1953), 300 ms^{-1} (Franke 1956) and 330 ms^{-1} (Tonndorf & Jahn 1981). Although reasonably consistent, these studies used only one or two subjects. These velocities are similar to that of sound through air (i.e. 340 ms^{-1}), which is surprising as bone is denser than air, which would be expected to result in faster velocity.

Transcranial delay for each ear, in μs, is shown in Figure 6.16. Limitations of time meant that subjects were required to complete the task of finding TA and TD once for each ear. For this reason no error bars are shown, because subjects did not repeat phase cancellation measurements.

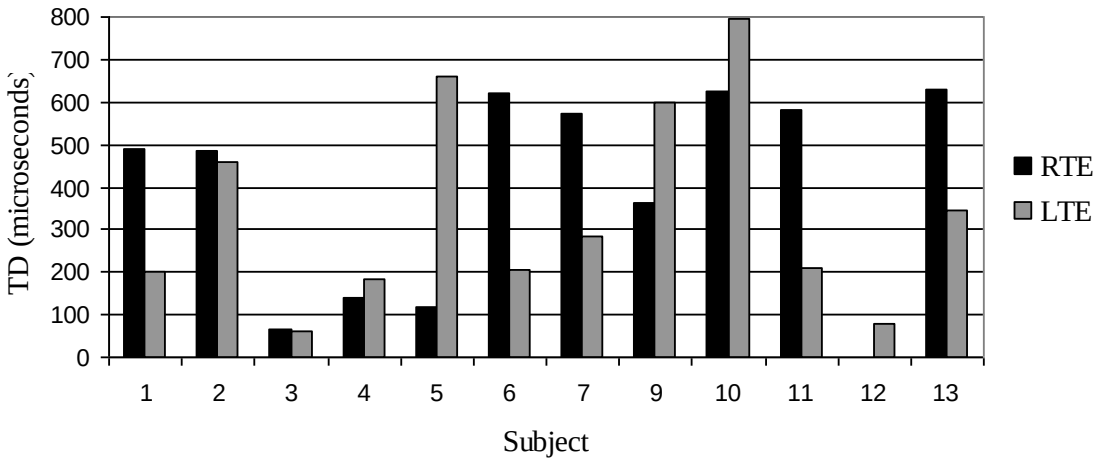


Figure 6.16 TD measured with right as test ear (RTE) and left as test ear (LTE). Subject 8 was unable to achieve phase cancellation and is therefore excluded.

Experiment 3 revealed overall mean TD of 366 μs (SD = 236 μs) with a wide range of TD (0 – 796 μs). Most subjects show asymmetry, the largest being 544 μs (Subject 5). Mean TD (N = 12) for right and left ears is shown in Figure 6.17.

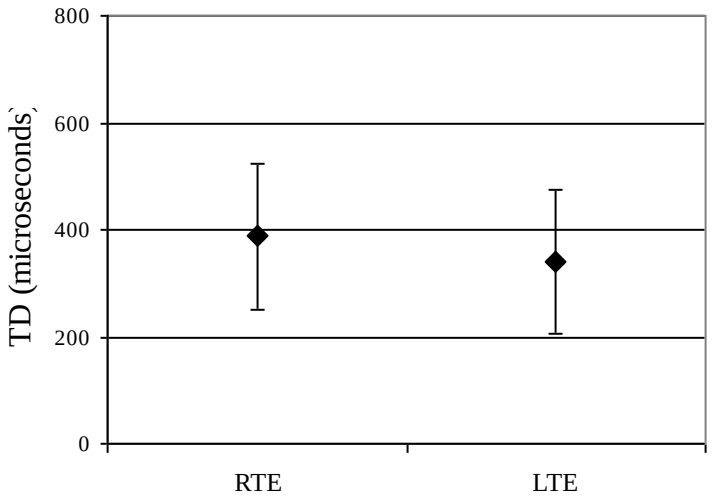


Figure 6.17 Mean TD measured with right as test ear (RTE) and left as test ear (LTE). (Error bars represent 95% confidence interval)

Mean TD is higher in the right ear (M = 387 μs, SD = 240 μs) than the left (M = 341 μs, SD = 237 μs), while between-subject variability, as indicated by SD, is similar in right and left ears. The boundaries of the CIs for mean RTE and LTE overlap, indicating a not significant difference in mean TD between the right and left ear.

A small number of subjects (N = 4, a total of 6 ears) gave extra time and repeated PC on two different days. Figure 6.18 shows mean TD measured in this subset on two occasions.

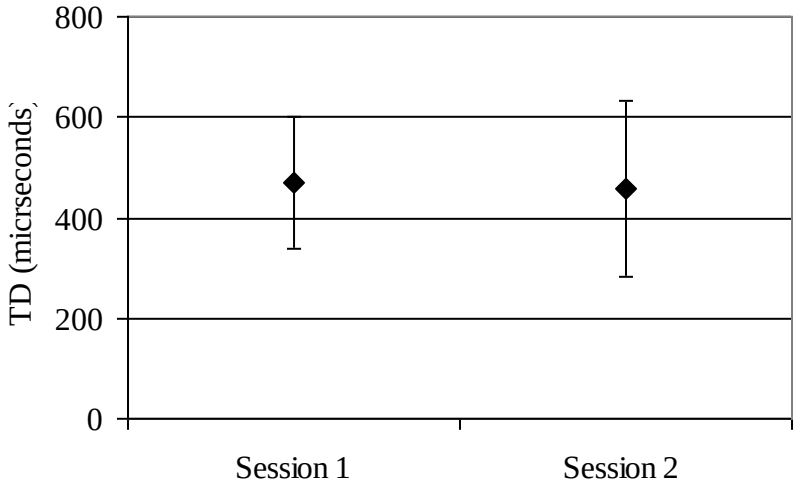


Figure 6.18 Variation in TD measured on two different days. (Error bars represent ± 1 SD)

Figure 6.18 shows good repeatability of TD when measured on two separate occasions. Mean TD estimated in session 1 (M = 470 μs, SD = 163 μs) was compared to mean TD for session 2 (M = 458 μs, SD = 218 μs). The greatest difference in TD was recorded by Subject 6 LTE with a variation of 105 μs with a mean difference in TD between sessions of 12 μs (SD = 63 μs). Difference in mean TD estimated on two different days is likely to be not significant as indicated by similar confidence interval boundaries. Transcranial delay seems to reasonably repeatable, an observation reported by Tonndorf & Jahn (1981). This study completed three repeats on three separate occasions, using the same trained subject.

The range of phase differences during which phase cancellation is perceivable was measured in a subset of subjects. When a subject reported that they had found the point of cancellation, they were asked to find the range of phase differences where a loudness difference in the two tones was perceivable. When a subject indicated that they had found it, they were asked to alter the phase until both tones became equally loud again and this phase difference was recorded. They were then asked to alter the phase in the opposite direction, passing through the point of maximum cancellation continuing until they perceived the tones as being equally loud again. The results are shown in Figure 6.19.

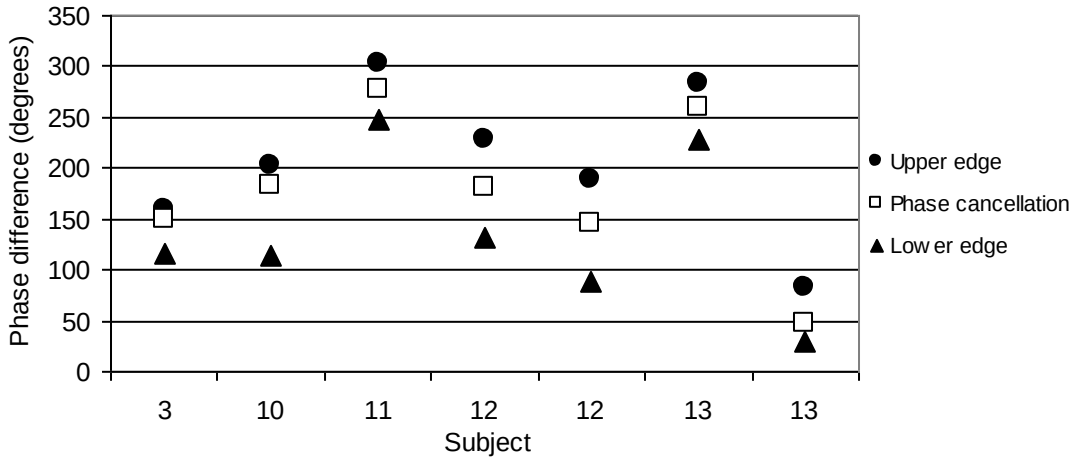


Figure 6.19 Range of phase difference through which phase cancellation was detectable.

The upper (circles) and lower (triangles) edges of phase cancellation reflect the phase differences when the monaural and binaural stimulus sounded similar in loudness. As phase difference of the BVs was altered between these two limits, the binaural stimulus became gradually quieter compared to the monaural stimulus until maximum cancellation was reached, before becoming louder again as it approached the opposite limit. The range of phase differences was 44 to 100 µs with a mean of 70 µs (SD = 23 µs).

In summary, inter-subject variation is wide, varying from 0 to 796 µs (377 to 4839 ms). These results are higher than previously reported for living bone (Zwislocki 1953; Franke 1956; Tonndorf & Jahn 1981), although these studies have used only one or two subjects. The estimation of TD seems to be repeatable with a mean difference of 12 µs. Tonndorf (1981) reports good repeatability of TD estimation.

6.5.4 Discussion: TD

Phase cancellation was used to estimate phase delay in twelve subjects using a 1250 Hz pure tone. A wide variation of TD was found between subjects, ranging from 0 to 796 µs, with a mean TD of 633 µs (SD = 236 µs). Comparison to previous studies was facilitated

by converting TD to speed of vibrations though the skull, and is shown in Table 6.3. Comparison is made difficult due to different transducers used and lack of within and between subject differences reported, often due to one subject being used. Mean propagation velocity of sound across the skull reported by the current study is high compared to previous studies.

Table 6.3 Comparison of studies using phase cancellation.

Author	Subjects	Transducer	Conclusion
Zwislocki 1953	1 normal hearing	AC/AC (PDR-10 earphone)	260 ms^{-1} >0.25 kHz
Tonndorf & Jahn 1981	1 normal hearing Masking to non-test ear	B72/B72	330 ms^{-1} (mean 0.1 to 4 kHz)
Boezeman et al. 1984	10 normal hearing Non-test ear not masked	TDH39/B71	BC time lag compared to AC 1.5 ms at 0.5 Hz. No time lag at 2 kHz
Current Experiment 3	12 normal hearing Masking to non-test ear	BEST/BEST	Mean TD 366 µs (SD 240 µs) at 1250 Hz Speed 1349 ms^{-1}

Experiment 3 revealed that most subjects appear to have asymmetric TD which is difficult to explain as distance from each mastoid to the contralateral ear would be expected to be similar on an individual's skull. However, it is unknown whether the resonant and antiresonant properties of the skull can affect TD in a similar way as with TA. Where vibration energy gets dissipated and can explain a high TA, maybe energy is also delayed resulting in a larger TD. Boezeman et al. found a frequency dependent difference in TD when cancelling a BC with an AC stimulus, reporting a 1.5 ms time lag at 500 Hz, but no lag at 2000 Hz.

Measurement error would be expected to play a part in the asymmetry shown. Repeatability was measured in only 4 subjects (6 ears), having a mean of 19^o (range 2 - 47^o) compared to 15^o reported by Tonndorf & Jahn (1981). Tonndorf found a

repeatability of 2^{o} when the BV was cemented to the mastoid bone and 15 ^{o} when stimulating through skin. Tonndorf used one subject only so no data is available regarding between-subject differences.

Repeatability could be impacted by the subjective nature of phase cancellation. All subjects were ignorant of phase cancellation and no one had experienced it prior to participating in this experiment. When subjects reported that they had found cancellation, they were asked to explore either side of the perceived drop in loudness to ensure they had reached maximum cancellation. However, the author cannot be totally sure that all subjects found maximal cancellation, especially when the loudness reduction was relatively shallow. This would be expected to contribute to difference in TD repeatability.

Boezeman (1984) notes that when converting phase angles into ms^{-1}, values are lower than previously reported and points out that the phase readings may contain an undetectable phase shift of 360^{o} as more than one cycle may be involved. If the speed of sound is greater through bone than air, the wavelength of a 1250 Hz tone would be greater than the distance from mastoid to contralateral cochlea and therefore the TD estimated may apply to the same cycle of the waveform, rather than a following one. The approximate distance from mastoid to contralateral cochlea on the author's head is 0.32 m over the top, and 0.2 m around the back. This makes knowing which cycle the phase relates to dependent on the BC pathway from mastoid to contralateral cochlea unclear, which very much complicates the picture. Zwislocki (1953), reports a between cochlear distance of 30 cm and velocity of 260 ms^{-1} for frequencies greater than 250 Hz. The wavelength of a 1250 Hz tone would be 0.21 m (260/1250), which is shorter than inter-cochlear distance. This implies that the reported PD wuld not be within the same cycle of the waveform because the inter-cochlear distance is further than the stimulus waveform. However, the current study reports a mean velocity of 1149 ms^{-1} which would give a wavelength of 0.92 m, which is larger than the mastoid to cochlear distance, implying the reported PD would be within the same stimulus cycle.

The resolution of this issue obviously requires further study. The structure of the human head consists of bone, cartilage, brain matter and fluids. Vibratory energy passing through the skull is subject to the influence of all of these elements, making the use of live subjects especially relevant.

Chapter 7

Experiment 3: Lateralisation

7.1 Introduction

This chapter starts by describing and discussing lateralisation ability using AC and BC in Experiment 3. Lateralisation was used to investigate whether individuals are able to access cues for binaural hearing using BC stimulation. Experiment 2 included the measurement of lateralisation ability although some individuals reported having difficulty with the task. Some subjects found it difficult to accurately transfer the perceived lateralisation of the stimuli in their head to a sliding scale on a monitor. The task used to measure lateralisation was therefore amended for Experiment 3. Instead of using a sliding scale subjects moved an 'acoustic pointer' to match the position of the perceived position of the stimulus. Details are discussed in Section 7.2

7.2 Additional methods: Lateralisation

As in Experiment 2, stimuli were presented via bilateral BVs for BC and insert earphones for AC. Stimuli were manipulated via five different ILDs (± 15 dB, ± 10 dB, 0dB) and IPDs (± 90^o, ± 45^o, 0^o) to produce a signal at set positions along the interaural axis. The method used to assess lateralisation ability in Experiment 2 was amended for use in Experiment 3. In Experiment 2, subjects used a sliding scale to indicate where they perceived the sound source to be located. Results indicate that some individual's lateralisation ability was not as good as expected. A number of subjects reported difficulty in transferring the perceived position of the stimulus from the interaural axis to a sliding scale on a computer monitor. The task was amended for the current experiment to the use of an 'acoustic pointer' to indicate the perceived origin of the stimulus, as described by Bernstein & Trahiotis (1985). Lateralisation ability has been shown to be affected by the type of stimuli used. Wide band widths are more easily lateralised than pure tones (Wightman & Kistler 1993). Pure tones were used during Experiment 2, while

a 1/3 octave narrowband noise, centred over the test frequency was used for Experiment 3.

The subject heard a total of four bursts of 1/3 octave narrowband noise. The first was a 'target', centred on 1250 Hz and manipulated via ILD and IPD. The second was an 'acoustic pointer', centred on 500 Hz and variable via interaural intensity difference. The target and acoustic pointer were then repeated. Different frequencies were used to make it easy to distinguish between the two stimuli. After hearing the pair of stimuli, twice, the subject moved the acoustic pointer to match the perceived position of the target. Pilot work prior to Experiment 3 revealed that this method required minimal training and subjects found it easy to use.

The task was completed by most people in three sessions, completed on three different days, incorporating air-conduction, bone-conduction, interaural level difference and interaural time difference (AC ILD, AC IPD, BC ILD and BC IPD). The order in which the four blocks were presented was randomised between subjects. The BVs were subjectively matched for loudness subject prior to measuring BC lateralisation ability.

7.3 Results: Lateralisation

Thirteen subjects were asked to lateralise narrow bands of noise centered on 1250 Hz and presented via AC and BC. Varying ILDs and IPDs were used to present each stimulus at a predetermined position along the interaural axis. Five trials were completed for each value of ILD and IPD using AC and BC. Graphs showing lateralisation performance using AC and BC with ILD and IPD can be found in Appendix D.

In theory, when listening via AC, subjects would be expected to perceive the stimuli with no ILD and IPD to be in the centre of their head. Differences in the fit of the inserts may have resulted in erroneous ILD and the subject would perceive the stimulus to be off centre. The mean ILD inserted by the subject (i.e. deviation from zero) when ILD and IPD were zero was used as a 'correction factor' to improve test/retest variability across

sessions (Trahiotis & Bernstein 1986). The mean adjustment applied was -1 dB (SD 3.52 dB) for AC. Such an adjustment was not made for BC as natural bias created by the skull would be a contributory factor and of interest to the study. Although not applied, the mean adjustment was calculated to be 2 dB (SD 7.00 dB).

Mean perceived position, across all subjects, relative to the target position for ILD is shown in Figure 7.1. Lateralisation ability using AC is accurate (i.e. the pointer ILD is similar to target ILD), whereas the position of the stimuli heard via BC were perceived as being less laterally diverse than the AC stimuli, (i.e. they were perceived to be closer to the centre of the head than out to each side).

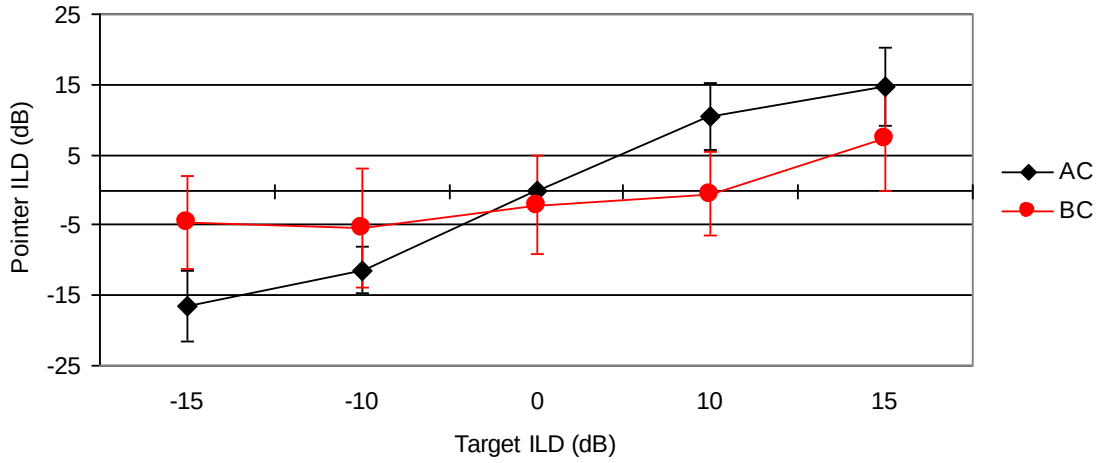


Figure 7.1 Mean lateralisation using AC and BC with targets set by interaural level difference (ILD). (Error bars represent ± 1 SD).

Mean lateralisation using AC and BC was found to be normally distributed at each target ILD. Paired-samples t-tests revealed the two-tailed significance values shown in Table 7.1.

Table 7.1. T-tests results comparing mean lateralisation ability using ILD AC and BC.

	t	*df*	*p* value
-15	-6.313	12	0.000 *
-10	-2.635	12	0.022 *
0	1.075	12	0.304
10	5.665	12	0.000 *
15	7.070	12	0.000 *

Table 7.1 reveals that the difference in perceived laterality between AC and BC is statistically significant, except when the target stimulus is directly to the front of the listener.

Figure 7.2 shows mean lateralisation using AC and BC stimulation, when using stimuli manipulated via IPD.

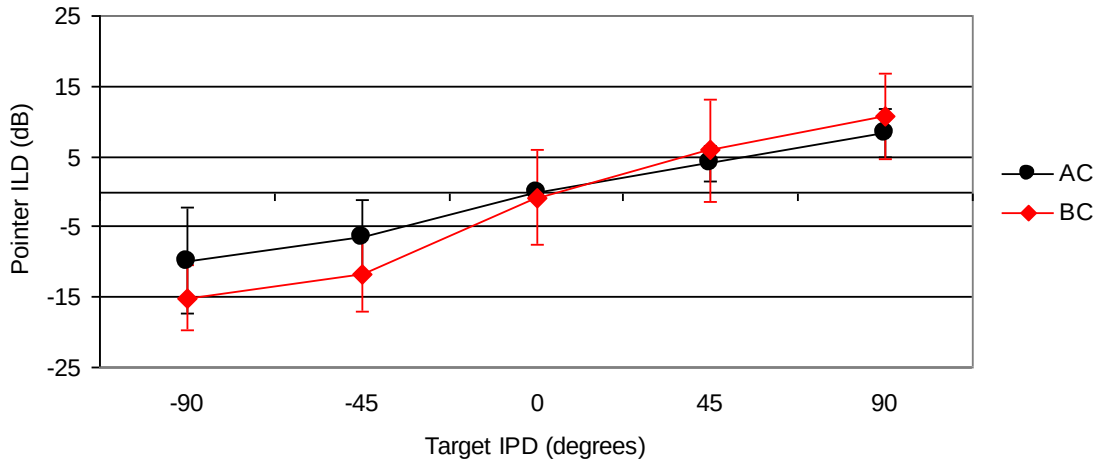


Figure 7.2 Mean lateralisation using AC and BC and targets set by interaural phase difference (IPD). (Error bars represent ± 1 SD).

Lateralisation ability using AC is evident, but not as lateral as with BC. However, the extent of laterality shown is in agreement with a previous study that reports laterality using a 1 kHz pure tone via AC of approximately ± 8 dB using targets set by IPD of ± 90^{o}

and a pointer using ILD (Bernstein & Trahiotis 1985). A striking feature of Figure 7.2 is the lateralisation ability using BC. Mean lateralisation with BC showed greater laterality than with AC i.e. a greater ILD was required to match the pointer to the target when using BC compared to AC.

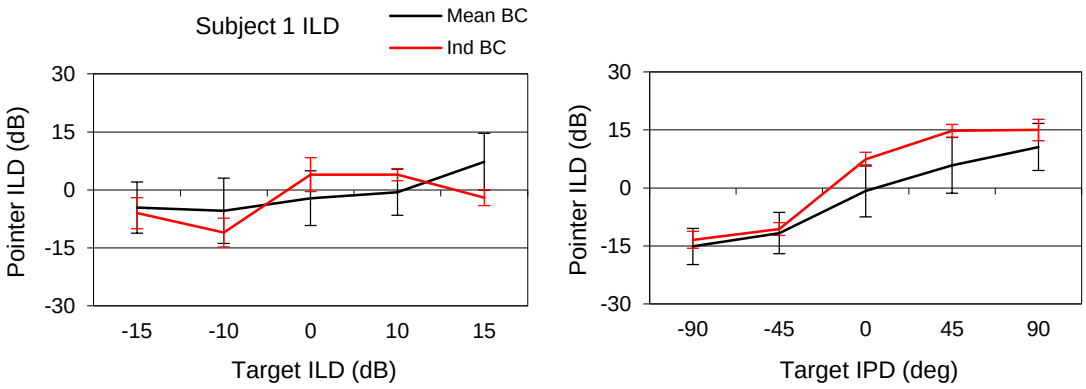
Mean lateralisation using AC and BC was found to be normally distributed at each target IPD. Paired-samples t-tests revealed the two-tailed significance values shown in Table 7.2.

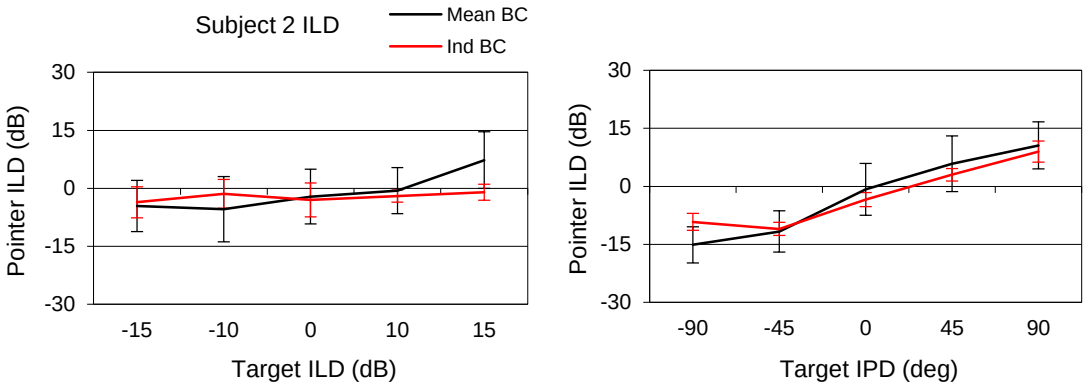
Table 7.2. T-tests results comparing mean lateralisation ability using IPD for AC and BC.

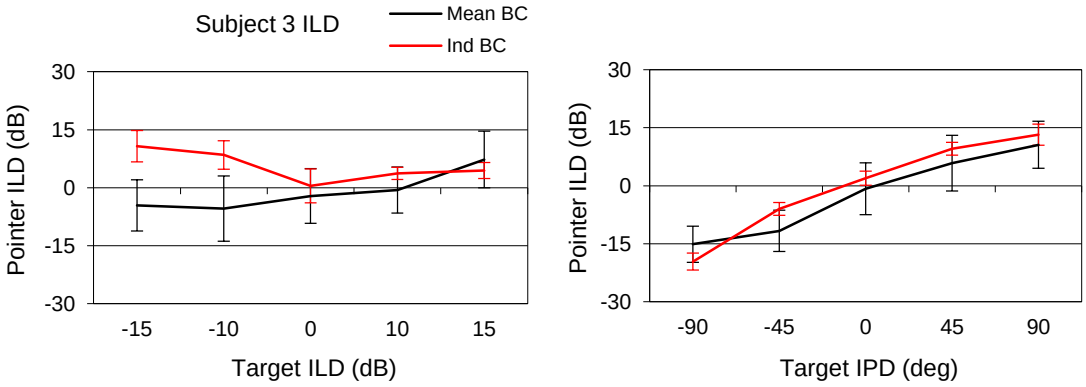
	t	*df*	*p* value
-90	2.828	12	0.015 *
-45	3.419	12	0.005 *
0	0.430	12	0.675
45	-1.058	12	0.311
90	-1.719	12	0.111

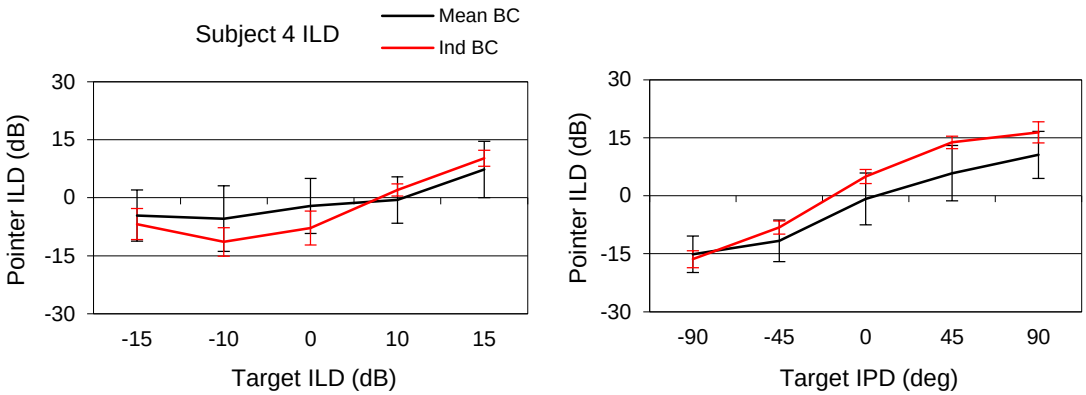
When using IPD, mean lateralisation ability using AC and BC is significantly different to for stimuli to the left of the subject, but not to the right.

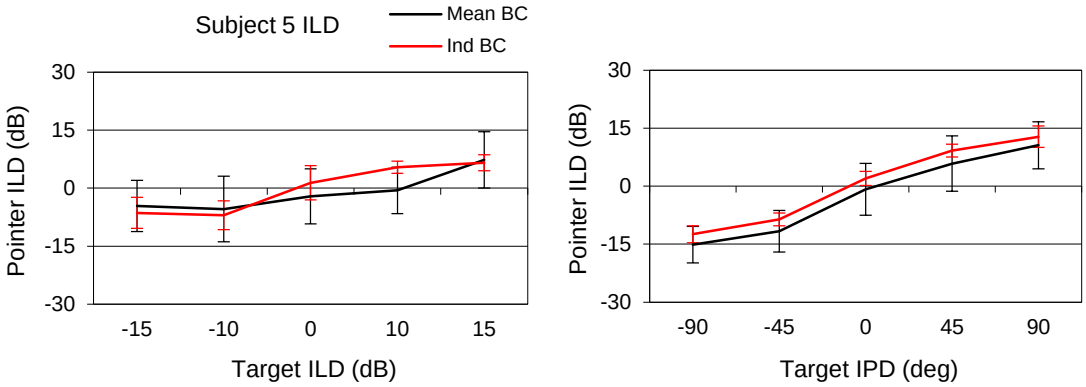
So far, mean data has been considered. Figure 7.3 compares each subject's BC lateralisation performance with mean BC lateralisation performance using stimuli manipulated via ILD and IPD.

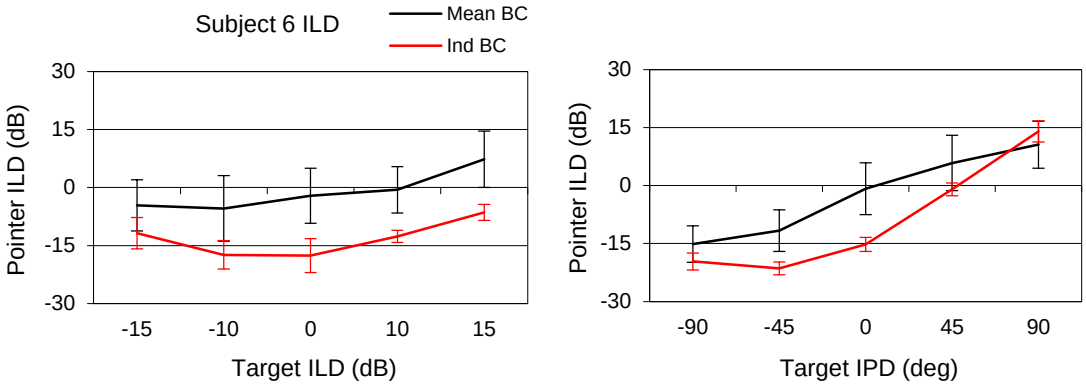

Subject 1 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)
Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)

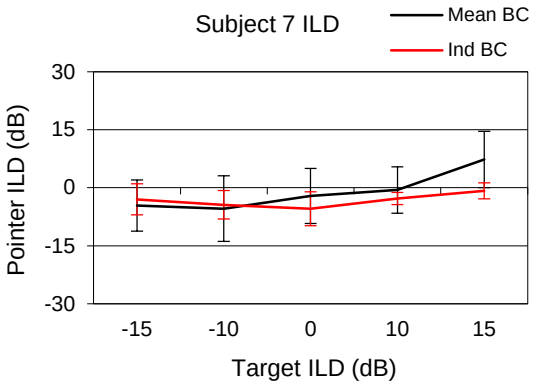

Subject 2 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)
Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 3 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)
Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 4 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)
Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 5 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)
Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 6 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)
Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 7 ILD
Mean BC
Ind BC
Pointer ILD (dB)
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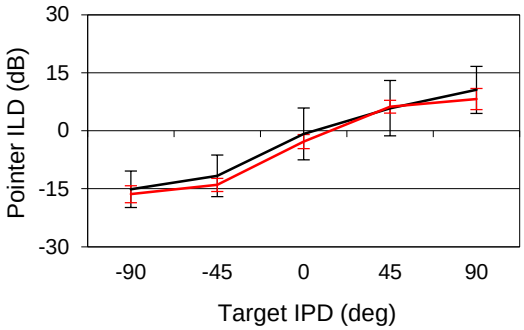
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)


Pointer ILD (dB)
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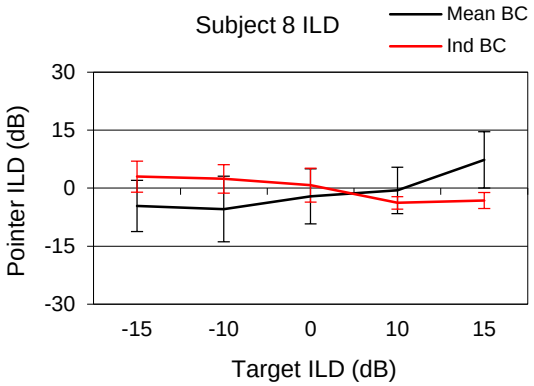
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 8 ILD
Mean BC
Ind BC
Pointer ILD (dB)
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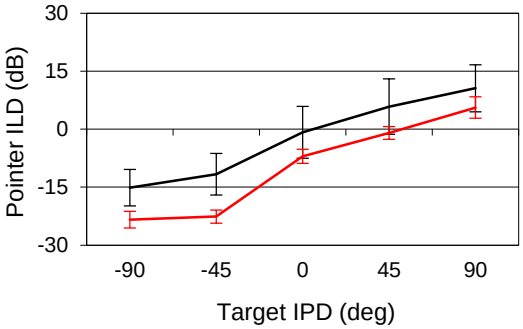
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)


Pointer ILD (dB)
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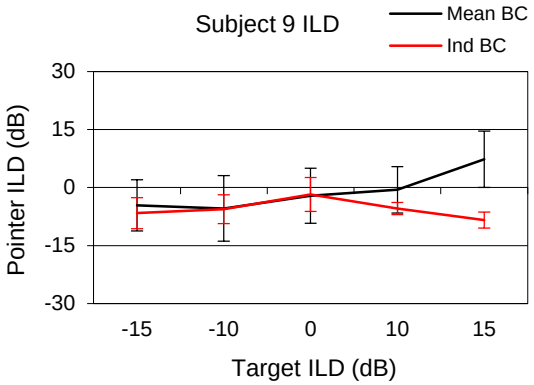
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 9 ILD
Mean BC
Ind BC
Pointer ILD (dB)
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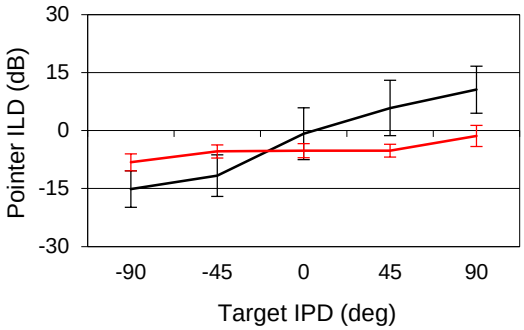
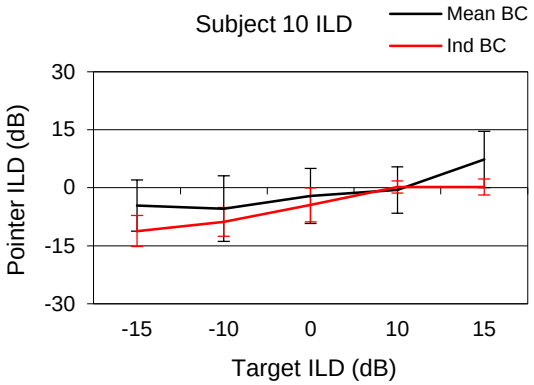
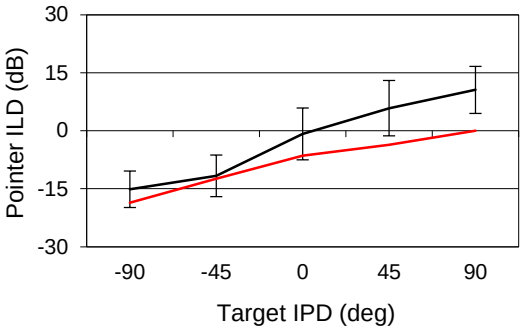
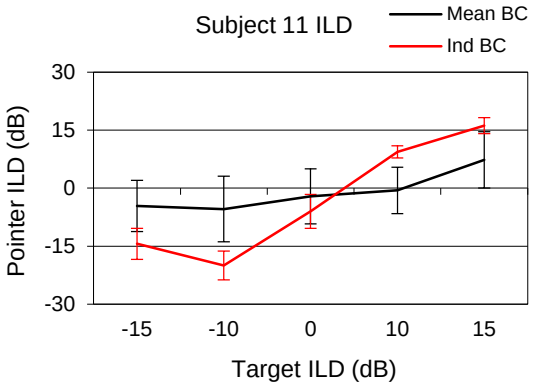
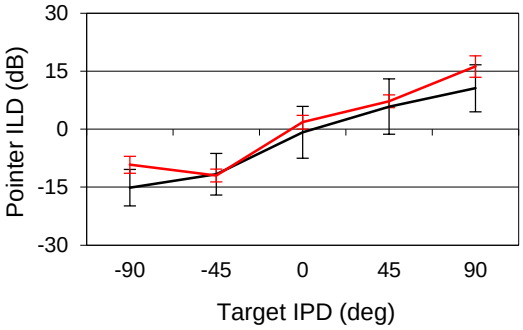
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)

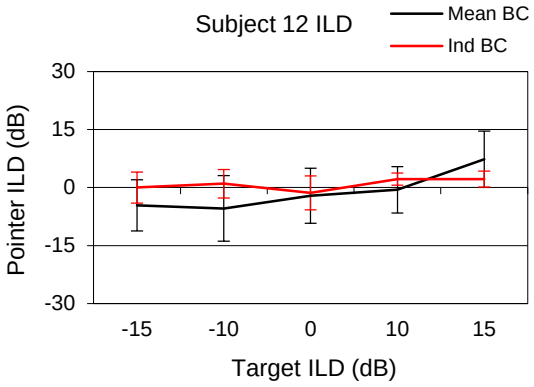

Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)

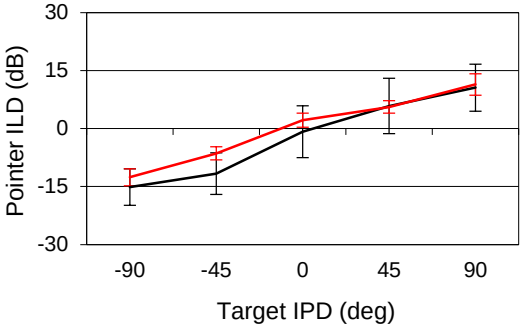

Subject 10 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)


Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 11 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)


Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)


Subject 12 ILD
Mean BC
Ind BC
Pointer ILD (dB)
30
15
0
-15
-30
-15
-10
0
10
15
Target ILD (dB)


Pointer ILD (dB)
30
15
0
-15
-30
-90
-45
0
45
90
Target IPD (deg)

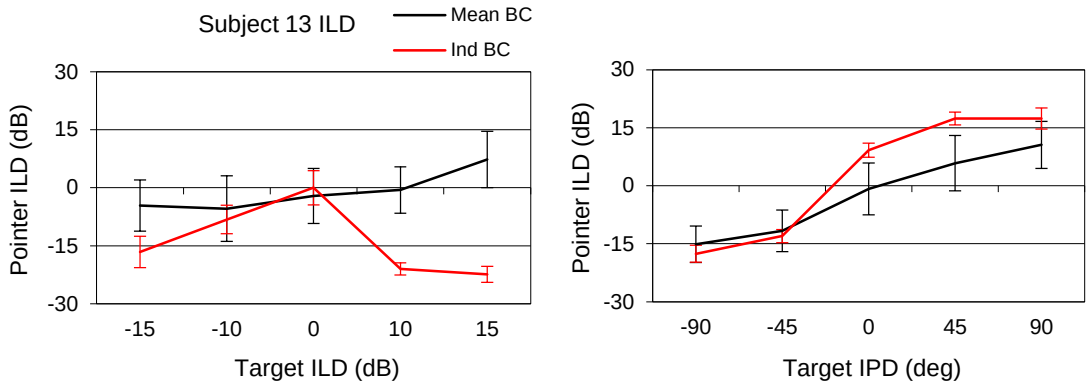


Figure 7.3 Individual subject BC lateralisation performance compared to mean BC lateralisation using stimuli manipulated via ILD and IPD.

A comparison of each subject's lateralisation performance using stimuli manipulated via ILD and IPD was investigated using Pearson correlation, a summary of which is shown in Table 7.3.

Table 7.3 Summary of Pearson correlation and associated statistical significance when comparing mean lateralisation performance to that of each subject using ILD and IPD. (ILD = interaural level difference, IPD = interaural phase difference).

Subject	BC Lateralisation (ILD)		BC lateralisation (IPD)	
	Pearson Correlation	Sig. (2 tailed)	Pearson Correlation	Sig. (2 tailed)
1	0.330	0.587	0.981	0.003 *
2	0.566	0.320	0.967	0.007 *
3	-0.431	0.469	0.964	0.008 *
4	0.946	0.015 *	0.991	0.001 *
5	0.840	0.075	0.999	0.000 *
6	0.803	0.102	0.915	0.030 *
7	0.766	0.131	0.995	0.000 *
8	-0.788	0.131	0.995	0.000 *
9	-0.488	0.404	0.836	0.077
10	0.798	0.105	0.979	0.004 *
11	0.858	0.063	0.973	0.005 *
12	0.536	0.352	0.989	0.001 *
13	-0.548	0.339	0.978	0.004 *
Range	-0.788 to 0.946		0.836 to 0.999	

The range of correlations shown for stimuli manipulated via ILD is greater than for IPD. All subject's seemed able to lateralise using IPD, showing similar ability to the mean. Furthermore all correlations were significant, except Subject 9, indicating the presence of a relationship between mean lateralisation performance and subject performance. Subject 9 showed a trace for ILD that sloped from left to right, but they perceived the stimulus to be to the front, lacking laterality shown by the mean trace.

Conversely, only Subject 4 showed a significant relationship between their performance and that of the mean when lateralising via ILD.

Table 7.4 summaries each subject's TA, TD and lateralisation performance, indicated by Pearson's correlation of subject compared to mean performance.

Table 7.4 Summary of transcranial attenuation (TA), transcranial delay (TD) and lateralisation performance for each subject. (ILD refers to interaural level difference, IPD refers to interaural phase difference, *r* depicts Pearson correlation).

Subject	TA (dB)			TD (μs)			BC (ILD)	BC (IPD)
	Right	Left	Mean	Right	Left	Mean	*r*	*r*
1	12	6	9	489	202	346	0.330	0.981
2	-3	3	0	487	460	474	0.566	0.967
3	2	10	6	67	62	65	-0.431	0.964
4	1	3	2	140	180	160	0.946	0.991
5	16	7	12	116	660	388	0.840	0.999
6	4	12	8	578	207	393	0.803	0.915
7	5	1	3	569	282	426	0.766	0.995
8	9	7	8		Not found		-0.788	0.995
9	-2	8	3	362	600	481	-0.488	0.836
10	-3	6	2	624	796	710	0.798	0.979
11	4	4	4	582	211	397	0.858	0.973
12	3	3	3	0	78	39	0.536	0.989
13	-2	-2	-2	631	347	489	-0.548	0.978
Range	-3 to 16	-2 to 12	-2 to 12	0 to 631	62 to 796	39 to 710	-0.788 to 0.946	0.836 to 0.999

Transcranial attenuation measured using threshold comparison, rather than phase cancellation is used in this section, because Subject 8 was unable to achieve cancellation so no value of TD and consequently TA via phase cancellation, is available for them. During Experiment 3, mean TA was 1 dB higher when measured by phase cancellation compared to threshold estimation which was not statistically significant. This implies that differences in TA measured using the two methods is likely to be due to chance variation.

Previous literature indicates that TA may increase with increasing frequency (Snyder 1973; Nolan & Lyon 1981; Reinfeldt et al. 2007; Stenfelt 2012), see Table 2.3 for overview. The present research estimated TA at one frequency only, so no comparisons can be made to previous literature regarding the effect of frequency on TA. However, TA measured in Experiments 2 and 3 is comparable to reported results from older previous studies. Using a stimulus of 1 kHz, Snyder (1973) reports mean TA of 7 dB, standard deviation of ±6.6 dB and a range of -5 to 25 dB using unilaterally deaf subjects. Using normal hearing subjects, Nolan & Lyon (1981) report mean TA of 7 dB, SD of ±5.3 dB and range between -5 and 20 dB. More recent studies have shown less TA at 1 kHz. Reinfeldt et al. (2007) report mean TA of 0 dB and Stenfelt (2012) report median TA of 1.5 dB with SD of ±4.9 dB and range between -5 and 13 dB. Results from Experiment 2 show mean TA to be 6 dB, SD of ±5 dB and a range of 0 to 15 dB. Experiment 3 reveals mean TA of 4 dB with SD of ±5dB and a range of -3 to 16 dB. Although some variation in reported TA is evident, the above studies are in agreement, including similarity in the range. The methods used in these studies are psychoacoustic, giving rise to variability due to the subjective nature of the method used. Large variability in mean TA has been reported across frequency by previous studies, as shown in Table 7.5.

Table 7.5 Range of TA (dB) measured at frequencies between 250 and 4000 Hz, as reported by previous studies.

	250	500	1000	2000	3000	4000
Snyder (1973)	35	35	30	40		45
Nolan & Lyon (1981) Group A	25	25	20	30	20	30
Nolan & Lyon (1981) Group B	20	40	25	30	25	50
Stenfelt 2012	38	44	18	33	24	38

Previous literature regarding the effect of frequency on TD is limited, however an increase in the speed of sound through the skull, i.e. a decrease in TD, is suggested by Franke (1956) and Boezeman et al. (1984) as frequency increases, see Table 2.5 for details. Of note is that Franke used only 2 subjects, while Boezeman used 10. Boezeman reports a time lag of approximately 1.5 ms using a 0.5 kHz stimulus and 0 ms using a 2 kHz stimulus. Tonndorf & Jahn (1981) used one subject to show that the velocity of sound through the skull seems to be independent of frequency above 2 kHz at 330 ms. This is in agreement with Zwislocki (1953) who suggest a value of 260 ms and Franke (1953) 300 ms. The present research found the speed of sound at 1.25 kHz of between approximately 400 and 800 ms in 50% of subjects, with the other 50% being faster at between 1000 and 4000 ms. The reason for this deviation from previous literature is unclear. Tonndorf and Boezeman report a reduction in the speed of sound propagation at approximately 0.4 and 2 kHz. Boezeman et al. (1984) report a similar deviation in the frequency range 0.4 to 0.8 kHz. This is likely due to resonance/anti-resonances found in the skull due to the complex nature of the structure of the skull (Zwislocki 1953; Stenfelt & Goode 2005). The present research estimated TD at one frequency only so no further contribution can be made to the question of whether TD if dependent on frequency. The present study did find large variation in TD between subjects and in some subjects, between right and left ears as shown in Table 6.2. Similar comparative data does not seem available in previous literature.

In order to explore the effect of TA and TD on lateralisation ability, the subjects were split into groups of low mean TA (<5 dB), medium mean TA (5 to 9 dB) and high mean TA (>9 dB). The low group consists of Subjects 2, 4, 7, 9, 10, 11, 12 and 13, the medium group of Subjects 1, 3, 6 and 8 and the high group of Subject 5 only. Mean correlation for the low mean TA group is 0.429 for ILD and 0.964 for IPD. Mean correlation for the medium group is 0.141 for ILD and 0.964 for IPD while the subject with the highest TA is 0.840 for ILD and 0.999 for IPD. Subject 5 has the highest TA and has strong correlations to mean BC performance for both ILD and IPD. However, the medium TA group have a lower correlation score than the low TA group for ILD and similar for IPD.

Subject 5 had a mid-range TD and was able to lateralise well. The low TA group contains subjects with the two highest TD (subjects 10 and 13) making it difficult to draw conclusions about the role of TD in lateralisation ability. Whilst interesting to explore, the group sizes are small (low N = 8, medium N = 4 and high N =1), making this analysis far from robust.

Little is understood about the role of TD in lateralisation ability. Logic suggests that the greater the delay the greater the interaural isolation and therefore the better the subject is expected to be able lateralise sound. TD is expected to play a role only when TA is either not large enough to prevent sound energy reaching the contralateral cochlea, or not so small that the stimulus is not delayed or attenuated at all during transcranial transmission. How large TA needs to be to create sufficient interaural isolation, for TD to be a useful mechanism for sound lateralisation is unclear. The range of mean TD revealed by Experiment 3 was 39 µs to 710 µs. Subject 12 was found to have the lowest TD and showed good ability to lateralise using IPD cues (r = 0.989) and poor ability using ILD cues (r = 0.536). Subjects 2, 9 and 13 have similar mean TD and the ability of Subjects 9 and 13 to lateralise using ILD is poor. Subject 9 showed the poorest ability to lateralise using IPD, while S13 was able. Subjects 9 and 13 have a large right/left ear mean TD asymmetry, although the largest asymmetry is in Subject 5 with a difference of 544 µs and they showed good lateralisation ability using ILD (r = 0.840) and IPD (r = 0.999). Subjects 1, 3, 7, 11 and 12 all show good ability to lateralise using IPD, with performance using ILD being poor except for S11 who showed reasonable ability to lateralise using ILD cues. Subjects 2, 3 and 4 have asymmetries of 40 µs or less, although what affect this has on lateralisation ability is difficult to ascertain.

Lateralisation performance using BC was similar in Experiment 2 and 3 using ILD. Although the ability to detect a sound to the right and left was revealed, stimuli was perceived to be in front of the listener, not as far to the right and left as would be expected. When using IPD, BC performance was better compared to using ILD. Interestingly, IPD performance appears to be stronger than ILD for BC lateralisation in Experiments 2 and 3. This implies that IPD cues are more robust than ILD cues, when interaural isolation is small, in comparison to AC. The relatively poor performance shown with BC and ILD may be partly explained by placement effects associated with the BVs. Although care was taken to reduce placement effects, a

difference of 10 dB has been shown to occur (Weston et al. 1967) which would add an extra erroneous ILD, with detrimental effects on lateralisation ability.

7.4 Does TA and/or TD have an influence on lateralisation performance?

Binaural hearing affords a listener significant benefits in terms of sound detection, localisation and speech intelligibility (Hafter & Trahiotis 1997). A normal hearing listener has access to cues required for binaural hearing due to having an ear positioned either side of the head creating large interaural isolation. Therefore, most normally hearing people have little difficulty judging the origin of a sound source. However, when listening via BC, interaural isolation is at least reduced, if not obliterated, by the cross pathways associated with listening via BC. For this reason, lateralisation with BC is expected to be more difficult than with AC. The current study demonstrates that some degree of lateralisation ability may be apparent with normal hearing subjects, using narrow band noise, when stimulated via BC.

The relationship between TA, TD and lateralisation performance using IPD and ILD is explored via scatterplots. Figures 7.4 to 7.9 show the interaction between mean TA and mean TD with the correlation of subject BC lateralisation performance compared to mean BC lateralisation performance using ILD and IPD.

Figure 7.4 depicts the relationship between TA and TD and shows that there not a robust relationship between TA and TD ($r^2 = 0.042$). In other words, on increase in one does not result in an increase in the other.

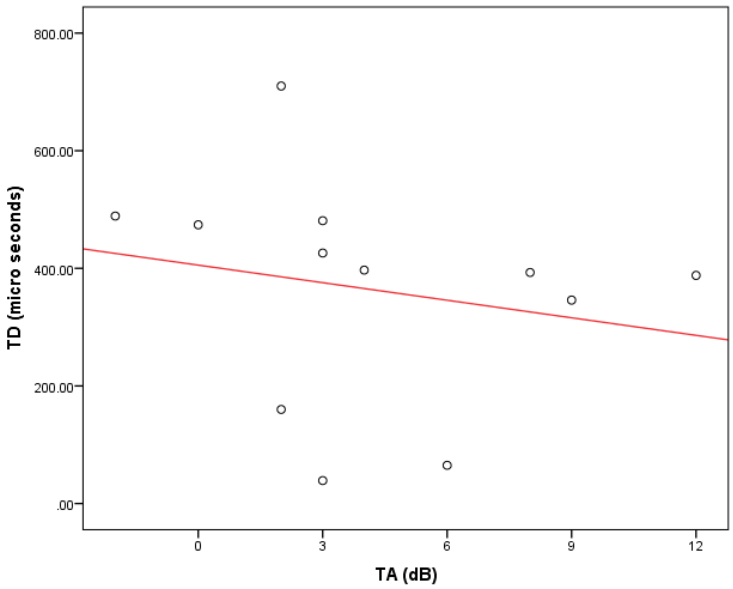


Figure 7.4 Scatterplot showing the relationship between TA and TD.

Figure 7.5 shows the relationship between lateralisation using ILD and IPD and again shows no relationship. Lateralisation performance with IPD was good irrespective of ILD performance ($r^2 = 0.085$).

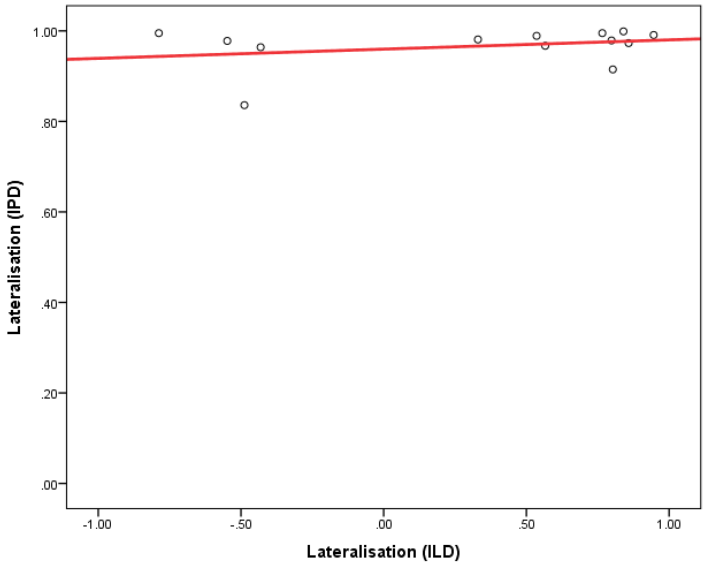


Figure 7.5 Scatterplot showing the relationship between lateralisation using ILD and IPD

Figure 7.6 implies that an increase in TA does not lead to an improvement in lateralisation performance using ILD ($r^2 = 0.006$).

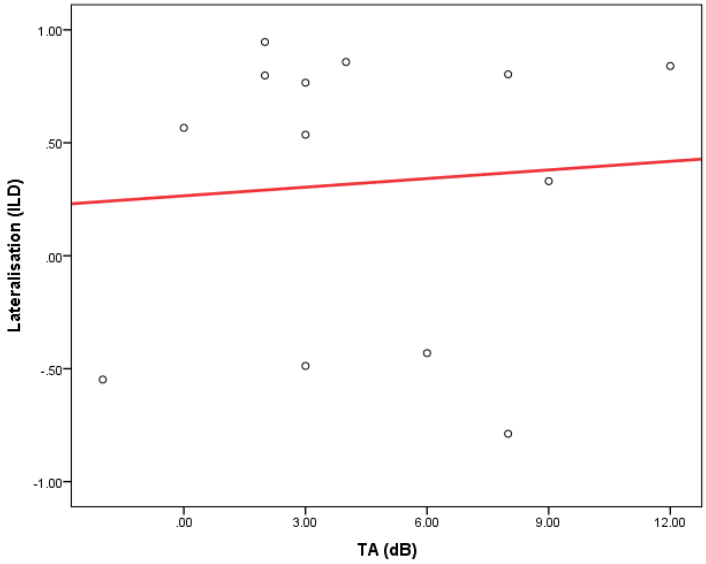


Figure 7.6 Scatterplot showing the relationship between TA and lateralisation using ILD

Figure 7.7 follows the same pattern, showing that subject's lateralisation performance using IPD was always good, irrespective of TA ($r^2 = 0.007$).

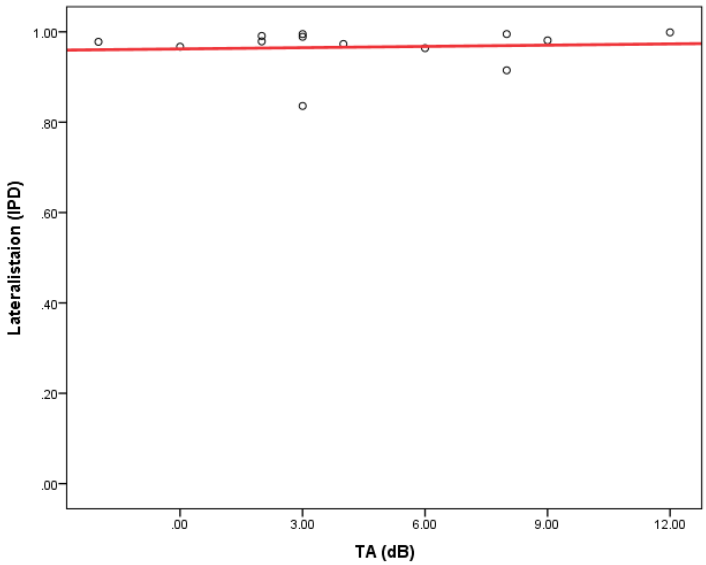


Figure 7.7 Scatterplot showing the relationship between TA and lateralisation via IPD

Figure 7.8 shows no strong correlation between differing levels of TD with lateralisation via ILD ($r^2 = 0.005$).

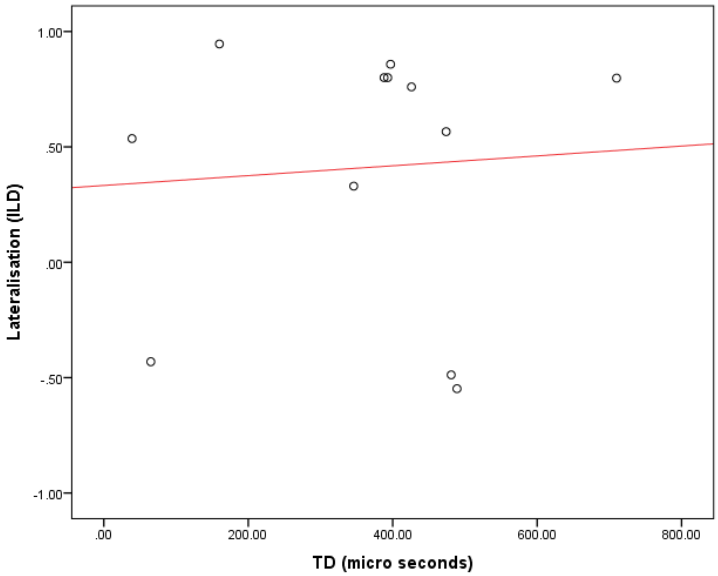


Figure 7.8 Scatterplot showing the relationship between TD and lateralisation via ILD

Figure 7.9 again suggests that lateralisation performance using IPD is not influenced by TD ($r^2 = 0.043$).

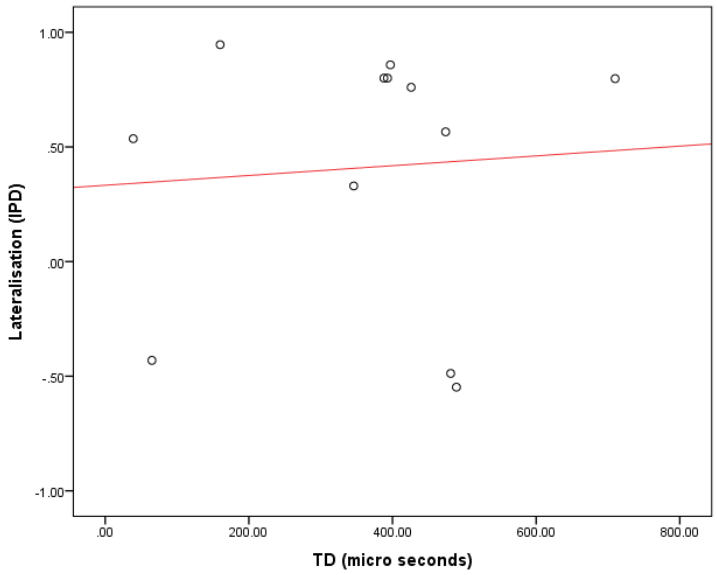


Figure 7.9 Scatterplot showing the relationship between TD and lateralisation via IPD

Pearson's correlation was used to further compare the relationship between the experimental parameters and are shown in Table 7.6.

Table 7.6 Pearson's correlations and significant values for all experimental parameters

		TA	TD	Lateralisation ILD	Lateralisation IPD
TA	Pearson Correlation	1	-0.205	0.255	0.031
	Sig. (2-tailed)		0.523	0.423	0.925
TD	Pearson Correlation	-0.205	1	0.072	-0.207
	Sig. (2-tailed)	0.523		0.824	0.519
Lateralisation ILD	Pearson Correlation	0.255	0.072	1	0.466
	Sig. (2-tailed)	0.423	0.824		0.126
Lateralisation IPD	Pearson Correlation	0.031	-0.207	0.466	1
	Sig. (2-tailed)	0.925	0.519	0.126	

Table 7.6 shows weak correlations for all permutations, except ILD and IPD which show a moderate correlation, however, no correlations reach statistical significance. In summary this implies that for the subject's used in Experiment 3, TA had no relationship with TD. Likewise ability to lateralise via BC using stimuli manipulated with ILD had no relationship with ability to lateralise with IPD. Furthermore, subject's TA and TD did not have an influence over ability to lateralise with either ILD or IPD.

7.5 Concluding remarks

Measurement uncertainty is known to be a factor in experiments involving stimulation via BC. Much care was taken during this study to minimise the detrimental effects of measurement error. In Experiment 3, two identical BVs were placed one on each mastoid concurrently and re-positioned until they were perceived as being equal in loudness. Transcranial attenuation and delay were then estimated without moving them.

Experiment 3 was demanding on the subjects in terms of time and effort. Regular breaks and refreshment were offered to reduce the risk of lack of motivation or concentration or fatigue adversely affects the results. While it would have been interesting to repeat Experiment 3 using other frequencies willingness of subjects to give more time made it prohibitive.

The use of pure tones for estimating BC HTL has been shown to create extreme responses due to anti-resonances in the skull (Stenfelt and Goode, 2005). To prevent this, modulated tones with a deviation of 8% have been used to estimate TA (Stenfelt and Zeitooni, 2013). The current study used pure tones and while antiresonances do occur in the skull around the frequency here used, the consistency of results between Experiments 2 and 3 and the achievement of phase cancellation in 12 out of 13 subjects, when the BV remained in place for the estimation of TA and TD, suggests that antiresonances in the skull did not create a problem in this research.

In summary, it is difficult to set out robust conclusions regarding the role of TA and TD in lateralisation ability via BC, using these results. The main reasons are,

1. Small sample. In Experiment 2, ten subjects yielded a range of TA that split into three nearly equal group sizes. Although each group contained only three or four subjects, a mean could be calculated. In Experiment 3, thirteen subjects produced only one subject with a TA of ten or more. This makes drawing conclusions inadvisable due to such small sample sizes.
2. Asymmetry. Some subjects have an asymmetrical TA and TD. For the analysis mean TA and TD were used. The effect of asymmetry of TA and TD on lateralisation ability is not known.
3. Limited repetition. Wide variation associated with measurements made using BC. In Experiments 2 and 3 the focus was on estimating TA, TD and lateralisation ability using BC. Great care was taken to minimise measurement error, but the time taken to complete the tasks, prevented a meaningful amount of repetition to be undertaken.

Chapter 8

Conclusions and future research

8.1 Conclusions and contribution to knowledge

The main aim of this study was to explore lateralisation ability using BC signals. Firstly a comparison of two types of BV was carried out, to ascertain whether the BEST or B71 would be most suitable for this research. The BEST was chosen due to its improved low frequency performance, compared to the B71 and similar high frequency performance.

Previous studies have demonstrated that lateralisation is achievable using BC, but little is understood about the underlying mechanics. Transcranial attenuation and delay were estimated as they may play a crucial role in our understanding of lateralisation using BC compared to AC. The method of phase cancellation was used to estimate TD. This method requires precision which can be a challenge when using BC signals. It is also time consuming, so a novel adjustment to the method was found, that made the estimation of TD easier and quicker for subjects.

A method was developed that explored the ability to access ILD and ITD cues that are important for lateralisation using AC, while presenting signals via BC. Lateralisation using ILD and ITD were measured separately to investigate whether normal hearing listeners are able to access these cues via BC. Lastly an attempt was made to relate inter-subject variation in TA and TD to inter-subject variation in lateralisation using BC.

This study was motivated by a small number of studies that indicate that localisation ability via BC is possible, at least in some subjects, although at first this might be assumed to not be the case. The justification for carrying out this study lies in both research and clinical settings. Lateralisation ability using BC and the estimation of TA and TD has previously been reported, although with a lack of agreement between papers. This makes each element of this study an important contribution to previously reported findings. Historically BAHAs have been fitted

unilaterally due to lack of interaural isolation. The results of this study indicate that further research in this area is warranted as some people may benefit from bilateral implantation.

In summary, the following conclusions can be drawn from this study.

Conclusion 1
At the frequency used for this study, the BEST produces a similar amount of ABRad compared to the B71.

Conclusion 2
When listening via BC, normal hearing subjects seem to be able to lateralise more accurately using IPD than ILD, when using a stimulus centred on 1.25 kHz

Conclusion 3
Inter-subject variation in TA and TD is large, at the frequency tested

Conclusion 5
There is no significant correlation between amount of TA and TD at 1.25 kHz.

Conclusion 6
There is no significant correlation between lateralisation performance using ILD and IPD with BC stimulation, at the frequency tested.

Conclusion 7
There is no significant correlation between amount of TA and/or TD and lateralisation performance using ILD and IPD with BC stimulation when using 1.25 kHz.

Additionally, a contribution has been made to research methodology. A novel modification to the method of phase cancellation is described in Section 6.5.1. Initially, the estimation of transcranial delay using phase cancellation was time consuming and difficult for subjects to

detect. This adjustment to the method facilitated the often subtle change in loudness crucial if phase cancellation is to be found. To the author's knowledge this has not been previously reported.

8.2 Future research

This research opens a number of avenues for discussion and further research.

Individuals who benefit from BAHA usually have a conductive hearing loss, whereas normal hearing people were used for this study. Transcranial attenuation, delay and lateralisation ability estimated using subjects implanted with bilateral BAHAs would provide more relevant results for this population.

The results reported in Experiment 3 are only relevant for a stimulus of 1.25 kHz. It cannot be assumed that a similar conclusion can be drawn if using lower or higher frequency stimuli. When listening via AC, the accessibility of ILD and IPD are frequency dependent. Experiment 3 indicated that IPD may have a stronger influence on lateralisation via BC compared to ILD, at the frequency tested. It maybe that ILD is disrupted to a greater extent than IPD. Further investigation into the role of IPD in the accessibility of binaural cues when listening via BC would be a worthy avenue to pursue. However, the method of phase cancellation proved to be time consuming and demanding on subjects. In order to further investigate the role of IPD, the development of an easier method of estimating TD would facilitate a more robust estimate of TD due to the potential of carrying out a greater number of repeats, using a greater number of subjects.

Lateralisation performance using AC is influenced by the stimuli used, a broadband stimulus being easier to lateralise than a narrow band stimulus. As long as sufficient interaural isolation is present, it would be expected that lateralisation ability using BC would be similarly affected. In theory, if interaural isolation is low, lateralisation ability would be expected to be poor using any type of stimuli. The measurement of lateralisation ability using a speech signal presented via BC would reveal interesting information.

The precedence effect, described in Section 2.2.8, may at least partially explain lateralisation ability using BC. Lateralisation ability with BC is widely thought to be compromised due to dual input to each cochlea due to sound transmission across the skull. The precedence effect describes the phenomenon whereby the auditory system is able to make sense out of multiple percepts of the same stimuli arriving at the cochlea. When listening using BC, the brain maybe using the initial acoustic information to locate a sound source and suppressing the input from the crossed pathway. The precedence effect could be investigated using the method described in Experiment 3. If a subject's TD is known, a stimulus would be presented bilaterally containing an ITD that removes the subject's natural TD. Delays of appropriate duration to explore the precedent effect would then be inserted. Lateralisation performance may be expected to improve when the delay causes the second percept to be suppressed.

This research is important in attempting to further understand the role of TA and TD in lateralisation performance. It is hoped that this study as well as future research, will contribute to the pool of knowledge that one day will enable individuals who rely on hearing via BC and are able to access cues for binaural hearing, to be fitted with bilateral BAHA. There is still much to understand about hearing via BC, making studies in this area valuable and desirable.

Appendices

Appendix A: Health questionnaire

Health Questionnaire

Please complete the following questionnaire. It is designed to ensure you are appropriate for and safe to participate in this study. Responses will be held in a confidential manner and used for the purpose of the experiment by the researcher only.

Name:

Sex: male female

Today's date:

	Yes	No
Do you have ringing, whistling, rushing noises in either ear?		
Have you ever had an ear drum perforation?		
Have you ever had a head injury requiring hospitalisation?		
Have you ever had surgery on either ear?		
In the last 2 weeks have you experiences any of the following:		
• Congestion/cold/flu		
• Pain in either ear		
• Discharge from either ear		
• An injury to either ear		
Any other comments		

Appendix B: Instruction sheets

Experiment 2: Lateralisation subject instructions

You are required to carry out a task that judges how well you are able to judge the direction of a sound source. Two types of hearing stimulation will be used – air conduction and bone conduction.

For this task you will hear a series of single tones some of which may appear quieter than others. Your task is to use the mouse to position the slider, to indicate the direction from which you perceive the sound to be coming. After each presentation, the slider will return to a random place, which is not indicative of the correct answer. Press 'replay' if you would like to hear the tone again.

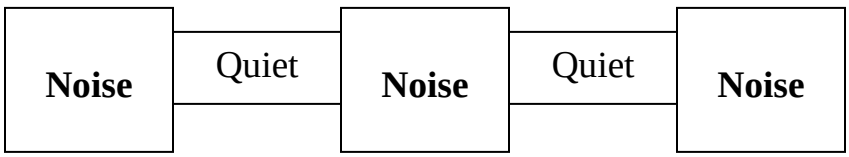
For the air conduction stimulation, I'll place a soft foam insert into both of your ear canals. For the bone conduction stimulation, a bone vibrator will be placed behind both ears at the same time. I'll also place a soft foam insert into each ear canal through which you'll hear a hissing noise. Please ignore this noise, just respond to the tone.

Important!

You should not experience any discomfort caused by the equipment or the loudness of the sounds. If you do, please let me know immediately and I will stop the test.

Experiment 2: TA subject instructions

I'm going to place a bone vibrator on the bone behind one of your ears and soft foam inserts into your ear canals. I'm then going to measure the quietest sound that you can hear. You will hear a beep in one ear and a hissing noise in the other. The hissing noise will remain the same loudness throughout, while the beep will get progressively quieter. You will hear 3 bursts of noise. You will hear the beep in one of the noise bursts, please indicate which by pressing the appropriate number on the keyboard. If you are unsure, please make a guess.



The task will take about 2 minutes to complete. I'll let you know when you have finished. I'll then place the bone vibrator behind the opposite ear and ask you to repeat the task.

Important!!

You should not experience any physical discomfort nor should the sounds become uncomfortably loud. If either does happen, please let me know immediately and I will stop the test.

Experiment 3: Lateralisation subject instructions

You are required to carry out a task that assesses how well you are able to judge the direction of a sound source. Two types of hearing stimulation will be used – air conduction and bone conduction. Your task is to use an acoustic pointer to match the lateral position of a 'target' with a 'pointer'.

You will hear a set of four bursts of noise. The first and third (the target), and the second and fourth (the pointer). Your task is to alter the position of the pointer until it matches that of the target. This is done by using the right/left adjustment on the screen, using the mouse. Press 'repeat' if you would like to hear the sound again.

For the air conduction stimulation, I'll place a soft foam insert into both of your ear canals. For the bone conduction stimulation, a bone vibrator will be placed behind both ears at the same time.

Important!

You should not experience any discomfort caused by the equipment or the loudness of the sounds. If you do, please let me know immediately and I will stop the test.

Experiment 3: TA subject instructions

Sound energy presented to one side of the head, will stimulate both cochleae. The amount of sound energy reaching the far compared to the near cochlea depends on anatomical characteristics of an individual's skull. This task measures the amount of energy lost, ('transcranial attenuation') as sound vibration travels across the head.

One ear will as assigned as the test ear and a bone vibrator will be placed on the mastoid of that ear. Masking noise will be presented to the non-test ear by way of an insert earphone. The hearing threshold level of the test-ear will be measured.

You will hear three bursts of noise. In one of those noise bursts you will also hear a tone. Use the keys '1' '2' or '3' on the keyboard to indicate which band of noise contained the tone. The loudness of the tone will steadily decrease until you are unable to hear it. When this happens, make a guess by pressing any one of the above keys. The screen will indicate when the task is complete. The bone vibrator will then be swapped to the mastoid opposite to the test ear and

your hearing threshold level will again be measured in the same way. The difference in hearing threshold levels will be taken as your transcranial attenuation.

This will then be repeated with the other ear as the ‘test ear’.

Important!

You should not experience any discomfort caused by the equipment or the loudness of the sounds. If you do, please let me know immediately and I will stop the test.

If you so wish, you are entitled to withdraw your consent to participate in the experiment at any time, without giving a reason.

Experiment 3: TD subject instructions

Sound energy presented to one side of the head, will stimulate both cochleae. The amount of sound energy reaching the far compared to the near cochlea depends on anatomical characteristics of an individual’s skull. This task measures the time taken, (‘transcranial delay’) for vibration energy to reach the cochlea from the mastoid on the opposite side. When a sound of identical frequency is presented bilaterally, the tone can be effectively cancelled by careful adjustment of the phase and level of one tone relative to the other.

One ear will as assigned as the test ear and masking noise will be presented to the non-test ear by way of an insert earphone. Bone vibrators will be placed on both mastoids. Your task is to alter the phase of one bone vibrator until you hear a difference in loudness.

Ignore the noise bursts. You will hear two beeps. Use the mouse to alter the phase of one bone vibrator by using the coarse adjustment as indicated on the screen. Listen out for the first tone to sound quieter than the second. Use the fine adjustment to find the phase difference at which the first tone appears to be at its quietest. Use the repeat button to preserve the phase difference, then adjust the level a little either way to see if you can make the first tone appear even quieter. When you are happy you have adjusted the phase and level until the tone is the quietest that you can get it, complete the task by pressing ‘accept’.

This will then be repeated with the other ear as the ‘test ear’.

Important!

You should not experience any discomfort caused by the equipment or the loudness of the sounds. If you do, please let me know immediately and I will stop the test.

Appendix C: Order of testing

Experiment 2

Subject	Session 1	Session 2	Session 3	Session 4
1	Screening Practice TA TA LTE L-R TA RTE R-L	Practice lateral AC Lateral AC x10 Lateral BC x10 TA RTE R-L TA LTE R-L	Lateral BC x10 Lateral AC x10 TA RTE R-L TA LTE L-R	
2	Screening Practice TA TA RTE R-L TA LTE L-R	Practice lateral AC Lateral AC x10 Lateral BC x10 TA RTE L-R	TA LTE L-R TA LTE R-L	TA RTE L-R Lateral AC x10 Lateral BC x10
3	Screening Practice TA TA RTE R-L TA LTE L-R TA RTE R-L	Practice Lateral Lateral AC x10 Lateral BC x10 TA RTE R-L TA LTE L-R	TA LTE L-R Lateral BC x10 Lateral AC x10	
4	Screening Practice lateral Lateral BC x10 Lateral AC x10	Practice TA TA LTE L-R TA RTE L-R Lateral AC x10 Lateral BC x10	TA RTE L-R TA LTE L-R	TA RTE R-L TA LTE R-L
5	Screening Practice TA TA RTE R-L TA LTE L-R	Practice lateral Lateral BC x10 Lateral AC x10 TA LTE R-L TA RTE L-R	Lateral AC x10 Lateral BC x10	TA RTE L-R TA LTE L-R
6	Screening Practice TA TA RTE L-R TA LTE L-R	Practice Lateral Lateral AC x10 Lateral BC x10 TA LTE L-R TA RTE R-L	Lateral BC x10 Lateral AC x10 TA RTE L-R TA LTE R-L	
7	Screening Practice TA TA LTE L-R TA RTE L-R Practice lateral	Lateral AC x10 Lateral BC x10 TA RTE R-L TA LTE R-L	TA RTE R-L TA LTE R-L Lateral BC x10 Lateral AC x10	
8	Screening Practice lateral Practice TA TA RTE R-L TA LTE L-R	Lateral BC x10 Lateral AC x10 TA LTE R-L TA RTE L-R	TA RTE L-R TA LTE R-L Lateral BC x10 Lateral AC x10	
9	Screening Practice TA TA RTE R-L TA LTE L-R	Practice lateral Lateral AC x10 Lateral BC x10 TA RTE R-L TA LTE R-L	Lateral BC x10 Lateral AC x10 TA LTE L-R TA RTE L-R	
10	Screening Practice lateral Practice TA TA LTE L-R TA RTE R-L	Lateral AC x10 Lateral BC x10 TA RTE R-L TA LTE R-L	Lateral AC x10 Lateral BC x10 TA LTE L-R TA RTE L-R	

Experiment 3: Order of testing

Subject	Session 1	Session 2	Session 3	Session 4
1	Screening Practice TA Practice lateral AC TA and TD RTE	TA and TD LTE Lateral AC ILD x 5 Lateral BC IPD x 5	TA and TD RTE Lateral AC IPD x 5 Lateral BC ILD x 5	
2	Screening Practice TA TA and TD RTE	Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	TA and TD LTE Lateral AC IPD x 5 Lateral BC ILD x 5	
3	Screening Practice TA TA and TD RTE	Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	TA and TD LTE Lateral AC IPD x 5 Lateral BC ILD x 5	
4	Screening Practice TA TA and TD RTE	TA and TD LTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	Lateral AC IPD x 5 Lateral BC ILD x 5	
5	Screening Practice TA TA and TD LTE TA and TD RTE	Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	Lateral AC ILD x 5 Lateral BC IPD x 5	
6	Screening Practice TA TA and TD LTE TA and TD RTE	TA and TD LTE TA and TD RTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	Lateral AC ILD x 5 Lateral BC IPDx 5	
7	Screening Practice TA TA and TD RTE	TA and TD LTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	TA and TD RTE Lateral AC ILD x 5 Lateral BC IPD x 5	
8	Screening Practice TA TA and TD RTE	TA and TD LTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	TA and TD LTE Lateral AC ILD x 5 Lateral BC IPD x 5	TA and TD RTE
9	Screening Practice TA TA and TD RTE	TA and TD LTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	Lateral AC ILD x 5 Lateral BC IPD x 5	
10	Screening Practice TA TA and TD RTE	TA and TD LTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	Lateral AC ILD x 5 Lateral BC IPD x 5	
11	Screening Practice TA TA and TD RTE	TA and TD LTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	Lateral AC ILD x 5 Lateral BC IPD x 5	
12	Screening Practice TA TA and TD RTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	Lateral AC ILD x 5 Lateral BC IPD x 5 TA and TD LTE		
13	Screening Practice TA TA and TD LTE TA and TD RTE	TA and TD RTE Practice lateral AC Lateral AC ILD x 5 Lateral BC IPD x 5	TA and TD LTE Lateral AC ILD x 5 Lateral BC IPD x 5	

Appendix D: Raw data

Experiment 1: Air-borne radiation measured using an artificial mastoid (dB SPL)

1 kHz	B71-1		B71-2		B71-3	
	Left	Right	Left	Right	Left	Right
Session 1	36.7	35.7	37.3	37.7	36.9	38.1
	39.1	34.9	36.0	36.6	36.1	35.6
	35.5	38.5	36.4	39.1	37.7	38.5
Session 2	36.7	37.8	37.2	36.4	40.8	38.6
	34.8	37.9	39.5	37.6	39.0	38.9
	39.5	39.1	36.2	39.5	40.5	39.7
Session 3	38.5	37.2	39.3	35.9	40.1	37.2
	36.6	35.2	36.7	37.1	38.7	38.6
	37.1	36.8	35.2	38.2	37.9	40.1

	BEST-1		BEST-2		BEST-3	
	Left	Right	Left	Right	Left	Right
Session 1	32.1	32.5	20.6	21.4	20.6	20.5
	31.9	32.0	19.8	22.8	23.0	21.6
	31.7	32.4	22.5	25.7	22.8	22.5
Session 2	31.8	32.3	24.8	28.8	23.2	27.0
	31.2	33.3	23.5	24.6	22.4	24.8
	33.0	32.1	20.3	22.9	21.6	23.7
Session 3	30.4	32.6	24.1	23.3	21.3	24.3
	32.2	31.7	20.9	26.7	19.7	22.2
	32.9	32.8	23.8	21.6	22.3	21.9

2 kHz	B71-1		B71-2		B71-3	
	Left	Right	Left	Right	Left	Right
Session 1	34.20	32.70	31.3	34.7	29.6	30.9
	30.80	30.30	33.2	32.2	30.7	30.5
	32.80	31.10	32.6	33.3	31.4	29.8
Session 2	30.0	31.3	30.2	34.6	30.2	29.0
	29.7	29.7	32.5	33.6	29.9	27.5
	30.7	31.4	32.2	32.3	30.2	27.2
Session 3	31.2	30.8	32.4	33.2	31.9	28.7
	29.3	27.9	33.1	32.9	31.7	29.2
	30.7	28.1	31.7	32.7	29.4	30.4

	BEST-1		BEST-2		BEST-3	
	Left	Right	Left	Right	Left	Right
Session 1	41.40	41.60	40.8	41.4	41.3	42.5
	41.10	41.80	40.6	41.6	41.0	42.1
	41.30	42.20	40.1	41.5	41.0	41.2
Session 2	38.4	41.1	38.7	39.2	38.8	39.4
	39.9	40.8	38.7	38.2	38.8	38.9
	38.9	39.7	37.5	38.1	39.2	39.1
Session 3	40.1	42.7	40.5	42.1	39.6	39.4
	39.9	39.8	39.7	40.9	38.9	40.3
	41.9	43.9	41.7	39.7	40.8	41.6

3 kHz	**B71-1**		**B71-2**		**B71-3**	
	Left	Right	Left	Right	Left	Right
Session 1	36.7	32.7	38.4	41.1	34.7	42.2
	32.7	32.3	35.1	36.0	35.9	41.6
	37.8	33.3	35.3	30.3	32.9	40.3
Session 2	39.0	42.4	34.0	39.8	39.4	39.2
	42.6	37.4	31.6	35.6	35.2	37.2
	40.1	39.6	34.5	38.5	35.4	40.0
Session 3	41.1	38.1	41.1	38.6	36.6	38.2
	38.9	34.9	39.1	40.4	34.2	40.6
	40.3	37.8	37.2	41.6	37.7	40.9

	BEST-1		BEST-2		BEST-3	
	Left	Right	Left	Right	Left	Right
Session 1	44.0	44.5	44.6	45.9	45.3	45.3
	44.5	44.1	43.5	45.8	44.4	45.1
	44.0	44.8	44.0	45.1	45.8	45.2
Session 2	43.2	45.4	43.8	45.0	43.8	45.4
	44.8	44.8	44.0	45.4	43.3	43.6
	43.0	45.0	44.3	44.6	43.2	43.4
Session 3	46.9	44.2	45.9	45.1	43.2	44.7
	44.2	45.1	43.2	44.9	43.4	45.2
	43.9	43.8	43.9	45.2	44.7	44.9

4 kHz	BEST-1		BEST-2		BEST-3	
	Left	Right	Left	Right	Left	Right
Session 1	56.0	55.9	55.5	56.8	53.7	55.0
	55.0	55.0	55.6	56.6	54.1	56.2
	55.8	55.8	55.6	57.0	55.1	53.9
Session 2	53.4	53.0	51.2	53.5	52.3	53.6
	54.2	53.5	51.6	53.5	52.6	52.9
	53.6	53.2	52.1	53.6	52.9	54.4
Session 3	56.1	55.7	56.0	54.8	54.4	52.9
	55.7	56.2	55.7	55.1	53.5	53.1
	54.8	57.0	53.9	56.2	53.2	53.5

	B71-1		B71-2		B71-3	
	Left	Right	Left	Right	Left	Right
Session 1	59.0	57.4	55.3	55.2	57.6	56.5
	59.3	57.4	53.7	55.8	57.2	56.0
	59.3	57.6	53.8	56.2	57.6	56.0
Session 2	56.2	54.0	54.9	54.6	58.7	52.6
	58.0	54.8	57.3	54.3	58.6	56.2
	56.4	53.5	55.2	53.8	56.4	55.3
Session 3	55.9	54.7	53.7	53.9	55.3	54.7
	56.2	53.2	54.2	55.1	55.7	55.1
	57.3	53.9	55.1	56.7	56.2	56.7

Experiment 1: Ear canal sound pressure level measured using human subjects (ECSPL)

	Mastoid placement											
1 kHz	**Ipsilateral**						**Contralateral**					
Subject	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3
1	69	76	68	73	75	71	72	68	71	75	67	71
	66	74	65	68	70	74	71	71	67	72	61	74
2	74	72	72	70	70	72	72	71	71	67	73	71
	76	72	72	68	72	70	71	69	71	64	73	65
3	73	72	73	71	74	70	67	66	68	69	69	68
	73	71	72	71	75	71	66	66	67	72	72	66
4	69	65	69	74	75	65	64	63	64	66	67	64
	68	63	65	69	76	62	63	62	64	68	66	62
5	66	66	68	67	76	66	62	63	61	61	61	62
	66	67	67	66	70	68	62	63	62	60	63	63
6	75	78	79	71	79	74	64	64	65	62	64	59
	77	73	78	72	77	70	63	63	63	60	65	59
7	76	74	75	74	78	79	66	65	68	64	62	66
	77	75	74	77	79	78	66	66	68	66	66	66
8	68	72	68	71	72	66	74	76	76	76	77	74
	67	74	66	68	72	65	75	75	75	76	78	74
9	66	69	68	64	69	65	66	65	65	63	65	62
	68	66	68	58	68	70	66	63	68	62	68	63
10	72	76	74	73	75	72	58	62	59	62	62	58
	74	75	74	72	75	75	59	61	60	60	63	59
11	75	69	74	70	69	76	73	71	72	66	62	65
	74	73	72	67	66	72	72	72	72	66	63	67
12	78	79	75	78	73	74	74	75	69	72	69	68
	75	80	77	80	75	72	74	76	73	75	69	70
13	73	74	73	77	80	76	59	60	60	60	61	63
	70	73	75	72	77	75	58	58	58	59	60	63

Mastoid placement												
2 kHz	**Ipsilateral**						**Contralateral**					
Subject	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3
1	60	58	62	58	59	60	48	54	53	46	45	48
	62	62	58	58	57	59	52	54	54	48	50	48
2	64	65	62	60	57	61	49	50	50	49	49	52
	68	63	63	63	57	60	45	51	51	49	49	53
3	64	62	61	55	60	54	50	54	54	53	51	50
	63	60	63	58	58	60	52	52	51	47	48	46
4	64	56	66	58	59	61	56	59	53	51	56	51
	55	55	60	53	54	61	55	58	56	52	56	51
5	54	56	58	53	62	57	49	48	49	45	46	45
	55	57	57	52	54	53	50	48	48	52	46	48
6	72	69	68	61	64	64	48	47	45	44	45	41
	68	69	63	63	62	65	46	48	44	43	47	44
7	61	65	62	63	65	61	51	49	50	50	49	51
	62	61	62	63	63	64	56	49	54	50	49	52
8	57	65	59	58	59	54	58	62	64	54	52	55
	58	67	56	58	56	58	58	59	61	54	49	54
9	55	57	55	53	61	58	45	46	44	42	49	43
	56	56	51	48	60	53	45	49	51	43	48	41
10	66	70	69	62	68	65	47	48	47	45	46	39
	70	70	71	61	67	67	49	48	49	43	46	42
11	68	67	68	63	64	68	57	56	54	46	53	53
	62	65	62	64	61	65	54	52	56	47	55	51
12	62	62	64	58	61	64	47	47	48	50	47	47
	60	59	58	62	62	61	48	52	47	52	47	48
13	66	66	63	64	62	67	55	55	53	52	53	50
	64	64	64	64	60	66	55	56	55	53	51	49

Mastoid placement												
3 kHz	**Ipsilateral**						**Contralateral**					
Subject	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3
1	62	62	62	61	60	64	61	62	57	57	54	56
	64	66	65	60	61	62	61	61	59	58	55	54
2	69	61	62	69	65	59	59	55	60	57	57	52
	69	58	62	71	66	60	59	56	60	58	57	53
3	70	73	75	68	71	67	61	58	59	56	57	54
	68	74	75	65	68	66	59	59	61	53	57	55
4	60	64	63	63	63	56	49	48	50	47	47	44
	62	64	63	65	64	61	49	50	47	47	49	46
5	63	61	60	64	67	62	48	55	49	52	48	50
	63	60	60	62	64	67	48	49	50	55	53	48
6	70	74	77	71	71	71	50	54	50	48	46	45
	72	72	76	72	71	69	54	53	53	48	47	47
7	73	68	70	71	71	66	55	54	55	52	49	54
	70	67	70	69	70	66	54	57	56	52	48	53
8	68	71	70	65	64	65	64	61	64	58	57	59
	67	70	67	64	64	61	62	59	63	60	57	56
9	66	63	75	63	65	60	49	51	56	50	49	48
	69	67	72	65	62	65	47	53	55	50	48	51
10	70	74	69	70	70	66	48	49	50	51	49	44
	68	71	73	70	71	67	48	50	50	48	49	43
11	72	70	73	66	63	65	64	56	59	53	48	56
	75	76	75	68	63	60	61	59	56	52	48	54
12	75	77	78	73	71	71	62	64	63	61	61	62
	77	80	82	71	69	73	60	65	65	59	62	62
13	75	75	76	67	69	64	62	61	61	62	60	60
	74	75	76	67	68	65	62	61	62	60	61	59

Mastoid placement												
4 kHz	**Ipsilateral**						**Contralateral**					
Subject	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3
1	83	83	78	83	81	80	67	69	65	70	68	67
	83	84	81	83	80	80	67	67	64	70	65	68
2	84	88	88	89	88	85	64	60	63	65	63	60
	84	87	80	89	88	84	64	61	62	63	64	62
3	87	89	85	84	81	81	59	66	62	68	64	64
	89	89	86	90	79	78	56	67	65	65	61	65
4	75	78	72	78	81	79	59	55	60	54	57	63
	78	81	75	78	82	79	62	60	61	54	60	61
5	79	86	80	83	82	80	58	61	58	61	55	56
	79	86	80	85	81	82	57	60	59	63	54	60
6	82	84	83	83	84	81	61	58	61	60	54	52
	85	83	83	84	84	83	61	57	62	59	53	54
7	74	85	78	81	81	83	60	64	55	56	56	59
	75	84	79	81	84	83	56	63	54	58	57	60
8	79	89	79	81	84	83	63	66	63	63	65	63
	82	91	80	81	83	83	62	68	59	63	62	64
9	74	81	74	75	74	72	54	63	60	59	68	63
	74	79	74	77	74	78	59	61	57	57	68	65
10	80	81	76	80	77	80	54	60	56	60	64	60
	75	84	76	79	78	83	55	62	57	59	63	60
11	90	93	90	90	88	78	65	57	67	56	60	58
	91	97	90	89	90	80	60	58	65	54	58	56
12	88	87	84	89	85	84	69	66	63	65	65	65
	90	91	88	90	88	83	69	67	65	67	68	66
13	83	93	89	90	92	91	62	64	64	66	68	65
	87	92	89	90	92	89	63	63	63	67	65	64

Forehead placement												
1 kHz	**Right**						**Left**					
Subject	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3
1	58	60	60	60	62	63	62	62	61	63	65	61
	59	61	60	60	62	64	62	60	61	62	66	58
2	68	66	64	72	65	66	66	69	69	66	62	60
	67	69	66	71	65	67	70	68	69	67	61	61
3	65	66	64	66	67	63	58	62	60	61	64	59
	65	65	65	65	70	61	59	62	60	61	62	58
4	67	62	60	67	73	67	61	59	58	63	63	61
	64	64	60	68	72	66	58	60	57	63	64	61
5	57	61	63	59	59	57	58	55	55	56	57	48
	65	62	63	57	57	57	56	56	56	56	56	50
6	70	67	68	71	71	74	65	63	65	62	65	66
	72	67	69	70	70	73	64	64	65	61	64	65
7	71	71	72	76	78	79	66	63	64	64	65	66
	72	71	72	76	78	78	66	62	64	65	65	69
8	61	62	60	57	60	56	66	64	65	58	58	64
	62	61	59	53	55	58	63	62	61	54	57	62
9	65	64	68	70	73	70	67	65	69	69	68	65
	71	69	70	70	71	71	68	65	70	70	66	64
10	67	65	64	64	71	67	59	58	60	59	61	58
	67	65	65	66	70	67	59	55	60	59	60	57
11	68	69	62	72	70	67	69	65	68	62	61	64
	69	69	71	68	69	68	70	64	66	60	57	64
12	71	69	64	71	70	64	67	62	63	65	68	69
	69	69	71	66	74	64	66	64	64	65	69	68
13	70	70	65	68	72	69	71	69	70	69	71	69
	70	71	72	68	72	68	67	71	68	67	69	69

Forehead placement												
2 kHz	**Right**						**Left**					
Subject	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3
1	49	48	50	52	49	46	49	49	49	51	48	45
	50	50	50	52	48	46	48	48	50	52	50	47
2	51	51	49	51	51	51	46	48	51	47	49	50
	48	49	52	49	50	52	47	48	52	49	50	52
3	52	52	53	47	51	46	54	52	53	50	51	49
	53	52	52	49	51	46	54	54	53	48	52	48
4	61	55	60	51	58	52	60	60	59	55	57	53
	62	55	60	53	57	51	60	59	60	56	55	53
5	52	49	48	50	45	46	45	45	45	45	42	43
	51	50	48	50	45	45	45	49	46	46	43	44
6	56	56	56	55	52	56	46	48	49	46	41	52
	57	55	57	56	53	57	47	47	48	47	46	53
7	54	56	57	50	56	55	48	51	53	48	48	49
	55	55	56	50	55	56	49	52	54	46	48	50
8	50	60	56	46	45	46	60	58	58	62	59	56
	53	57	55	46	45	44	58	56	55	63	59	56
9	67	62	64	61	55	54	62	55	63	53	48	50
	67	63	65	60	55	55	63	54	63	53	48	50
10	52	52	53	51	50	50	50	44	48	45	42	43
	51	51	52	53	52	52	45	45	50	45	41	44
11	60	61	57	51	47	48	62	63	59	53	49	50
	60	60	57	51	44	50	62	62	59	53	46	52
12	64	53	62	60	55	61	61	54	61	57	59	60
	64	52	62	63	59	64	58	53	60	59	59	60
13	55	58	55	54	55	57	56	53	55	51	50	53
	56	57	57	55	56	58	57	54	57	52	51	53

Forehead placement												
3 kHz	**Right**						**Left**					
Subject	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3
1	61	59	60	56	54	53	56	56	55	57	53	57
	62	60	57	57	53	53	56	58	58	56	56	58
2	58	60	56	60	60	58	60	61	60	60	58	58
	59	60	58	60	58	55	60	60	57	61	60	54
3	61	61	62	58	55	55	63	61	62	58	59	59
	61	60	62	56	56	56	59	61	59	60	55	57
4	53	58	56	47	52	48	51	57	52	45	49	45
	53	55	59	48	54	47	50	54	56	45	49	49
5	47	50	53	51	47	49	56	56	59	50	54	52
	49	51	54	50	50	50	51	52	57	48	55	51
6	64	59	56	57	57	56	54	55	50	55	54	56
	63	56	57	55	60	57	53	55	52	53	52	56
7	63	59	63	60	58	62	57	54	56	55	55	57
	63	60	61	62	62	61	59	57	58	57	56	56
8	63	69	61	65	64	57	65	67	67	61	59	57
	63	65	63	66	65	58	62	65	65	61	59	56
9	60	58	63	57	62	62	66	59	62	60	61	64
	62	57	65	58	61	64	65	59	63	58	63	63
10	60	59	60	56	61	57	59	57	55	60	61	59
	62	61	59	61	60	61	59	56	58	58	59	60
11	65	64	64	71	68	65	55	61	58	62	60	57
	66	65	67	68	68	64	57	60	58	58	59	58
12	68	69	67	71	67	70	64	64	62	68	66	67
	68	69	66	67	71	63	64	62	60	67	66	70
13	62	63	61	58	60	56	59	59	61	56	59	55
	62	61	60	58	61	56	62	61	61	56	57	56

Forehead placement												
4 kHz	**Right**						**Left**					
Subject	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3	B71-1	B71-2	B71-3	BEST-1	BEST-2	BEST-3
1	67	69	67	69	67	71	61	66	60	69	68	63
	69	67	66	73	71	69	65	66	61	66	69	65
2	77	68	66	70	70	70	78	71	72	68	73	68
	77	70	70	72	70	67	76	71	69	71	72	70
3	64	69	68	72	73	70	74	75	70	69	75	76
	67	69	69	71	72	69	74	72	70	71	74	76
4	57	69	67	72	74	74	60	68	62	67	70	71
	59	67	67	68	73	74	60	68	61	67	70	71
5	75	66	69	74	71	71	71	71	75	76	71	76
	74	66	70	74	73	71	70	73	74	76	72	73
6	67	71	68	68	70	71	66	66	61	62	64	65
	67	72	69	68	71	70	66	66	61	62	67	64
7	69	74	71	70	75	71	65	68	70	64	70	69
	69	73	71	68	73	71	65	66	70	65	70	68
8	72	82	71	72	78	75	72	79	75	73	77	77
	74	81	72	73	79	77	73	78	77	73	77	78
9	67	77	70	71	67	71	70	75	72	72	69	76
	68	73	71	70	65	74	70	74	72	73	68	76
10	67	66	64	68	70	71	67	68	67	65	67	70
	67	67	66	65	69	69	67	70	66	65	68	71
11	75	86	80	72	73	75	71	76	68	64	71	74
	76	85	82	66	76	74	70	76	66	69	71	75
12	74	68	72	71	68	73	76	72	74	73	74	74
	74	68	72	73	67	74	76	73	74	78	73	75
13	72	68	68	62	72	69	68	72	66	69	69	77
	71	66	66	64	73	68	68	72	66	73	68	77

Experiment 2: Hearing threshold level measurements (dB HL)

	Right as test ear		Left as test ear	
	BV on right	**BV on left**	**BV on left**	**BV on right**
Subject 1				
Session 1	1, 2, 1	12, 13, 11	0, 1, -3	6, 11, 11
Session 2	2, 3, 5	6, 6, 6	-2, -3, -2	10, 11, 9
Session 3	-3, 1, -5	8, 6, 7	1, 3, 3	8, 11, 13
Subject 2				
Session 1	5, 2, 1	3, 2, 4	0, 6, 4	7, 8, 9
Session 2	10, 12, 11	9, 10, 11	2, 4, -1	2, 3, 3
Session 3	5, 7, 7	6, 7, 7	0, 2, 2	6, 6, 5
Subject 3				
Session 1	5, 2, 0	7, 9, 6	6, -2, 3	2, 5, 1
Session 2	0, 2, 2	1, 8, 6	-8, -5, -4	-1, 0, 0
Session 3	8, 9, 6	9, 7, 6	1, 2, -2	1, 2, 6
Subject 4				
Session 1	-4, 1, 0	7, 5, 6	-3, -3, -4	5, 3, 8
Session 2	-6, -4, -5	0, 2, 1	-4, -5, -5	3, 6, 3
Session 3	1, 5, 9	9, 11, 10	2, 3, 5	5, 8, 8
Subject 5				
Session 1	-5, -6, -1	11, 10, 10	-5, -5, -9	5, 5, 6
Session 2	-3, -3, -4	13, 11, 11	-6, -6, -8	5, 5, 2
Session 3	-5, -2, -4	12, 14, 11	-5, -8, -6	3, 5, 1
Subject 6				
Session 1	6, 7, 5	12, 5, 10	6, 8, 1	12, 11, 10
Session 2	2, 1, 1	11, 11, 14	11, 10, 12	13, 11, 11
Session 3	4, 3, 3	9, 10, 8	2, 7, 8	14, 12, 14
Subject 7				
Session 1	-1, 3, 0	15, 10, 13	-4, -3, 0	11, 13, 11
Session 2	2, 0, 4	6, 12, 8	2, 1, -3	14, 12, 10
Session 3	0, 1, -1	12, 11, 14	3, 3, 0	5, 8, 8
Subject 8				
Session 1	1, 5, 7	9, 7, 11	3, 1, 1	3, 3, 3
Session 2	5, 3, 3	8, 5, 0	1, 3, 4	9, 7, 5
Session 3	8, 2, 3	12, 8, 7	2, 2, -2	6, 10, 9

Subject 9				
Session 1	9, 5, 7	11, 15, 11	2, 1, 2	6, 3, 2
Session 2	2, 4, 5	16, 16, 15	0, 4, 7	9, 9, 12
Session 3	2, 1, -4	13, 17, 16	0, 1, 5	4, 6, 6
Subject 10				
Session 1	2, 3, 2	10, 13, 12	4, 4, 3	13, 14, 15
Session 2	3, -1, 1	15, 12, 14	3, 2, 4	10, 12, 10
Session 3	1, 0, 1	12, 14, 13	3, 5, 4	11, 10, 11

Experiment 2: Lateralisation using ILD and IPD via air-conduction

	ILD					IPD				
Subject 1	-15.00	-10.00	0.00	10.00	15.00	0.00	0.00	0.00	0.00	0.00
Session 1	0.00	0.00	0.00	0.00	0.00	-90.00	-45.00	0.00	45.00	90.00
	0.10	0.26	0.31	0.89	0.89	0.18	0.41	0.38	0.95	0.76
	0.01	0.22	0.39	1.00	1.00	0.19	0.41	0.47	0.70	0.62
	0.18	0.12	0.30	0.71	0.94	0.10	0.08	0.63	0.91	0.89
	0.08	0.17	0.89	0.97	1.00	0.19	0.28	0.50	0.87	0.87
	0.11	0.16	0.75	0.74	0.80	0.19	0.28	0.74	0.82	0.90
	0.06	0.11	0.47	0.92	0.83	0.39	0.39	0.49	0.91	0.93
	0.00	0.20	0.36	0.81	1.00	0.24	0.75	0.31	0.64	0.81
	0.16	0.26	0.44	0.83	0.93	0.19	0.41	0.38	0.74	0.85
	0.00	0.12	0.73	0.94	1.00	0.21	0.26	0.85	0.63	0.98
	0.16	0.14	0.22	0.86	0.92	0.24	0.37	0.85	0.83	0.78
Session 2	0.03	0.19	0.58	0.62	1.00	0.10	0.32	0.42	0.71	0.74
	0.00	0.20	0.46	0.69	1.00	0.13	0.27	0.34	0.49	0.81
	0.00	0.27	0.67	0.86	0.96	0.38	0.43	0.49	0.52	0.97
	0.09	0.09	0.44	0.88	0.95	0.14	0.49	0.89	0.92	0.89
	0.02	0.10	0.75	0.85	1.00	0.26	0.48	0.46	0.84	0.63
	0.00	0.24	0.18	0.74	1.00	0.16	0.46	0.48	0.26	0.73
	0.16	0.19	0.53	0.86	1.00	0.24	0.23	0.88	0.65	0.89
	0.17	0.09	0.34	0.83	1.00	0.11	0.73	0.53	0.56	0.46
	0.12	0.08	0.49	0.62	1.00	0.23	0.44	0.56	0.29	0.70
	0.05	0.00	0.41	0.86	1.00	0.16	0.33	0.48	0.47	0.89

	ILD					IPD				
Subject 2 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.05	0.33	0.37	0.63	0.74	0.27	0.22	0.65	0.80	0.78
	0.10	0.19	0.56	0.83	0.77	0.21	0.39	0.45	0.72	0.78
	0.15	0.32	0.67	0.64	0.83	0.30	0.11	0.59	0.64	0.86
	0.09	0.23	0.58	0.58	0.80	0.28	0.36	0.44	0.67	0.72
	0.36	0.34	0.72	0.69	0.81	0.14	0.15	0.72	0.63	0.82
	0.35	0.31	0.24	0.80	0.66	0.11	0.33	0.74	0.72	0.80
	0.33	0.30	0.65	0.59	0.80	0.14	0.36	0.58	0.82	0.73
	0.21	0.07	0.45	0.80	0.74	0.19	0.37	0.59	0.78	0.93
	0.17	0.15	0.43	0.65	0.66	0.15	0.41	0.62	0.86	0.63
	0.10	0.39	0.36	0.75	0.78	0.12	0.31	0.40	0.65	0.78
Session 2	0.00	0.25	0.27	0.76	0.67	0.05	0.00	0.00	0.76	0.73
	0.38	0.31	0.51	0.60	0.84	0.19	0.22	0.72	0.23	0.74
	0.23	0.29	0.37	0.75	0.76	0.06	0.26	0.55	0.73	0.75
	0.00	0.45	0.76	0.30	1.00	0.13	0.68	0.30	0.75	0.77
	0.30	0.22	0.22	0.78	1.00	0.33	0.40	0.76	0.72	0.77
	0.36	0.20	0.71	0.79	0.97	0.20	0.19	0.52	0.72	0.78
	0.18	0.16	0.29	0.00	0.71	0.09	0.12	0.66	0.38	1.00
	0.01	0.36	0.30	0.82	1.00	0.00	0.14	0.50	0.84	0.82
	0.01	0.10	0.54	0.77	1.00	0.00	0.19	0.44	0.88	1.00
	0.20	0.31	0.30	1.00	1.00	0.00	0.00	0.54	0.70	0.79

	ILD					IPD				
Subject 3 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.34	0.58	0.51	0.50	0.65	0.35	0.52	0.51	0.71	0.65
	0.06	0.52	0.52	0.50	0.94	0.49	0.21	0.28	0.56	0.69
	0.12	0.55	0.66	0.50	0.45	0.51	0.53	0.29	0.54	0.90
	0.47	0.07	0.54	0.55	0.49	0.51	0.52	0.51	0.52	0.51
	0.51	0.44	0.55	0.80	0.52	0.52	0.52	0.67	0.64	0.59
	0.51	0.32	0.58	0.45	0.50	0.28	0.58	0.49	0.50	0.29
	0.29	0.50	0.53	0.53	0.80	0.33	0.20	0.31	0.69	0.52
	0.53	0.72	0.54	0.95	0.05	0.50	0.53	0.52	0.40	0.45
	0.50	0.42	0.57	0.58	0.80	0.43	0.51	0.53	0.55	0.51
	0.49	0.48	0.54	0.57	0.97	0.39	0.68	0.33	0.51	0.55
Session 2	0.40	0.87	0.43	0.97	0.92	0.25	0.43	0.55	0.43	0.56
	0.47	0.47	0.33	0.54	0.86	0.45	0.57	0.59	0.22	0.96
	0.86	0.47	0.46	0.33	0.80	0.25	0.36	0.67	0.52	0.26
	0.81	0.11	0.52	0.76	0.88	0.33	0.01	0.23	0.55	0.52
	0.36	0.31	0.52	0.70	0.90	0.51	0.79	0.52	0.69	0.90
	0.34	0.42	0.39	0.28	0.65	0.25	0.07	0.97	0.81	0.64
	0.26	0.50	0.50	0.65	0.94	0.27	0.53	0.56	0.97	0.93
	0.45	0.51	0.57	0.73	0.88	0.51	0.47	0.15	0.86	0.49
	0.38	0.56	0.50	0.09	0.64	0.34	0.02	0.52	0.47	0.47
	0.23	0.14	0.51	0.90	0.71	0.23	0.35	0.05	0.46	0.48

	ILD					IPD				
Subject 4 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.35	0.35	0.56	0.73	0.80	0.39	0.47	0.75	0.48	0.66
	0.11	0.25	0.69	0.55	0.57	0.38	0.40	0.63	0.66	0.67
	0.19	0.14	0.47	0.80	0.71	0.50	0.50	0.47	0.70	0.74
	0.15	0.25	0.64	0.65	0.78	0.36	0.49	0.25	0.47	0.54
	0.35	0.40	0.57	0.68	0.75	0.40	0.54	0.49	0.90	1.00
	0.16	0.22	0.63	0.78	0.86	0.29	0.41	0.34	0.70	0.58
	0.29	0.30	0.27	0.66	0.83	0.36	0.26	0.63	0.56	0.66
	0.29	0.39	0.58	1.00	0.80	0.38	0.29	0.55	0.69	0.76
	0.31	0.08	0.56	0.61	0.80	0.62	0.24	0.55	0.56	0.71
	0.32	0.35	0.17	0.73	0.90	0.42	0.56	0.64	0.71	0.68
Session 2	0.06	0.27	0.37	0.68	0.61	0.06	0.32	0.24	0.63	0.48
	0.17	0.28	0.49	0.60	0.59	0.22	0.64	0.51	0.50	0.60
	0.26	0.27	0.49	0.62	0.74	0.33	0.35	0.53	0.69	0.65
	0.01	0.13	0.74	0.77	0.71	0.36	0.18	0.49	0.61	0.67
	0.25	0.45	0.50	0.49	0.71	0.30	0.26	0.49	0.53	0.72
	0.31	0.26	0.50	0.70	0.71	0.48	0.28	0.52	0.67	0.75
	0.24	0.32	0.73	0.64	0.63	0.17	0.22	0.48	0.31	0.49
	0.14	0.26	0.56	0.71	0.69	0.31	0.23	0.50	0.68	0.62
	0.21	0.39	0.55	0.62	0.50	0.38	0.64	0.47	0.29	0.65
	0.28	0.34	0.53	0.67	0.76	0.27	0.58	0.52	0.80	0.54

	ILD					IPD				
Subject 5	-15.00	-10.00	0.00	10.00	15.00	0.00	0.00	0.00	0.00	0.00
Session 1	0.00	0.00	0.00	0.00	0.00	-90.00	-45.00	0.00	45.00	90.00
	0.15	0.33	0.63	0.72	0.66	0.16	0.70	0.67	0.80	0.78
	0.26	0.29	0.30	0.69	0.70	0.06	0.11	0.60	0.64	0.90
	0.40	0.25	0.64	0.88	0.94	0.13	0.19	0.55	0.60	0.67
	0.16	0.16	0.89	0.88	0.81	0.40	0.00	0.83	0.82	0.90
	0.02	0.24	0.69	0.63	1.00	0.11	0.08	0.75	0.70	0.78
	0.18	0.13	0.60	0.61	1.00	0.81	0.41	0.80	0.80	0.76
	0.00	0.06	0.12	0.63	0.90	0.84	0.12	0.55	0.36	0.79
	0.14	0.25	0.20	1.00	1.00	0.12	0.22	0.33	0.66	0.65
	0.11	0.45	0.72	0.85	0.92	0.10	0.09	0.68	0.85	0.67
	0.05	0.43	0.73	0.84	0.91	0.05	0.23	0.65	0.89	0.87
Session 2	0.30	0.06	0.81	0.78	0.90	0.88	0.67	0.87	0.89	0.89
	0.38	0.13	0.91	0.85	0.90	0.63	0.35	0.85	0.93	0.81
	0.10	0.14	0.30	0.88	0.99	0.10	0.11	0.09	0.92	0.83
	0.21	0.15	0.84	0.78	0.76	0.15	0.13	0.29	0.93	0.84
	0.23	0.24	0.07	0.88	0.70	0.10	0.30	0.65	0.27	0.84
	0.24	0.11	0.86	0.83	0.68	0.11	0.15	0.69	0.85	0.92
	0.13	0.12	0.27	0.83	0.78	0.08	0.10	0.92	0.83	0.77
	0.17	0.11	0.65	0.89	0.90	0.04	0.12	0.33	0.75	0.88
	0.28	0.21	0.67	0.87	0.85	0.19	0.08	0.83	0.78	0.93
	0.14	0.18	0.88	0.87	0.87	0.10	0.08	0.76	0.91	0.64

	ILD					IPD				
Subject 6 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.41	0.27	0.16	0.77	0.76	0.26	0.06	0.17	0.52	0.76
	0.37	0.44	0.39	0.95	0.96	0.34	0.20	0.32	0.60	0.58
	0.04	0.70	0.48	0.76	0.96	0.44	0.22	0.41	0.66	0.73
	0.08	0.28	0.78	0.81	0.65	0.21	0.23	0.51	0.74	0.80
	0.22	0.78	0.59	0.91	0.78	0.39	0.45	0.74	0.96	0.98
	0.38	0.31	0.37	0.72	0.98	0.27	0.48	0.32	0.59	0.74
	0.30	0.33	0.55	0.76	0.64	0.22	0.24	0.53	0.75	0.83
	0.34	0.32	0.38	0.44	0.80	0.14	0.42	0.57	0.82	0.53
	0.31	0.42	0.72	0.78	0.69	0.18	0.16	0.52	0.56	0.77
	0.30	0.40	0.25	1.00	0.94	0.15	0.18	0.37	0.60	1.00
Session 2	0.14	0.44	0.53	0.80	0.69	0.37	0.46	0.13	0.66	0.58
	0.09	0.32	0.52	0.60	0.95	0.49	0.50	0.56	0.58	0.71
	0.25	0.48	0.56	0.83	0.90	0.50	0.14	0.65	0.57	0.78
	0.27	0.39	0.47	0.88	0.65	0.13	0.29	0.46	0.69	0.87
	0.05	0.44	0.39	0.78	0.80	0.52	0.29	0.49	0.53	0.65
	0.21	0.23	0.78	0.56	0.73	0.46	0.46	0.60	0.56	0.47
	0.26	0.51	0.53	0.76	0.97	0.24	0.28	0.29	0.35	0.53
	0.34	0.32	0.69	0.71	0.93	0.39	0.55	0.61	0.63	0.73
	0.45	0.32	0.52	0.71	1.00	0.44	0.33	0.34	0.66	0.85
	0.29	0.24	0.29	0.70	0.52	0.39	0.28	0.46	0.62	0.63

	ILD					IPD				
Subject 7	-15.00	-10.00	0.00	10.00	15.00	0.00	0.00	0.00	0.00	0.00
Session 1	0.00	0.00	0.00	0.00	0.00	-90.00	-45.00	0.00	45.00	90.00
	0.08	0.50	0.60	0.99	0.67	0.00	0.25	0.30	0.89	0.85
	0.43	0.34	0.65	0.77	0.66	0.76	0.26	0.55	0.38	0.89
	0.02	0.45	0.57	0.77	0.77	0.57	0.70	0.56	0.81	0.73
	0.00	0.20	0.83	0.79	0.93	0.33	0.38	0.27	0.80	0.82
	0.40	0.32	0.56	0.83	0.74	0.20	0.44	0.57	0.65	0.64
	0.24	0.55	0.54	0.65	0.80	0.59	0.41	0.44	0.71	0.60
	0.28	0.46	0.24	0.68	0.94	0.51	0.26	0.81	0.63	0.64
	0.00	0.28	0.70	0.44	0.99	0.28	0.16	1.00	0.77	0.67
	0.00	0.14	0.21	0.86	1.00	0.20	0.32	0.59	0.65	0.67
	0.46	0.26	0.91	0.71	0.77	0.10	0.27	0.62	0.66	0.77
Session 2	0.13	0.34	0.59	0.75	0.77	0.22	0.21	0.56	0.64	0.69
	0.01	0.08	0.75	0.80	0.67	0.17	0.28	0.55	0.61	0.75
	0.11	0.34	0.83	0.61	0.98	0.57	0.59	0.49	0.79	0.94
	0.22	0.21	0.60	0.90	0.52	0.26	0.33	0.48	0.47	0.65
	0.20	0.22	0.60	0.84	0.70	0.31	0.33	0.67	0.59	0.48
	0.09	0.07	0.39	0.78	0.57	0.55	0.46	0.36	0.81	0.68
	0.04	0.11	0.54	0.83	0.74	0.19	0.35	0.66	0.71	0.60
	0.03	0.21	0.43	0.64	0.77	0.36	0.43	0.62	0.47	0.67
	0.14	0.00	0.90	0.68	0.57	0.57	0.40	0.42	0.75	0.77
	0.00	0.38	0.56	0.69	0.84	0.31	0.43	0.54	0.68	0.66

	ILD					IPD				
Subject 8 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.08	0.24	0.45	0.88	0.92	0.20	0.49	0.47	0.81	0.87
	0.06	0.50	0.33	0.89	0.85	0.25	0.14	0.47	0.89	0.84
	0.09	0.13	0.76	0.73	0.83	0.32	0.83	0.04	0.80	0.70
	0.09	0.11	0.65	0.85	0.91	0.06	0.07	0.14	0.90	0.76
	0.09	0.28	0.83	0.87	0.79	0.10	0.16	0.47	0.65	0.80
	0.25	0.16	0.16	0.86	0.83	0.12	0.08	0.13	0.48	0.77
	0.06	0.12	0.78	0.82	0.98	0.13	0.04	0.61	0.83	0.88
	0.03	0.18	0.24	0.83	0.92	0.12	0.28	0.09	0.78	0.87
	0.06	0.17	0.18	0.82	0.93	0.08	0.12	0.47	0.48	0.64
	0.05	0.07	0.38	0.84	0.58	0.20	0.18	0.22	0.87	0.94
Session 2	0.76	0.09	0.03	0.82	0.86	0.13	0.05	0.75	0.82	0.92
	0.22	0.91	0.87	0.86	0.85	0.12	0.13	0.01	0.78	0.77
	0.04	0.09	0.85	0.92	0.88	0.06	0.28	0.13	0.82	0.72
	0.07	0.30	0.85	0.58	0.94	0.07	0.86	0.88	0.69	0.81
	0.20	0.06	0.07	0.84	0.86	0.08	0.24	0.81	0.14	0.87
	0.03	0.12	0.77	0.82	0.99	0.08	0.17	0.50	0.86	0.83
	0.20	0.05	0.80	0.57	0.95	0.11	0.10	0.07	0.96	0.87
	0.08	0.18	0.87	0.77	0.95	0.18	0.11	0.50	0.89	0.98
	0.09	0.04	0.81	0.81	0.90	0.07	0.83	0.96	0.86	0.88
	0.89	0.16	0.48	0.67	0.96	0.41	0.50	0.35	0.88	0.95

	ILD					IPD				
Subject 9	-15.00	-10.00	0.00	10.00	15.00	0.00	0.00	0.00	0.00	0.00
Session 1	0.00	0.00	0.00	0.00	0.00	-90.00	-45.00	0.00	45.00	90.00
	0.15	0.11	0.41	0.62	1.00	0.64	0.55	0.73	0.79	0.56
	0.21	0.25	0.49	0.68	1.00	0.39	0.62	0.49	0.40	0.54
	0.17	0.25	0.37	0.90	0.89	0.23	0.26	0.62	0.72	0.71
	0.16	0.43	0.60	0.70	0.78	0.49	0.31	0.94	0.66	0.87
	0.37	0.35	0.48	0.77	0.75	0.55	0.61	0.31	0.63	0.58
	0.08	0.07	0.43	0.71	0.86	0.68	0.38	0.61	0.76	0.78
	0.19	0.49	0.41	0.81	0.76	0.50	0.49	0.50	0.60	0.74
	0.36	0.20	0.56	0.77	0.88	0.65	0.40	0.42	0.70	0.72
	0.16	0.20	0.60	0.74	0.90	0.65	0.39	0.62	0.65	0.66
	0.48	0.47	0.46	0.79	1.00	0.49	0.53	0.63	0.49	0.58
Session 2	0.27	0.49	0.38	0.52	0.81	0.32	0.57	0.69	0.61	0.73
	0.25	0.77	0.57	0.62	0.79	0.44	0.26	0.48	0.45	0.34
	0.19	0.29	0.52	0.87	0.69	0.36	0.27	0.15	0.65	0.75
	0.09	0.09	0.39	0.58	0.79	0.38	0.29	0.59	0.56	0.53
	0.01	0.23	0.27	0.77	0.80	0.23	0.13	0.56	0.75	0.67
	0.12	0.33	0.57	0.70	0.79	0.31	0.68	0.34	0.62	0.56
	0.11	0.20	0.36	0.81	0.83	0.29	0.54	0.59	0.70	0.68
	0.21	0.33	0.47	0.64	0.78	0.47	0.47	0.61	0.49	0.68
	0.16	0.44	0.57	0.75	0.82	0.33	0.57	0.33	0.55	0.62
	0.12	0.81	0.67	0.47	0.89	0.34	0.42	0.55	0.49	0.74

	ILD					IPD				
Subject 10 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.10	0.17	0.03	0.81	0.98	0.36	0.41	0.36	0.73	0.84
	0.03	0.23	0.72	0.96	0.97	0.03	0.36	0.55	0.36	0.66
	0.11	0.10	0.72	0.79	0.69	0.29	0.25	0.64	0.55	0.76
	0.29	0.19	0.85	0.99	1.00	0.26	0.59	0.65	0.64	0.71
	0.13	0.37	0.74	0.84	1.00	0.34	0.41	0.25	0.80	0.56
	0.22	0.16	0.68	0.93	0.87	0.45	0.36	0.46	0.56	0.75
	0.05	0.07	0.62	0.96	0.97	0.12	0.44	0.66	0.65	0.74
	0.16	0.00	0.86	0.80	0.91	0.36	0.25	0.34	0.43	0.77
	0.05	0.57	0.68	0.97	0.98	0.22	0.46	0.50	0.79	0.61
	0.14	0.35	0.76	0.94	0.92	0.42	0.65	0.50	0.86	0.83
Session 2	0.33	0.07	0.89	1.00	0.96	0.22	0.65	0.68	0.66	0.65
	0.23	0.21	0.92	0.96	1.00	0.19	0.20	0.37	0.66	0.60
	0.13	0.29	0.77	0.97	0.95	0.53	0.35	0.42	0.76	0.87
	0.19	0.00	0.53	1.00	0.96	0.32	0.31	0.51	0.71	0.85
	0.05	0.39	0.64	0.89	0.90	0.36	0.45	0.49	0.56	0.89
	0.15	0.33	0.92	0.91	0.84	0.29	0.46	0.35	0.75	0.76
	0.20	0.18	0.93	1.00	0.96	0.47	0.55	0.24	0.74	0.90
	0.11	0.29	0.72	1.00	0.97	0.13	0.29	0.55	0.77	0.90
	0.12	0.11	0.64	0.69	0.98	0.25	0.28	0.65	0.61	0.70
	0.14	0.29	0.59	0.84	1.00	0.22	0.35	0.24	0.83	0.66

Experiment 2: Lateralisation using bone conduction

	ILD					IPD				
Subject 1 Session 1	-15.00	-10.00	0.00	10.00	15.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	-90.00	-45.00	0.00	45.00	90.00
	0.56	0.58	0.51	0.98	1.00	0.08	0.15	0.37	0.41	0.75
	0.07	0.20	0.29	0.95	1.00	0.05	0.17	0.70	0.20	0.51
	0.20	0.26	0.23	1.00	1.00	0.05	0.17	0.22	0.46	0.86
	0.14	0.29	0.25	0.88	0.99	0.06	0.23	0.15	0.49	0.66
	0.09	0.12	0.18	0.95	1.00	0.08	0.07	0.25	0.36	0.78
	0.11	0.10	0.44	0.84	1.00	0.07	0.12	0.25	0.60	0.62
	0.25	0.17	0.21	0.92	0.91	0.05	0.20	0.36	0.28	0.46
	0.10	0.22	0.11	0.93	1.00	0.06	0.21	0.23	0.79	0.89
	0.08	0.19	0.49	0.95	0.96	0.10	0.19	0.14	0.44	0.88
	0.33	0.40	0.80	0.79	1.00	0.09	0.19	0.32	0.74	0.77
Session 2	0.31	0.18	0.22	0.79	0.90	0.09	0.24	0.24	0.83	0.94
	0.04	0.34	0.38	0.02	0.95	0.05	0.12	0.24	0.94	0.86
	0.37	0.24	0.29	0.97	0.73	0.01	0.07	0.33	0.84	0.95
	0.42	0.49	0.37	0.39	0.18	0.09	0.14	0.58	0.71	0.99
	0.23	0.45	0.27	0.85	0.79	0.00	0.18	0.22	0.71	1.00
	0.74	0.33	0.30	0.43	0.80	0.00	0.29	0.38	0.78	0.88
	0.41	0.48	0.34	0.34	0.71	0.15	0.18	0.19	0.73	1.00
	0.32	0.61	0.65	0.59	0.88	0.00	0.16	0.28	0.74	0.88
	0.35	0.30	0.20	0.22	0.91	0.05	0.09	0.34	0.81	1.00
	0.03	0.76	0.48	0.61	0.81	0.00	0.00	0.36	0.77	0.89

	ILD					IPD				
Subject 2 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	1.00	0.77	0.49	0.70	1.00	0.83	0.63	0.61	0.86	0.82
	0.68	0.77	0.61	0.81	1.00	0.69	0.51	0.48	0.76	1.00
	0.80	0.75	0.78	0.80	1.00	0.79	0.46	0.51	0.78	0.84
	0.84	1.00	0.53	1.00	1.00	0.63	0.51	0.59	0.69	1.00
	0.63	0.72	0.51	0.77	1.00	0.89	0.36	0.53	1.00	0.96
	1.00	0.82	0.99	1.00	0.81	0.78	0.64	0.65	1.00	0.77
	1.00	0.70	0.71	0.75	1.00	0.76	0.62	0.70	0.95	1.00
	0.81	0.83	0.76	0.21	1.00	0.76	0.63	0.50	0.75	1.00
	0.82	0.80	0.49	1.00	1.00	0.49	0.34	0.63	0.79	1.00
	1.00	0.75	0.53	0.78	1.00	0.79	0.64	0.87	0.76	0.78
Session 2	0.77	0.52	0.54	1.00	1.00	0.00	0.18	0.75	0.80	0.81
	0.73	0.53	0.52	1.00	0.81	0.00	0.20	0.69	0.76	0.69
	0.76	0.50	0.75	0.87	1.00	0.00	0.20	0.80	0.71	1.00
	0.53	0.55	0.56	0.82	1.00	0.00	0.14	0.89	0.73	1.00
	0.68	0.50	0.74	1.00	0.74	0.16	0.52	0.53	0.83	0.78
	0.48	0.82	0.79	1.00	1.00	0.00	0.24	0.51	0.77	1.00
	0.72	0.71	1.00	1.00	1.00	0.00	0.23	0.81	0.76	0.78
	0.49	0.49	0.65	1.00	1.00	0.00	0.29	0.53	0.82	0.76
	0.80	0.77	0.52	0.77	0.81	0.24	0.19	0.79	1.00	0.78
	0.51	0.53	0.51	1.00	0.74	0.15	0.20	0.77	1.00	0.83

	ILD					IPD				
Subject 3 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.41	0.42	0.68	0.62	0.53	0.39	0.18	0.63	0.52	0.43
	0.46	0.32	0.40	0.47	0.96	0.34	0.24	0.53	0.60	0.49
	0.62	0.39	0.63	0.68	0.62	0.50	0.42	0.36	0.17	0.45
	0.12	0.53	0.58	0.65	0.69	0.39	0.45	0.55	0.86	0.46
	0.46	0.27	0.53	0.83	0.77	0.31	0.47	0.38	0.26	0.73
	0.52	0.07	0.63	0.95	0.78	0.35	0.41	0.55	0.72	0.37
	0.61	0.67	0.58	0.55	0.69	0.14	0.51	0.52	0.49	0.46
	0.16	0.78	0.53	0.55	0.78	0.19	0.47	0.57	0.57	0.47
	0.53	0.49	0.66	0.60	0.74	0.51	0.26	0.30	0.70	0.70
	0.67	0.55	0.49	0.63	0.71	0.05	0.77	0.51	0.54	0.70
Session 2	0.57	0.66	0.39	0.55	0.93	0.47	0.12	0.63	0.59	0.99
	0.75	0.47	0.40	0.60	0.78	0.50	0.25	0.41	0.50	0.68
	0.78	0.31	0.62	0.95	0.65	0.31	0.38	0.38	0.53	0.49
	0.60	0.77	0.53	0.95	0.73	0.78	0.09	0.12	0.50	0.57
	0.93	0.29	0.15	0.69	0.60	0.02	0.28	0.11	0.72	0.43
	0.57	0.64	0.40	0.50	0.56	0.36	0.24	0.44	0.49	0.69
	0.55	0.89	0.59	0.86	0.19	0.53	0.33	0.23	0.51	0.53
	0.17	0.46	0.19	0.82	0.77	0.16	0.03	0.56	0.74	0.77
	0.82	0.48	0.50	0.51	0.96	0.16	0.14	0.30	0.88	0.63
	0.89	0.75	0.22	0.60	0.90	0.54	0.06	0.48	0.84	0.48

	ILD					IPD				
Subject 4 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.75	0.67	0.62	0.68	0.65	0.29	0.54	0.79	0.89	0.73
	0.73	0.65	0.63	0.61	0.77	0.50	0.53	0.75	0.60	0.74
	0.71	0.92	0.56	0.72	0.80	0.39	0.48	0.77	0.89	0.83
	0.62	0.83	0.63	0.71	0.79	0.24	0.54	0.85	0.90	0.86
	0.73	0.68	0.69	0.73	0.86	0.37	0.51	0.71	0.70	0.86
	0.60	0.80	0.62	0.70	0.56	0.24	0.58	0.62	0.91	0.84
	0.62	0.65	0.56	0.74	0.70	0.27	0.47	0.96	0.81	0.85
	0.74	0.66	0.90	0.78	0.84	0.08	0.62	0.64	0.82	0.81
	0.79	0.59	0.76	0.72	0.68	0.24	0.69	0.72	0.82	0.78
	0.75	0.65	0.79	0.76	0.65	0.28	0.51	0.77	0.84	0.64
Session 2	0.75	0.77	0.50	0.60	0.64	0.67	0.34	0.65	0.71	0.65
	0.61	0.54	0.71	0.67	0.57	0.32	0.63	0.52	0.81	0.76
	0.60	0.76	0.63	0.55	0.67	0.28	0.52	0.57	0.66	0.68
	0.88	0.62	0.67	0.57	0.52	0.28	0.38	0.73	0.64	0.66
	0.63	0.63	0.70	0.63	0.76	0.18	0.41	0.60	0.82	0.90
	0.66	0.69	0.67	0.56	0.68	0.25	0.46	0.53	0.67	0.60
	0.84	0.67	0.62	0.73	0.67	0.21	0.40	0.65	0.84	0.96
	0.67	0.66	0.67	0.75	0.67	0.30	0.58	0.68	0.69	0.83
	0.71	0.61	0.58	0.61	0.64	0.11	0.36	0.98	0.78	0.71
	0.57	0.63	0.70	0.63	0.49	0.18	0.45	0.58	0.59	0.83

	ILD					IPD				
Subject 5	-15.00	-10.00	0.00	10.00	15.00	0.00	0.00	0.00	0.00	0.00
Session 1	0.00	0.00	0.00	0.00	0.00	-90.00	-45.00	0.00	45.00	90.00
	0.10	0.31	0.84	0.84	0.86	0.25	0.12	0.27	0.81	0.60
	0.10	0.21	0.19	0.88	0.75	0.15	0.14	0.24	0.87	0.89
	0.36	0.39	0.67	0.69	0.90	0.15	0.10	0.64	0.68	0.69
	0.20	0.13	0.16	0.67	0.84	0.29	0.24	0.90	0.71	0.89
	0.06	0.06	0.65	0.81	0.86	0.13	0.18	0.67	0.91	0.40
	0.23	0.19	0.79	0.91	0.76	0.13	0.58	0.64	0.85	0.88
	0.13	0.15	0.66	0.87	0.99	0.14	0.12	0.75	0.79	0.57
	0.30	0.58	0.79	0.89	0.85	0.11	0.17	0.23	0.74	0.79
	0.18	0.55	0.17	0.86	0.80	0.11	0.10	0.29	0.79	0.84
	0.13	0.35	0.19	0.90	0.88	0.26	0.62	0.83	0.84	0.91
Session 2	0.22	0.35	0.96	0.62	0.56	0.18	0.66	0.83	0.58	0.68
	0.12	0.26	0.35	0.89	0.56	0.14	0.70	0.22	0.74	0.67
	0.17	0.25	0.61	0.66	0.74	0.40	0.37	0.84	0.77	0.61
	0.12	0.12	0.79	0.57	0.86	0.75	0.72	0.78	0.56	0.78
	0.15	0.14	0.62	0.70	0.78	0.14	0.75	0.22	0.86	0.91
	0.09	0.10	0.59	0.90	0.77	0.24	0.38	0.59	0.95	0.70
	0.24	0.20	0.81	0.85	0.60	0.32	0.76	0.08	0.77	0.90
	0.26	0.16	0.68	0.78	0.62	0.72	0.21	0.17	0.86	0.84
	0.16	0.21	0.89	0.88	0.58	0.74	0.18	0.86	0.85	1.00
	0.30	0.19	0.80	0.80	0.58	0.82	0.20	0.80	0.23	0.85

	ILD					IPD				
Subject 6 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.32	0.02	0.80	0.65	1.00	0.18	0.19	0.53	0.54	0.91
	0.23	0.00	0.60	0.96	0.66	0.07	0.14	0.55	0.79	0.47
	0.10	0.09	0.93	1.00	0.92	0.14	0.16	0.89	0.60	0.18
	0.07	0.17	0.78	0.76	0.46	0.28	0.30	0.61	0.69	0.22
	0.00	0.01	0.83	0.54	0.29	0.28	0.34	0.71	0.69	0.66
	0.00	0.00	0.56	0.73	0.98	0.35	0.17	0.50	0.61	0.74
	0.11	0.21	0.53	0.95	0.66	0.07	0.20	0.87	0.70	0.18
	0.07	0.02	0.97	0.70	0.59	0.21	0.12	0.65	0.54	0.18
	0.00	0.00	0.70	0.74	0.82	0.00	0.28	0.89	0.88	0.76
	0.26	0.12	0.92	0.59	0.96	0.07	0.20	0.68	0.75	1.00
Session 2	0.50	0.74	0.62	0.68	0.53	0.09	0.28	0.63	0.70	0.65
	0.34	0.88	0.72	0.87	0.60	0.06	0.42	0.66	0.83	0.61
	0.44	0.50	0.53	0.53	0.85	0.08	0.29	0.70	1.00	0.61
	0.45	0.46	0.68	0.52	1.00	0.18	0.04	0.52	0.78	0.76
	0.51	0.76	0.87	0.96	0.74	0.07	0.36	0.61	0.79	0.99
	0.49	0.44	0.79	0.82	0.90	0.33	0.13	0.68	0.70	0.62
	0.33	0.95	0.66	0.96	0.70	0.23	0.28	0.72	0.94	0.82
	0.47	0.39	0.65	0.84	0.73	0.27	0.18	0.35	1.00	0.57
	0.32	0.66	0.53	0.67	0.40	0.14	0.45	0.65	0.55	0.83
	0.53	0.13	0.70	0.69	1.00	0.22	0.36	0.68	0.59	0.62

	ILD					IPD				
Subject 7 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.49	0.69	0.81	0.61	0.89	0.41	0.56	1.00	0.93	0.78
	0.06	0.54	0.74	0.77	0.88	0.43	0.46	0.63	1.00	0.81
	0.40	0.84	0.99	0.73	0.56	0.19	0.63	0.63	0.69	0.61
	0.52	0.49	0.62	0.71	0.68	0.24	0.44	0.74	0.70	0.58
	0.19	0.46	0.97	0.80	0.83	0.30	0.49	0.89	0.73	0.61
	0.22	0.57	1.00	1.00	1.00	0.34	0.37	0.69	1.00	0.72
	0.30	0.36	0.61	0.69	0.58	0.27	0.38	1.00	0.87	0.69
	0.60	0.57	0.72	1.00	0.77	0.00	0.43	0.81	0.79	0.73
	0.36	0.41	0.66	1.00	0.86	0.27	0.46	0.61	0.76	0.56
	0.39	0.61	0.79	0.92	0.99	0.15	0.46	0.72	0.96	0.81
Session 2	0.00	0.44	0.73	0.41	0.69	0.16	0.34	0.71	0.63	0.42
	0.64	0.59	0.60	0.63	0.81	0.15	0.38	0.76	0.82	0.47
	0.39	0.56	0.71	1.00	0.67	0.38	0.34	0.92	0.86	0.67
	0.17	0.37	0.67	0.82	1.00	0.22	0.38	0.62	0.75	0.44
	0.35	0.57	0.31	0.58	1.00	0.20	0.47	0.71	0.75	0.51
	0.00	0.33	0.77	0.72	0.99	0.21	0.37	0.61	0.70	0.61
	0.22	0.11	0.69	0.85	0.62	0.21	0.43	0.60	0.65	0.50
	0.06	0.38	0.76	0.90	0.94	0.27	0.58	0.66	0.63	0.66
	0.64	0.23	0.64	0.54	0.80	0.25	0.39	0.75	0.48	0.57
	0.00	0.33	0.62	0.70	0.53	0.03	0.31	0.71	0.54	0.57

	ILD					IPD				
Subject 8 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.01	0.04	0.82	0.12	0.42	0.11	0.18	0.88	0.99	0.74
	0.01	0.24	0.85	0.12	0.41	0.02	0.19	0.67	0.86	0.90
	0.00	0.14	0.88	0.20	0.42	0.14	0.24	0.67	0.99	0.24
	0.01	0.33	0.82	0.26	0.46	0.05	0.31	0.86	0.88	0.85
	0.11	0.04	0.80	0.21	0.68	0.10	0.19	0.73	0.96	0.93
	0.02	0.21	0.78	0.18	0.52	0.09	0.21	0.83	0.84	0.80
	0.02	0.15	0.86	0.45	0.22	0.21	0.47	0.84	0.98	0.93
	0.14	0.03	0.58	0.40	0.09	0.10	0.14	0.81	0.89	0.90
	0.02	0.25	0.74	0.25	0.45	0.11	0.21	0.64	0.91	0.78
	0.04	0.16	0.74	0.33	0.21	0.07	0.25	0.87	0.89	0.85
Session 2	0.12	0.08	0.78	0.10	0.20	0.12	0.17	0.61	0.90	0.80
	0.15	0.11	0.78	0.25	0.05	0.12	0.91	0.56	0.87	0.85
	0.06	0.08	0.67	0.43	0.85	0.03	0.11	0.54	0.89	0.81
	0.34	0.10	0.85	0.07	0.16	0.03	0.08	0.67	0.84	0.76
	0.05	0.13	0.68	0.43	0.44	0.09	0.33	0.69	0.92	0.78
	0.11	0.02	0.70	0.79	0.15	0.22	0.15	0.89	0.79	0.92
	0.10	0.09	0.77	0.23	0.14	0.04	0.15	0.62	0.86	0.38
	0.00	0.06	0.19	0.20	0.09	0.07	0.18	0.14	0.75	0.80
	0.11	0.75	0.83	0.89	0.77	0.15	0.64	0.07	0.88	0.86
	0.04	0.10	0.88	0.43	0.84	0.04	0.23	0.80	0.90	0.91

	ILD					IPD				
Subject 9	-15.00	-10.00	0.00	10.00	15.00	0.00	0.00	0.00	0.00	0.00
Session 1	0.00	0.00	0.00	0.00	0.00	-90.00	-45.00	0.00	45.00	90.00
	0.25	0.19	0.60	0.24	0.82	0.31	0.74	0.26	0.55	0.71
	0.00	0.18	0.29	0.80	0.58	0.26	0.27	0.35	0.65	0.62
	0.06	0.05	0.26	0.66	0.75	0.39	0.20	0.22	0.61	0.61
	0.00	0.12	0.42	0.54	0.58	0.22	0.16	0.28	0.26	0.28
	0.09	0.06	0.09	0.68	0.56	0.15	0.17	0.26	0.20	0.23
	0.00	0.10	0.20	0.40	0.69	0.17	0.41	0.23	0.36	0.30
	0.00	0.05	0.22	0.64	0.68	0.34	0.26	0.68	0.59	0.14
	0.05	0.13	0.23	0.62	0.68	0.14	0.23	0.36	0.21	0.25
	0.03	0.30	0.24	0.51	0.78	0.35	0.25	0.60	0.79	0.80
	0.00	0.89	0.58	0.54	0.72	0.34	0.35	0.26	0.36	0.62
Session 2	0.14	0.11	0.19	0.06	0.73	0.31	0.62	0.27	0.68	0.90
	0.24	0.21	0.12	0.78	0.94	0.30	0.65	0.61	0.28	0.57
	0.33	0.09	0.62	0.53	0.70	0.63	0.56	0.69	0.37	0.53
	0.05	0.25	0.27	0.21	0.78	0.61	0.11	0.30	0.35	0.32
	0.57	0.23	0.25	0.58	0.30	0.20	0.27	0.72	0.35	0.76
	0.19	0.29	0.35	0.76	0.66	0.27	0.12	0.13	0.38	0.53
	0.12	0.22	0.29	0.68	0.78	0.32	0.64	0.21	0.67	0.56
	0.11	0.75	0.20	0.36	0.27	0.75	0.70	0.21	0.57	0.66
	0.18	0.56	0.67	0.30	0.80	0.28	0.58	0.31	0.67	0.36
	0.32	0.14	0.30	0.34	0.54	0.22	0.13	0.25	0.62	0.43

	ILD					IPD				
Subject 10 Session 1	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
	0.16	0.12	0.80	0.93	0.87	0.04	0.36	0.59	0.72	0.80
	0.00	0.38	0.72	0.91	0.83	0.16	0.09	0.53	0.93	0.97
	0.08	0.79	0.74	0.90	1.00	0.04	0.35	0.58	0.77	0.78
	0.00	0.56	0.90	1.00	0.92	0.00	0.28	0.62	0.99	0.89
	0.00	0.00	0.75	0.89	0.94	0.06	0.37	0.63	0.87	0.80
	0.39	0.30	0.74	0.88	1.00	0.14	0.61	0.41	0.80	0.92
	0.28	0.18	0.78	0.94	0.96	0.02	0.28	0.69	0.83	0.96
	0.10	0.00	0.73	0.90	0.84	0.17	0.10	0.83	0.95	0.76
	0.23	0.08	0.84	1.00	1.00	0.05	0.33	0.27	0.93	1.00
	0.50	0.30	0.88	0.93	1.00	0.12	0.29	0.84	0.60	0.90
Session 2	0.00	0.28	0.54	1.00	1.00	0.05	0.21	0.91	0.93	0.85
	0.17	0.10	0.83	0.99	0.82	0.00	0.25	0.61	0.98	0.80
	0.09	0.14	0.81	0.96	1.00	0.09	0.09	0.77	0.98	1.00
	0.11	0.42	0.76	0.99	0.88	0.04	0.19	0.64	0.87	1.00
	0.00	0.28	0.82	0.97	0.96	0.00	0.24	0.71	1.00	0.68
	0.38	0.13	0.78	0.91	1.00	0.04	0.27	0.48	0.81	0.96
	0.33	0.80	0.96	0.94	0.94	0.11	0.25	0.66	0.87	0.89
	0.03	0.00	0.43	0.89	0.96	0.00	0.34	0.90	0.85	1.00
	0.41	0.93	0.58	0.82	1.00	0.07	0.85	0.77	0.81	0.92
	0.00	0.17	0.61	0.93	0.95	0.00	0.19	0.53	0.92	0.70

Experiment 3: Hearing threshold level measurements (dB HL)

	Right as test ear						Left as test ear					
	BV on right		**Mean**	**BV on left**		**Mean**	**TA**	**BV on left**		**Mean**	**BV on right**		**Mean**	**TA**
Subject 1														
Session 1	-9	11	-10	2	2	2	**12**	-4	-4	-4	0	3	2	**6**
Subject 2														
Session 1	12	8	10	7	6	7	**-3**	10	8	9	12	12	12	**3**
Session 2								9	10	10	2	0	1	**-9**
Subject 3														
Session 1	12	10	11	13	13	13	**2**	1	1	1	11	11	11	**10**
Session 2								8	8	8	15	13	14	**6**
Subject 4														
Session 1	8	7	8	9	9	9	**1**	9	7	8	13	9	11	**3**
Subject 5														
Session 1	-1	1	0	14	18	16	**16**	7	2	5	12	12	12	**7**
Session 2								8	6	7	14	9	12	**5**
Subject 6														
Session 1	-6	-3	-5	-2	0	-1	**4**	-2	-6	-4	8	7	8	**12**
Session 2	-6	-11	-9	-3	-3	-3	**6**	-10	-12	-11	3	0	2	**13**
Subject 7														
Session 1	12	10	11	12	19	16	**5**	12	8	10	14	8	11	**1**
Session 2	10	9	10	15	14	15	**5**							

Subject 8														
Session 1	5	5	5	11	17	14	**9**	-3	-3	-3	5	3	4	**7**
Session 2	5	3	4	17	15	16	**12**	-6	0	-3	2	3	3	**6**
Subject 9														
Session 1	13	13	13	11	10	11	**-2**	4	6	5	14	12	13	**8**
Subject 10														
Session 1	0	-2	-1	-4	-4	-4	**-3**	-8	-8	-8	-1	-3	-2	**6**
Subject 11														
Session 1	6	0	3	7	7	7	**4**	-11	-13	-12	-8	-8	-8	**4**
Subject 12														
Session 1	-2	-5	-4	-1	-1	-1	**3**	0	1	0	3	2	3	**3**
Subject 13														
Session 1	7	5	6	6	2	4	**-2**	8	7	8	8	4	6	**-2**
Session 2								18	16	17	10	10	10	**-7**

Experiment 3: TA measured during TD (dB)

	First attempt		Second attempt	
Subject	Right as test ear	Left as test ear	Right as test ear	Left as test ear
1	12	5	8	
2	-4	-1		
3	2	10		
4	0	-3		
5	12	9		
6	2	6	5	5
7	6	2	3	
9	2	5		
10	2	9		
11	6	3		
12	2	2		
13	-2	-5	-2	1

Experiment 3: Lateralisation using AC

	ILD					IPD				
	-15.00 0.00	-10.00 0.00	0.00 0.00	10.00 0.00	15.00 0.00	0.00 -90.00	0.00 -45.00	0.00 0.00	0.00 45.00	0.00 90.00
Subject 1	-27.00	-17.00	5.00	5.00	23.00	-4.00	-3.00	1.00	5.00	11.00
	-28.00	-25.00	-2.00	-6.00	13.00	-8.00	-3.00	0.00	8.00	7.00
	-22.00	-16.00	-4.00	0.00	10.00	-5.00	-3.00	2.00	5.00	11.00
	-22.00	-15.00	-7.00	5.00	7.00	-2.00	-2.00	0.00	4.00	7.00
	-20.00	-19.00	-9.00	5.00	11.00	-8.00	-4.00	2.00	8.00	10.00
Subject 2	-15.00	-5.00	8.00	22.00	20.00	-9.00	-3.00	5.00	11.00	12.00
	-10.00	-10.00	-1.00	16.00	28.00	-6.00	-5.00	4.00	7.00	13.00
	-14.00	-5.00	8.00	17.00	18.00	-11.00	-1.00	4.00	11.00	11.00
	-18.00	-4.00	-2.00	9.00	20.00	-7.00	-4.00	6.00	9.00	5.00
	-17.00	-15.00	2.00	19.00	18.00	-9.00	-5.00	4.00	7.00	14.00
Subject 3	-11.00	-16.00	-2.00	10.00	10.00	-6.00	-7.00	1.00	0.00	14.00
	-23.00	-9.00	2.00	8.00	11.00	-12.00	-14.00	8.00	3.00	10.00
	-16.00	-6.00	-1.00	24.00	16.00	-6.00	-9.00	-1.00	9.00	10.00
	-18.00	-11.00	4.00	12.00	14.00	-13.00	-2.00	-1.00	-2.00	8.00
	-18.00	-12.00	4.00	9.00	17.00	-7.00	0.00	2.00	3.00	10.00

Subject 4	-11.00	-12.00	4.00	31.00	22.00	-9.00	-3.00	0.00	8.00	12.00
	-30.00	-13.00	1.00	16.00	35.00	-8.00	0.00	-1.00	6.00	11.00
	-34.00	-13.00	-7.00	20.00	30.00	-8.00	-5.00	3.00	10.00	10.00
	-18.00	-18.00	-7.00	23.00	21.00	-5.00	-5.00	1.00	5.00	11.00
	-17.00	-13.00	4.00	12.00	26.00	-9.00	-8.00	3.00	4.00	11.00
Subject 5	-22.00	-14.00	1.00	15.00	18.00	-1.00	-9.00	7.00	6.00	6.00
	-22.00	-6.00	0.00	16.00	10.00	-1.00	19.00	0.00	6.00	4.00
	-12.00	0.00	5.00	20.00	14.00	-7.00	-2.00	-2.00	3.00	13.00
	-15.00	-11.00	0.00	9.00	14.00	-2.00	4.00	6.00	5.00	15.00
	-10.00	-7.00	-4.00	7.00	8.00	-10.00	-2.00	6.00	6.00	5.00
Subject 6	-34.00	-22.00	-12.00	9.00	11.00	-21.00	-13.00	3.00	14.00	19.00
	-21.00	-14.00	-3.00	2.00	12.00	-22.00	-13.00	3.00	13.00	15.00
	-18.00	-11.00	4.00	6.00	11.00	-24.00	-12.00	9.00	9.00	9.00
	-25.00	-6.00	4.00	6.00	7.00	-16.00	-16.00	12.00	9.00	13.00
	-25.00	-12.00	-10.00	8.00	18.00	-22.00	-6.00	12.00	5.00	17.00
Subject 7	-10.00	-5.00	-1.00	8.00	10.00	-9.00	-3.00	-2.00	4.00	8.00
	-12.00	-7.00	3.00	10.00	9.00	-5.00	-1.00	3.00	5.00	6.00
	-16.00	-12.00	-2.00	4.00	15.00	-10.00	-3.00	4.00	6.00	7.00
	-15.00	-10.00	-1.00	7.00	11.00	-7.00	-5.00	-2.00	6.00	5.00
	-11.00	-10.00	-1.00	6.00	13.00	-6.00	-5.00	-1.00	7.00	7.00
Subject 8	-2.00	-5.00	-4.00	8.00	20.00	-8.00	-7.00	1.00	8.00	9.00
	-14.00	-2.00	1.00	10.00	1.00	-9.00	-2.00	-3.00	6.00	1.00
	-8.00	-10.00	-3.00	10.00	12.00	-9.00	-6.00	-9.00	1.00	13.00
	-6.00	-6.00	-5.00	11.00	13.00	-8.00	-1.00	-2.00	0.00	15.00
	-9.00	-13.00	6.00	14.00	14.00	-5.00	-2.00	-3.00	2.00	16.00
Subject 9	-14.00	-8.00	4.00	9.00	10.00	10.00	-4.00	-3.00	0.00	2.00
	-4.00	-15.00	3.00	10.00	7.00	-6.00	2.00	-6.00	-3.00	-7.00
	-3.00	-15.00	4.00	-2.00	1.00	0.00	-2.00	-1.00	-1.00	2.00
	-7.00	-9.00	1.00	5.00	9.00	-3.00	-8.00	-2.00	-5.00	3.00
	-13.00	-7.00	2.00	-5.00	0.00	-2.00	-3.00	6.00	5.00	3.00
Subject 10	-16.00	-8.00	2.00	14.00	14.00	-3.00	-4.00	3.00	6.00	9.00
	-13.00	-8.00	6.00	15.00	22.00	-6.00	-3.00	3.00	2.00	7.00
	-17.00	-15.00	2.00	14.00	22.00	-6.00	-2.00	2.00	7.00	9.00
	-17.00	-10.00	2.00	9.00	16.00	-4.00	1.00	0.00	6.00	9.00
	-19.00	-7.00	6.00	11.00	14.00	-9.00	-1.00	2.00	2.00	9.00
Subject 11	-24.00	-12.00	1.00	9.00	19.00	-13.00	-10.00	0.00	7.00	15.00
	-21.00	-18.00	1.00	14.00	10.00	-4.00	-5.00	-6.00	17.00	12.00
	-15.00	-9.00	4.00	10.00	19.00	-6.00	2.00	1.00	7.00	8.00
	-6.00	-12.00	-1.00	4.00	25.00	-2.00	-8.00	1.00	11.00	13.00
	-11.00	-23.00	1.00	14.00	12.00	-3.00	-16.00	-1.00	-1.00	9.00
Subject 12	-17.00	-6.00	3.00	12.00	10.00	-14.00	-2.00	2.00	3.00	10.00
	-11.00	-7.00	-7.00	13.00	8.00	-1.00	-1.00	0.00	0.00	8.00
	-15.00	-9.00	0.00	12.00	24.00	-5.00	-6.00	1.00	4.00	4.00
	-8.00	-10.00	3.00	10.00	15.00	-11.00	-1.00	3.00	5.00	7.00
	-5.00	-5.00	-4.00	9.00	8.00	-2.00	-1.00	2.00	4.00	9.00

Subject 13	-22.00	-11.00	11.00	19.00	24.00	-13.00	17.00	12.00	-10.00	-10.00
	-17.00	-15.00	2.00	21.00	21.00	-12.00	5.00	14.00	-2.00	-5.00
	-25.00	-2.00	8.00	15.00	20.00	1.00	2.00	11.00	-3.00	-16.00
	-14.00	-14.00	5.00	9.00	25.00	11.00	0.00	15.00	-11.00	-5.00
	-11.00	-10.00	1.00	20.00	25.00	-4.00	1.00	14.00	-13.00	-10.00

Experiment 3: Lateralisation using BC

	ILD					IPD				
	-15.00	-10.00	0.00	10.00	15.00	0.00	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	-90.00	-45.00	0.00	45.00	90.00
Subject 1	-6.00	-11.00	0.00	2.00	3.00	-16.00	-12.00	10.00	16.00	19.00
	-15.00	-9.00	-3.00	6.00	2.00	-14.00	-11.00	8.00	16.00	16.00
	-12.00	-14.00	-1.00	5.00	-1.00	-10.00	-12.00	5.00	13.00	13.00
	-12.00	-4.00	-8.00	3.00	1.00	-14.00	-10.00	7.00	16.00	12.00
	-6.00	-11.00	4.00	4.00	-2.00	-13.00	-8.00	7.00	13.00	15.00
Subject 2	-10.00	1.00	0.00	-1.00	0.00	-8.00	-14.00	-4.00	2.00	6.00
	10.00	13.00	5.00	-2.00	8.00	-9.00	-13.00	-5.00	5.00	12.00
	12.00	4.00	6.00	9.00	5.00	-9.00	-7.00	-4.00	7.00	9.00
	-15.00	-9.00	-11.00	-11.00	-11.00	-16.00	-12.00	-4.00	-2.00	10.00
	-15.00	-16.00	-15.00	-5.00	-7.00	-4.00	-9.00	0.00	3.00	8.00
Subject 3	9.00	12.00	2.00	3.00	2.00	-19.00	-9.00	3.00	6.00	14.00
	16.00	2.00	-4.00	1.00	6.00	-19.00	-3.00	4.00	11.00	12.00
	8.00	15.00	1.00	5.00	5.00	-19.00	-6.00	4.00	14.00	10.00
	10.00	5.00	3.00	6.00	5.00	-18.00	-8.00	1.00	11.00	13.00
	12.00	7.00	1.00	3.00	4.00	-23.00	-4.00	-2.00	6.00	17.00
Subject 4	10.00	-5.00	-1.00	0.00	2.00	-13.00	-6.00	3.00	16.00	13.00
	-15.00	0.00	-9.00	-3.00	0.00	-15.00	-14.00	5.00	15.00	16.00
	-6.00	-16.00	-2.00	5.00	14.00	-16.00	-3.00	7.00	10.00	15.00
	-9.00	-20.00	-24.00	-2.00	13.00	-21.00	-6.00	5.00	14.00	19.00
	-14.00	-16.00	-3.00	10.00	22.00	-17.00	-12.00	5.00	14.00	19.00
Subject 5	3.00	4.00	8.00	19.00	11.00	-13.00	-8.00	3.00	7.00	15.00
	2.00	4.00	10.00	9.00	18.00	-12.00	-6.00	0.00	11.00	11.00
	4.00	2.00	6.00	10.00	17.00	-13.00	-7.00	-4.00	10.00	14.00
	-19.00	-28.00	-5.00	-1.00	-10.00	-12.00	-9.00	6.00	11.00	14.00
	-22.00	-17.00	-12.00	-10.00	-3.00	-12.00	-13.00	5.00	7.00	10.00
Subject 6	-8.00	-7.00	-18.00	-12.00	-8.00	-25.00	-24.00	-19.00	0.00	13.00
	-9.00	-18.00	-4.00	-14.00	-8.00	-14.00	-25.00	-18.00	10.00	21.00
	-5.00	-10.00	-21.00	-22.00	-10.00	-25.00	-18.00	-11.00	-22.00	12.00
	-17.00	-17.00	-35.00	-7.00	-3.00	-19.00	-25.00	-9.00	-1.00	11.00
	-20.00	-35.00	-10.00	-8.00	-3.00	-15.00	-15.00	-19.00	8.00	13.00

Subject 7	-7.00	-5.00	-8.00	-4.00	-5.00	-19.00	-17.00	0.00	5.00	10.00
	-5.00	-5.00	-6.00	-8.00	-4.00	-13.00	-14.00	-3.00	9.00	10.00
	-6.00	-9.00	-6.00	-6.00	-2.00	-18.00	-9.00	-4.00	8.00	5.00
	5.00	-3.00	-3.00	-2.00	6.00	-20.00	-15.00	-5.00	3.00	7.00
	-2.00	0.00	-4.00	6.00	1.00	-12.00	-15.00	-2.00	6.00	9.00
Subject 8	-1.00	2.00	-2.00	-4.00	-3.00	-22.00	-25.00	-12.00	1.00	4.00
	5.00	0.00	2.00	-9.00	1.00	-25.00	-17.00	-5.00	-6.00	3.00
	2.00	2.00	4.00	-7.00	-1.00	-24.00	-25.00	1.00	2.00	9.00
	6.00	8.00	-4.00	-1.00	-4.00	-22.00	-24.00	-5.00	1.00	10.00
	3.00	0.00	4.00	2.00	-9.00	-24.00	-22.00	-14.00	-3.00	2.00
Subject 9	-3.00	15.00	6.00	9.00	-13.00	-4.00	-6.00	-2.00	-15.00	-5.00
	1.00	3.00	1.00	-10.00	-13.00	4.00	-6.00	-9.00	-8.00	-7.00
	-19.00	-20.00	0.00	-1.00	-15.00	-16.00	-8.00	-7.00	9.00	6.00
	-5.00	-17.00	-4.00	-12.00	6.00	-10.00	-4.00	-2.00	-11.00	-3.00
	-7.00	-9.00	-12.00	-13.00	-7.00	-15.00	-3.00	-6.00	-1.00	2.00
Subject 10	-11.00	-9.00	-7.00	0.00	0.00	-23.00	-10.00	-5.00	-2.00	0.00
	-12.00	-10.00	-3.00	-1.00	0.00	-16.00	-18.00	-7.00	-3.00	0.00
	-13.00	-9.00	-3.00	2.00	-1.00	-16.00	-14.00	-6.00	-5.00	-1.00
	-10.00	-10.00	-6.00	1.00	-1.00	-17.00	-11.00	-7.00	-3.00	2.00
	-10.00	-6.00	-3.00	-1.00	3.00	-21.00	-9.00	-7.00	-5.00	-1.00
Subject 11	-11.00	-21.00	-12.00	8.00	18.00	-13.00	-13.00	5.00	15.00	13.00
	-11.00	-13.00	-5.00	6.00	13.00	-15.00	-12.00	3.00	6.00	24.00
	-25.00	-23.00	1.00	8.00	13.00	-6.00	-16.00	-1.00	-1.00	16.00
	-9.00	-18.00	-9.00	13.00	12.00	-4.00	1.00	4.00	5.00	13.00
	-16.00	-25.00	-5.00	12.00	25.00	-8.00	-20.00	-2.00	11.00	15.00
Subject 12	2.00	5.00	-3.00	2.00	1.00	-11.00	-9.00	4.00	10.00	10.00
	0.00	-5.00	-5.00	0.00	6.00	-10.00	-4.00	7.00	4.00	9.00
	2.00	0.00	1.00	3.00	4.00	-18.00	-1.00	4.00	5.00	11.00
	-6.00	2.00	-2.00	5.00	-2.00	-15.00	-9.00	0.00	6.00	20.00
	2.00	3.00	2.00	1.00	2.00	-9.00	-9.00	-4.00	3.00	7.00
Subject 13	-13.00	17.00	12.00	-10.00	-10.00	-18.00	-14.00	9.00	17.00	13.00
	-12.00	5.00	14.00	-2.00	-5.00	-18.00	-11.00	8.00	20.00	22.00
	1.00	2.00	11.00	-3.00	-16.00	-17.00	-15.00	9.00	16.00	19.00
	11.00	0.00	15.00	-11.00	-5.00	-20.00	-10.00	13.00	21.00	18.00
	-4.00	1.00	14.00	-13.00	-10.00	-15.00	-15.00	7.00	13.00	15.00

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