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# How much can horizontal head movements influence the real-ear measurement accuracy of open-canal fittings?

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# Declaration

I, Sean Lau, declare that the thesis is my own work, except where acknowledged, and that the research reported in this thesis was conducted in accordance with the principles for the ethical treatment of human subjects as approved for this research by the Ethics Committee at the Institute of Sound and Vibration Research, University of Southampton.

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Finally, I would like to dedicate this project to my family, Mum, Dad, James and Jenna, for their love and support throughout the course, especially during this challenging period.

# Abstract

The modified pressure with stored equalisation (MPSE) method of soundfield equalisation is universally recommended for use in clinical practice during the real-ear measurement (REM) verification of open-canal (OC) hearing aids. This is because the MPSE method deactivates the reference microphone for aided measurements and so is not susceptible to the leakage of amplified sound from the open ear canal when fitting OC devices. However, the deactivation of the reference microphone means that the MPSE method will be susceptible to errors resulting from head movements during aided measurements and the magnitude of such errors has not been well explored in the literature. Therefore, this study aimed to investigate how much small horizontal head movements can influence the accuracy of REMs when using the MPSE method.

Real-ear unaided responses (REURs) were measured in 28 participants at horizontal head deviations of 0°, ±5°, ±10°, ±15°, and ±20° azimuth relative to the two loudspeaker-to-client azimuths of 0° and 45°. The difference between the baseline REUR measured when no head deviation was made and the REURs measured for each head deviation was then calculated so that the magnitude of REM errors arising from these head movements could be determined.

Statistical analysis revealed no significant difference between the REM errors for the 0° and 45° loudspeaker-to-client azimuths. REM errors of typically less than 1 dB were obtained when no head deviation was made (i.e. 0° head deviation), indicating that no clinically significant errors are introduced when using the MPSE method provided patients keep their heads still. However, the REM errors were found to increase with increasing head deviation up to ±20° where the errors were typically less than 2 dB. The magnitude of these head movement induced errors are not clinically significant on their own but it is recommended that head movements are minimised as much as possible so that REM targets can be matched more accurately.

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# 1 Introduction

## 1.1 Real Ear Measurements (REMs)

Real-ear measurement (REM) is the collective term used for all of the different range of ear canal measurements performed directly on the patient's ear with a probe-tube microphone during the fitting of a hearing aid (British Society of Audiology and British Academy of Audiology, BSA and BAA, 2007). The purpose of REMs is to provide an objective method for verifying that the hearing aid gain in the patient's ear matches the prescribed target. This is important because various acoustical factors can influence the performance of a hearing aid, including the impedance characteristics of the ear, the acoustic properties of the attached ear mould and tubing, and the natural resonance of the ear canal (Northern, 1992). These acoustical factors are unique for each individual and can affect the gain provided by the hearing aid, potentially resulting in the over or under amplification of sound to the patient. Therefore, without REMs, the audiologist would be unable to determine whether the performance of the hearing aid is optimally adjusted to meet the amplification needs of the patient (Dillon, 2001). REMs also enable the audiologist to customise the hearing aid fitting for each individual by making gain adjustments to take into account the unique acoustical characteristics of the patient's ear, thereby avoiding the problems associated with using normative data.

### 1.1.1 Equipment

All REM systems are comprised of the following: a soundfield speaker, a reference microphone, a probe-tube microphone and a computerised microprocessing unit (Northern, 1992). The loudspeaker provides the sound source for the REM stimulus by delivering the test signal generated by the system to the sound field. The reference microphone is responsible for calibrating the sound field and can be positioned just below or above the ear. It records the amplitude and spectrum of the sound field at the position of the microphone sound inlet, called the field reference point, to regulate the sound level near the ear by adjusting the loudspeaker signal to the required level (Dillon, 2001; Revit, 2002). The probe-tube microphone is a very soft and slim silicone rubber tube, one end of which is inserted into the ear canal and positioned close to the tympanic membrane to obtain measurements, and the other end is connected outside the ear to a small microphone housing. A sliding black marker sleeve is usually placed around the probe tube to enable the marking of the desired ear canal insertion depth (Northern, 1992).

### 1.1.2 REM Terminology

The commonly performed ear canal measurements conducted during the REM fitting of a hearing aid have associated terminology to describe them. These measurements can be expressed in terms of either a response measurement (e.g. real-ear unaided response), a measure of absolute output in sound pressure level (SPL), or a gain measurement (e.g. real-ear unaided gain), a difference measure in decibels (dB) between the absolute output level and the specified input level (Revit, 2002). The following definitions, as published by the British Standards Institution (BSI) in the ISO 12124:2001 standard, describe the most commonly used REM procedures and the clinical applications of each. The term "measurement point" in each definition refers to the location of the probe-tube microphone in the ear canal where the measurement is made.

#### 1.1.2.1 Real-ear unaided response (REUR)

The REUR is defined as the "SPL as a function of frequency at the measurement point for a specified test signal level with an un-occluded ear canal" (BSI, 2001). The REUR is essentially a representation of the natural amplification attributed by the resonance properties of the unoccluded ear canal and concha. The unaided ear therefore benefits from a boost in high frequency SPL due to this natural amplification, producing a peak in an average adult REUR of approximately 17 dB at around 2700 Hz (Mueller, 1992). The REUR is most commonly used in clinic to provide a reference value for calculating the insertion gain, which is a measure of the extra sound presented to the eardrum when the hearing aid is inserted into the ear (Dillon, 2001). Since most hearing aid prescriptive methods are based on the measure of insertion gain, which requires the REUR for its calculation, the REUR is a crucial measurement for the REM process of fitting a hearing aid and it is usually the first measurement that is performed.

#### 1.1.2.2 Real-ear occluded response (REOR)

The REOR is defined as the "SPL as a function of frequency at the measurement point for a specified test signal level with the hearing aid in place and turned off" (BSI, 2001).When a hearing aid or ear mould is fitted into the ear, the natural amplification of the REUR is altered and the measured effect is the REOR. The REOR usually falls substantially below the REUR depending on the ear mould or hearing aid style and also reflects the attenuation attributed by the tightness of the fit (Mueller, 1992). The measured response will typically show an attenuation of the high frequencies and a gain of about 0 dB at the low frequencies due to the passage of sounds through vents and other leakage paths alone (Dillon, 2001).The main clinical application of the REOR is in trouble-shooting a venting or ear mould problem. The REOR can also provide an indirect indication of the occlusion effect attributed by the ear mould since the occlusion sensation experienced by the patient generally increases as the REOR falls further below the REUR (Mueller, 1992).

#### 1.1.2.3 Real-ear aided response (REAR)

The REAR is defined as the "SPL as a function of frequency at the measurement point for a specified test signal level with a hearing aid in-situ and turned on" (BSI, 2001).The REAR is therefore the output of a hearing aid that is switched on when measured in the ear canal. Similar to the REUR, the main clinical application of the REAR is to serve as a reference value in the calculation of the insertion gain (Mueller, 1992). However, despite the popularity of insertion gain as the method of choice in the verification of hearing aid performance, some prescriptive methods specify targets in terms of REAR making this measurement necessary in these situations to verify the success of the fitting (Pumford and Sinclair, 2001).

#### 1.1.2.4 Real-ear insertion gain (REIG)

The REIG is defined as the "The difference in dB as a function of frequency between the real-ear aided response and the real-ear unaided response or between the real-ear aided gain and the real-ear unaided gain" (BSI, 2001). The REIG is calculated by subtracting the REUG from the REAG and represents the amount of gain that the hearing aid provides alone at a specific frequency without the contribution of the REUR which is always present in the patient (Revit, 2002). It is therefore a net acoustic increase presented at or near the eardrum that the patient did not have previously as a result of inserting a hearing aid (Mueller 1992). This measure of net benefit, or insertion gain, is commonly adopted by fitting strategies for prescribing hearing aid gain and frequency response. The REIG was previously known as the real-ear insertion response (REIR), the gain provided by the insertion of a hearing aid across all measured frequencies, but this term was changed to reflect the fact that the calculation of insertion gain is always expressed as a difference measurement (Pumford and Sinclair, 2001). The primary clinical application of the REIG is to verify the success of a hearing aid fitting by determining whether a particular setting matches the insertion gain target of the chosen prescription formula (Mueller, 1992).

### 1.1.3 Procedural considerations for REMs

Accurate REMs are essential for ensuring that a hearing aid is optimally fitted to meet the amplification needs of the patient. Any substantial variability that can influence the measurements may result in the over or under amplification of sound which can limit the benefit a hearing aid can provide to the patient. Sources of measurement variability can be introduced by decisions regarding how REM procedures will be carried out and these procedural decisions can impact on both reliability and validity.

#### 1.1.3.1 Loudspeaker-to-client distance

The choice of the distance between the REM loudspeaker and the patient, also known as loudspeaker-to-client distance, is a procedural consideration that can affect measurements. Mueller (1992) explains that a large loudspeaker distance of greater than 1.0 m can result in the increased influence of ambient noise and room reverberation whereas a distance of less than 0.5 m yields little advantage. Therefore a distance of 0.5 m was advocated to be desirable by Mueller (1992) although a distance of 0.5-1.0 m is also considered acceptable. More recently, a study by Stone and Moore (2004) provided evidence to support the loudspeaker-to-client distance recommended by Mueller (1992). The study showed that errors associated with changes in loudspeaker distance from the patient decreased progressively from 1.9 dB at 0.3 m to 1.4d B at 0.6 m. Stone and Moore (2004) commented that errors from loudspeaker misplacement are more dominant at a distance of 0.3 m whilst reverberation errors are more dominant at a distance of 0.6 m and it was therefore concluded that a distance of 0.4-0.5 m represents a good compromise.

### 1.1.3.2 Loudspeaker-to-client azimuth

Another procedural variable that needs to be considered is the horizontal angle of the loudspeaker measured from the front relative to the patient, which is also known as loudspeaker-to-client azimuth. Two commonly used loudspeaker-to-client azimuths are 0° and 45°, either of which will result in reasonably accurate REMs (Mueller, 1992). However, some studies have aimed to investigate which of the two azimuths produce the most reliable REMs. Killion and Revit (1987) investigated the test-retest variability of the 0° and 45° loudspeaker-to-client azimuths and found that the 45° azimuth produced significantly less variability than the 0° azimuth. Stone and Moore (2004) also investigated the variability in REMs due to loudspeaker placement. The study found that errors from loudspeaker misplacement were generally small and less than 2 dB but the 0° azimuth produced slightly less variability than 45° azimuth which appears inconsistent with the results of Killion and Revit (1987). Stone and Moore (2004) argues though that in the study by Killion and Revit (1987), care was taken to consistently set the patient's angular position relative to the loudspeaker and that such precision would not be routinely carried out in the clinical environment. The authors therefore suggested that a 0° azimuth would be preferable to a 45° azimuth in the clinical setting.

### 1.1.3.3 Reference microphone location

The reference microphone of REM systems can be positioned at a variety of locations to maintain a constant SPL near the ear with the most popular choices being at-the-ear, over-the-ear and on-the-cheek (Mueller, 1992). A few studies have shown that the location of the reference microphone can introduce variability in the measurement of REMs. Feigin et al. (1990) found sizeable differences between the input SPL measured at the two reference microphone locations of on-the-cheek and over-the-ear compared to that measured at the microphone of a behind-the-ear (BTE) hearing aid which was 9.5 dB greater than the former reference microphone location and 3 dB greater than the latter. A loudspeaker-to-client azimuth of 0° was maintained throughout. The study suggested that these SPL deviations from the reference microphone would have the greatest impact on measures of absolute SPL in the ear canal, or REAR, and so the location of the reference microphone can result in substantial differences being observed. Ickes et al. (1991) also found that the REAR, as well as the REIR, can be affected by the location of the reference microphone although the differences between locations were only relatively small for the loudspeaker-to-client azimuths of 0° and 45°, and confined to frequencies above 2500 Hz.

#### 1.1.3.4 Probe-tube insertion depth

The location of the probe-tube in the ear canal is also a very important procedural consideration because it represents how accurate the measured SPL is in comparison to the SPL at the eardrum (Revit, 2002). Due to the interference between sounds entering the ear and sounds reflected from the eardrum, pressure nulls can be created along the ear canal from the partial cancellation of the incident and reflected waves when they interact and the two are half a cycle out of phase (Dillon, 2001). For each frequency the pressure null will occur at a distance from the eardrum equal to one quarter of the sound's wavelength and so the SPL measured by the probe-tube at such a location is much lower compared to that actually occurring at the eardrum (Mueller, 1992). A study by Dirks and Kincaid (1987) found that frequencies lower than 2000 Hz are only affected slightly by the problem of pressure nulls but the accuracy of high frequency measurements decrease the further away the probe-tube is placed from the eardrum. The authors suggested that the probe-tube should ideally be placed as close to the eardrum as practically possible and recommended a placement distance of within 6 mm which should give a measurement accuracy of within 2 dB up to 6000 Hz.

### 1.1.4 Soundfield Calibration

The test environment where REMs are carried out may present certain obstacles to obtaining accurate measurements. For example, the acoustic uniformity of the test sound field can vary considerably from one clinical environment to another and can be influenced by the location of the REM equipment, the position of the patient and audiologist, and the presence of other objects in the room (Revit, 2002). The level and spectrum of the test sound field in a given clinical space is thus highly unpredictable but this problem can be solved by the process of soundfield equalisation, where the REM signal is controlled so that the desired SPL is maintained in the soundfield (Northern, 1992).

#### 1.1.4.1 Stored and Concurrent equalisation

REM systems can perform sound field equalisation in two ways. Stored or off-line equalisation records the equalisation data prior to making the measurement and stores it for use as a reference for subsequent measurements in the ear canal. Concurrent or on-line equalisation however simultaneously monitors and adjusts the sound source at the time of the measurement. The level of the sound at the field reference point consequently remains at the desired SPL throughout the measurement process (Mueller, 1992). Stored and concurrent equalisation can be implemented by two commonly used methods, the substitution and the modified pressure method.

#### 1.1.4.2 Substitution method

The substitution method can only utilise stored equalisation and involves the equalisation of the sound field with the patient absent initially. A microphone is placed at a test point in the room corresponding to where the centre of the patient's head will be positioned when he or she is seated for the measurements. The microphone measures the signal produced by the loudspeaker and data necessary for equalising the sound field is stored. The patient is then positioned at the exact test point and probe measurements are made with reference to the free-field equalisation data stored previously (Hawkins and Mueller, 1992). Figure 1 illustrates the substitution method.

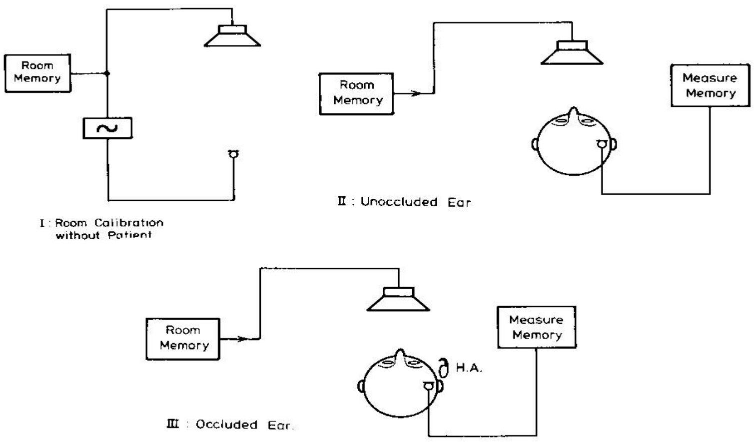


**Figure 1:** *Illustration of the substitution method of soundfield equalisation in three stages: Calibration of the test point without the patient present (I), unaided measurement with patient's head present at test point and probe tube inserted (II), and aided measurement with hearing aid inserted (III). From Mueller (1992), used with permission.*

#### 1.1.4.3 Modified pressure method

The modified pressure method however can utilise either concurrent or stored equalisation. This method uses a second microphone, called the reference microphone, in addition to the ear canal probe tube microphone. The reference microphone is positioned close to the test ear and measures or regulates the SPL generated by the loudspeaker. The data necessary for sound field equalisation is then measured at the location of the reference microphone (Revit, 2002). Figure 2 illustrates the modified pressure method.

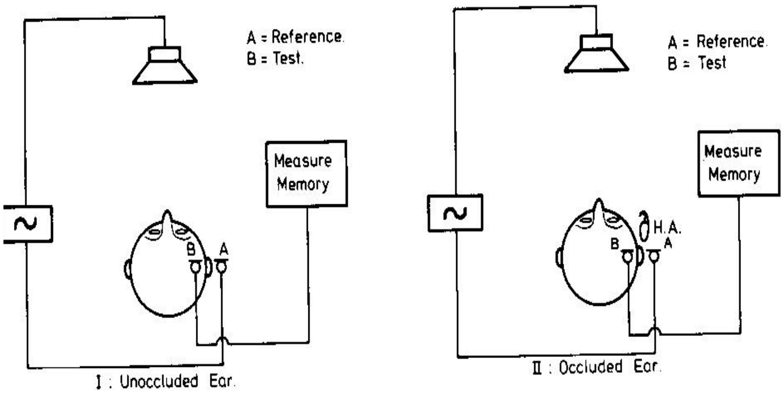


**Figure 2:** *Illustration of the modified pressure method of soundfield equalisation with the reference (A) and test/probe-tube microphone present (B), during unaided measurement (I) and aided measurement (II). From Mueller (1992), used with permission.*

If concurrent equalisation is used with the modified pressure method, then it is called the modified pressure method with concurrent equalisation (MPCE). Calibration or equalisation of the test point is not necessary with the MPCE method prior to positioning the patient because the reference microphone monitors and regulates the loudspeaker SPL to ensure that it is at a constant level throughout the measurement process. The reference microphone achieves this by adjusting the loudspeaker output to maintain the desired SPL if any deviation from the specified value is detected (Lantz et al., 2007). Alternatively, if the modified pressure method utilises stored equalisation then it is termed the modified pressure method with stored equalisation (MPSE). This method is a hybrid of the modified pressure and substitution method. However, unlike the MPCE method, an initial calibration procedure with the patient present is required prior to testing which is similar to the substitution method except that the reference microphone is present and positioned near the patient's ear. During this calibration procedure, which usually takes place during the REUR measurement stage, the soundfield is equalised with the patient present and the measured data is stored for use as a reference during subsequent measurements. The use of the stored reference data allows the reference microphone to be switched off during aided measurements (Hawkins and Mueller, 1992; Lantz et al., 2007).

The substitution method of sound field equalisation has a major disadvantage in that subject movement during REM measurements can result in changes in the sound field and influence the results. For example, the measured ear canal SPL will increase during a forward head movement towards the speaker and decrease with a backwards movement from the speaker, resulting in a potential alteration of the hearing aid output by up to 7 dB (Hawkins and Mueller, 1992). Killion and Revit (1987), using data extracted from a study by Shaw (1974), showed that horizontal head movements can cause a change of approximately -1.5 dB to +1.9 dB in the ear canal SPL per 10° head rotation when using the substitution method. The patient must therefore remain completely still at the test location throughout the measurement process in order to minimise inaccuracies during the procedure. In contrast, the MPCE method has a clear advantage over the substitution method. The reference microphone measures and maintains a constant SPL in the sound field so that head movements that occur are compensated for and do not affect the measurement so long as the movements are minor (Revit, 2002). This major advantage has led to the MPCE method often being recommended as the sound field equalisation method of choice (Dillon, 2001; Hawkins and Mueller, 1992).

## 1.2 Open-canal hearing aids

An open-canal (OC) or open-fit hearing aid involves the coupling of a non-occluding, universal silicone tip, of various sizes, to a small BTE hearing aid via a thin tube. The pre-formed thin tube hooks over the ear and replaces the conventional earhook and tygon tubing in delivering the hearing aid output, terminating in the ear canal as a replaceable, soft, vented silicone tip (Smith et al., 2008). Figure 3 illustrates an example of an OC hearing aid. The openness of OC hearing aids means that they typically have minimal impact on ear canal acoustics when the system is in place but switched off. This can be demonstrated by the fact that during REMs, the REUR is usually equal or similar to the REOR (Yanz and Olson, 2006). In some cases however, the difference between the REUR and REOR can be substantial depending on the ear tip vent size and insertion depth. Therefore OC devices cannot be described as entirely "acoustically transparent" but they mostly present minimal influence on the passive entry of sound into the ear canal (Fabry, 2006).

**Figure 3:** *Example of an OC hearing aid system (left image) and the associated thin tube with vented ear tip (right image). From Kiessling et al. (2003), available online at: http://journals.lww.com/thehearingjournal/Fulltext/2003/09000/Researchers_report_on_a_field_test_of_a.6.aspx.*

The effectiveness of modern OC fittings has been made possible by advancements in hearing aid technology over recent years. In particular, sophisticated feedback-reduction algorithms have provided an additional 8 to 15 dB of feedback-free gain available for these devices which have made them suitable for a wider range of patients (Parsa, 2006). However, the primary limiting factor of OC fittings is the amount of feedback-free gain that can be provided to the open ear. The large vent sizes used provides a significant pathway for sound to escape which increases the likelihood of acoustic feedback occurring (Fabry, 2006). The increased potential for acoustic feedback with OC hearing aids therefore limits their suitability to patients with mild to moderate hearing impairment (Kim and Barrs, 2006). A rough guidance used by Smith et al. (2008) suggests that OC fittings are suitable for patients with hearing thresholds of better than 40 dB HL for frequencies up to 1000 Hz and better than 60 dB HL for frequencies thereafter.

## 1.3 Potential advantages of open-canal hearing aids

The most commonly reported reasons for the rejection of hearing aids include unnatural sound quality, feedback, the occlusion effect and discomfort from wearing an ear mould, as well as cosmetic and lifestyle issues (Yanz and Olson, 2006). OC fittings have the potential to overcome many of these perceived limitations of conventional amplification in the areas of comfort, cosmetics, and performance in most listening conditions.

### 1.3.1 Reduced occlusion effect

One of the primary potential benefits of OC hearing aids is the alleviation or minimisation of the occlusion effect, the hollow or "blocked" sensation that hearing aid users can experience with their own voice when speaking with an ear mould in (Dillon, 2001). It occurs as a result of low frequency energy generated during vocalisation resonating in the ear canal and being unable to leave the ear due to the presence of the ear mould, causing an increase in SPL within the residual canal (Mueller et al., 1996). The vented tip and thin tube of OC hearing aids offer the potential to reduce the occlusion effect by enabling these internally generated sounds to leak out of the ear canal. Kuk et al. (2005) and Mackenzie (2006) both objectively evaluated the occlusion effect of OC hearing aids by comparing REM responses for the unoccluded ear and with the OC devices fitted. Both studies found only minimal differences between the two responses at the low frequencies, suggesting that minimal occlusion is experienced with OC hearing aids. Subjective measures in studies have also found that users of new OC hearing aids rated their satisfaction with their own voice significantly higher than closed canal hearing aid users (Kiessling et al., 2003; Taylor, 2006).

### 1.3.2 Improved comfort and cosmetics

Another purported advantage of OC hearing aids over traditional systems is that the open ear tip and thin tube employed by these devices make less physical contact with the ear canal, thus offering a more comfortable fitting in the ear than can be provided by custom ear moulds. The thin tube and small ear tip are also less visible than a traditional ear mould which may be more cosmetically appealing to patients, especially those dissatisfied with the appearance of conventional ear moulds and so may encourage greater use (Smith et al., 2008). Reports from manufacturer research and hearing aid dispensers have suggested increased user satisfaction in the areas of cosmetics and wearer comfort with open fittings (Kuk et al., 2005; Johnson, 2006). Similarly positive findings have also been reported outside of the industry. Taylor (2006) used self-report outcome measures to investigate the real-world benefit and satisfaction of OC users compared with users of traditional hearing aids. The study reported that participants fitted with OC devices regarded the appearance of their hearing aids to be more visually appealing and were significantly more satisfied with the comfort of the fit and than those fitted with traditional non-open devices.

### 1.3.3 Immediate fitting

The availability of OC hearing aids in a variety of ear tip and tube sizes means it is not necessary for a custom ear mould to be made, which may enable an immediate hearing aid fitting to be performed following the audiometric assessment. Smith et al. (2008) explains that this potential advantage has attracted particular interest within the UK National Health Service (NHS) setting, where there are policies to promote the minimisation of multiple hospital appointments wherever possible. The use of OC fittings may prove advantageous if a patient is suitable by enabling the possibility of combining the separate sessions of assessment and fitting into one session since there is no need for the manufacture of a custom ear mould. A multicenter trial was conducted by Smith et al. (2008) to investigate the feasibility of using OC fittings to achieve an assess-and-fit service in the UK audiological setting. Of the 453 new patients fitted with hearing aids at 12 NHS audiology departments, 297 (66%) patients were suitable for and had an OC hearing aid fitted. The results of this multicenter trial therefore suggest that a considerable proportion of new patients entering the NHS hearing aid service can benefit from an immediate fitting when OC hearing aids are used.

## 1.4 Issues regarding the MPCE method for open fittings

The MPCE method has long been the recommended soundfield equalisation procedure for REMs since it is less affected by head movements due to the role of the reference microphone and therefore provides the most reliable results. However, the function of the reference microphone can create a problem for the MPCE method when sound leaks out of the ear. Sound leakage is particularly a problem when using open fittings as the open ear canal provides a pathway for the amplified sound energy to escape from the ear and into the reference microphone (Hallenbeck, 2008). The leaked sound can then combine with the loudspeaker signal and exceed the preset input SPL. The reference microphone detects the combined sound pressure and the level of the loudspeaker signal is subsequently reduced to maintain the intended SPL. Therefore a reduced SPL is measured in the ear canal and it might be incorrectly concluded that the hearing aid output is lower than it actually is (Lantz et al., 2007; Hallenbeck, 2008).

In contrast, REMs using stored equalisation, such as the substitution method or the MPSE method, are unaffected by the influence of sound leakage from the ear canal. The substitution method does not use a reference microphone and so the leaked sound is not detected whilst the reference microphone in the MPSE method is deactivated for aided measurements and the previously stored equalisation data is used (Lantz et al., 2007). Measurements with a stored equalisation method can therefore represent the "true" SPL in the ear canal when there is a risk of substantial sound leakage occurring (Mueller and Ricketts, 2006).

### 1.4.1 The effect of sound leakage for the MPCE method

The mechanism by which sound leakage from open fittings can cause inaccuracies for the MPCE method is theoretically sound but evidence to actually confirm the size of these inaccuracies was limited early on. However, an early study by Moskal and Goldstein (1992) was able to provide evidence to indicate the amount by which sound leakage from the ear can influence REM results. The authors proposed that the measured results of REM systems can be affected by the specific equalisation method used and in combination with the choice of hearing aid gain measurement. They therefore investigated the effect of the substitution and MPCE (called modified comparison in this study) methods on the REAG and REIG measurements. The authors were aware of the potential for sound leakage to cause problems for the MPCE method and so elected to include the two conditions of open and closed ear moulds to investigate the effect when using the different equalisation methods. Twelve subjects participated in the study. An occluding ear mould was used for the closed ear mould condition and the open ear mould condition consisted of a conventionally used tygon tube (#13) secured by an acrylic concha rim ear mould. The REAG and REIG were measured for each of the two equalisation methods using both ear mould conditions. The results revealed a significant reduction for both the REAG and REIG with the MPCE method compared to the substitution method at the high frequencies of 2000 to 5000 Hz when using the open mould. The greatest reduction occurred in the 3000 to 3500 Hz frequency range, as can be seen in Table 1, where the mean REIG and REAG for the MPCE method is 4.3-4.9 dB and 4.4-6.3 dB less than the substitution method respectively.

| | REIG | | | | REAG | | | |
|---|---|---|---|---|---|---|---|---|
| **Frequency** | **Open Earmould** | | **Closed ear mould** | | **Open Earmould** | | **Closed ear mould** | |
| **(Hz)** | **Sub[a]** | **Mod Com[b]** | **Sub[a]** | **Mod Com[b]** | **Sub[a]** | **Mod Com[b]** | **Sub[a]** | **Mod Com[b]** |
| **750** | -0.4 | 0.1 | -3.2 | -3.1 | 1.1 | -0.7 | -1.9 | -3.7 |
| **1000** | 1.7 | 1.7 | 4.0 | 4.2 | 3.4 | 1.9 | 5.7 | 4.0 |
| **1500** | 8.7 | 7.8 | 12.3 | 11.9 | 11.0 | 11.2 | 15.3 | 14.2 |
| **2000** | 21.3 | 19.1 | 19.6 | 19.8 | 30.1 | 26.6 | 28.4 | 26.6 |
| **2200** | 21.6 | 18.4 | 17.3 | 16.8 | 33.0 | 27.8 | 28.5 | 25.7 |
| **2500** | 18.3 | 15.8 | 13.1 | 11.8 | 31.5 | 26.3 | 26.0 | 22.6 |
| **2600** | 17.3 | 14.8 | 11.3 | 10.7 | 31.1 | 25.5 | 25.2 | 21.7 |
| **3000** | 19.3 | 15.0 | 13.3 | 12.7 | 32.2 | 25.9 | 25.5 | 23.9 |
| **3500** | 20.7 | 15.8 | 15.7 | 14.3 | 31.2 | 26.8 | 25.2 | 25.9 |
| **4000** | 16.8 | 13.8 | 14.0 | 10.8 | 26.3 | 25.2 | 22.0 | 22.7 |
| **5000** | 14.3 | 12.2 | 10.9 | 8.6 | 17.5 | 17.1 | 15.6 | 13.4 |

Sub[a], substitution. Mod Com[b], modified comparison.

**Table 1:** *Mean REIG and REAG (dB) for the substitution and the MPCE method, called by the previously used term "modified comparison method" in this study, for open and closed earmould conditions. Table reproduced from Moskal and Goldstein (1992).*

In contrast, the results for the closed ear mould condition revealed no significant difference for the REIG measurement between the two methods. These results indicate that a significant reduction in hearing aid gain only occurs with an open mould when using the MPCE method and that the reduction is limited to the high frequencies. Moskal and Goldstein (1992) concluded that the reduction is caused by sound leakage from the ear canal when using the open mould due to the fact that no reduction was observed with the closed ear mould condition. The authors explained that when an occluding ear mould is used, sound is prevented from leaking out of the ear and being detected by the reference microphone and so no erroneous adjustments are made to the loudspeaker level. The loudspeaker output therefore remains fixed resulting in the REIG when using the MPCE method being similar to that of the substitution method.

Overall, the results of this early study by Moskal and Goldstein (1992) have demonstrated that the MPCE method can indeed underestimate the hearing aid output by as much as approximately 6 dB at the high frequencies due to sound leakage from an open mould. The authors therefore concluded that the MPCE method would not be appropriate for use with an open fitting. The findings of this study raise important implications for the fitting of modern, non-occluding OC hearing aids. If the gain underestimation can be as much as 6 dB at the high frequencies with an open mould then it may be theorised that the ear tips of OC hearing aids, which leaves the ear canal even more open, would enable more sound leakage resulting in an even greater reduction in hearing aid output.

### 1.4.2 The effect of digital feedback suppression (DFS) for the MPCE method

Advancements in digital feedback suppression (DFS) technology have enabled more acoustic feedback to be eliminated without having to turn down the gain, providing modern hearing aids with more feedback-free gain than ever before (Lantz et al., 2007). However, the use of these sophisticated feedback algorithms in modern OC devices have also significantly increased the potential for inaccurate REMs when using the MPCE method by allowing more amplified sound to leak back to the reference microphone (Mueller and Ricketts, 2006).This has forced the importance of re-evaluating the recommended soundfield equalisation method for REM verification in light of the unique acoustical considerations that modern open technology presents. A proposed solution to the problem posed by open fittings for the MPCE method is to use the MPSE method for soundfield equalisation instead, as the use of the previously stored reference data in this hybrid method allows the reference microphone to be switched off during aided measurements. Therefore the sound leakage from the ear canal will be not be detected when using the MPSE method with OC fittings and so cannot influence the erroneous adjustments to the loudspeaker stimulus that occurs with the MPCE method (Lantz et al., 2007).

### 1.4.3 Studies examining the magnitude of the MPCE error for open fittings

Recent studies have demonstrated the magnitude of the reduction in hearing aid gain when using the MPCE method for the REM verification of OC hearing aids. A study by Olsen and Hernvig (2005) gave an early indication as to how much measurement error can arise from using the MPCE method to fit OC devices compared to the MPSE method. The study was presented at the 21st Danavox Symposium and the aim was to evaluate an objective method for assessing the performance of DFS in a digital hearing aid and the accuracy of maximum stable gain (MSG). To achieve this, the authors compared MPCE measurements, which are affected by sound leakage, and MPSE measurements, which are unaffected by sound leakage and so represents the "true" gain obtained when using DFS. Therefore the study also indirectly provided data that can be used to assess the amount of MPCE measurement errors. Figure 4 shows the outcome of the measurements using both methods.

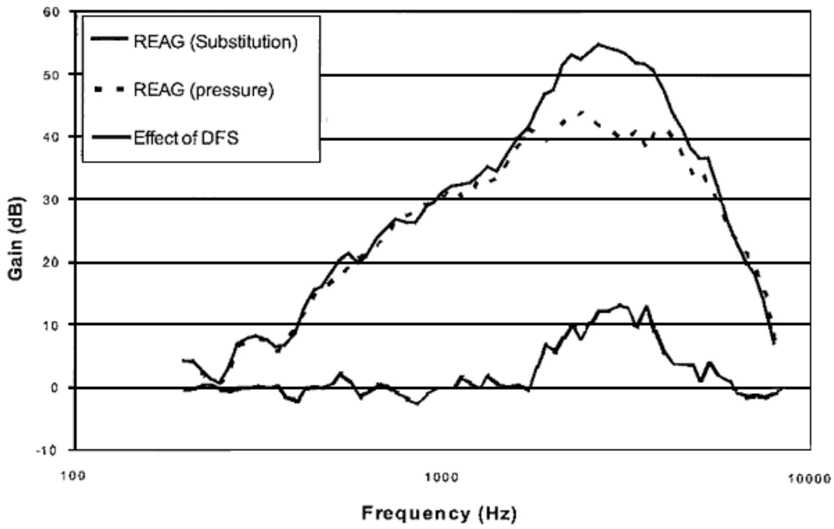


**Figure 4:** *REAG measurement for the MPSE (called modified substitution method in this study) and the MPCE method (called pressure method in this study). The difference between the two measurements is indicated by the "Effect of DFS" line. From Olsen and Hernvig (2005), unpublished presentation hand-out.*

It can be seen in Figure 4 that the MPCE curve falls below the MPSE curve at the high frequencies. This difference therefore represents the amount by which the MPCE method underestimates the true hearing aid gain, as demonstrated by the MPSE method, and the underestimation can be seen to be up to 13-14 dB at the high frequencies. These findings are in agreement with those of Moskal and Goldstein (1992) in that sound leakage can cause a considerable reduction in the high frequency hearing aid output when using the MPCE method for OC fittings. However, it is interesting to find that the MPCE error was considerably greater in this study than the 4-6 dB error reported by Moskal and Goldstein (1992). The greater error value may be due to the fact that OC hearing aids leave the ear canal more open and so causes a greater amount of sound leakage than the open mould used by Moskal and Goldstein (1992), resulting in a greater influence on the reference microphone. Also, a linear hearing aid with no DFS was used by Moskal and Goldstein (1992) whilst a digital hearing aid with DFS was used by Olsen and Hernvig (2005). This difference is likely to have enabled the digital hearing aid to reach a higher feedback-free gain than the linear hearing aid, thus potentially contributing to the greater MPCE error in the

Olsen and Hernvig (2005) study as even more sound leakage would occur at the higher gain levels.

As part of a paper explaining issues regarding OC hearing aids, Mueller and Ricketts (2006) described an experiment they conducted that also investigated the amount of error that can result from the out-flow of amplified sound when fitting OC devices with the MPCE method. This investigation examined the amount of MPCE measurement error in more detail than Olsen and Hernvig (2005) by revealing how the errors vary as a function of increasing gain. The authors compared the REIG response obtained from two different REM systems using the MPSE with the MPCE methods on one patient fitted with an OC hearing aid. The hearing aid gain was progressively increased in 2 dB steps to observe the region where differences occurred between the two methods, the increments then continuing until audible feedback was heard.

Interestingly, the results revealed no difference between the two methods up to a REIG range of 20-25 dB but beyond this an approximate 5 dB difference at frequencies greater than 2000 Hz was observed in the 25-30 dB range. When the experiment was repeated with the second REM system using the same patient and hearing aid, a region of separation was again observed for the MPCE method but it occurred around the 20 dB REIG range and a similar gain underestimation of about 5 dB was obtained. The authors reported that the 5 dB error was similar to that found in unpublished reports from hearing aid manufacturers. It was concluded that the use of the MPCE method can result in an underestimation of the hearing aid output at the high frequencies by as much as 5 dB but this error does not appear to arise until a REIG of approximately 20-25dB is exceeded. The MPSE was therefore recommended as the equalisation method of choice when conducting REM verification for OC fittings. It is interesting that the 5 dB difference found by Mueller and Ricketts (2006) is very similar to the 4-6 dB difference reported by Moskal and Goldstein (1992). The former study used the MPSE whilst the latter used the substitution method in comparison to the MPCE. The fact that similar differences were obtained indicates that the amount of MPCE error can be expected to be approximately the same whenever stored equalisation is used.

The findings of Mueller and Ricketts (2006) supplement those of Olsen and Hernvig (2005) by again demonstrating a reduction in the high frequency hearing aid output when using the MPCE method and also that this reduction does not occur until a certain gain level is reached.

However the MPCE error values reported by the two investigations do not conform with each other, with a reported 5 dB by Mueller and Ricketts (2006) but a greater value of more than 10 dB by Olsen and Hernvig (2005). The difference between the reported values may be explained by the hearing aid gain settings used in each experiment. Both investigations increased the hearing aid gain to the highest level possible before acoustic feedback was audible. Although unspecified, it is possible that the DFS system used by Olsen and Hernvig (2005) enabled a greater maximum feedback-free gain than the 25-30 dB reached in the Mueller and Ricketts (2006) experiment, thereby measuring a greater error at the higher gain. Another possible explanation for the difference between the reported values could be due to the location of the reference microphone. Olsen and Hernvig (2005) placed the reference microphone at the BTE hearing aid microphone and so the distance to the canal opening was the same for both. In contrast, Mueller and Ricketts (2006) placed the reference microphone at 1 inch above and 1.5 inch below the opening of the ear canal for the first and second REM systems respectively. The difference in distance could have influenced the amount of sound leakage detected at the reference microphone, with possibly more detected in the Olsen and Hernvig (2005) study. This would result in a greater reduction in the loudspeaker output and subsequently a greater underestimation of the hearing aid output.

However, the studies by Olsen and Hernvig (2005) and Mueller and Ricketts (2006) have a number of limitations. It should be emphasised that the sample size of one patient in the experiment by Mueller and Ricketts (2006) is insufficient for the results regarding the magnitude of the MPCE error to be reasonably generalised. Similarly, it is also unclear as to whether the findings by Olsen and Hernvig (2005) can be reasonably generalised due to the absence of sample size data in the study. Information regarding some REM procedural considerations, such as loudspeaker-to-client distance and azimuth, is absent in the methodology described by Mueller and Ricketts (2006). This makes it difficult for other researchers to repeat the investigation and the decisions made regarding REM procedural considerations could have influenced the results, which make it difficult to assess the validity and reliability of the findings. Similarly, the study by Olsen and Hernvig (2005) was not published in a peer-reviewed journal and so the study design, methodology, and results have not been scrutinised by other expert researchers in the field to check for validity, reliability and significance. Therefore, despite highlighting a similar trend regarding the use of the MPCE method during OC fittings, the measurement error values reported by the two studies cannot be generalised until they have been found to be consistent with the findings of other peer-reviewed studies in this field.

The magnitude of the MPCE error as a function of gain has also been examined by the more recent studies of Lantz et al. (2007) and Olsen (2008). Lantz et al. (2007) performed REIG measurements on 21 hearing impaired subjects during the fitting of a micro BTE OC hearing aid. Two REIG measurements were conducted in each ear, the first using the MPCE and the second using MPSE method. To represent data for typical amplification levels and high levels that would require DFS to provide feedback-free gain, the authors employed two measurement conditions; the manufacturers recommended prescribed gain for the former and the maximum stable gain (MSG), the highest gain level attainable without the presence of audible feedback, for the latter. The two REIG measurements were performed for each condition, resulting in a total of four measurements for each ear.

Similarly, Olsen (2008) collected and compared MPCE and MPSE data as part of a study to evaluate a proposed objective method for assessing DFS benefit. In contrast to the previous study though, Olsen (2008) performed simulated REMs on a Knowles Electronics manikin for acoustic research (KEMAR) (Burkhard and Sachs, 1975), which is a manikin of human proportions commonly used to evaluate the performance of hearing aids. The same micro BTE OC hearing aid model (ReSound AIR) as used by Lantz et al. (2007) was also used for all experiments in this study, which also adopted a very similar investigation procedure. However, REAR rather than REIG measurements were conducted throughout in this study, first with the MPSE and then repeated with the MPCE method. REAR measurements were performed at a starting hearing aid insertion gain of 2 dB for both equalisation methods and then repeated in 2 dB increments to a maximum of 32 dB.

The results of both studies have identified similar trends. Lantz et al. (2007) found a mean difference between the REIG measurements of the two equalisation methods at the high frequencies for both conditions of typical and high hearing aid gain. The mean REIG measured using the MPCE at the manufacturers prescribed gain was approximately 5 dB less than that measured using the MPSE at the high frequencies. This difference increased to a maximum of approximately 18 dB at the MSG (high hearing aid gain) condition. To further investigate the error obtained when increasing the hearing aid gain, Lantz et al. (2007) also compared the MPSE and MPCE measurements in one subject with increasing gain settings from 5 to 35 dB in 10 dB increment steps. The results can be seen in Figure 5 which shows a difference between the two methods only becomes apparent beyond 15 dB of gain, but above which the difference can be seen to increase with increasing gain.

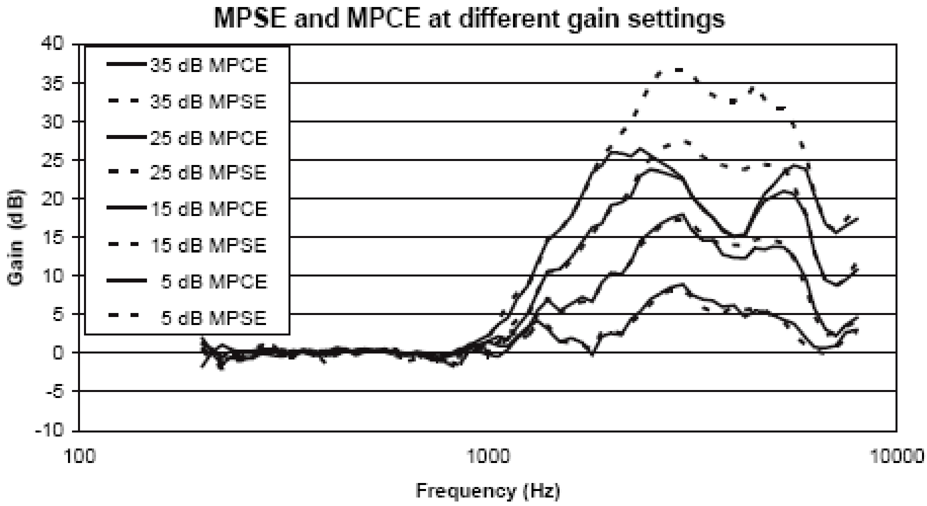


**Figure 5:** *REIG measurements for the MPCE and MPSE methods obtained at four different gain settings for a single subject. From Lantz et al. (2007), used with permission.*

Olsen (2008) also reported a deviation between the MPSE and MPCE measurements at the high frequencies and again noted a similar trend in that a small difference, about 3 dB, is observed at a low hearing aid gain (manufacturer prescribed gain), but a larger difference of approximately 15 dB at a high gain (MSG). This can be seen in Figure 6.

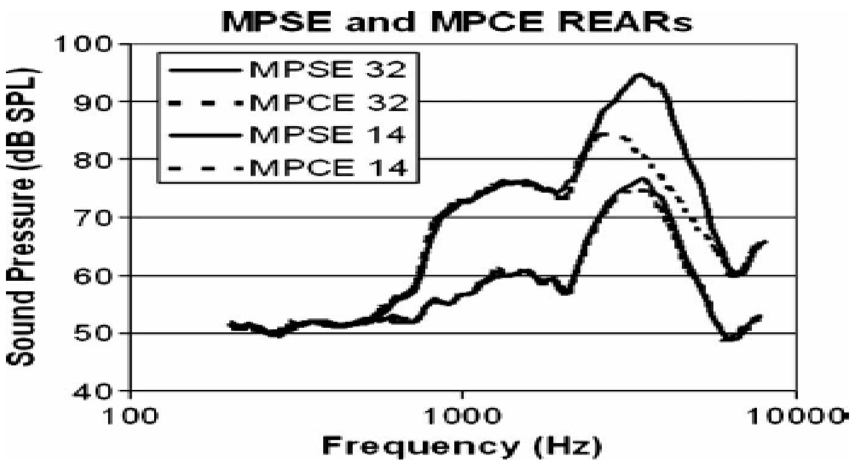


**Figure 6:** *Results of MPSE and MPCE measurements obtained at the gain settings of 14 dB and 32 dB. From Olsen (2008), used with permission.*

Like the findings of Mueller and Ricketts (2006), the results of both studies again indicate that there won't be a measured error when using the MPCE method until a certain gain value is reached (approximately 14-15 dB in these two studies), but beyond which the amount of gain underestimation increases with increasing hearing aid gain. The two studies shared very similar methodologies making the comparison more valid but there are key differences between the two that can be considered as potential limitations. Lantz et al. (2007) performed REMs on human subjects whereas Olsen (2008) performed simulated REMs on a KEMAR manikin. The ear canal properties of KEMAR are based on average normative values and do not take into account individual ear canal differences. Therefore the results may not be entirely representative of real life situations. The decision by Lantz et al. (2007) to use a loudspeaker-to-client distance of 1.3 m may also have had an influence on the results. Stone and Moore (2004) recommended a loudspeaker-to-client distance of 0.4-0.5 m because using a larger distance increases the risk of REMs being more susceptible to the influences of reverberation. The large loudspeaker distance used by Lantz et al. (2007) could therefore have influenced the accuracy of the measurements due to the increased risk of room reverberation. The insertion depth of the probe-tube could also have influenced the REM accuracy in the Lantz et al. (2007) study as no value was stated regarding this. It is therefore unknown whether the recommended insertion depth of within 6mm of the tympanic membrane (Dirks and Kincaid, 1987; BSI, 2001) was used in this study to account for this. This issue is not a factor for Olsen (2008) as probe-tubes are not used with KEMAR.

## 1.5 Issues regarding the MPSE method for open fittings

Having been established as the soundfield equalisation method of choice, the MPSE method is now routinely encouraged for use when fitting OC hearing aids. However, the re-emergence of the previously under-used stored equalisation, as part of the MPSE procedure, has raised issues as to how much is known about the reliability of the MPSE method. In particular, data regarding the test-retest reliability of the modern equipment when using stored equalisation is very limited and one of the greatest concerns raised about this method is the influence of head movements on the measured insertion gain (Ricketts and Mueller, 2009).

### 1.5.1 Test re-test reliability of the MPSE method

Ricketts and Mueller (2009) have reported results of some test-retest data for the MPSE method when fitting OC hearing aids on two participants. The two participants were instructed to keep their heads still and test-retest data was collected by removing the OC hearing aid and probe tube after the initial testing before replacing them again, hence simulating a different test session. The authors reported standard deviations ranging from 0.5 to 2.9 dB for the key frequencies of 1000 to 4000 Hz and the greatest variance was found to occur at 4000 Hz. These test-retest standard deviations for the MPSE were found to be very similar to those reported for the conventionally used MPCE method. The results of the investigation by Ricketts and Mueller (2009) therefore indicate that REMs using stored equalisation for open fittings can be quite reliable provided that the patient is instructed to restrict head movements. However, details of the investigation methodology are not elaborated on so it is not known whether any methodological flaws in the study design could have influenced the results. Also a sample size of two participants is too small for generalised conclusions about reliability to be made and it is difficult to comment on the validity of the results without other similar investigations to compare with. More studies in this field are therefore required before the test-retest reliability of stored equalisation can be fully evaluated.

### 1.5.2 Implications of head movements for the substitution method

Killion and Revit (1987) explain that head movements during REMs can introduce variability in the measured response as a result of two components. The first component is due to the sound field not being uniform so that relatively large changes in SPL can result from seemingly small motions. This effect becomes more dominant in regions of relative minimum pressure. The second component results from the directional properties of the head which changes the SPL during angular head movements, even in a uniform sound field. The variability incurred from minor head movements is kept to a minimum by the MPCE method due to the monitoring role of the reference microphone but it presents a problem for the substitution and MPSE method which uses stored equalisation. The reference microphone in the MPSE method is deactivated after the initial calibration procedure and the stored equalisation data is used thereafter so it will be prone to inaccuracies caused by head movements during aided measurements, which will no longer be taken into account.

The amount of influence that movements of the head can have when using stored equalisation has been reported by some researchers. The relationship between angular head position in the horizontal plane and measured ear canal SPL using the substitution method was summarised in an early study by Shaw (1974), the results of which were tabulated in numerical form by Shaw and Vaillancourt (1985). Shaw (1974) investigated horizontal head-related transfer functions for sound sources located at 15° azimuth intervals around the head to determine how much the SPL of a sound is altered going from a sound source in the free field to the eardrum. Table 2 displays some of the tabulated results from Shaw and Vaillancourt (1985) for sound sources at angles of azimuths up to ±45° around the head.

| **Azimuth (degrees)** | **Frequency (kHz)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **0.25** | **0.5** | **1** | **2** | **3** | **4** | **6** |
| **+15** | 0.4 | 1.1 | 1.4 | 1.2 | 2.1 | 2.1 | 2.6 |
| **+30** | 0.8 | 2.2 | 2.7 | 2.3 | 3.7 | 3.5 | 5.1 |
| **+45** | 1.2 | 3.2 | 3.8 | 3.0 | 4.8 | 4.0 | 5.1 |
| **-15** | -0.4 | -1.1 | -1.9 | -1.3 | -2.4 | -2.6 | -2.6 |
| **-30** | -0.8 | -2.0 | -3.9 | -2.7 | -4.5 | -5.8 | -5.5 |
| **-45** | -1.1 | -2.4 | -5.4 | -4.3 | -6.1 | -9.3 | -8.9 |

**Table 2**: *Amount by which the ear canal SPL changes, in dB, when a sound source positioned at 0° to the head is rotated horizontally at ±15°, ±30°, and ±45° azimuth around the head. Table reproduced from Shaw and Vaillancourt (1985).*

A positive horizontal rotation of the sound source relative to the head is equivalent to a negative head turn relative to the sound source. Therefore it can be seen from Table 2 that a +15° and -15° movement of the sound source relative to the head, which is the same as a -15° and +15° head movement from a sound source at the front respectively, can result in a change to the measured ear canal SPL which is lowest at the low frequencies (-1.1 to 1.1 dB) and increases gradually at the mid (-1.3 to 1.4 dB) and high (2.6 to 2.6 dB) frequencies. The change in ear canal SPL can also be seen in Table 2 to increase at each frequency as the rotation of the sound source increases, which alternatively indicates that a greater change in the ear canal SPL will be measured with increasing head turn from the front.

In addition to horizontal head rotations, Hawkins and Mueller (1992) have also provided some data regarding how head movements in the forwards and backwards plane can affect the amount of change in ear canal SPL when using the substitution method (see Figure 7).

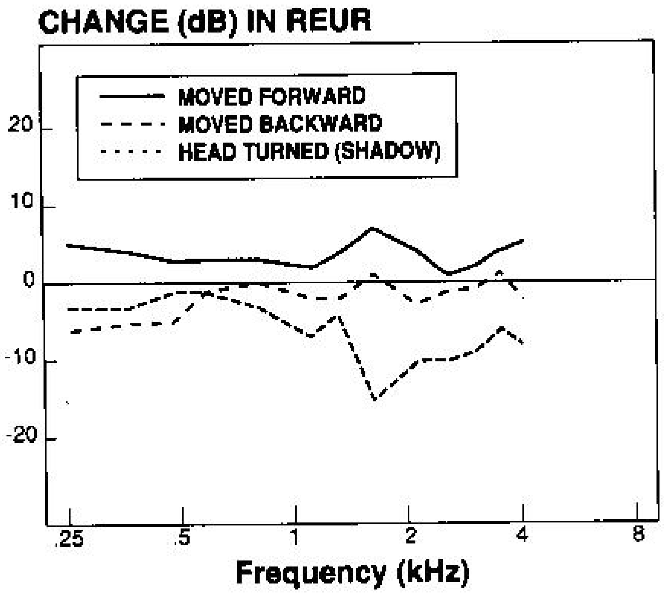


**Figure 7:** *Effect of a forward and backwards head movement and a horizontal rotation of 45° to the side on the measured REUR. From Hawkins and Mueller (1992), used with permission.*

As illustrated in Figure 7, an increased change in the REUR can be observed when the head is moved forwards by an unspecified amount with the greatest change occurring between 1000 to 2000 Hz by up to 7 dB. In contrast, a backwards head movement, again of an unspecified amount, results in a noticeable change at the low frequencies but only minor changes in the frequencies thereafter. Hawkins and Mueller (1992) also stated that head movements in the horizontal plane can produce a head shadow effect which particularly affects the higher frequencies. This is illustrated in Figure 7 where a considerable reduction in the measured REUR can be seen at the high frequencies for the "head turned" line, which is as a result of a 45° head turn from looking straight ahead, especially near 2000 Hz where a reduction of approximately 15 dB can be seen.

### 1.5.3. Implications of head movements for the MPSE method

The data provided by Shaw (1974) and Hawkins and Mueller (1992) have provided an indication of the potential magnitude of change that head movements can have on the measured ear canal SPL when using the substitution method, which uses stored equalisation. Similarly, the MPSE method also utilises stored equalisation and so the reliability of REMs using this method for open fittings would be expected to be influenced by head movements too. Therefore obtaining accurate REMs with the MPSE method would be heavily dependent on making sure that the patient remains as still as possible throughout testing. The recommended protocol for all REMs regardless of the soundfield equalisation method used involves instructing patients to keep their heads still to minimise inaccuracies caused by head movements (BSA and BAA, 2007). Therefore, if the reliability of stored equalisation can indeed be considered clinically acceptable when the patient remains still, as indicated by Ricketts and Mueller (2009), then an important issue that this raises is the amount of inaccuracy that can arise if the patient does make head movements. For example, a patient's attention may be distracted by events in the clinical environment such as the audiologist's task of matching REM targets displayed on the computer monitor. This may potentially prompt a considerable head rotation or even a forwards or backwards leaning motion from the patient towards the event of interest. The MPSE measurements would be particularly susceptible to inaccuracies induced by such head movements during aided measurements. However, there is limited knowledge in the literature regarding the magnitude of the head movement induced inaccuracies when using the MPSE method. To date, only a very recent study by Shaw (2010) has attempted to specifically investigate head movement effects on the accuracy of REMs when using the MPSE method for open fittings.

Shaw (2010) states that a patient's head is unlikely to remain at an exact location during REMs if several REIG measurements are required as is often the case. The author argues that the magnitude of errors resulting from these deviations in head position may be clinically significant enough to invalidate the hearing aid verification. The study aim therefore attempted to determine if the MPSE method, which is especially susceptible to head deviations, produces clinically significant errors with head movements induced by a typical OC hearing aid fitting. The author set out to achieve this by comparing, in each participant, an initial REUR in one ear with a second REUR recorded after the insertion of a non-functioning OC hearing aid in the contralateral ear designed to simulate a realistic fitting procedure. Twenty young participants, with a mean age of 23, took part in the study. The MPSE method was selected which performs soundfield equalisation during the REUR measurement stage and then switches to the use of stored equalisation thereafter. The participants were positioned at a distance of 0.5 m from the loudspeaker and the probe-tube insertion depth of 27 mm was used, both in accordance with BSA and BAA (2007) recommended guidelines. Two loudspeaker-to-client azimuth conditions of 0° and 45° were used in the study and a marker on the wall of the test room was used by the author to help the participants to achieve the 45° azimuth position. The participants were instructed to remain still at all times and a REUR measurement was recorded at the 0° loudspeaker azimuth followed by the insertion of an OC hearing aid in the contra-lateral ear to simulate a realistic hearing aid fitting. A second REUR measurement was recorded and the whole procedure was repeated at the 45° azimuth condition. The results of the two REUR measurements were then compared to determine any difference between them. The author stated that a zero difference would be indicative of a fixed head position being maintained by the participant.

The study found no statistically significant mean differences between the first and second REUR measurements for both azimuth conditions, with mean differences reported to be less than 1 dB (1 SD = <1.5 dB). Figure 8 illustrates the study findings for both azimuth conditions and it can be seen that head movement induced errors for the majority (95%) of participants (2 SD) are within 3 dB of the mean difference values.

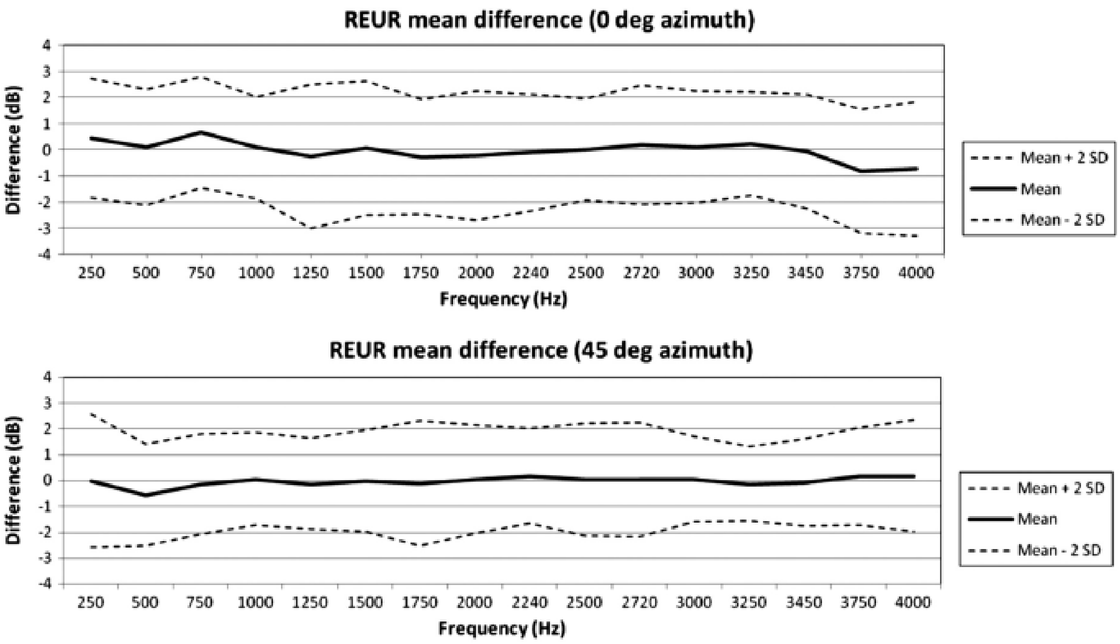


**Figure 8:** *Mean difference between the REUR measured prior to and following the insertion of a contralateral hearing aid, obtained at a loudspeaker azimuth of 0° and 45°. From Shaw (2010), used with permission.*

On the basis of the results obtained, Shaw (2010) concluded that no significant errors will arise from head movements induced by the routine fitting of an OC hearing aid when using the MPSE method. The study has therefore provided evidence to demonstrate that the MPSE method can produce reliable REMs provided that the patient's head remains still throughout the testing. The study also found that the mean difference measures for both loudspeaker-to-client azimuths of 0° and 45° were of the same magnitude. However, it should be emphasised that the author took care to minimise head movements at the 45° azimuth position by instructing the participants to focus on a marker on the wall. This procedure would not routinely be carried out so precisely in clinical practise and it may have enabled participants to maintain a fixed head position more accurately at this azimuth position. Therefore, the results of the 45° azimuth position in the study by Shaw (2010) may not be representative of a typical clinical setting. Stone and Moore (2004) found that the 45° loudspeaker azimuth produced more variability than the 0° azimuth, which suggests that patients are poorer at keeping their heads still at the 45° azimuth position. This means that the errors due to head movements measured for the 45° azimuth position in the study by Shaw (2010) could have potentially been greater if the participants were not helped by a target on the wall to maintain accurate head fixation. It is therefore possible that clinically significant errors can arise when using a loudspeaker azimuth of 45° when using the MPSE method until proven otherwise. In addition, Shaw (2010) states that the participants in this study were of a young adult population who may be more likely to comply with instructions to keep still and maintain a fixed head position longer than the elderly population, who are more likely have cognitive and health impairments. Consequently, Shaw (2010) pointed out that the results may not be representative of the typical elderly population who are assessed for a hearing aid.

The methodology used by Shaw (2010) appears to be sound with a sufficient sample size for results to be generalised and REM procedural considerations that are in accordance with recommended guidelines. However a potential limitation of the study is the author's decision to insert the non-functioning hearing aid in the contra-lateral ear for the purpose of simulating a hearing aid fitting. The reason for this decision using the contra-lateral ear is not explained in the study. It is possible that the author considered the insertion of the hearing aid in the test ear could potentially alter the probe tube insertion depth and thus influence the accuracy of the REUR measurements. However, in this study, the author was interested in head movements induced by the process of inserting a hearing aid but the decision to use the contra-lateral ear does not provide a realistic representation of this. The absence of a probe tube in the contra-lateral ear may have made it much easier to insert the hearing aid ear tip into the ear canal, thereby minimising any head movements this process may incur on the participant. In an actual hearing aid fitting session though, the ear tip would have to be inserted with the probe tube present which can complicate the process a lot more. Care has to be taken to avoid moving the probe tube during this process which can be difficult and challenging. Any movement of the probe tube as a result of inserting the ear tip can potentially elicit a sensitive reaction from the patient , for example a cough reflex, which may result in a head movement. Therefore, in addition to being more realistic, inserting the hearing aid into the test ear with the probe tube theoretically has more potential to influence head movements compared to the contra-lateral ear. If the author had decided to use the test rather the contra-lateral ear then a more realistic simulation would have been achieved, one that may potentially induce more head movements and possibly resulting in a greater mean difference being observed between the REUR measurements.

## 1.6 Motivation and clinical relevance of the present study

The MPCE method has long been established as providing the most accurate measurements for the real-ear verification of traditional hearing aids due to its ability to account for minor head movements. However, studies have shown that this conventional method produces inaccurate measurements during the REM verification of OC hearing aids due to the outflow of amplified sound from the open ear, resulting in an underestimation of the true hearing aid gain (Mueller and Ricketts, 2006; Lantz et al., 2007; Olsen, 2008). This problem has significant implications for the REM verification of OC devices because the audiologist may be unaware that the output displayed is invalid when using the MPCE method. This might result in the increasing of gain to meet the prescribed fitting target, causing an over-amplification of the frequency region where the mistake is taking place.

The MPSE method avoids the problem of sound leakage influencing the loudspeaker output and so it has been universally recommended for use with OC fittings by all researchers in the field. However, there is limited research regarding the accuracy of this previously under-used method in the literature. A few studies have demonstrated the MPSE method to be reasonably accurate provided that patients keep their head still during REMs (Ricketts and Mueller, 2009; Shaw, 2010). However, the influence of head movements on the accuracy of REMs when using the MPSE method has still been unexplored. It is important to investigate this aspect because even after being instructed to remain still there is still a possibility that patients will move their heads during REMs. For example, Shaw (2010) raised an important point that elderly subjects may be less likely to understand instructions and be able to maintain a constant head position during REMs as a result of cognitive and health impairments. Consequently, there may be an especially increased risk of inaccurate REMs being measured in the elderly who are representative of the population typically assessed for a hearing aid. This can have a significant impact on clinical practice by potentially limiting the benefit they receive from an OC device due to a failure in matching prescribed targets accurately.

Recently unpublished findings reported by Mueller (2009) have indicated that a significant horizontal head turn can cause a considerable 5-8 dB mismatch to the REM target when using the MPSE method, although the degree of this head turn was not investigated. However, the degree of head turn at which the errors become significant and whether the magnitude of the error varies with increasing head rotation has not been examined in current research. Investigating these two unexplored areas could help provide clinicians with a more accurate estimate of the size of errors that can be expected when the patient makes a certain degree of head movement during the REM fitting of an OC hearing aid. Knowledge of this may influence clinicians' decision to adjust the fitting more accordingly if they feel the REM measurements obtained do not accurately represent the true measurements as a result of the head turn. This experiment therefore aims to investigate how much horizontal head turns of 0°, ±5°, ±10°, ±15°, ±20° azimuth can influence the accuracy of REMs of when fitting OC hearing aids with the MPSE method of soundfield equalisation.

# 2 Method

## 2.1 Aim

The aim of this experiment was to determine whether horizontal head turns of certain azimuths can significantly influence the accuracy of REMs when using the MPSE method for fitting OC hearing aids. To investigate this, REUR measurements were taken with participants' heads turned to each of the different azimuths under investigation and compared with the REUR obtained when no head turns were made. The amount of REM error produced by each head turn under investigation could then be determined by calculating the difference between the REUR when a head turn is made and when a head turn is not made. This difference between the REUR measurements is referred to as "mismatch" throughout the report. The amount of mismatch was investigated for nine different horizontal head turns or deviations of 0° (i.e. no head turn), +5°, +10°, +15°, +20°, -5°, -10°, -15°, and -20° relative to the two loudspeaker-to-client azimuth positions of 0° and 45°. Additionally, the study aimed to investigate whether the two loudspeaker-to-client azimuth positions of 0° and 45° had a significant effect on the amount of mismatch obtained for these nine head deviations. The study also aimed to investigate whether the amount of mismatch differed between gender and the frequency measured.

## 2.2 Hypotheses

**Hypotheses**

1. The amount of mismatch measured when no head turn is made will not be significant (i.e. the REUR measured for the 0° head deviation will not be significantly different to the REUR measured at the primary head positions of 0° and 45° loudspeaker azimuth).
2. Significant mismatch values will be obtained for head deviations of +5°, +10°, +15°, +20°, -5°, -10°, -15°, and -20°

3. There will be a significant positive correlation between head deviation and the amount of mismatch measured (i.e. as the degree of head deviation increases, so will the amount of mismatch).

4. The mismatch measured for males will not be significantly different to that of females.

5. The mismatch measured for the 0° loudspeaker-to-client azimuth will be significantly different to that measured for the 45° loudspeaker-to-client azimuth.

6. The mismatch measured will significantly differ depending on the frequency measured.

## 2.3 Design

There were three independent variables in this study; loudspeaker-to-client azimuth (0° and 45° azimuth), head deviation (0°, ±5°, ±10°, ±15°, ±20°) and the frequency measured. The dependent variable was the mean difference, or "mismatch", between the REUR measured at the primary head positions of 0° and 45° loudspeaker-to-client azimuth and each of the REUR measured for the head deviations of 0°, ±5°, ±10°, ±15°, and ±20°, in dB. The experiment used a repeated measures design where each participant completed all the experimental conditions so as to minimise the effect of random individual variations between participants. Testing was performed only on the participants' right ears and each participant completed 18 experimental conditions as illustrated in Table 3. In order to reduce order effects from occurring, the order of conditions were randomised by assigning half of the participants to begin the experiment at 0° and half at 45° loudspeaker-to-client azimuth. Order effects were further reduced by assigning half of the participants in each loudspeaker-to-client azimuth group to start with head turns in the positive direction (+5° to +20°) and half to start in the negative direction (-5° to -20°).

| Condition | Loudspeaker-to-client azimuth (degrees) | Head deviation from primary head position (degrees) |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 0 | +5 |
| 3 | 0 | +10 |
| 4 | 0 | +15 |
| 5 | 0 | +20 |
| 6 | 0 | -5 |
| 7 | 0 | -10 |
| 8 | 0 | -15 |
| 9 | 0 | -20 |
| 10 | 45 | 0 |
| 11 | 45 | +5 |
| 12 | 45 | +10 |
| 13 | 45 | +15 |
| 14 | 45 | +20 |
| 15 | 45 | -5 |
| 16 | 45 | -10 |
| 17 | 45 | -15 |
| 18 | 45 | -20 |

**Table 3**: *The 18 experimental conditions performed on the right ear of each participant.*

## 2.4 Sample Size Calculation

Based on the results of the study by Shaw (2010), a sample size calculation for this study was performed using the program Sample Power and with the following criteria:

- An effect size of 1 dB (mean difference of REUR measurements obtained by Shaw, 2010).
- A standard deviation of 1.5 dB (as obtained by Shaw, 2010).

According to the Sample Power calculation, a minimum of 20 participants were required to achieve a statistical power of 0.8 and significance level of 0.05. As this study aimed to extend the scope of the Shaw (2010) study by additionally investigating the effect of horizontal head turns, it was decided that 28 participants would be recruited to increase the statistical power of the study.

## 2.5 Participants

Twenty-eight adult participants were recruited amongst friends and students by opportunistic sampling from the Institute of Sound and Vibration Research (ISVR) and the University of Southampton. Sixteen participants were female and twelve were male, all were aged between 18 and 38 with a mean age of 26. Participants were required to have otologically normal middle ear function as indicated by otoscopy and tympanometry. The exclusion criteria included the following abnormalities; tympanic membrane perforation, ear infections, discharge, otalgia (complaint of pain in ears) and excessive wax. A screening questionnaire (see Appendix A) was used to obtain a history of the participant's otological condition. Prospective participants were given an instruction sheet (see Appendix B) to read first informing them of the study aim and their expected task during the experiment. They were then required to complete a consent form (see Appendix C) prior to taking part in the experiment. All participants who agreed to take part did so voluntarily and did not receive any monetary payment.

## 2.6 Equipment

Otoscopic examination was performed using a Heine 2000 otoscope with disposable speculae. A GSI Tympstar tympanometer, calibrated to BS EN 60645:2005 standards, was used for the purpose of screening for normal middle ear function prior to commencement of testing.

Probe microphone measurements were performed using a GN Otometrics Aurical REM system which had been calibrated according to manufacturer recommendations and the system used the NOAH Aurical REM software.

A conventional laser level, which projects a clearly visible red line on the wall when switched on, was used for the purpose of tracking horizontal head movements (see Figure 9). This was achieved by securing the laser level using a clip on the device onto a headband which is worn by the participant, thus affixing the laser level on the top of the participant's head. Therefore as the participant makes a horizontal head movement, the laser level affixed to their head will also move to the same degree which can be tracked by observing the laser line projected on the wall. The device uses a Class 2 laser (wavelength 635mm) which is the lowest category for visible lasers and conforms with the EN 60825-1 standards governing safety of laser products in Europe.


**Figure 9:** *Photograph of headband and laser level*

## 2.7 Test Room Setup

A soundproof room within the ISVR department was used to conduct all testing. This was done to achieve a low ambient noise level so that the effects of unwanted external noise interfering with the test signal would be minimised, thereby ensuring greater accuracy with the REM measurements obtained (BSA and BAA, 2007). The soundproof room was acoustically treated to reduce the effects of reverberation from reflective surfaces by the use of sound absorptive material. The walls were lined with sound absorbent padding, the ceiling was lined with sound absorbent foam cones and the floor was carpeted.

The Aurical REM system was positioned on the edge of a desk at a height approximately level with the participant's head when seated. A chair on which the participant would be seated was positioned at a distance of 0.5 m and 0° azimuth from the Aurical loudspeaker as recommended by BSA and BAA (2007) guidelines and this chair position was marked with tape on the floor to ensure the correct distance could be easily re-attained if the chair was moved. As recommended by BSA and BAA (2007) guidelines, a piece of string of 0.5 m length was taped centrally on the Aurical REM loudspeaker to provide a means of checking that the distance between the participant's nose and the loudspeaker was correct.

The degrees of head turn that this study aimed to investigate were 0°, ±5°, ±10°, ±15°, and ±20° relative to the primary head positions of 0° and 45° loudspeaker-to-client azimuth. Therefore black tape markers were positioned on the test room wall corresponding to the azimuths under investigation for the 0° loudspeaker-to-client azimuth conditions, whilst blue markers were used and positioned on the wall for the 45° loudspeaker-to-client azimuth conditions. This was done to ensure that the participant's head would be in the desired deviation position when they align the laser line with the corresponding marker. The experimental setup in the test room is shown in Figure 10.

The decision to test only the right ear of participants was due to the practical limitations imposed by the test room. Due to the physical limitations of the test room dimensions, it was not possible to set up the full set of markers to investigate both left and right ears of participants. The layout of the test room offered better practicality for testing the right ear and so it was decided to test the right ear of all participants only.

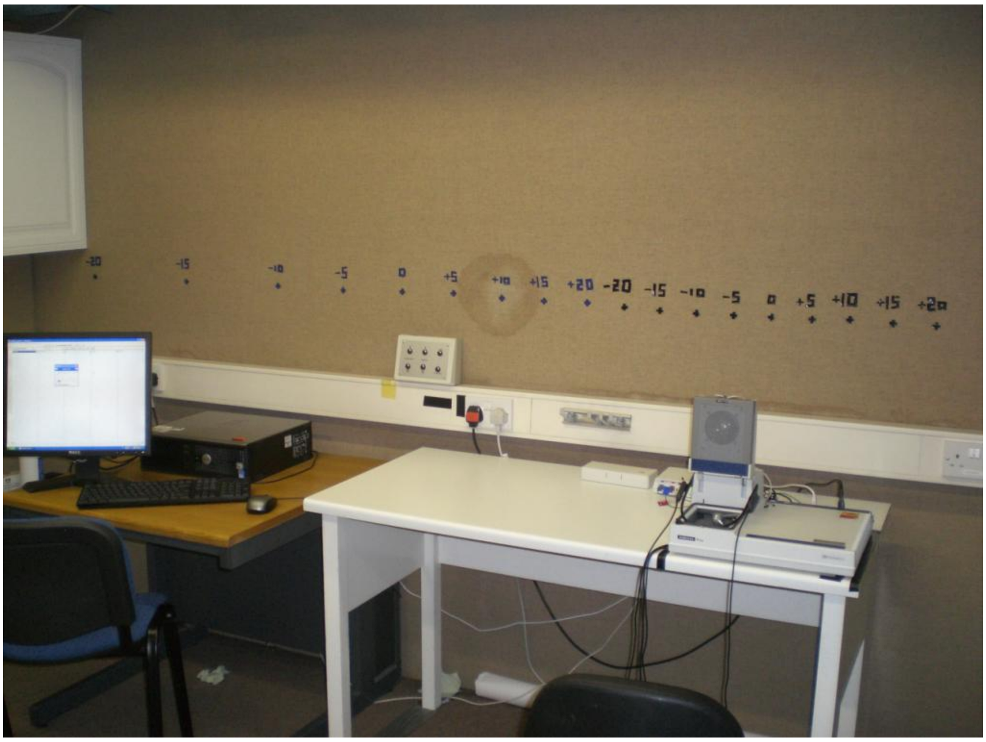


**Figure 10:** *Photograph of test room setup.*

## 2.8 Test Protocol

### 2.8.1 Preparation

Prior to each day of testing, daily checks were performed on the tympanometer and Aurical REM system. The tympanometer was checked daily by using a 2cc test cavity to test for accurate ear canal volume measurements and the performance of the device was also checked on the ear of the researcher to ensure consistent biological measurements. A visual inspection of the Aurical REM system was performed to check that all leads and wires were correctly connected and without any visible signs of damage.

All necessary equipment that would be required during testing was conveniently positioned within the test room so that they could be easily accessed when needed. The Aurical REM system was positioned at the edge of the table and the participant's chair was positioned at a distance of 0.5 m and, depending on the participant's allocated starting position, at an azimuth of 0° or 45° from the Aurical loudspeaker. Auditbase System 4 was opened on the computer and the participant's details were entered and saved. The REM module was then selected in NOAH-3 and opened. The OpenREM mode for use with OC fittings was selected so that the REM system would adopt the MPSE method for testing after the REUR has been measured. A 65 dB input stimulus was selected so as to represent an average speech intensity level and a pure-tone frequency sweep stimulus type was chosen as the conventionally used broad-band noise stimulus is not supported in OpenREM mode (BSA and BAA 2007). The prescriptive formula was set to NAL-NL1 and REAG was selected as the measurement type to enable any differences to be seen onscreen which would not otherwise be displayed visually when using REIG.

Probe tube calibration was performed each time prior to testing to enable the probe tube's acoustic characteristics to be measured and removed from subsequent measurements by the REM system, thereby ensuring that the resulting real ear responses are accurate. This involved attaching a new probe tube to both the right and left housings of the REM headset. The tip of the probe tubes were held at a close position to the reference microphone by attaching them to the holding grips of the REM housing. The REM headset was then held at a distance of 0.5 m from the loudspeaker in accordance with BSA and BAA (2007) recommended procedure and the probe tube calibration was performed.

### 2.8.2 Screening

The participant was brought into the test room and was verbally informed about the purpose of the study and the nature of the task involved, as well as being provided with written information in the form of the instruction sheet. The screening questionnaire was then given to the participant to fill out in order to obtain an otological history so that normal middle ear function could be assessed. Prior to the commencement of testing, a consent form was given to the participant to read and only if they were happy to proceed were they instructed to sign the form. On receipt of the written consent, the screening tests of otoscopy and tympanometry were performed to further assess normal otological function. Otoscopy was performed according to BSA (2010) recommended procedure to enable visual checking for contraindications to performing tympanometry and REMs, such as excessive wax, the presence of infection and discharge, and any visible tympanic membrane perforation. Tympanometry was then performed in accordance with BSA (1992) recommended procedure to assess middle ear function if otoscopy revealed no abnormalities. The results were required to be within the normative values of 0.3 to 1.6 $cm^3$ for middle ear compliance, 0.6 to 2.0 ml for ear canal volume, and -50 to +50 daPa for middle ear pressure. Participants were excluded from the study if they met any of the exclusion criteria for the screening questionnaire, otoscopy or tympanometry.

### 2.8.3 Procedure

The participant was seated in the chair previously positioned to be at a distance of 0.5 metres from the Aurical loudspeaker and at an azimuth of either 0° or 45° depending on the participant’s allocated starting position. The height of the chair was also adjusted to ensure that the participant was approximately level with the height of the loudspeaker as much as possible. The distance between the participant’s nose and the loudspeaker was checked by using the string attached to the loudspeaker to ensure that it was indeed 0.5 m and adjustments were made if necessary to achieve this desired distance. The participant was then informed that a laser level would be affixed to their head via a headband for the purpose of tracking the degree of horizontal head movement made. They were also informed that a probe tube would be placed in their right ear and that the Aurical loudspeaker in front of them would be presenting some sounds. An explanation of the participant's task was given; that they were to try and maintain the laser line trained on the wall marker requested by the researcher as accurately as possible and, when instructed, to turn their heads horizontally to align the laser line on the next marker. Finally, they were advised to remain quiet during the experiment unless they wished to notify the researcher of any discomfort they experienced or if they wished to withdraw from the experiment.

Otoscopy was performed prior to placing the REM headset over the participant's ears. To aid in greater practicality during testing, it was decided that both housings of the REM headset would be used to measure REM responses in the participant's right ear. The right housing was used to obtain measurements for the 0° loudspeaker-to-client azimuth conditions and the left housing for the 45° loudspeaker-to-client azimuth conditions. Therefore the right housing was positioned on the right side of the headset as is normal in routine clinical practice if a participant was assigned to start the experiment at 0° azimuth first. For participants assigned to start at 45° azimuth first, the headset ear hooks were rotated around 180° so that the left housing would be situated on the right side of the headset when placed on the participant. Such an unorthodox approach essentially enables all 18 experimental conditions to be measured in the right ear within the same REM session; the nine 0° loudspeaker azimuth conditions can be measured under the right ear screen of the session using the right housing as normal, followed by reversing the headset and toggling to the left ear screen of the session so that a further nine measurements can be obtained in the right ear using the left housing for the remaining nine 45° loudspeaker azimuth conditions. This provides a practical advantage over keeping all right ear measurements under the right ear screen of the REM session, as is routine clinical practice, which would incur considerable inconvenience from having to use several REM sessions just to measure all conditions for one participant (see Section 2.9 for a more detailed explanation). The probe tube marker was set to 27mm for both male and females and the probe tube was then inserted into the right ear canal until the black marker was positioned at the tragal notch of the participant's pinna (see Figure 11). This insertion depth is recommended by BSA and BAA (2007) guidelines to ensure that the probe tube would be within approximately 5mm of the tympanic membrane when inserted so as to reduce standing wave effects. A thin holding wire was used to minimise any alterations in the position of the probe tube by holding it more securely in the ear canal, thus ensuring a greater degree of measurement consistency between conditions.

**Figure 11:** *Probe tube in-situ. Left image shows the right REM housing on right ear for measuring the 0° loudspeaker-to-client azimuth conditions whilst right image shows the left REM housing on the right ear for measuring the 45° loudspeaker-to-client azimuth conditions.*

The headband was then placed on the participant's head and the laser level was secured under the headband strap, thus affixing it to the head and the device was switched on. Care was taken to ensure that the laser level was orientated in line with the participant’s nose to ensure that it was pointed directly straight ahead. The REM session was toggled to the right ear screen for participants starting at 0° azimuth or toggled to the left ear screen for those starting at 45°azimuth. To achieve the correct starting position, participants assigned to start the experiment at the 0° azimuth position were instructed to look directly straight ahead facing the loudspeaker and keep the laser line aligned on the black 0° marker on the wall (see Figure 12, left image), thus achieving the primary head position for the 0° loudspeaker-to-client azimuth conditions. Participants assigned to start the experiment at the 45° azimuth position were instructed to look straight ahead first and then rotate the chair to the left until the laser line was aligned with the blue 0° marker on the wall, thus achieving the primary head position for the 45° loudspeaker-to-client azimuth conditions (see Figure 12, right image).

**Figure 12:** *Photograph of the starting or primary head positions for the 0° (left image) and 45° (right image) loudspeaker-to-client azimuth conditions.*

The REUR was measured at the primary head position and this measurement will be referred to as the primary REUR throughout the report. Following this measurement, the participant was instructed to keep their head still and a second REUR was recorded at the same primary position so as to represent the REM response obtained from a horizontal head deviation of 0°. This was achieved in a practical way by recording the REOR despite no ear mould, ear tip or hearing aid being present in the ear and so the ear canal was left unoccluded, thus essentially making this measurement a second REUR measurement. The participant was then instructed to turn their head until the laser line was aligned with the +5° or -5° wall marker, depending on the assigned randomisation order, so as to achieve a horizontal head deviation of +5° or -5° from the primary head position. A REUR measurement was obtained at this position in a practical way by recording the REAR 1.

The participant was then instructed to turn their head in sequence to each of the remaining wall markers corresponding to the head deviations of +10°, +15°, and +20°, or -10°, -15°, and -20° depending on the assigned randomisation order by again aligning the laser line with the marker. A REUR was measured at each of these markers by recording the REAR 2, REAR 3 and REAR 4 respectively. Once the REAR 4 was measured at +20° or -20°, the data was exported to an Excel spreadsheet and saved. A screenshot of the REM session (see Figure 13) was also taken and saved for later comparison and analysis with the exported data. The data for REAR 1, REAR 2, REAR 3 and REAR 4 were then deleted so as to free them up for the next set of measurements to be taken.

Next, the participant was instructed to turn their head in sequence to each of the markers in the opposite direction to that in which they started; therefore those who started with positive head turns of +5°, +10°, +15°, and +20°, were now instructed to make negative head turns of -5°, -10°, -15°, and -20° and vice versa. Again, a REUR was measured at each of these markers in the opposite direction by recording the REAR 1, REAR 2, REAR 3 and REAR 4 respectively. The data for these set of measurements were exported to a new Excel spreadsheet after the REAR 4 had been taken and saved. Another screenshot of the REM session illustrating the results of these measurements was taken, again for comparison and analysis at a later time.

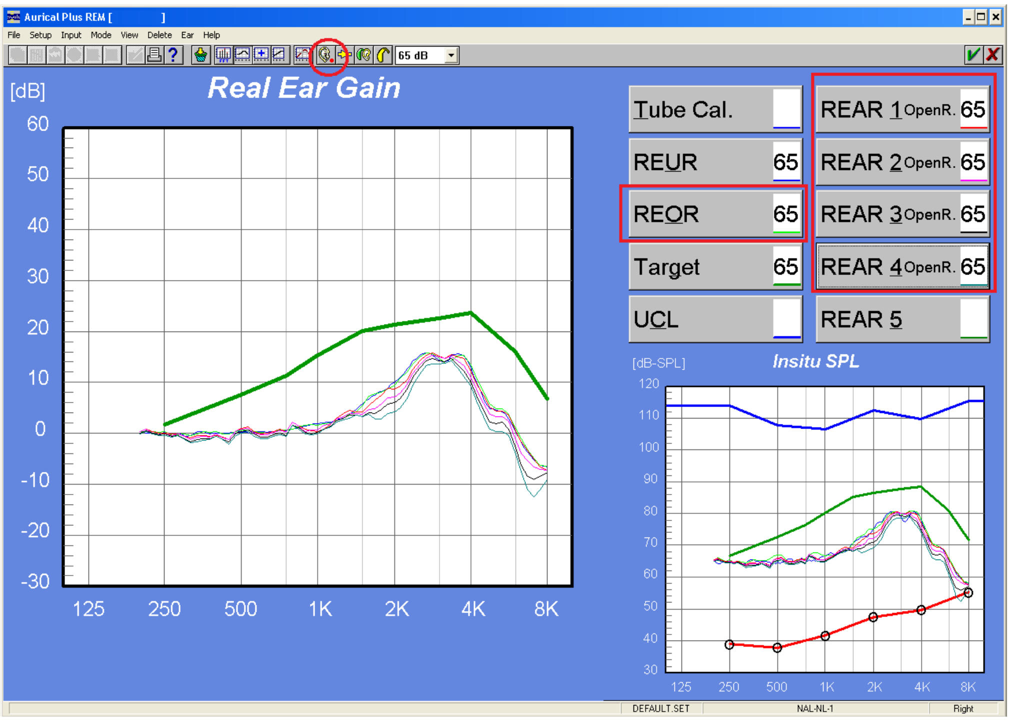


**Figure 13:** *Example of a screenshot taken during testing. Right ear screen icon (red circle) indicates that the results displayed are for the 0° loudspeaker-to-client azimuth conditions. REOR and REAR 1, 2, 3, 4 (red rectangles) represent REUR measurements for 0° and ±5°, ±10°, ±15°, ±20° head deviations respectively.*

Once all nine conditions of the starting loudspeaker-to-client azimuth had been recorded, the entire procedure was performed again for the second loudspeaker-to-client azimuth. Therefore participants who started the experiment at 0°azimuth were tested at 45° azimuth next and vice versa. This was achieved by first withdrawing the existing probe tube from the ear canal followed by removing the REM headset and reversing the ear hooks so that the opposite housing would be situated on the side of the right ear. The probe tube of this housing was then inserted into the right ear in accordance to the same procedure performed previously. The REM session was toggled from the right ear screen to the left ear screen for those who started at 0° azimuth and vice versa for those who started at 45° azimuth. The same test procedure was then performed for this second loudspeaker-to-client azimuth in exactly the same way as for the azimuth position that the participant started with. Testing was completed once all nine conditions of the second azimuth position had been measured. There were a total of 18 measurements for each participant and the average testing time was 25 minutes. Data was exported a total of 4 times in a single session from the REM module, producing 4 separate Excel spreadsheets and a total of 4 screenshots were obtained in each session for comparison to their corresponding Excel spreadsheets.

## 2.9 Pilot Study

Prior to performing the experiment, a pilot study was conducted on a volunteer MSc Audiology student of the ISVR in order to enable familiarisation with the test protocol and equipment as well as to highlight any potential problems which may have arisen during testing. The experiment was originally planned to be performed by using the right housing of the REM headset only to measure the REURs in the participants' right ears as would be common in normal clinical practise. However, the pilot study identified this method to be most impractical due to the limitation of only four aided measurement slots (i.e. REAR 1-4) being available for each ear in Auricle OpenREM mode. Once the four aided measurement slots had been used to record the measurements for the head deviations of 5°, 10°, 15°, and 20° in one direction, there were no further measurement slots available to record the remaining measurements for the head deviations in the opposite direction. Therefore, to keep measurements always on the right ear screen of the REM session, it was necessary to save the current session and open a new one to record the remaining opposite head deviations. This meant that a total of four REM sessions were needed to measure all the conditions just for one participant, resulting in tube calibration and the insertion of the probe tube being carried out four times thus increasing the length of the test procedure unnecessarily. The impractical nature of this original method was not highlighted until the pilot study was performed and consequently the test protocol was modified to that explained in Section 2.8.3 to improve efficiency during testing.

## 2.10 Data Management

Data was exported from the REM module a total of four times throughout each session into an Excel spreadsheet. The mean difference values between the primary REUR and each of the nine REURs measured for the head deviations of 0°, ±5°, ±10°, ±15°, and ±20° were calculated for both loudspeaker-to-client azimuths at each of the following 17 frequencies: 250, 500, 750, 1000, 1250, 1500, 1800, 2000, 2240, 2500, 2800, 3000, 3350, 3550, 3750, 4000, 6000Hz. The measurement curves of the screenshots taken during testing were compared to the corresponding raw numerical data of the spreadsheets to check that the data exported was accurate and no errors occurred during the exporting process. The data was then statistically analysed using the SPSS statistical program employing a four-way mixed repeated measures Analysis of Variance (ANOVA) and with a 0.05 level of significance.

# 3 Results

## 3.1 Introduction

The aim of this research project was to investigate the amount by which horizontal head movements can affect the accuracy of REMs when using the MPSE method for fitting OC hearing aids. This involved measuring REURs at each of the nine different head deviations under investigation (0°, ±5°, ±10°, ±15°, ±20°) relative to the loudspeaker-to-client azimuths of 0° and 45° in 28 otologically normal participants (12 male and 16 female). There were a total of 18 conditions in the experiment from the combination of two loudspeaker-to-client azimuths and nine head deviations being investigated (see Table 3, Section 2.3). Results were obtained in the participants' right ears only and for 17 frequencies (250-6000 Hz in approx 250 Hz intervals where possible) to allow for comparison with the results obtained by the Shaw (2010) study. All 28 participants completed the investigation. At the end of testing for each participant, the REUR data was exported into a Microsoft Excel spreadsheet where they were collated and then later analysed using the statistical software SPSS 17.0 once testing of all 28 participants was completed. This was performed to determine whether the results showed any statistically significant difference between the REUR values measured at the primary head position of each loudspeaker azimuth and those measured at the head deviations under investigation. However, it was decided that the large number of frequencies being examined in the study (17 frequencies at each head deviation) would be highly impractical for the statistical analysis stage, requiring the need for 306 variables to be entered into SPSS. Therefore, once testing was completed, the data values in dB were first averaged into low (250, 500, 750 Hz), mid (1000, 1250, 1500, 1800, 2000, 2240, 2500, 2800 Hz) and high (3000, 3350, 3550, 3750, 4000, 6000 Hz) frequency bands for all participants before being entered into SPSS so as to vastly reduce the number of variables and enable greater practicality for statistical analysis.

## 3.2 Descriptive Statistics

For each loudspeaker-to-client azimuth condition (0° and 45°), the amount of mismatch was calculated in Microsoft Excel by subtracting the REUR values obtained at each of the head deviations from the REUR value measured at the primary head position of 0° or 45°. For example, the mismatch value for a +5° head deviation relative to the 0° loudspeaker-to-client azimuth (i.e. 0° + 5°) was obtained by subtracting the REUR of the +5° head deviation from the REUR measured at the primary head position of 0° azimuth. In contrast, the mismatch value for a +5° head deviation relative the 45° loudspeaker-to-client azimuth (i.e. 45° + 5°) was obtained by subtracting the REUR of the +5° head deviation from the REUR measured at the primary head position of 45° azimuth. If there is no difference between the two REUR values then the mismatch value obtained will be zero. A positive or negative mismatch value indicates that the REUR value measured for the head deviations is greater or lower than that measured at the primary head position respectively. The mean mismatch and standard deviation for all 18 test conditions were calculated and are shown in Appendix D. The mean and standard deviation for each head deviation, at the 0° and 45° loudspeaker-to-client azimuths as well as averaged across both azimuth positions, are displayed in Table 1 and Table 2 of Appendix D for positive and negative head deviations respectively. Both tables show that the mean mismatch value becomes progressively greater as the head deviation increases in either direction from 0° to ±20° for all frequency bands.

Additionally, the mean mismatch and standard deviation for the 0° head deviation at each loudspeaker-to-client azimuth was calculated for the 17 frequencies that the REUR data was extracted in. This was performed to allow for comparison with the results of the Shaw (2010) study. These are displayed in Table 4 and which indicates that the mean mismatch values were all less than 1 dB with ±1 standard deviation less than 1.4 dB. The mean mismatch values with ±2 standard deviation are illustrated in Figure 14 and Figure 15 for the 0° and 45° loudspeaker-to-client azimuth positions respectively. The two figures show that for ±2 standard deviation (95% Confidence Interval) the amount of measured mismatch for both 0° and 45° loudspeaker azimuth will generally be within 3 dB of the mean values.

| | Frequency (Hz) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 250 | 500 | 750 | 1000 | 1250 | 1500 | 1800 | 2000 | 2240 | 2500 | 2800 | 3000 | 3350 | 3550 | 3750 | 4000 | 6000 |
| 0° Mean Mismatch (dB) | 0.3 | -0.1 | -0.1 | -0.2 | -0.3 | -0.5 | 0.1 | 0.0 | -0.3 | -0.2 | 0.2 | 0.2 | 0.1 | 0.0 | 0.0 | 0.2 | 0.7 |
| Std. Deviation | 0.8 | 0.6 | 0.7 | 1.1 | 0.9 | 1.0 | 0.9 | 0.9 | 1.2 | 0.8 | 0.8 | 0.7 | 1.1 | 1.0 | 0.9 | 0.8 | 0.8 |
| 45° Mean Mismatch (dB) | 0.1 | 0.4 | -0.1 | 0.0 | -0.1 | -0.3 | -0.4 | -0.8 | -0.6 | -0.2 | -0.2 | -0.4 | -0.5 | -0.2 | 0.0 | 0.3 | 0.3 |
| Std. Deviation | 0.5 | 0.8 | 0.8 | 1.1 | 0.8 | 0.6 | 0.8 | 1.0 | 0.7 | 0.9 | 1.0 | 1.3 | 0.9 | 1.0 | 0.6 | 0.6 | 0.8 |

**Table 4:** *Mean mismatch and standard deviation values for the 0° head deviation at both 0° and 45° loudspeaker-to-client azimuth.*

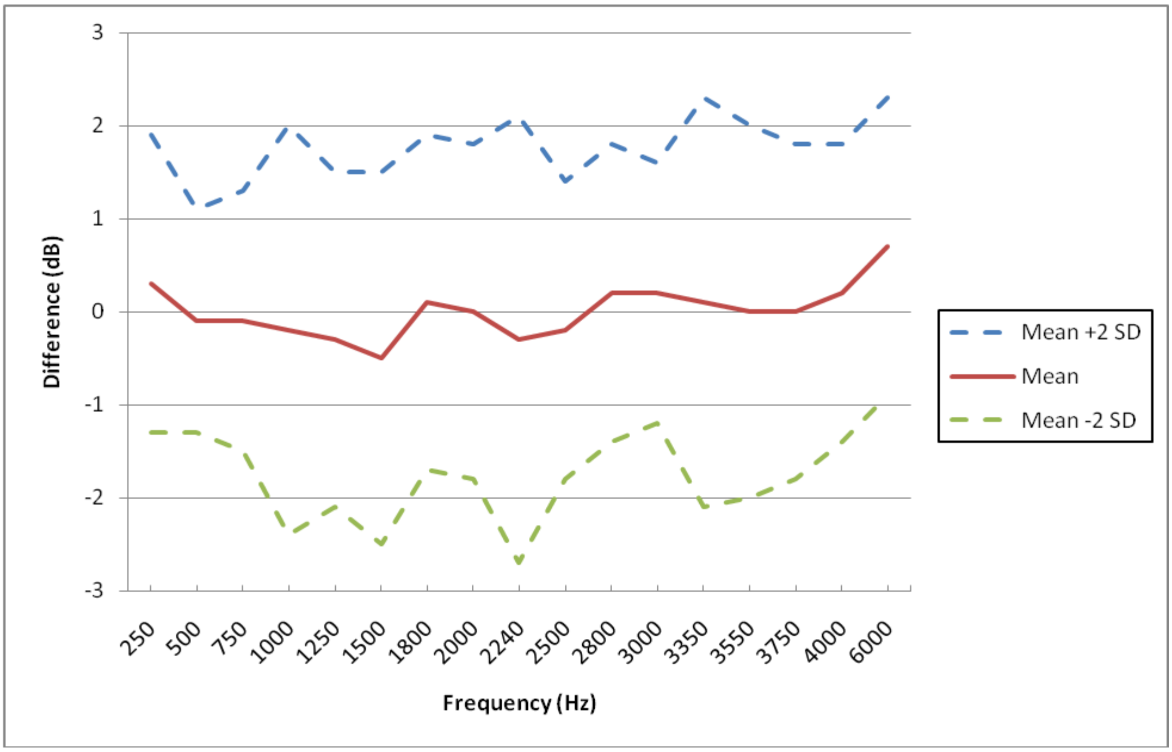


**Figure 14:** *Mean mismatch (difference) in dB for 0° head deviation at 0° loudspeaker-to-client azimuth.*

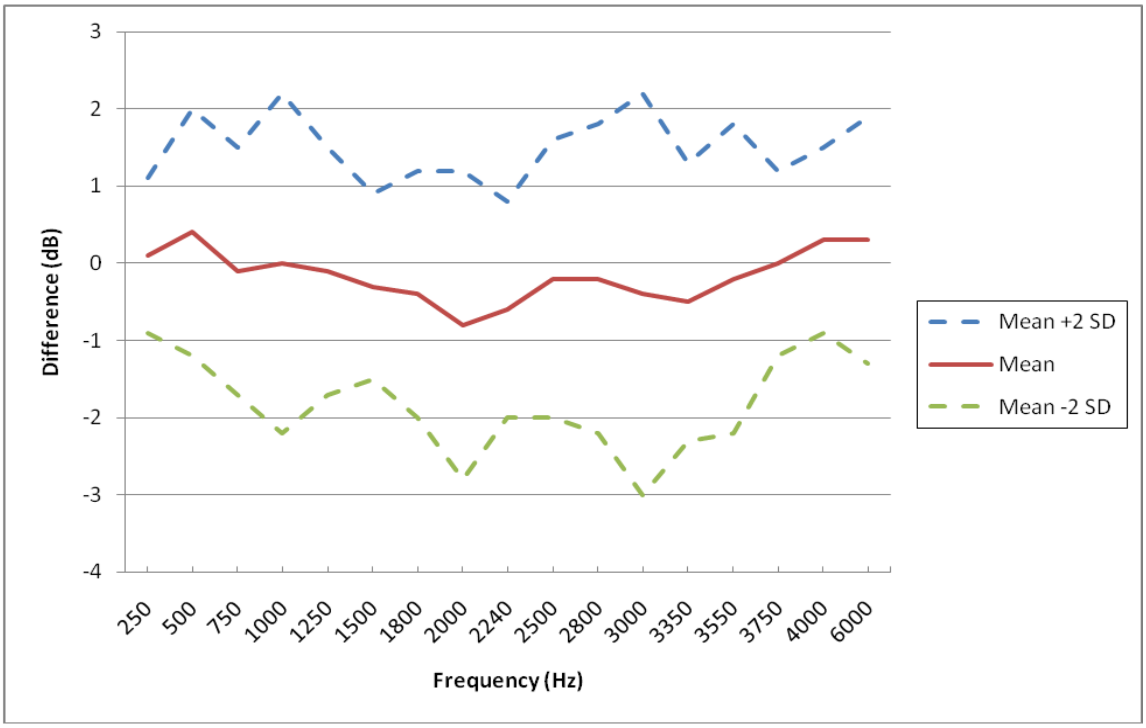


**Figure 15:** *Mean mismatch (difference) in dB for 0° head deviation at 45° loudspeaker-to-client azimuth.*

## 3.3 Data Distribution

The data for all test conditions at each frequency band was entered into SPSS in order to test for normality and there was a total of 54 variables. As the number of participants in the study was less than 50, the Shapiro-Wilk test was used which revealed that the majority of the conditions were normally distributed with a significance value of greater than 0.05. The minority of conditions that were not normally distributed were examined by looking at normality probability (Q-Q) plots and histograms which showed that they were only slightly skewed and did not deviate significantly from normal distribution. Therefore on basis of this, it was decided to use parametric tests for the statistical analysis of the data. An example of a normally distributed and not normally distributed histogram and normality probability (Q-Q) plot in this study is shown in Appendix E.

## 3.4 Statistical Analysis

A four-way mixed repeated measures Analysis of Variance (ANOVA) was then performed to examine the effects of the independent variables (loudspeaker-to-client azimuth, head deviation, and frequency) and the between-subjects factor (gender) in the study on the dependent variable which was the amount of mismatch measured in dB. The within-subjects factors were loudspeaker-to-client azimuth (0° and 45° azimuth), head deviation (0°, ±5°, ±10°, ±15°, ±20°) and the frequency band measured (low, mid, and high frequency). The between-subjects factor was gender. The data was analysed for main effects and Mauchly's Test of Sphericity was used to determine if sphericity could first be assumed. The Greenhouse-Geisser epsilon was used to adjust the degrees of freedom (df) whenever sphericity could not be assumed ($p<0.05$) for any within-subject factor as indicated by Mauchly's Test of Sphericity.

### 3.4.1 Effect of gender on the amount of measured mismatch

To investigate whether the amount of mismatch measured differed according to gender, male and female participant data were averaged across all conditions and frequency bands and analysed in the ANOVA. The mean mismatch and standard deviation values for each gender is shown in Table 5.

| Gender | Mean Mismatch (dB) | Std. Deviation |
|---|---|---|
| Male | -0.033 | 1.335 |
| Female | -0.161 | 1.363 |

**Table 5:** *Mean mismatch and standard deviation values for males and females, averaged across all conditions.*

According to Table 5, a greater mean mismatch is measured in females than in males with the negative values indicating that the mean mismatch values for both gender is lower than the REUR value measured at the primary head position. However, the results of the ANOVA indicated that there was no significant main effect of gender, $F(1, 26) = 3.000$, $p = >0.05$, $r = 0.26$. Therefore, gender was not examined separately for subsequent analyses.

### 3.4.2 Effect of loudspeaker-to-client azimuth on the amount of measured mismatch

The data was examined to determine the effect of loudspeaker-to-client azimuth on the amount of mismatch measured. All the condition combinations were averaged across loudspeaker-to-client azimuth and the mean and standard deviation obtained for 0° and 45° azimuth are displayed in Table 6.

| Loudspeaker-to-client azimuth | Mean Mismatch (dB) | Std. Deviation |
|---|---|---|
| 0° | -0.027 | 1.697 |
| 45° | -0.185 | 0.874 |

**Table 6:** *Mean mismatch and standard deviation values for 0° and 45° loudspeaker-to-client azimuth, averaged across all conditions.*

The negative mean mismatch values in Table 6 indicates that the REUR value averaged across all head positions and all frequency bands is lower than the REUR value at the primary head position. Table 6 also shows that a greater mean mismatch is measured at the 45° loudspeaker-to-client azimuth than the 0° loudspeaker-to-client azimuth. However, the results of the ANOVA indicated that there was no significant main effect of loudspeaker-to-client azimuth, $F(1, 26) = 3.256$, $p = >0.05$, $r = 0.27$. Therefore, loudspeaker-to-client azimuth was not examined separately for subsequent analyses.

### 3.4.3 Effect of frequency on the amount of measured mismatch

The results of the ANOVA were analysed to determine if there was a significant difference between the amount of mismatch measured for each frequency band. Table 7 shows the mean and standard deviation values of each frequency band, averaged across all participants and conditions, whilst Figure 16 illustrates these values graphically.

| Frequency band | Mean mismatch (dB) | Std. Deviation |
|---|---|---|
| **Low (250-750 Hz)** | 0.073 | 0.783 |
| **Mid (1000-2800 Hz)** | -0.328 | 1.392 |
| **High (3000-6000 Hz)** | -0.062 | 1.690 |

**Table 7:** *Mean mismatch and standard deviation values for each frequency band (low, mid and high), averaged across all conditions.*

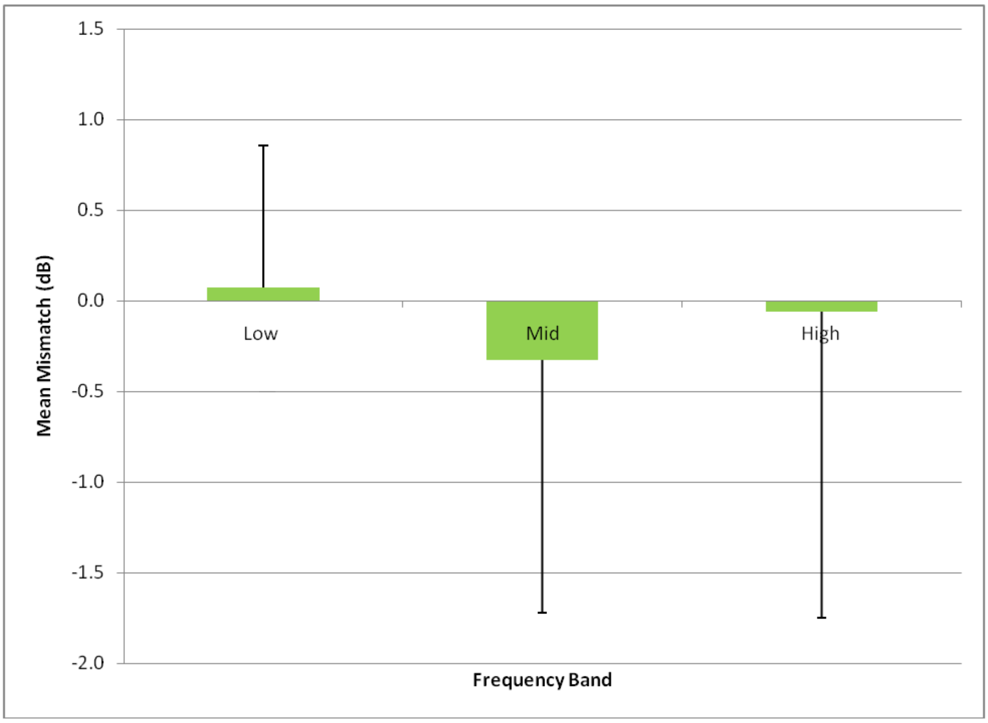


**Figure 16:** *Mean mismatch and standard deviation values for each frequency band (low, mid and high), averaged across all conditions. Error bars show 1 SD.*

It can be seen in Table 7 and Figure 16 that the greatest mean amount of mismatch is measured at the mid frequency band with the negative value indicating that the mismatch value is lower than the primary REUR value. They also show that the mean amount of mismatch measured for the low and high frequency bands are quite similar but the positive low frequency value indicates that the mismatch value is greater than the primary REUR value, whereas the negative high frequency value indicates the opposite. The standard deviations in Table 7 show that the variation from the mean increase from the low to mid and then high frequency band. Examination of the frequency data using Mauchly's Test of Sphericity revealed that the assumption of sphericity had not been violated, $c^2$ (2) = 1.191, p = >0.05, and so no adjustments were made to the degrees of freedom. Analysis of the ANOVA results indicated that there was a significant main effect of frequency, F(2, 52) = 7.580, p = <0.05, with an approximately medium effect size (r = 0.44) and the power was high (0.95).

The ANOVA pairwise comparisons were then examined to determine which frequency bands were statistically significantly different from each other. A Bonferroni adjustment for multiple comparisons was selected in SPSS and applied to the ANOVA significance value. Table 8 shows the mean difference, standard error and significance value for each frequency band pairwise comparison. The results revealed a significant difference in the mean mismatch values between the low and mid frequency bands only, $CI_{95\%}$ = 0.165 (lower), 0.654 (upper), p = <0.05, and no other comparisons were significant (p = >0.05).

| Frequency band | Mean difference (dB) | Std. Error | p |
|---|---|---|---|
| Low x Mid | 0.409 | 0.096 | 0.001* |
| Low x High | 0.138 | 0.109 | 0.646 |
| Mid x Low | -0.400 | 0.096 | 0.001* |
| Mid x High | -0.271 | 0.116 | 0.081 |
| High x Low | -0.138 | 0.109 | 0.646 |
| High x Mid | 0.271 | 0.116 | 0.081 |

*alpha = <0.05. Bonferroni adjustment for multiple comparisons applied.

**Table 8:** *Pairwise comparisons of the low, mid and high frequency bands.*

### 3.4.4 Effect of head deviation on the amount of measured mismatch

All condition combinations were averaged across head deviation to investigate the effect of head deviation on the amount of measured mismatch. The mean mismatch and standard deviation measured for each head deviation is shown in Table 9 and illustrated graphically in Figure 17.

| Head Deviation (degrees azimuth) | Mean Mismatch (dB) | Std. Deviation |
|---|---|---|
| **0** | -0.032 | 0.488 |
| **+5** | -0.433 | 0.593 |
| **+10** | -0.858 | 0.747 |
| **+15** | -1.335 | 0.928 |
| **+20** | -1.808 | 1.119 |
| **-5** | 0.402 | 0.626 |
| **-10** | 0.761 | 0.821 |
| **-15** | 1.057 | 1.057 |
| **-20** | 1.294 | 1.276 |

**Table 9:** *Mean mismatch and standard deviation for each head deviation, averaged across all conditions.*

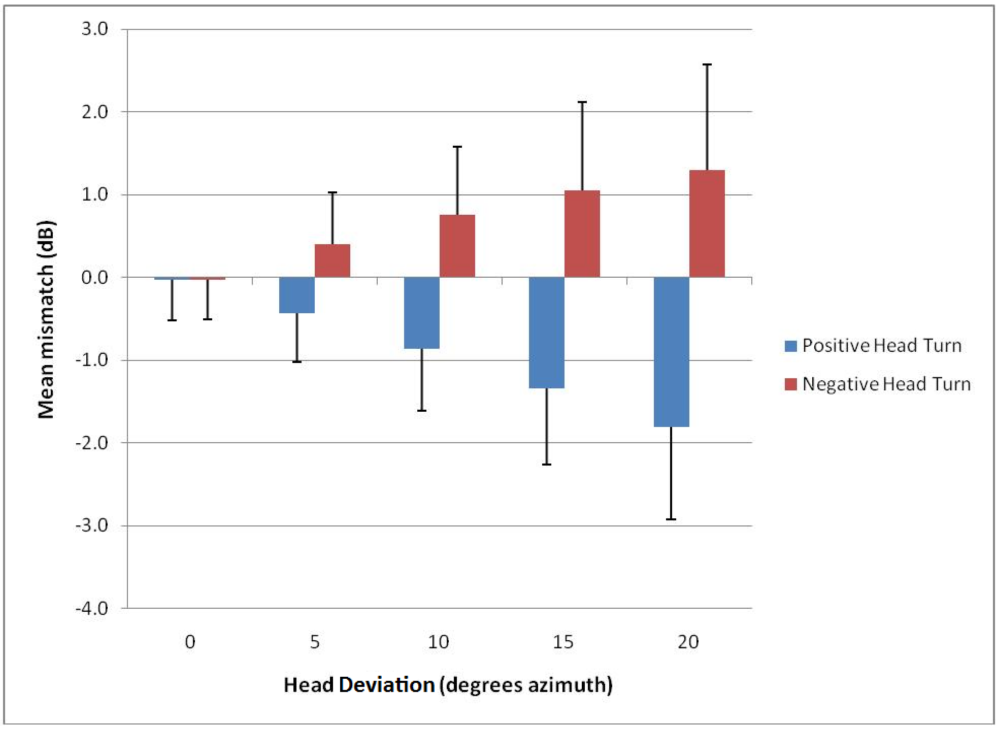


**Figure 17:** *Mean mismatch for each head deviation, averaged across all conditions. Error bars show 1 SD.*

As indicated in Table 9 and Figure 17, the mean mismatch measured is smallest for the 0° head deviation and progressively increases with increasing head deviation from 0° to 20° in both the positive and negative directions. It can also be seen in Table 9 that a head turn in the positive direction generally produces a slightly greater mean mismatch than the corresponding head turn in the negative direction. Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, $c^2$ (35) = 367.460, p = <0.001, and therefore the degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity (e = 0.175). The ANOVA results revealed that there was a significant main effect of head deviation, F(1.400, 36.409) = 1186.819, p = <0.001, with a large effect size (r = 0.99) and the power was high (1.00).

The ANOVA pairwise comparisons, with a Bonferroni adjustment applied to account for multiple comparisons, were then examined to determine which head deviations were significantly different from each other. The results indicated that all nine head deviations were significantly different from each other, p = <0.001.

A correlations coefficient using Pearson's r was then calculated to assess the relationship between mean mismatch value and head deviation. The correlation between these two variables is displayed in scatter plots for positive head deviations in Figure 18 and for negative head positions in Figure 19. Statistically significant correlations of 1.00 (p = <0.001) for positive head deviations and 0.99 for negative head deviations (p = <0.001) were found, indicating an extremely strong positive correlation for head deviations in both directions, i.e. as head deviation increases from either 0° to +20° or 0° to -20° so does the mean mismatch value.

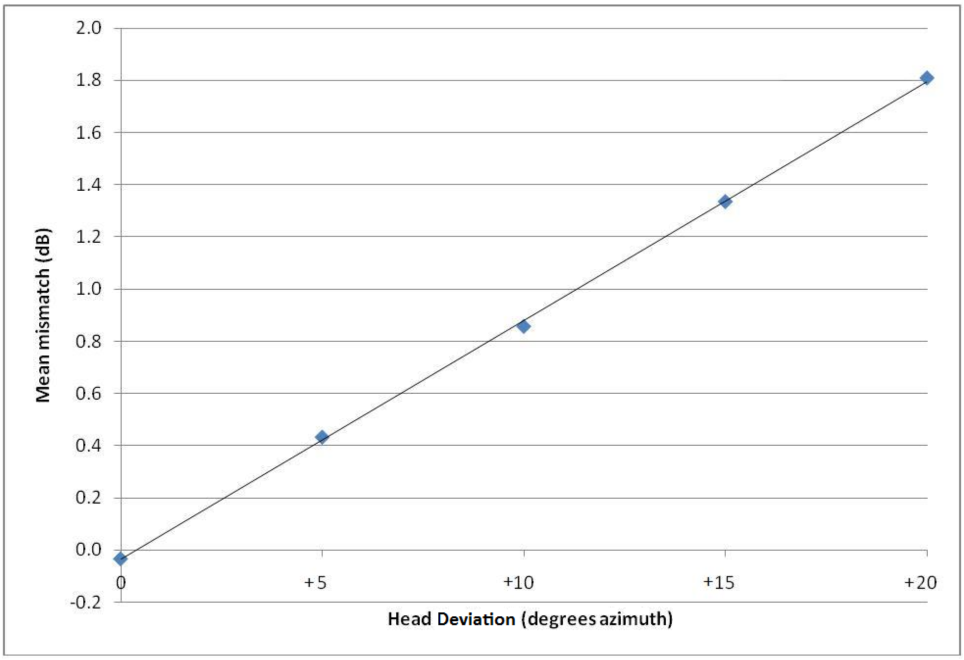


**Figure 18:** *Scatter plot showing the correlation between mean mismatch and head deviations in the positive direction.*

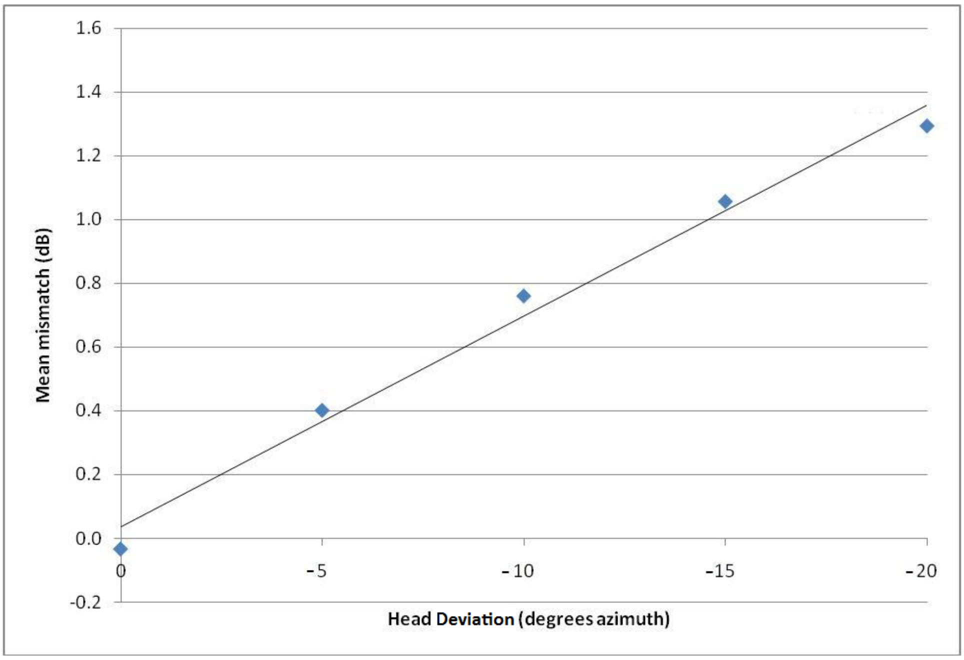


**Figure 19:** *Scatter plot showing the correlation between mean mismatch and head deviations in the negative direction.*

### 3.4.5 Examination of interaction effects

The results of the ANOVA revealed a significant interaction effect for the variables of head deviation and frequency, $F(1.625, 42.263) = 38.619$, $p = <0.001$, with an approximately large effect size ($r = 0.76$) and high power (1.00). The Greenhouse-Geisser estimate of sphericity ($e = 0.102$) was used to correct the degrees of freedom as Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, $c^2$ (135) = 906.541, $p = <0.001$. To investigate this interaction effect further, the data was examined to determine at which frequency bands were the head deviations significantly different from each other. Table 10 shows the mean mismatch and standard deviation values of all head deviations at each frequency band. According to Table 10, the mean mismatch for each frequency band is lowest for the 0° head deviation. It can also be seen that each frequency band follow a similar trend in that the mean mismatch values increase progressively with each subsequent head deviation in both directions as the head turns further away from 0°, reaching a maximum for the ±20° head deviations.

| **Head Deviation** | **Mean and Std. Deviation** | **Low Frequency (250-750 Hz)** | **Mid Frequency (1000-2800 Hz)** | **High Frequency (3000-6000 Hz)** |
|---|---|---|---|---|
| 0° | Mean Mismatch (dB) | 0.086 | -0.241 | 0.059 |
| | Std. Deviation | 0.491 | 0.410 | 0.496 |
| +5° | Mean Mismatch (dB) | -0.124 | -0.674 | -0.502 |
| | Std. Deviation | 0.482 | 0.471 | 0.672 |
| +10° | Mean Mismatch (dB) | -0.362 | -1.181 | -1.030 |
| | Std. Deviation | 0.517 | 0.575 | 0.842 |
| +15° | Mean Mismatch (dB) | -0.657 | -1.751 | -1.598 |
| | Std. Deviation | 0.566 | 0.733 | 1.021 |
| +20° | Mean Mismatch (dB) | -0.947 | -2.376 | -2.102 |
| | Std. Deviation | 0.596 | 0.903 | 1.208 |
| -5° | Mean Mismatch (dB) | 0.363 | 0.281 | 0.563 |
| | Std. Deviation | 0.410 | 0.555 | 0.820 |
| -10° | Mean Mismatch (dB) | 0.573 | 0.674 | 1.037 |
| | Std. Deviation | 0.410 | 0.699 | 1.127 |
| -15° | Mean Mismatch (dB) | 0.772 | 1.028 | 1.372 |
| | Std. Deviation | 0.432 | 0.845 | 1.520 |
| -20° | Mean Mismatch (dB) | 0.952 | 1.283 | 1.647 |
| | Std. Deviation | 0.454 | 1.019 | 1.858 |

**Table 10:** *Mean mismatch and standard deviations for each head deviation at each frequency band.*

The differences between the head deviations at each frequency band are also illustrated graphically in Figure 20 for positive head turns (0° to +20°) and in Figure 21 for negative head turns (0° to -20°). Figure 20 shows that for each head deviation in the positive direction, the mean amount of mismatch measured is greatest at the mid frequency band followed by the high and then low frequency bands. In contrast, Figure 21 shows that the mean amount of mismatch is greatest at the high frequency band followed by the mid and then low frequency bands at every head deviation in the negative direction with the exception of 0°.

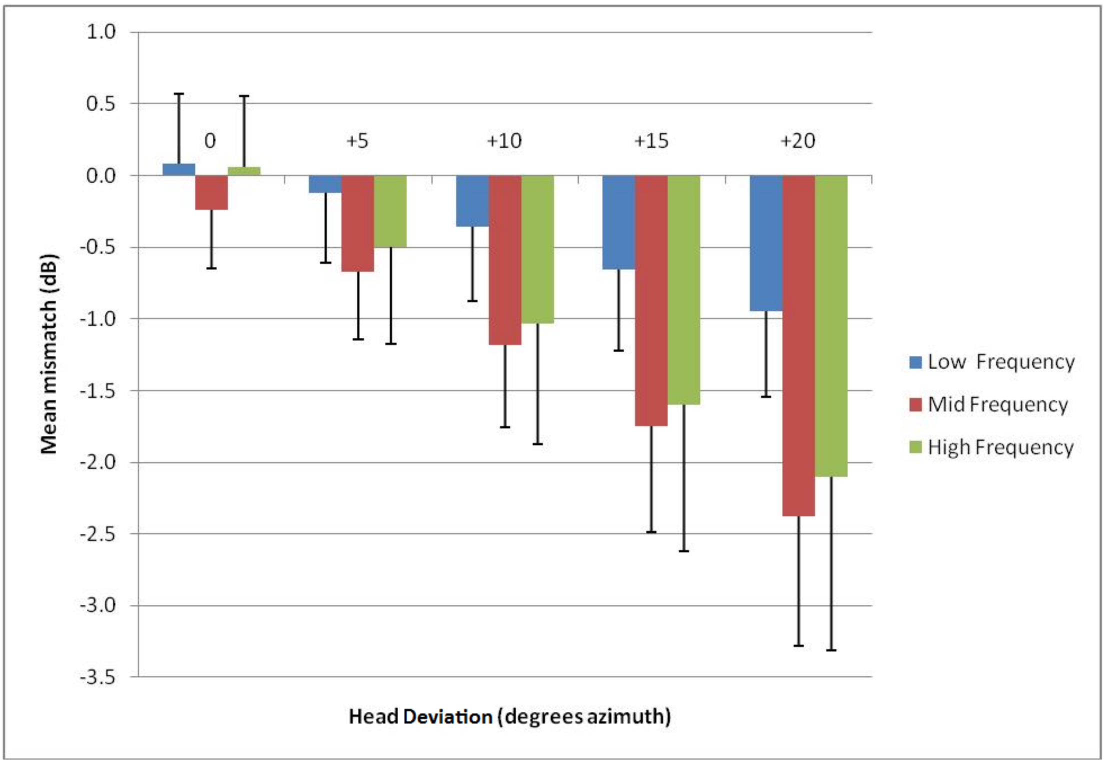


**Figure 20:** *Mean mismatch for head deviations in the positive direction at each frequency band. Error bars show mean +1 SD.*

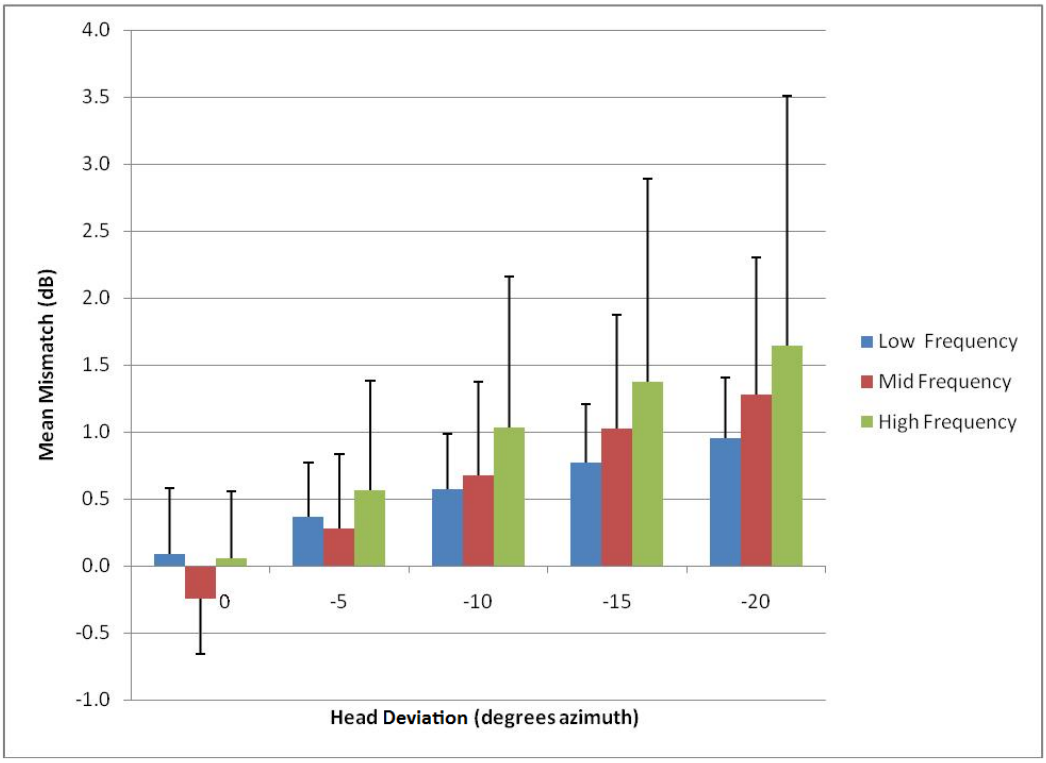


**Figure 21:** *Mean mismatch for head deviations in the negative direction at each frequency band. Error bars show mean +1 SD.*

The data was then examined to investigate whether the differences between each head deviation at each of the three frequency bands were significant. Three repeated measures ANOVA were performed, one for each of the three frequency bands. The within-subjects factors were loudspeaker-to-client azimuth and head deviation whilst the dependent variable was the mean mismatch value for each frequency band. The within-subjects factors were averaged and pairwise comparisons, with a Bonferroni adjustment applied to account for multiple comparisons, were performed for each factor at each frequency band. Examination of the results revealed that the mean mismatch measured for each head deviation is significantly different to every other head deviation in all frequency bands.

The results of the main ANOVA also revealed significant effects for all the interactions involving loudspeaker-to-client azimuth. For the interaction of Azimuth x Head Deviation, Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, $c^2$ (35) = 316.592, p = <0.001, and therefore the degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity (e = 0.202). A significant effect was found, F(1.613, 41.943) = 293.477, p = <0.001, with a high effect size (r = 0.96) and high power (1.00), suggesting that the effect of loudspeaker-to-client azimuth varies with head deviation.

A significant interaction effect was found for Azimuth x Frequency, $F(1.522, 39.572) = 9.326$, $p = <0.05$, suggesting that the effect of loudspeaker-to-client azimuth varies with frequency. The effect size was approximately medium ($r = 0.48$) and the power was high (0.99). Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, $c^2$ (2) = 9.424, $p = <0.05$, and therefore the degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity ($e = 0.761$). Finally, the interaction effect for Azimuth x Head Deviation x Frequency was also found to be significant, $F(2.070, 53.833) = 40.032$, $p = <0.001$, with an approximately high effect size ($r = 0.76$) and high power (1.00). Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated, $c^2$ (135) = 717.109, $p = <0.001$, and therefore the degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity ($e = 0.129$). However, due to the non significant main effect of Azimuth, all three interactions involving loudspeaker-to-client azimuth were not investigated further. No significant effects were found for any other interactions.

### 3.4.6 Examination of the significance of REUR values for each head deviation from the REUR value of the primary head position

The results have shown that the mean mismatch values measured for each head deviation are all significantly different to each other at all frequency bands. However, they have not indicated whether the mean REUR values measured for each head deviation are significantly different from the REUR at the primary head position. Therefore to investigate this, the raw primary REUR values and raw REUR values measured for each head deviation were averaged across frequency into low, mid and high frequency bands and these mean values were entered into SPSS. Twenty-seven paired samples t-tests were conducted with a Bonferroni adjustment applied to account for the multiple t-tests by dividing the significance value of 0.05 by 27 to produce a new adjusted significance value of $p = <0.002$. Table 11 displays the results of the 27 t-tests that were conducted for the positive head deviations. The results show that a statistically significant difference can be found in only one and two frequency bands for a 0° and +5° head deviation respectively, but beyond which a significant difference in all three frequency bands can be found for all subsequent head deviations. Table 12 displays the results of the 27 t-tests that were conducted for the negative head deviations. The results show that there is a significant difference in all three frequency bands between the primary REUR and the REUR of a negative head deviation of -5° and above.

| | Frequency | | |
|---|---|---|---|
| **Head Deviation** | **Low (250-750 Hz)** | **Mid Freq (1000-2800 Hz)** | **High Freq (3000-6000 Hz)** |
| **0°** | | | |
| t | -1.257 | 3.803 | -0.845 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.219 | 0.001* | 0.406 |
| **+5°** | | | |
| t | 2.054 | 9.507 | 5.171 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.050 | 0.000* | 0.000* |
| **+10°** | | | |
| t | 6.180 | 16.025 | 8.340 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.000* | 0.000* | 0.000* |
| **+15°** | | | |
| t | 11.122 | 22.263 | 11.388 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.000* | 0.000* | 0.000* |
| **+20°** | | | |
| t | 16.227 | 27.861 | 13.034 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.000* | 0.000* | 0.000* |

* Bonferroni adjustment: alpha = <0.002

**Table 11:** *Results of paired T-tests showing the significance between the primary REUR values and the REUR values of each head deviation in the positive direction.*

| | Frequency | | |
|---|---|---|---|
| **Head Deviation** | **Low (250-750 Hz)** | **Mid Freq (1000-2800 Hz)** | **High Freq (3000-6000 Hz)** |
| **0°** | | | |
| t | -1.257 | 3.803 | -0.845 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.219 | 0.001* | 0.406 |
| **-5°** | | | |
| t | -6.553 | -3.951 | -6.462 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.000* | 0.001* | 0.000* |
| **-10°** | | | |
| t | -9.735 | -8.608 | -9.694 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.000* | 0.000* | 0.000* |
| **-15°** | | | |
| t | -13.242 | -12.402 | -10.500 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.000* | 0.000* | 0.000* |
| **-20°** | | | |
| t | -16.436 | -14.484 | -11.620 |
| df | 27.000 | 27.000 | 27.000 |
| Sig | 0.000* | 0.000* | 0.000* |

* Bonferroni adjustment: alpha = <0.002

**Table 12:** *Results of paired T-tests showing the significance between the primary REUR values and the REUR values of each head deviation in the negative direction.*

# 4 Discussion

The present study aimed to investigate how much the accuracy of REMs using the MPSE method can be affected by horizontal head turns of progressively increasing degrees. Real-ear unaided responses were measured at the head deviations of 0°, ±5°, ±10°, ±15° and ±20° relative to the primary head positions of 0° and 45° loudspeaker-to-client azimuth, and the difference between these measures was calculated to determine the amount of mismatch produced by each head deviation. The amount of measured mismatch was examined with regards to head position, loudspeaker-to-client azimuth, frequency measured and gender. The results of this study are discussed below in terms of the relevance to clinical practice and the comparison with previously published findings.

## 4.1 Comparison of results with the Shaw (2010) study

In this experiment, it was decided that a head deviation of 0° would be investigated so as to determine the amount of mismatch that can arise when no horizontal head turn was made. Table 4 displays the mean mismatch values for the 0° head deviation at both 0° and 45° loudspeaker azimuths. The values were all less than 1 dB with ±1 standard deviation less than 1.4 dB. Figures 14 and 15 illustrate the mean mismatch values with ±2 standard deviation for the 0° and 45° loudspeaker azimuth positions respectively and it can be seen that the mismatch will generally be within 3 dB of the mean values for 95% of young adult clients (see Figure 8, Section 1.5.3 for comparison with Shaw, 2010). These findings are in close agreement with those of Shaw (2010) and are important clinically because they provide further support that no significant errors will arise during the REM verification process of OC hearing aids using the MPSE method as long as patients keep their heads still.

## 4.2 Analysis of the effect of gender on the amount of measured mismatch

The effect of gender was examined to determine whether the amount of measured mismatch differed significantly between males and females. The values displayed in Table 5 indicate a trend that a greater mean mismatch is measured in females than in males with the negative sign indicating that the mean mismatch value underestimates the primary REUR. However, this trend between males and females was revealed to be not significant when statistical analysis was performed. The experimental hypothesis (hypothesis 4) that the mismatch measured for males will not be significantly different to that for females is therefore accepted. It was hypothesised prior to testing that there would be no significant difference between males and females in the amount of mismatch measured. This hypothesis was based on the reasoning that despite evidence indicating the average ear canal volume for males is larger than for females (Aaarts and Caffee, 2005), the participants of both gender in this study performed the same degree of head rotation and so the difference should be the same for both gender irrespective of the ear canal volume size. The results of the statistical analysis appears to support this reasoning although there is no literature available regarding the amount of head movement induced mismatch measured for males and females to draw comparisons of findings with.

## 4.3 Analysis of the effect of loudspeaker-to-client azimuth on the amount of measured mismatch

The amount of mismatch measured for the loudspeaker-to-client azimuths of 0° and 45° was examined to determine if the values were significantly different from each other. The mean mismatch values for both loudspeaker positions are displayed in Table 6. The values displayed in Table 6 indicate a trend that a greater mean mismatch is measured at the 45° loudspeaker-to-client azimuth than the 0° loudspeaker-to-client azimuth and the negative values indicate both underestimate the REUR measured at the primary head position. Statistical analysis of the results however revealed that this trend was not significant as no significant difference was found between the two loudspeaker positions. The standard deviation for the 0° azimuth is greater than that for the 45° azimuth, indicating that there is more variation around the mean at the 0° azimuth out of the two.

It was hypothesised that the 0° loudspeaker azimuth would produce a significantly greater mismatch than the 45° azimuth. This was based on the comment by Dillon (2001) who theorised that a 45° azimuth will allow for greater head movements than a 0° azimuth without adversely affecting the REM measurement accuracy, since patients will have to turn their heads a longer distance before the acoustic shadow region of the head begins to influence the ear being measured at this azimuth. However, the finding was not statistically significant and the mean mismatch values in Table 6 suggest the opposite of this experimental hypothesis.

This means that experimental hypothesis 5, which states that the mismatch measured for the 0° loudspeaker azimuth will be significantly different to that measured for the 45° azimuth, is rejected. The non significant effect of loudspeaker-to-client azimuth may possibly be due to the mismatch measures used in this study being obtained by averaging the REUR difference values from the two loudspeaker azimuths. Since the 0° azimuth showed the greater amount of variation of the two, the mismatch value may well be larger at the 0° than the 45° azimuth for specific individual frequencies and head deviations.

The study finding of no significant effect of loudspeaker-to-client azimuth is in agreement with the findings of Shaw (2010) who also found mean difference measures for 0° and 45° loudspeaker azimuths to be not statistically significant. This finding has important implications for clinical practice, by demonstrating that the choice between using a 0° or 45° loudspeaker azimuth will not significantly influence the mean mismatch that can arise from horizontal head movements of up to ±20°. Therefore clinicians are free to choose either loudspeaker azimuth during the REM verification of OC hearing aids using the MPSE method, safe in the knowledge that neither is advantageous over the other in terms of REM accuracy.

However, in agreement with the recommendations by Stone and Moore (2004) and Shaw (2010), a 0° loudspeaker azimuth would likely be more advantageous in a clinical setting despite showing more variability from the mean than the 45° azimuth. Shaw (2010) explains that positioning the patient in front of the loudspeaker at 0° azimuth is more practical than at 45° because the use of visual markers on the clinic wall to help maintain a 45° head position is not commonly employed in routine practice. Also, it is important to emphasise that in this study head movements were tracked by the use of a laser level and visual markers on the wall but the angular position of the patient's head would not be set so accurately in clinical practice. Therefore, it would be more difficult for the patient to maintain a 45° azimuth relative to the loudspeaker without the equipment used in this study, whereas the loudspeaker at a 0° azimuth position would provide a visual target to help patients better maintain their head position. Shaw (2010) also commented that the use of a 45° loudspeaker azimuth would require two patient positions compared to just one for the 0° azimuth when fitting bilateral hearing aids. On the basis of the practical advantages offered in the clinical setting, this study recommends that a 0° loudspeaker azimuth should be used when fitting OC hearing aids with the MPSE method although a loudspeaker azimuth of 45° is also acceptable and should not produce significantly different errors.

## 4.4 Analysis of the effect of frequency on the amount of measured mismatch

The effect of frequency was examined to determine whether the amount of measured mismatch differed significantly between low (250-750 Hz), mid (1000-2800 Hz) and high (3000-6000 Hz) frequency bands. The mean mismatch results for the three frequency bands are displayed in Table 7 and illustrated graphically in Figure 16. The results show that the greatest amount of mismatch occurred at the mid frequency band (-0.328 dB) where there is an underestimation of the primary REUR. The least amount of mismatch occurred at the high frequency band (-0.062 dB) where there is also an underestimation of the primary REUR. The mismatch measured at the low frequency band (0.073 dB) is very similar and only slightly greater in magnitude than that of the high frequency band but it shows an overestimation of the primary REUR rather than an underestimation. Statistical analysis found a significant difference for the mismatch between the frequency bands although further examination using pairwise comparisons (see Table 8, Section 3.4.3) revealed that only the mismatch for low and mid frequency bands were significantly different. The experimental hypothesis (hypothesis 6) that the mismatch measured will significantly differ depending on the frequency measured is therefore accepted.

The results of the pairwise comparisons indicate that that a significantly greater mismatch is measured at the mid frequency than the low frequency band. The reason behind this finding is likely to be explained by the head shadow effect. Head turns away from the loudspeaker will result in the head casting a progressively greater acoustical shadow. This head shadow occurs for frequencies with small wavelengths compared to the size of the head and so significantly affects frequencies of over about 1500 Hz, whereas diffraction can occur for low frequencies which have long wavelengths and so are able to bend around the head (Dillon, 2001). Consequently, it would be expected for low frequencies to be least affected by head turns whilst the mid frequencies onwards would be affected more substantially and this was the basis for hypothesis 6. This finding is also supported by the results of Shaw and Vaillancourt (1985) which showed a similar trend using a loudspeaker azimuth of 0°, as the mean mismatch values for a ±15° horizontal turn were greater at the mid frequencies (1.6 dB) than at the low frequencies (0.9 dB). These mean mismatch values are also consistent with those found for the ±15° head deviation in this present study of 1.4 dB and 0.7 dB for the mid and low frequencies respectively. However, the lack of a significant difference between the high and mid frequency bands as well as between the high and low frequency band was unexpected because wavelength decreases as frequency increases. Therefore the head shadow effect should be even more significant for the high than the mid and low frequencies but this was not the case as indicated by the results. This is also not in accordance with the Shaw and Vaillancourt (1985) findings, where the mean mismatch values for a ±15° head turn at the high frequencies (2.4 dB) were greater than those for the mid and low frequencies. This finding may possibly be explained by the standard deviation of the high frequency band, which is the largest out of the three. This suggests that there was a large amount of variation around the mean in the mismatch values for the high frequencies, indicating that the values can vary from being greater than those at the mid frequency band or lower than those at the low frequency band.

Overall, these findings have important implications for clinical practice by informing clinicians that the REM errors caused by head turns of up to ±20° when using the MPSE method will typically be lowest at the low frequencies, greatest at the mid frequencies and most variable at the high frequencies. This means that the intelligibility of the speech frequencies and high frequency consonants are likely to be most affected by head turns of up to ±20° which could negatively impact on the amount of benefit received from the OC hearing aid. Clinicians should therefore be particularly aware of the mid and high frequency measurements if a head turn is made as adjustments to the hearing gain at these frequencies may need to be considered to ensure that REM targets are matched as accurately as possible.

## 4.5 Analysis of the effect of head deviation on the amount of measured mismatch

The mean mismatch results for the nine head deviations are shown in Table 9 and illustrated graphically in Figure 17. They both show that the amount of measured mismatch is lowest for the 0° head deviation but increases with progressive positive and negative head turns up to the 20° head deviation, producing an underestimation and overestimation of the REUR compared to the primary head position respectively. Similarly, the standard deviations can be seen to increase gradually from 0° to 20° in both positive and negative directions, with 0° producing the least variation from the mean and ±20° producing the most in their respective directions. Statistical analysis confirmed that there was a main significant effect of head deviation and further examination using pairwise comparisons revealed that the mean mismatch values of each head deviation were significantly different to each other. Therefore experimental hypothesis 2, which states that significant mismatch values will be obtained for head deviations of 5° and above in the positive and negative directions, is accepted.

As the pairwise comparisons revealed that the results for each head position were significantly different to each other, a correlation coefficient was performed to determine if there was any relationship between head position and mean mismatch value obtained. The scattergrams of Figures 18 and 19 revealed an essentially perfect positive correlation between head position and mean mismatch, strongly confirming that the mismatch value increases as head position increases. Therefore experimental hypothesis 3, which states that there will be a significant positive correlation between head deviation and the amount of mismatch measured, is accepted.

The reason for the difference in mismatch values between the head deviations can be readily explained by the head shadow effect. As already explained in Section 4.4, the head begins to cast a progressively greater acoustical shadow on an ear as it turns further away from the loudspeaker. For both the 0° and 45° loudspeaker azimuths, an increasing positive head turn from the primary head position (i.e. 0° or 45°) will result in the right ear moving progressively further away from the loudspeaker and the head becoming more of an acoustical barrier for sounds travelling to the right ear. Therefore it would be expected that the REUR measured for each subsequent positive head deviation will become gradually more attenuated and their values being lower than that measured at the primary head position and this is supported by the negative mismatch values in the results. The result is that a gradual increase in the amount of mismatch measured is observed as the positive head turn increases. In contrast, the right ear will move progressively closer to the loudspeaker with an increasing negative head turn from the primary head position, and so the acoustic shadow region casted on the right ear will decrease. The REUR measured for each subsequent negative head deviation will then become progressively greater than that measured at the primary head position and this is again supported by the gradually increasing positive mismatch values of the results. These findings are in agreement with the results of Shaw and Vaillancourt (1985), which showed that the amount of mismatch increased as the azimuth of the loudspeaker relative to the participant increased from 0° to ±15°. The finding that positive and negative head turns produce REURs that underestimate and overestimate the primary REUR respectively is also supported by the results of Shaw and Vaillancourt (1985) which showed the same pattern.

The finding of a significant difference in the mean amount of measured mismatch between the head deviations has important implications for clinical practice. The results indicate that clinicians can expect the amount of mismatch measured to be minimal if the patient's head remains still (i.e. 0° head deviation), as also explained in Section 4.1 above. However, the mismatch value will increase for every ±5° head rotation up to ±20°, with the REM errors typically being below 1 dB for head turns up to ±10° and below 2 dB for head turns up ±20°. These REM errors are relatively small and it can be argued they are not important for clinical practice as they are well within the acceptable tolerance of ±5 dB at 250-2000 Hz and ±8 dB at 3000-4000 Hz for matching REM targets as specified by the Modernising Hearing Aid Services (MHAS) guidelines (Gatehouse et al., 2001). However, the BSA and BAA (2007) REM guidelines state that these MHAS recommended tolerances only provide a rough guidance for clinicians and closer matches to REM targets result in greater patient benefit. Shaw (2010) also argues these inaccuracies caused by head movements are not the only source of REM error and they can add up with other different sources of error, such as the up to 3 dB intra-tester test-retest reliability reported by Valente et al. (1990) when measuring REIG. These combined inaccuracies may invalidate a seemingly accurate match to target and so impact negatively on the benefit received from the hearing aid. Therefore, in agreement with Stone and Moore (2004) and Shaw (2010), it is recommended that even the small REM error values caused by head movements found in the present study should be minimised by ensuring patients keep their head still so that REM targets can be matched as accurately as possible.

The results of the present study also found a significant interaction effect of Head Deviation x Frequency and so the amount of mismatch measured for each head deviation at each frequency band was examined. These results are displayed in Table 10 and the values are illustrated graphically in Figures 20 and 21 for head deviations in the positive and negative directions respectively. The amount of mismatch can again be seen to increase at each frequency band as the head deviation increases in both directions, with positive and negative head turns producing negative and positive mismatch values respectively for each frequency band, in accordance with the same pattern described earlier in this section. Pairwise comparisons of three repeated measures ANOVAs performed, one for each frequency band, revealed that the mean mismatch measured for each head deviation is significantly different to every other head deviation in all frequency bands.

It can be clearly seen in Figure 20 that the greatest amount of mismatch occurs at the mid frequency band for all head deviations in the positive direction whilst Figure 21 shows that the greatest mismatch for all negative head deviations occur in the high frequency band. The results of Figure 21 were as expected but the results for Figure 20 were not expected. This is because wavelength decreases as frequency increases and so the head baffle and head shadow effect should have the greatest influence on the higher frequencies (Dillon, 2001). Whilst this explains why errors from a negative head turn (right ear moving towards the loudspeaker) affected the high frequencies the greatest due to the effect of head baffle, it does not explain why the greatest error occurred at the mid frequencies and not at the high frequencies for positive head turns (right ear moving away from the loudspeaker). This finding may have occurred due an unknown reason. However, a similar trend was also observed by Hawkins and Mueller (1992) (see "head turned" line of Figure 7, Section 1.5.2) where the greatest mismatch can also be observed taking place at the mid frequencies for a 45° head turn away from the loudspeaker, although no explanation was given as to why.

This finding is important clinically by indicating that REM errors from a positive head turn will affect the mid frequencies the most whilst errors from a negative head turn will affect the high frequencies the most. This provides clinicians with an estimate of the frequencies at which errors are most likely to arise in with head turns in the positive and negative direction.

## 4.6 Analysis of the significance of REUR values at each head deviation from the REUR value of the primary head position

In order to investigate at which head deviation does the REUR begins to significantly differ from the REUR measured at the primary head position, the raw REUR values for each head deviation were analysed using paired t-tests at each frequency band. These results are displayed in Table 11 and 12 for positive and negative head positions respectively.

The results of Table 11 for the 0° head deviation indicates that no significant difference from the primary REUR is observed at the low and high frequency bands when participants are instructed to keep their heads still at 0° or 45° azimuth (i.e. no head turns made). However, a significant difference was found for the mid frequencies. This finding was unexpected as a 0° head deviation means that the participants' heads should still be in the same position as when the primary REUR was measured and so there should be no difference observed between these two measures. However, a large number of participants in this study commented that they found it difficult to consistently maintain the laser line aligned with the visual markers on the wall for long. This difficulty may explain why a significant difference was found at the mid frequency band for the 0° head deviation as some participants may have made some slight non-voluntary head movements whilst trying to maintain the primary head position. Despite a significant difference being observed at the mid frequency band, this finding is mainly in agreement with that of Shaw (2010) as the majority of the frequency bands investigated (high and low) were found to be not significantly different. Also, Shaw (2010) did not investigate the significant differences in terms of frequency making a direct comparison of the results difficult.

Table 11 also shows that for head turns in the positive direction a significant difference in the REUR at the mid and high frequency bands can already be observed for a head turn as small as +5°, although the low frequency band showed no significant difference which indicates that this frequency range will not be significantly affected. A further increase in head turn to a head deviation of +10° results in all three frequency bands being significantly different to the primary REUR and this is also true for the subsequent head deviations of +15° and +20°. In contrast, the results of Table 12 show that a significant difference from the primary REUR can already be observed at all three frequency bands with a head turn of -5° and this is true for all subsequent head deviations.

These findings of the present study are relevant to clinical practice by providing clinicians with an indication of how much horizontal head turn can be made before significant errors begin to arise. Shaw (2010) found that no significant errors will arise during the routine fitting of OC hearing aids using the MPSE method if patients keep their head still. This study therefore supplements the findings of Shaw (2010) by demonstrating that if patients make a head turn during REMs using the MPSE method, a horizontal turn as small as ±5° and onwards can cause significant errors at all frequencies to arise although the magnitude of these errors up to ±20° will be small as discussed in Section 4.5. It is therefore unlikely that these small errors will significantly impact on the success of matching REM targets accurately at all frequencies but they should nevertheless be minimised due to the reasons explained earlier.

## 4.7 Analysis of interaction effects

With the exception of the Head Deviation x Frequency interaction and the interactions involving loudspeaker-to-client azimuth, no other interaction effects were found to be significant. The significant interaction found for Azimuth x Head Deviation suggested that the effect of loudspeaker-to-client azimuth varies with head deviation. However, this interaction was not examined further because even if it was found that, for example, the 0° loudspeaker azimuth produced greater amounts of mismatch at some head deviations than the 45° azimuth, it would not influence the decision to recommend the use of one over the other since the main effect of loudspeaker-to-client azimuth was revealed to be not significant overall. Similarly, the significant interactions of Azimuth x Frequency and Azimuth x Head Deviation x Frequency were not investigated further due to the same reason as for the Azimuth x Head Deviation interaction.

## 4.8 Limitations of the present study

The present study implemented certain precautions throughout the experiment so as to increase the validity of the results as much as possible. These precautions were based on the BSA and BAA (2007) recommended REM protocols and the findings of published research in the field. For example, the test room was set up identically for each participant, equipment and calibration checks were performed daily, participants were consistently instructed whilst great care was taken to ensure they were positioned correctly, and the test procedure was strictly adhered to at all times during testing. However, despite these precautions, the accuracy of the results obtained may have been affected by several limitations of this study.

One of the main limitations of the experiment is that many participants reported difficulty in consistently maintaining the laser line aligned with the visual markers. In particular, participants reported this problem to be more difficult for the 45° loudspeaker azimuth set of markers. It is likely that this is due to the 45° loudspeaker azimuth markers being a further distance away along the clinic wall, making it more difficult to maintain the laser line on these targets since minor head shakes will cause the laser to travel further off the target than they would at the closer 0° loudspeaker azimuth markers. The inability of the participants to accurately maintain the desired head positions at times could have introduced variability in the results obtained as the experiment may not have been testing at exactly the head deviation that was intended. For example, the results measured for the +5° head deviation may in fact have been measured at +7° due to a non-voluntary minor head movement made whilst trying to maintain the +5° position. Therefore it cannot be confidently concluded that all the measurements obtained in this experiment were from the exact head deviations of 0°, ±5°, ±10°, ±15° and ±20°. This limitation could be prevented in a future study by using a KEMAR manikin which would be able to remain perfectly still, thereby eliminating the problem of involuntary head movements influencing the results.

Another main limitation of the experiment is that only the right ears of participants were tested due to room dimension constraints. Therefore the results can only be reasonably generalised for right ears and it is unknown whether the same findings would have been obtained for left ears. Also, it is not known whether slight anatomical differences between ears, such as in ear canal length and shape, could have significantly affected the results.

The issue of repeatability is also another limitation of the study as repeats of the measurements were not conducted due to time constraints and to reduce participant discomfort resulting from the multiple insertion and removal of the probe tube that would be required to investigate this. The repeatability of the measurements in this study therefore cannot be commented on. Preliminary findings by Ricketts and Mueller (2009) have suggested that REMs using stored equalisation for open fittings can be quite reliable provided that the patient is instructed to restrict head movements. However, these findings of Ricketts and Mueller (2009) cannot be generalised to the present study which specifically investigated the effect of head movements on the accuracy of REMs using the MPSE method. Therefore it is not possible to comment on how accurate the present results are likely to be and how likely they are to have occurred by chance, especially since the left ears were also not tested.

The need to remove the REM tube and insert a new one in the participant's right ear to measure the conditions for the second loudspeaker azimuth could also have influenced the results. This procedure was necessary due to the constraints of the Aurical OpenREM mode only being able to record four aided measurements per ear. Although great care was taken to ensure that the same probe tube insertion depth was consistently achieved by aligning the black marker with the tragal notch, slight differences in the positioning of the second probe tube in the ear canal could have occurred. This would make the comparison between the results of 0° and 45° loudspeaker azimuth conditions less valid.

In addition, participants in this study were required to have otologically normal middle ear function and had a mean age of 26 years. However, this young adult sample is not representative of the older population that is typically assessed for hearing aids and who may also potentially have outer or middle ear abnormalities. It is therefore not reasonable to generalise the study findings to the typical hearing aid population.

A final limitation in this study is the application of a Bonferroni adjustment on the multiple t-tests performed during the analysis of the results. This was necessary to set the significance value at a higher level so as to overcome the increased likelihood of finding an effect when multiple tests are performed (Kinnear and Gray, 2004). However, the Bonferroni adjustment makes quite a severe adjustment to the significance level which makes it much more difficult to find a significant effect.

## 4.9 Further Research

The findings of the present study have provided an indication of the potential areas where further research could be investigated in this field. An obvious direction for future studies to undertake would be to repeat the present study but with several modifications to help overcome some of the current study limitations. For example, the testing of both ears instead of just the right ear would be strongly recommended as well as taking repeated measurements. This would provide an indication of the reliability of the results which could not be commented on in the present study and may help to strengthen the current findings if similar results were obtained. The variability in head movements caused by the much reported difficulty in trying to maintain a stable head position could possibly be reduced in future studies by moving the loudspeaker relative to participant instead. Participants could be instructed to look straight ahead and keep still at all times whilst the loudspeaker is moved to the desired azimuths around them so as to simulate the effect of head turns. Such an approach may be more advantageous because participants would only have to maintain a single head position throughout testing rather than the multiple deviations required in the present study. This would make the participant's task easier and would increase the validity and accuracy of the results obtained. Alternatively, measurements could be obtained from a KEMAR manikin instead of human participants as this would have the added benefit of ensuring that a constant head deviation is maintained consistently, thereby reducing any variability in the results still further. However a possible limitation of this approach is that KEMAR does not take into account the individual ear canal differences of everyday people and so the results may not be entirely representative of real life. A further improvement to the present study would be to test participants with an older mean age, such as the elderly population, so that the results obtained can be more readily generalised to the typical hearing aid user population.

A natural expansion on this study would be to additionally investigate the effects of forwards and backwards head movements. Whilst this study has provided an indication of how much REM measurement error can arise with small horizontal head turns when using the MPSE method, this has not been investigated for linear head movements. According to Hawkins and Mueller (1992), a forwards head movement towards the loudspeaker during REMs using the substitution method will cause an increase in the measured ear canal SPL, up to a reported 7 dB at the mid frequencies, whilst a backwards movement will result in a measured decrease in SPL. However, the authors did not describe the magnitude of these movements and so it is not known how big a head movement was investigated. Therefore it would be clinically relevant to investigate such linear head movements to provide clinicians with an estimate of how much measurement error can occur for a specified forwards and backwards movement and when these errors begin to become significant. Similarly, it would also be clinically useful to investigate the effects of vertical head movements, which has also been unexplored, when using the MPSE method for the same reasons as described above.

# 5 Conclusion

The present study has found that no significant errors will arise during the REM verification of OC hearing aids when using the MPSE method as long as patients keep their heads still, with error values being typically less than 1 dB. This finding is in support of the results found by Shaw (2010) and indicates that the MPSE method will produce clinically accurate REMs in routine practice if patients restrict horizontal head movements.

The present study has also provided supplementary findings to the Shaw (2010) study by demonstrating that horizontal head turns of up to ±20° can result in REM errors of typically less than 2 dB to arise. These errors were found to be significant at all frequencies from a head turn of as small as ±5° and will generally be greatest in size at the mid frequencies. The magnitude of the errors were found to increase as the degree of head movement increased, with a head turn of up to ±10° producing errors of less than 1 dB and then increasing to less than 2 dB for head turns of up to ±20°. The small magnitude of these errors may be considered not clinically significant on their own as they are well within the acceptable tolerances of the MHAS guidelines for REMs. However, it is argued that every attempt should be made to minimise these errors by making sure patients restrict their head movements to avoid them contributing to other sources of REM error and thereby allowing REM targets to be matched as accurately as possible, resulting in greater patient benefit. In addition, a very strong positive correlation was found between the error value and head deviation which confirmed that the amount of head movement induced errors will increase progressively as the horizontal head turn increases. Therefore clinically significant errors from head movements alone are likely to be observed eventually with head turns of greater than ±20° azimuth.

Finally, errors from head movements of up to ±20° azimuth were not found to be significantly different between a loudspeaker-to-client azimuth of 0° and 45°, which is again in agreement with the Shaw (2010) findings. This suggests that a choice of either 0° and 45° loudspeaker-to-client azimuth will not significantly influence the accuracy of REMs using the MPSE method and both can be recommended for use by clinicians for fitting OC hearing aids. The error values measured for male participants were also found to be not significantly different to that measured for female participants, indicating that any anatomical differences of the ear between genders do not influence the accuracy of REMs using the MPSE method.

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# 7 Appendices

## Appendix A – Screening Questionnaire

**Screening Form**

Participant Number:

Name:

Age:

1) Have you ever had a perforation in either of your ears? YES/NO

____________________________________________________________

____________________________________________________________

2) Do you have a current ear infection? YES/NO

____________________________________________________________

____________________________________________________________

3) Have you recently had any discharge from your ears? YES/NO

____________________________________________________________

____________________________________________________________

4) Have you recently suffered from any ear pain? YES/NO

____________________________________________________________

____________________________________________________________

5) Have you ever had any surgery on your ears? YES/NO

____________________________________________________________

____________________________________________________________

6) Do you suffer from troublesome tinnitus in either of your ears? YES/NO

____________________________________________________________

____________________________________________________________

## Appendix B – Participant Instruction Sheet

# Instruction Sheet for Participants

Project Title

"How much can horizontal head movements influence the real-ear measurement accuracy of open-canal fittings?"

Researcher

Mr Sean Lau, MSc Audiology, University of Southampton.

Aim of Project

The aim of this project is to investigate how much horizontal head turns can affect the accuracy of real-ear measurements when fitting an open-canal hearing aid.

Instructions

Two quick screening tests will first be performed on you to determine if you are able to participate in the experiment. Your ears will be checked for wax by otoscopy and tympanometry will be used to assess the function of your middle ear. You will also be asked to answer a few questions related to the condition of your ears via a short screening form. Following these screening tests you will be sat in front of a loudspeaker and a headband will be placed on your head. A small laser pointer will then be secured on your head using the headband for the purpose of tracking your head movements and will only be switched on when the device is on your head. A soft, thin rubber tube will be placed down the ear canal of your right ear. Throughout the experiment, the researcher will instruct you to turn your head and maintain certain horizontal head positions by aligning the laser line from the laser pointer to specific markers on the wall. At each different head position you will be briefly exposed to some moderate sounds from the loudspeaker for measurements to be obtained. A total of 18 measurements will be made. You are free to withdraw from the experiment at any time should you wish to do so without the need to provide a reason for withdrawing.

# Appendix C – Consent Form

***Consent form to be completed by adult subjects taking part in an experiment***
*(Adults are 18 years of age or older.)*

**Exposure Number:** ................

**University of Southampton**
**Institute of Sound and Vibration Research**

Before completing this form, please read the list of contra-indications which has been provided by the experimenter on the reverse of this form.

This consent form applies to a subject volunteering to undergo an experiment for research purposes. The form is to be completed before the experiment commences.

I, ..........................................................................................................................

of ..........................................................................................................................
(address or department)

consent to take part in ..........................................................................................

to be conducted by..................................................................................................

during the period ..................................... to ............................................... 19 ............

---

The purpose and nature of this experiment have been explained to me. I understand that the investigation is to be carried out solely for the purposes of research. I am willing to act as a volunteer for that purpose on the understanding that I shall be entitled to withdraw this consent at any time, without giving any reasons for withdrawal. My replies to the above questions are correct to the best of my belief, and I understand that they will be treated by the experimenter as confidential.

Date: .................................... Signed: ...........................................................................
(Volunteer subject)

I confirm that I have explained to the subject the purpose and nature of the investigation which has been approved by the Human Experimentation Safety and Ethics Committee.

Date: .................................... Signed: ...........................................................................
(Researcher in charge of experiment)

**This form must be submitted to the Secretary of the Human Experimentation Safety and Ethics Committee on completion of the experiment.**

## Appendix D – Descriptive Statistics

### Table 1 - Mean mismatch and standard deviation for positive head turns

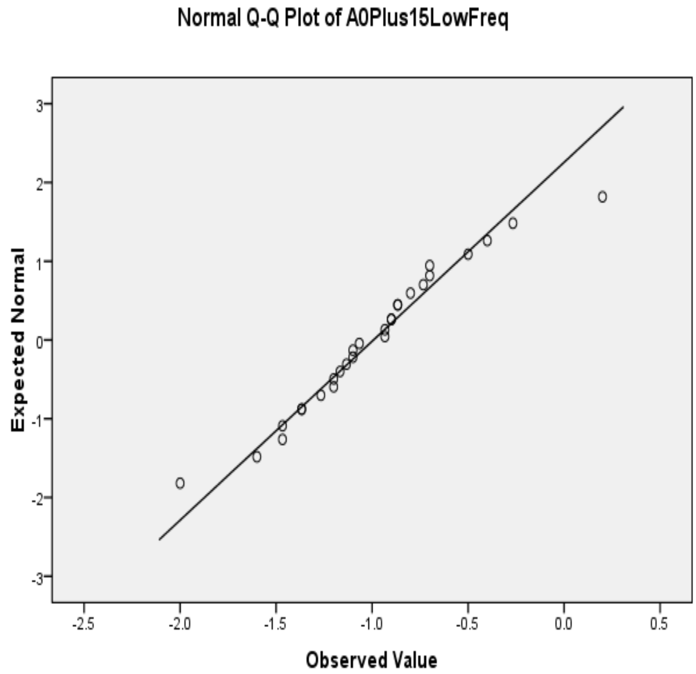
| Head Deviation (degrees azimuth) | Frequency (Hz) | | |
|---|---|---|---|
| | Low Frequency (250-750Hz) | Mid Frequency (1000-2800Hz) | High Frequency (3000-6000Hz) |
| **0° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | 0.1 | -0.2 | 0.1 |
| Std. Deviation | 0.5 | 0.4 | 0.5 |
| **0° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.0 | -0.1 | 0.2 |
| Std. Deviation | 0.5 | 0.4 | 0.5 |
| **0° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.2 | -0.3 | -0.1 |
| Std. Deviation | 0.5 | 0.4 | 0.5 |
| **+5° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | -0.1 | -0.7 | -0.5 |
| Std. Deviation | 0.5 | 0.5 | 0.7 |
| **+5° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | -0.3 | -0.8 | -0.6 |
| Std. Deviation | 0.4 | 0.4 | 0.7 |
| **+5° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.1 | -0.5 | -0.4 |
| Std. Deviation | 0.5 | 0.4 | 0.6 |
| **+10° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | -0.4 | -1.2 | -1.0 |
| Std. Deviation | 0.5 | 0.6 | 0.8 |
| **+10° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | -0.6 | -1.5 | -1.3 |
| Std. Deviation | 0.4 | 0.5 | 0.9 |
| **+10° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | -0.1 | -0.8 | -0.8 |
| Std. Deviation | 0.5 | 0.5 | 0.7 |
| **+15° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | -0.7 | -1.8 | -1.6 |
| Std. Deviation | 0.6 | 0.7 | 1.0 |
| **+15° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | -1.0 | -2.3 | -2.1 |
| Std. Deviation | 0.4 | 0.5 | 1.1 |
| **+15° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | -0.3 | -1.2 | -1.1 |
| Std. Deviation | 0.5 | 0.5 | 0.8 |
| **+20° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | -0.9 | -2.4 | -2.1 |
| Std. Deviation | 0.6 | 0.9 | 1.2 |
| **+20° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | -1.3 | -3.1 | -2.7 |
| Std. Deviation | 0.5 | 0.6 | 1.3 |
| **+20° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | -0.6 | -1.7 | -1.5 |
| Std. Deviation | 0.5 | 0.5 | 0.8 |

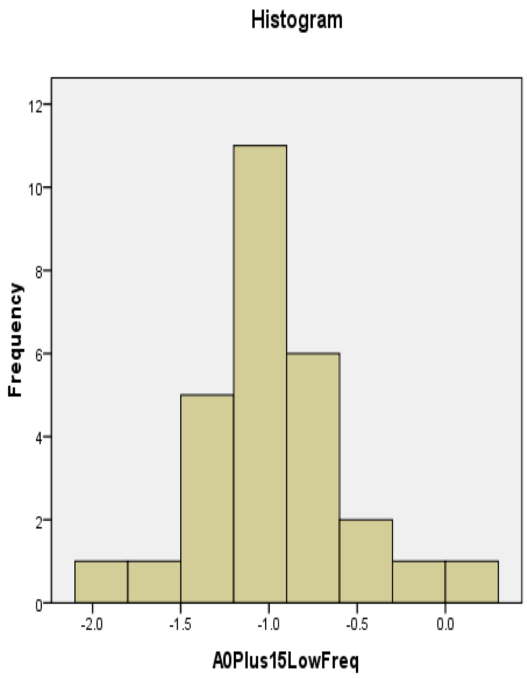
## Table 2 - Mean mismatch and standard deviation for negative head turns

| Head Deviation (degrees azimuth) | Frequency (Hz) Low Frequency (250-750Hz) | Mid Frequency (1000-2800Hz) | High Frequency (3000-6000Hz) |
|---|---|---|---|
| **0° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | 0.1 | -0.2 | 0.1 |
| Std. Deviation | 0.5 | 0.4 | 0.5 |
| **0° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.0 | -0.1 | 0.2 |
| Std. Deviation | 0.5 | 0.4 | 0.5 |
| **0° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.2 | -0.3 | -0.1 |
| Std. Deviation | 0.5 | 0.4 | 0.5 |
| **-5° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | 0.4 | 0.3 | 0.6 |
| Std. Deviation | 0.4 | 0.6 | 0.8 |
| **-5° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.3 | 0.6 | 1.0 |
| Std. Deviation | 0.4 | 0.5 | 0.7 |
| **-5° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.4 | 0.0 | 0.2 |
| Std. Deviation | 0.4 | 0.4 | 0.8 |
| **-10° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | 0.6 | 0.7 | 1.0 |
| Std. Deviation | 0.4 | 0.7 | 1.1 |
| **-10° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.6 | 1.1 | 1.8 |
| Std. Deviation | 0.4 | 0.6 | 0.9 |
| **-10° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.6 | 0.2 | 0.3 |
| Std. Deviation | 0.5 | 0.5 | 0.9 |
| **-15° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | 0.8 | 1.0 | 1.4 |
| Std. Deviation | 0.4 | 0.8 | 1.5 |
| **-15° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.9 | 1.7 | 2.5 |
| Std. Deviation | 0.4 | 0.6 | 1.0 |
| **-15° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.7 | 0.4 | 0.2 |
| Std. Deviation | 0.5 | 0.5 | 0.9 |
| **-20° Head Deviation, all conditions combined** | | | |
| Mean Difference (dB) | 1.0 | 1.3 | 1.6 |
| Std. Deviation | 0.5 | 1.0 | 1.9 |
| **-20° Head Deviation, 0° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 1.1 | 2.1 | 3.2 |
| Std. Deviation | 0.4 | 0.7 | 1.0 |
| **-20° Head Deviation, 45° Loudspeaker-to-client Azimuth** | | | |
| Mean Difference (dB) | 0.8 | 0.5 | 0.1 |
| Std. Deviation | 0.5 | 0.5 | 1.0 |

# Appendix E – Examples of normally and not-normally distributed histograms and normality probability (Q-Q) plots

## Normally distributed probability (Q-Q) plot and histogram




## Not-normally distributed probability (Q-Q) plot and histogram