Transducer influence on Auditory Steady State Evoked Potentials

BY

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ABSTRACT

Title: Transducer Influence on ASSEP

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Preliminary studies have stirred the hope that sound-field stimulation through auditory steady state evoked potentials can be used to assess aided thresholds in the difficult-to-test population. Before the introduction of ASSEP into the clinical field, as a technique for the prediction of aided thresholds in the difficult-to-test population, a question arises concerning its clinical validation. The application of ASSEP through sound field stimulation, in the determination of aided thresholds and for the evaluation of amplification fittings, is dependent on the determination of unaided responses. Subsequently the estimation of unaided thresholds in the hearing impaired population is dependent on the establishment of normative data from the normal hearing population.

The aim of this study was to determine the influence of insert earphones and sound field speaker presentation on threshold estimations using monotic auditory steady state evoked potentials, in a group of normal hearing adults. To achieve the aim of the study, a comparative, within-group experimental design was selected. The results of the current study indicated that the monotic single ASSEP technique under both insert earphone- and sound field conditions provided a reasonable estimation (25-35 dB HL for inset earphones; 20-33 dB HL for sound field speaker presentation) of the behavioural pure tone thresholds. The minimum response levels obtained under insert earphone conditions differed significantly from those obtained under sound field conditions for all the frequencies tested except 2 kHz ($p < 0.01$). Subsequently, the current study indicates that minimum response levels obtained using a specific

transducer should serve as the basis of comparison with behavioural thresholds obtained under the same transducer. Therefore, behavioural pure tone thresholds obtained under insert earphone conditions will not suffice as a basis of comparison for minimum response levels obtained for the ASSEP technique under sound field conditions, and vice versa.

This research endeavour concluded that the monotic ASSEP technique under both insert earphone and sound field conditions provide useful information for the estimation of frequency specific thresholds, but that the results are transducer specific and that comparison across transducers should be avoided.

Key terms: Objective audiometry, minimum response levels, transducers, stimulus presentations, auditory steady state evoked potential, estimated pure tone thresholds, sound field, insert earphones, sound field speakers

OPSOMMING

Titel: Die Invloed van Omvormers op OSOP

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Voorlopige studies het die hoop laat ontstaan dat Ouditief Standhoudende Ontlokte Potensiale (OSOP) in vrye-veld aanbieding gebruik sal kan word vir die evaluering van versterkte drempels in die moeilik-toetsbare populasie. Voordat OSOP egter as 'n drempel bepalende tegniek vir die moeilik toetsbare populasie beskou kan word, moet sekere vrae ten opsigte van die kliniese toepaslikheid beantwoord word. Die toepaslikheid van OSOP in die vrye-veld toets omgewing, aangewend vir die evaluasie van versterkte drempels en gehoor apparaatpassings, word bepaal deur die tegniek se vermoë om onversterkte drempels akkuraat te bepaal. Gevolglik hou die vermoë van OSOP om onversterkte drempels te bepaal verband met die vermoë om gehoordrempels in normaalhorende individue te bepaal.

Die doel van hierdie studie was om te bepaal wat die invloed van insteek-oorfone en vrye-veld aanbieding van stimuli is op die drempel bepalingsvermoë van monogotiese OSOP in 'n groep normaalhorende proefpersone. Om hierdie doel te bereik, is 'n vergelykende in-groep eksperimentele navorsingsontwerp geselekteer.

Die resultate van die huidige studie het getoon dat tydens die aanbieding van OSOP stimuli, beide die insteek oorfone en vrye-veld aanbieding redelike akkurate gedragsdrempels voorspel het (25-35 dB HL vir insteek oorfone; 20-33 dB HL vir vrye-veld aanbieding). Die minimum response vlakke wat bepaal is tydens die aanwending van insteek oorfone het beduidend verskil van die minimum respons vlakke in die vrye-veld kondisies behalwe vir 2kHz ($p < 0.01$). Gevolglik dui die huidige studie daarop dat minimum respons vlakke aangebied deur 'n spesifieke omvormer afhang van die gedragsdrempels bepaal deur dieselfde omvormer. Dus kan drempels wat gerkry is deur insteek oorfone nie dien as vergelykende basis vir minimum respons vlakke verkry tydens vrye-veld aanbieding nie, en omgekeerd.

Die gevolgtrekking waartoe hierdie huidige studie gekom het, is dat monogotiese OSOP tydens insteek oorfoon- en vrye-veld aanbieding bruikbare inligting verskaf tot frekwensie spesifieke drempel bepaling, maar dat die vergelyking tussen omvormers eerder vermy moet word.

Sleutel Terme: Objektiewe oudiometrie, minimum respons vlakke, omvormers, stimulus aanbieding, ouditief standhoudende ontlokte potensiaal, geskatte suiwertoon drempels, vrye-veld, insteek oorfone, vrye-veld luidsprekers

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LIST OF ABBREVIATIONS:

ABR(s)	- Auditory Brainstem Response(s)
AEP(s)	- Auditory Evoked Potential(s)
AM	- Amplitude Modulation
ANSI	- American National Standards Institute
ASSEP(s)	- Auditory Steady State Evoked Potential(s)
cm	- Centimeter
cm^3	- Cubic Centimeter
dB	- Decibel
DWTs	- Dampened Wavetrains
EEG	- Electro-Encephalo-Gram
EP	- Evoked Potential
ER	- Evoked Response
FFT	- Fast Fourier Transform
FM	- Frequency Modulated
HL	- Hearing Level
Hz	- Hertz
ISO	- International Standards Organization
kHz	- Kilo Hertz
m	- meter
MASTER	- Multiple Auditory Steady State Evoked Response
MRI	- Magnetic Resonance Imaging
MRL	- Minimum Response Level
ms	-Millisecond
mV	- Micro Volt
nHL	- Normal Hearing Level
NIH	- National Institutes of Health
OAE(s)	- Oto-Acoustic-Emission(s)
REIG	- Real Ear Insertion Gain
SABS	- South African Bureau of Standards
SD	- Standard Deviation
sec	- Second

SPL	- Sound Pressure Level
SSEP(s)	- Steady State Evoked Potential(s)
SSR(s)	- Steady State Response(s)
Wave V	- Wave V of the Auditory Brainstem Response

CHAPTER ONE: BACKGROUND AND RATIONALE OF THE STUDY

This chapter aims to introduce the problem this study confronts, to provide the orientation, to describe the terminology used, and to present an overview of the content and organization of the study.

1.1 Introduction

Audiology, in itself, can be broadly defined by two interdependent components, namely **diagnosis**[1] (which consists of detection and differential diagnosis) and **rehabilitation**[2] (Roeser, Buckley & Stickney, 2000a). These two components cannot be seen as two separate entities, as they function as a synergistic unit within the field of audiology. According to Katz (1994) the primary goal of any diagnostic procedure is rehabilitation, and successful rehabilitation of any auditory impairment is therefore dependent on reliable and valid diagnosis of such impairment.

The logical starting point for any diagnosis, and subsequent rehabilitation, is early identification (**detection**[3]) of hearing impairment. Researchers and clinicians alike have proposed several methods such as auditory brainstem responses (Durieux-Smith, Picton, Bernard, MacMurray & Goodman, 1991; Galambos, Wilson & Silva, 1994), oto-acoustic emissions (Smurzynski, Jung, Lafreniere, Kim, Vasudeva-Kamath, Rowe, Holman & Leonard, 1993) and, most recently, the auditory steady state evoked potential (Rickards, Tan, Cohen, Wilson, Drew & Clark, 1994; Rance, Rickards, Beer & Clark, 1998) to facilitate earlier identification. The identification of hearing-impaired infants within the first few months of life, as well as the subsequent treatment of these infants, in effect, has created a larger difficult-to-test population.

[1] "The distinctive characterization in precise terms of a genus…" (Oxford Dictionary, 1990:321). In this case hearing impairment. Diagnosis can be subdivided into detection and differential diagnosis.

[2] "Restore to effectiveness or normal life by training…" (Oxford Dictionary, 1990:1012). Rehabilitation within the hearing-impaired population has its focus on the normalizing or minimizing of problems associated with hearing loss.

[3] For the aim of this study detection is seen as the identification of a hearing impairment, and does not involve the characterization of the specific hearing loss (e.g. a sloping high frequency sensorineural hearing loss).

This implies greater responsibility on the part of the audiologist to ensure appropriate intervention. The first of these responsibilities has its focus on the **diagnosis**[4] of the hearing impairment. For most people with a hearing impairment who are able to comply with voluntary audiometry, behavioural response audiometry is the least expensive and most definitive of all approaches in obtaining hearing thresholds. For certain difficult-to-test populations, of which infants form a very large group, hearing thresholds, can only be obtained using electro-physiological measures that do not require any voluntary responses from the individual (Goldstein & Aldrich, 1999).

The initial treatment (**habilitation**) of the hearing-impaired individuals will involve the selection and fitting of amplification devices (Picton, Durieux-Smith, Champagne, Whittingham, Moran, Giguére & Beauregard, 1998), as well as the subsequent adaptation programme, and aims to bridge the gap between diagnosis and rehabilitation. Measures, such as functional gain, as well as objective measures, such as real-ear probe measurements, have been developed and specifically adapted to ensure appropriate amplification of these difficult-to-test individuals (Harford, 1980; Hawkins & Haskell, 1982; Moodie, Seewald & Sinclair, 1994; Seewald, Ross, & Spiro, 1985). In this population who cannot reliably respond to behavioural audiometry the problem surrounding the appropriate selection and fitting of amplification originates from the fact that both functional gain measures and real-ear probe measures are reliant on accurate unaided thresholds (Picton et al., 1998; Stelmachowicz & Lewis, 1988).

Research within the field of Audiology has, up to now, had its primary focus on two of its responsibilities, namely diagnosis and rehabilitation. Thus, there is an abundance of information regarding detection and differential diagnosis, as well as rehabilitation. There is, however, a definite lack of information when it comes to the interdependent nature between diagnosis and rehabilitation, and this process has been described as being dependent on "a matter of luck and intuition" (Picton et al., 1998:329).

[4] For the purpose of this study diagnosis involves the characterization of a hearing impairment, which has already been defined.

Recent studies (Cone-Wesson, Parker, Rickards, Rance, Liburti-Persi, Poulis, May, Tan & Pollard, 2001; Picton et al., 1998) have stirred the hope that Auditory Evoked Potentials (AEPs), and specifically, Auditory Steady State Evoked Potentials (ASSEPs) might have an application in bridging the gap between diagnosis and rehabilitation (appropriate selection and fitting of hearing aids). Although its focus at present has been the establishment of accurate and objective hearing thresholds as an assessment tool in the fitting of hearing aids, ASSEP may also play a role in demonstrating the function of hearing aids (Picton, Dimitrijevic, Van Roon et al., 2002b). Picton et al (1998) demonstrated that ASSEPs can be recorded when multiple stimuli are presented simultaneously through a sound-field speaker and amplified using a hearing aid. Therefore this procedure seems more useful than those procedures using transient stimuli. Transient stimuli, such as clicks, are more likely to be distorted by either the sound-field speaker or the hearing aid amplifier (Picton, John & Dimitrijevic, 2002a).

Because these potentials can be recorded down to near-threshold intensities in persons with no or unreliable thresholds, whether it be behavioural or electro-physiological (Picton et al., 2002a), it seems that ASSEPs can be used to demonstrate that the hearing aid is working. However, its application is limited as ASSEPs cannot provide information regarding how well the aid is working, seeing that most of the current hearing aid technology employs non-linear amplification (Picton et al., 2002a). Also, ASSEPs might be utilized to assess supra threshold hearing, as other measures (within-the-canal measurements) does not provide information regarding what the aided sound is perceived as, following processing in the brain (Picton et al., 2002a). The next section of this chapter will focus on the application of ASSEPs as a method to bridge the gap between diagnosis and rehabilitation.

1.2 Perspectives on Threshold Estimation: Diagnosis of Hearing Loss within the Difficult-To-Test Population

A global trend towards earlier identification and intervention concerning infants with hearing impairments has led to an increase in difficult-to-test populations. These infants are unable to part take in voluntary behavioural audiometry and are easily fatigued by conditioning techniques (Fulton & Lloyd, 1969). The importance of obtaining frequency specific hearing thresholds for these infants is not only limited to accurate diagnosis, but also plays a critical role in the appropriate selection and fitting of hearing aids.

The logical procedural follow-up on behavioural audiometry in co-operative patients with hearing loss entails the selection and fitting of amplification devices. Appropriate selection and fitting of amplification in persons who can respond to behavioural audiometry, is achieved by incorporating the individual's subjective responses (Picton et al., 1998). Since behavioural testing of infants, very young children and developmentally delayed children is unreliable, alternative assessment techniques had to be developed in order to obtain reliable responses to auditory stimuli (Rance et al., 1998).

Similarly, the process can be traced in the difficult-to-test population, with the primary distinction being the techniques used to obtain information when the conventional methods are inconclusive. Specific procedures have been developed to evaluate the difficult-to-test population in order to ensure accurate diagnosis of hearing thresholds. These procedures include oto-acoustic emissions (OAE), auditory brainstem responses (ABR) and most recently the ASSEP. A short discussion of the role of these techniques in differential diagnosis will subsequently follow.

Oto-acoustic emissions (White & Behrens, 1993) and auditory brainstem responses (Hyde, Riko & Malizia, 1990; Durieux-Smith et al., 1991) provide complementary information from which inferences regarding the hearing status of the infant can be made. The presence of OAEs, as a response to sound, has shown to be consistent with normal or near-normal-hearing, but is limited in its application because of its sensitivity to middle ear pathologies and greater than mild to moderate hearing losses (Rance et al., 1998).

The auditory brainstem response (ABR), as an evoked potential technique, appeared to be the most useful instrument for estimating hearing level in very young children (Picton, Durieux-Smith & Moran, 1994). Although a close relationship between hearing level and click-ABR threshold level has been established (Gorga, Whorthington, Reiland, Beauchaine & Goldar et al., 1985) the procedure has very definite shortcomings. Maximum intensity levels for stimulation are limited and the threshold advantage, seen for pure tones, is not obtained (Rance et al., 1998). This advantage is related to the fact that short duration stimuli does not allow for the temporal integration seen for pure tones. This implies that the possibility of residual hearing at profound levels cannot be investigated thoroughly. Furthermore, click-ABR thresholds correlate most strongly with behavioural thresholds in the 1 kHz to 4 kHz frequency range (Durieux-Smith et al., 1991) and as a result useful low frequency thresholds are not detected (Rance et al., 1998).

Reasonably frequency specific stimuli, such as brief tone bursts or tone pips, have been used in a number of studies to elicit the ABR (Stapells, Gravel & Martin, 1995; Stapells, Picton, Durieux-Smith, Edwards & Moran, 1990). Although these measures offer some insight pertaining to low frequency hearing functioning, they are still limited in their clinical application due to restrictions in presentation levels (Rance et al., 1998). Both these procedures are time consuming and at present the commercial availability of ABR equipment does not allow for objective frequency specific response detection (Stürzebecher, Cebulla & Pschirrer, 2001).

A recent addition to objective threshold estimation in young children has been the auditory steady state evoked potential (Rance et al., 1998). These responses arise from the scalp in response to regularly repeating stimuli such as sinusoidal amplitude and/or frequency modulated tones (Picton et al., 1998; Rance et al 1998). The ASSEP has several advantages to other auditory evoked potentials (AEP). It is reliably recordable in sleeping or sedated individuals, when modulation rates of 70 - 110 Hz are used, (Cohen, Rickards & Clark, 1991) and reliably present in children of all ages, including neonates (Rickards et al., 1994). Detection of the ASSEP is objective in that no interpretation is required from the tester.

Furthermore, the continuous nature of the ASSEP stimuli offers presentation level advantages over other short duration stimuli. These advantages are related to the fact that the modulated tones used during ASSEP testing are similar to warble tones used in behavioural testing (Rance et al., 1998). This implies that the corrections associated with tone burst and clicks are not required and the stimuli can, therefore, be presented at levels that extend to 120 dB HL. The ASSEP technique is therefore able to investigate minimal amounts of residual hearing (Rance et al., 1998). Lastly, because the threshold estimates obtained from ASSEP testing are frequency specific (Lins, Picton, Boucher, Durieux-Smith, Champagne, Moran, Perez-Abalo, Martin, & Savio, 1996) it allows for testing across the audiometric range and for the generation of evoked potential audiograms (Rance et al., 1998).

Although measures have been developed to accurately diagnose hearing levels in the difficult-to-test population, previous attention regarding the measurement of aided thresholds within this population has been limited to functional gain and real-ear probe measures (Picton et al., 1998). Except for its dependency on accurate unaided thresholds, real-ear probe measures, in neonates and others within the difficult-to-test population can present certain challenges as far as probe tube placement and its maintenance is concerned (Picton, 1998). These measures are extremely important since the exact amount of amplification required is dependent on the unaided thresholds and therefore on the degree, configuration and type of hearing loss (Yoshinaga-Itano, 2001). Aided thresholds are used to verify the amplification fitting, as well as for the performance evaluation of the amplification.

Behavioural audiometry incurs problems associated with inaccuracy and reliability (Rance et al., 1998), in the detection and differential diagnosis of hearing impairment within the difficult-to-test population. It logically follows then, that it will be inconclusive in the determination of the initial aided thresholds for this population. Rehabilitation therefore is dependent, as in the co-operative population, on measures such as functional gain, insertion gain and real ear measurements.

1.3 Perspectives on Amplification Fitting: Bridging the gap between Diagnosis and Rehabilitation

Audiology as a profession dates back as far as the Second World War. Its responsibility in the prescription of appropriate amplification seems to have originated around this time. The earliest attempts to prescribe amplification advocated by Knudson and Jones (1935) did not involve evaluation of the amplification fitting; it simply aimed to **mirror the audiogram**. Mirroring of the audiogram involved matching the gain of the hearing aid, dB-for-dB, with the amount of the hearing loss

(Punch, 2000). This amount of gain proved to be much more than persons with sensorineural hearing loss could tolerate. The concept of listening comfort was introduced when Watson & Knudson (1940) suggested providing a comfortable amount of gain that produced equal loudness across all frequencies. According to Lybarger (1944) the appropriate amount of gain need not be more than one half of the hearing loss. His **half-gain rule** became the basis for many subsequent prescriptive fitting formulas, several of which are still used today (Punch, 2000).

One method for evaluating amplification is **functional gain**. Measurement of the amount of functional gain is calculated as the difference between aided and unaided thresholds at each specific frequency obtained through free-field testing (Mueller, Hawkins & Northern, 1992) and is defined as the relative decibel difference between the aided and unaided thresholds. Many audiologists, during hearing aid selection and fitting commonly use functional gain to evaluate whether (a) the amount of amplification meets the requirements of the hearing loss characteristics, (b) to demonstrate improved hearing and (c) informally to demonstrate the listening advantages of amplification (Mueller et al., 1992). Although it supplies the audiologist with critically important information regarding the rehabilitation process, the functional gain hearing aid evaluations have certain limitations.

Since this technique is based on voluntary behavioural procedures, the inherent degree of variability to which behavioural threshold measurements are subjected (Kidd, 2002) will also influence functional gain measurements (Mueller et al., 1992). As this technique is conducted in a sound-field situation, careful attention should be paid to accurate calibration of stimuli to limit the influence of standing waves (and masking of the non-test ear). It is, however, important to realize that functional gain can only be calculated once the unaided audiometric thresholds are known (Picton et al., 1998) and that without this data the hearing aid cannot be adjusted to match the prescriptive targets (Stelmachowicz & Lewis, 1988).

Since functional gain measures are usually made at octave levels, inter-octave peaks and troughs are easily overlooked (Northern, 1992). Thus, the technique does not supply the audiologist with sufficiently comprehensive frequency specific information. Furthermore, small changes in the electro-acoustic output of the hearing aid, or acoustic modifications created by the manipulation of the acoustic coupling system may create alterations in the frequency response and gain characteristics of the hearing aid that will not be noted in the functional gain measurement.

The preferred procedure introduced to verify hearing aid fitting was **real-ear probe-microphone measurements or real-ear insertion gain**. Sound pressure measurements are taken with, and without, the fitted hearing aid in place. Insertion gain is then determined as the difference, in decibels, between the two response curves. Real-ear measurements reveal not only those aspects of hearing aid performance that require electro-acoustic adjustments, but also the immediate effects of those adjustments (Punch, 2000). The ability of real-ear equipment to reveal output or gain at fine frequency gradations is one of its greatest advantages. The same information cannot be found, for example, with measures of functional gain, which are made at selected audiometric frequencies. Once again advances in technology provided a considerable advantage over previous efforts, but as Hawkins (1987) noted, the use of real-ear measures alone does not result in a better hearing aid fitting.

Within a clinical set-up, and with specific reference to the neonatal population, clinicians experience difficulty with probe tube placement (Picton et al., 1998). It is, furthermore, important to note that real-ear measurements are electro-acoustic measures, and only provides information regarding the output of the hearing aid at the eardrum. These measures provide no information regarding neuro-physiological functioning of the auditory system (Picton et al., 2002a).

Hearing aid selection and fitting have undergone a systematic evolution in the past five decades. The technological sophistication of hearing aids continues to grow rapidly. In many ways, these advances in technology have outpaced our ability to fit hearing aids to individual needs. Increasingly sophisticated fitting methods are needed to close the gap (Punch, 2000). The need for a technique that offers accurate, objective estimation of frequency specific hearing thresholds within this population, who in most instances cannot comply with supra-aural headphone or insert earphone testing (Picton et al., 1998), becomes critical for the effective rehabilitation through amplification.

Auditory evoked potentials (AEP) have been used in the past to assess the functioning of hearing aids. The technique that received most attention in the evaluation of hearing aids was the ABR (Mahoney, 1985; Beauchaine & Gorga, 1988). This procedure involved the adjustment of the hearing aid until the latency of wave V of the ABR has decreased to within normal limits (Picton et al., 1998). The brief nature of stimulation led to various technical problems. Due to the specific stimulation characteristics the signal can undergo distortion in both the sound-field speaker and the hearing aid. This will result in stimulus artifacts that can make accurate diagnosis problematic (Hall & Ruth, 1985). The most significant limitation concerning this technique stems from the fact that hearing aids react differently to rapidly changing stimuli than to more continuous stimuli (Beauchaine & Gorga, 1988; Mahoney, 1985; Picton et al., 1998). The ABR technique only supplies information regarding the rapidly changing stimuli and no information regarding more continuous tones such as speech stimuli.

Interest in ASSEP (Galambos, Makeig & Talmachoff, 1981; Rickards & Clark, 1984; Rodriguez, Picton, Linden, Hamel & Laframboise, 1986; Stapells, Linden, Suffield, Hamel & Picton, 1984) has led to the identification of several advantages over transient evoked potentials such as the ABR. While the ASSEP has experienced limited exploration concerning its application in terms of amplification (**initial habilitation**), as was the case initially with ABR, these limitations are now being addressed through research. The advantages of the ASSEP technique form the rationale of this study. Its application within early management and aided threshold testing, forms the impetus of the current study, and will be explored in more detail in the following section.

1.4 Rationale

In an attempt to clarify the rationale behind the current research endeavour, the following section aims to delineate the suitability of the ASSEP technique in the exploration of aided thresholds. Steady state evoked potentials (SSEP) have long been used in the evaluation of visually evoked potentials (Regan, 1989). More recently these SSEPs have been used more extensively to record auditory steady state evoked potentials (Aoyagi et al., 1994; Aoyagi et al., 1996; Azzena et al., 1995; Galambos & Makeig, 1998; John et al., 1998; Lins & Picton, 1995; Lins et al., 1995; Lins et al., 1996; Pantev et al., 1996; Picton et al., 1998; Rance et al., 1998; Rance et al., 1995; Suzuki et al., 1994; Rickards et al., 1994. ASSEPs occur when the frequency constituents of a response are stable in amplitude and phase (Regan, 1989). These responses are usually elicited using periodic stimuli and measured at the frequency of stimulation or one of its harmonics (John, Dimitrijevic & Picton, 2001).

Recently ASSEP have become available as a clinical objective hearing test option (Rance et al., 1998). Several researchers have denoted the current applications of the ASSEP technique within the scope of audiology. The technique has been shown to be useful in the estimation of hearing thresholds with normal and impaired hearing (Aoyagi et al., 1994; Aoyagi, Suzuki, Yokota, Furuse, Watanabe & Itoh, 1999; Lins, Picton, Picton, Champagne & Durieux-Smith, 1995; Lins & Picton, 1995; Lins et al., 1996; Picton et al., 1998; Rance et al., 1995; Rance et al., 1998; Rickards et al., 1994). It has been reliably recorded in sleeping or awake infants, as well as in sleeping adults (Aoyagi, Yoshinori, Suzuki, Fuse & Koike, 1993; Maurizi, Almadori, Paludetti, Ottaviani, Rosignoli & Luciano, 1990; Stapells, Galambos, Costello & Makeig, 1988; Suzuki & Kobayashi, 1984). The ASSEP technique has furthermore been identified as a reliable tool for newborn hearing screening (Aoyagi et al., 1994; Lins et al., 1996; Picton et al., 1998; Rance et al., 1995), as it provides reliable results in infants with normal and impaired hearing. The introduction of the multiple auditory steady state evoked response (MASTER) technique, with multiple carrier frequencies, each modulated by its own signature modulation frequency, evokes multiple steady state responses and may significantly reduce test-time (John et al., 1998).

Studies on the use of amplitude-modulated tones to stimulate responses (Lins et al., 1996; Hood, 1998) have highlighted significant advantages over other objective techniques. The computer program interprets the presence of responses. ASSEP equipment has utilized averaging techniques that make the recording of responses, more objective than that of the ABR for example (Stürzebecher et al., 2001). In the auditory system these responses can be recorded using amplitude modulated tones that are frequency specific and stable over a period of time (Picton et al., 1998). These responses are consequently less likely to be distorted during sound-field stimulation (Picton et al., 2002a).

The considerable advantages of the ASSEP technique over other AEP techniques during the detection and differential diagnosis of hearing impairment have stirred the hope that it will gain clinical application within the scope of aided threshold detection and evaluation of amplification fittings. Pilot and preliminary studies (Cone-Wesson et al., 2001; Picton et al., 1998) noted the unlikely distortion of the stimuli by both the sound-field speaker and the hearing aid itself and were able to record aided ASSEPs at near threshold intensities (Picton et al., 1998). It is, however, important to validate preliminary findings (Cone-Wesson et al., 2001; Picton et al. 1998) concerning the application value of ASSEP, using sound-field presentation, in the estimation of frequency specific aided thresholds and the evaluation of amplification fittings.

1.5 Problem Statement

In an attempt to determine the validity of any audiometric procedure, it is important to establish the procedure's ability to perform as intended (Roeser, Valente & Hosford-Dunn, 2000b). In the case of sound-field stimulation by means of auditory steady state evoked potentials (ASSEP) it is necessary to determine whether thresholds can be estimated and if so how they compare with the data obtained from the same procedure using insert earphones. Thus a need arises for normative studies to validate sound-field presentation results.

Preliminary studies (Picton et al., 1998) and pilot studies (Cone-Wesson et al., 2001) have stirred the hope that sound-field stimulation through auditory steady state evoked potentials can be used to assess aided thresholds in the difficult-to-test population. Validating these results through further research will establish a frequency specific, objective procedure for estimating aided thresholds in difficult-to-test populations.

Before the introduction of ASSEP into the clinical field, as a technique for the prediction of aided thresholds in the difficult-to-test population, a question arises concerning its clinical validation. Reliability and validity is paramount to the establishment of the ASSEP technique within the clinical arena. In other words, the application of ASSEP through sound-field stimulation, in the determination of aided thresholds and for the evaluation of amplification fittings, is dependent on the determination of unaided responses. Subsequently the estimation of unaided thresholds in the hearing-impaired population is dependent on the estimation of thresholds within the normal-hearing population. The question now arises:

How accurate is monotic auditory steady state evoked potentials in the prediction of thresholds using sound-field stimulation, when compared to insert earphone stimulation, in a group of normal-hearing adults?

1.6 Division of Chapters

In order to answer this question a research endeavour consisting of both an empirical and theoretical component was conducted. In order to delineate the process behind the research endeavour, the following section will delineate the division of chapters and will furthermore provide a short summary of the contents of each chapter.

Chapter one: Orientation and Statement of the Problem

This chapter provides an overview of the importance of diagnostic procedures and rehabilitation, as well as the interdependent nature of these two components. It describes the responsibilities faced by the global trend towards earlier identification, as the initial step of rehabilitation, and subsequent evaluation of aided thresholds in hearing-impaired infants. It introduces the ASSEP as a technique for the estimation of aided thresholds in the difficult-to-test population and delineates the purpose of this study: to determine the clinical application value of the monotic ASSEP technique in the estimation of aided thresholds and the evaluation of amplification fitting, through sound-field presentation.

Chapter two: Theoretical perspectives on Auditory Steady State Evoked Potentials using Sound-field presentation

This chapter is divided into three sections, namely Perspectives on Sound-field Audiometry, Perspectives on ASSEPs and Sound-field Testing as a possible application within the ASSEP domain. It will discuss sound-field audiometry, its applications and limitations and recommendations for valid and reliable testing under sound-field conditions. Further discussion concentrates on the current clinical applications of ASSEP and research applications. The existing measures available for the estimation of aided thresholds, as well as their limitations are discussed. The critical evaluation of these procedures serves as the background to the discussion of the monotic ASSEP. Thorough theoretical and clinical advantages of how the ASSEP might address the limitations of existing procedures is provided along with the effect of sound-field stimulation and the results of other preliminary studies.

Chapter Three: Research Methodology

This chapter provides the operational framework implemented to conduct the empirical research. This framework dictates the scientific process implemented to determine the clinical validity of the monotic ASSEP to estimate thresholds through sound-field presentation.

Chapter Four: Results and Discussion

This chapter presents the results obtained through statistical analysis. The results are presented according to the sub-aims stipulated in chapter three. An interpretation and discussion of its value in relation to the literature follows each result.

Chapter Five: Conclusions and Implications

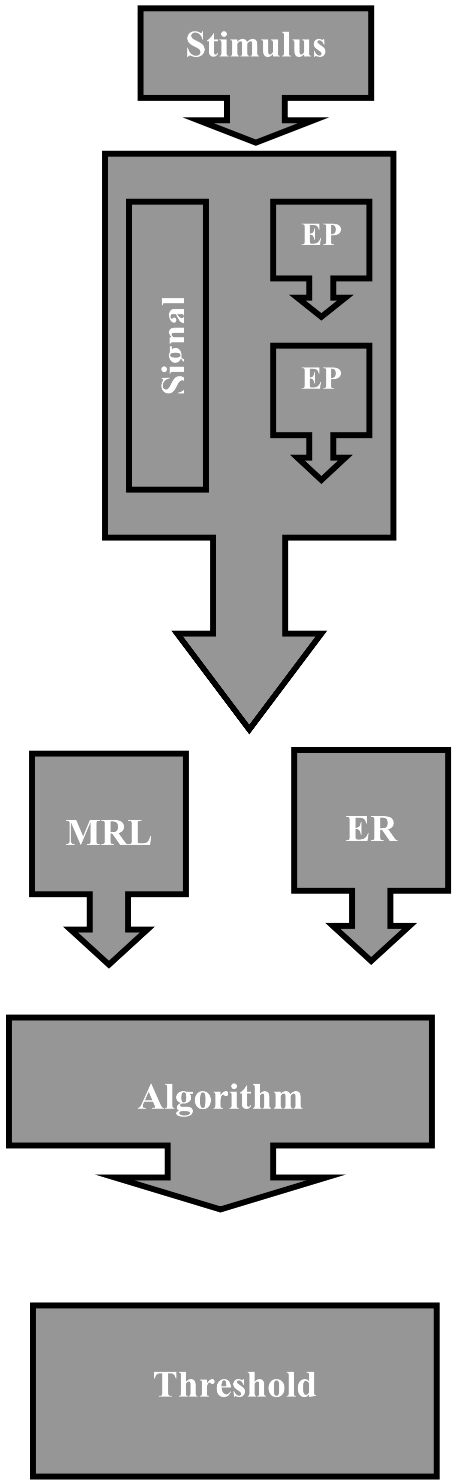
This chapter summarizes the results obtained and provides an outline of the significant results and the extent to which they contribute to current literature. Future research recommendations are provided and a conclusion regarding the current study is formulated.

1.7 Conceptual Orientation and Description of Definitions

Table 1.1 provides definitions for terminologies that are used throughout the empirical component of this research endeavour.

Table 1.1 Definition of Terminology

- **Stimulus:** A Stimulus is that which excites or produces a temporary increase of vital action, either in the whole organism or in any of its parts; especially any substance or agent capable of evoking the activity of a nerve, or capable of producing an impression upon a sensory organ or more specifically upon its end organ (Oxford Dictionary, 1990).
- **Evoked Potential (EP):** "Coming into action…" (Oxford Dictionary, 1990:932). Within the auditory system, potentials consist of alternating positive and negative waves (electrical current) that were evoked by a stimulation of the auditory system.
- **Signal:** "A prearranged sign conveying information…" (Oxford Dictionary, 1990:1129). Within the human body cells communicate with one another by signals. These signals include small organic molecules (e.g. adrenaline), larger molecules (e.g. proteins), and electrical- and chemical signals. Within the setting of the current study, namely auditory evoked potentials, the focus will be on electrical signals.
- **Minimum Response Level (MRL):** The minimum level at which a response is present. In other words the intensity where the last significant response was recorded (Herdman & Stapells, 2001).
- **Evoked Response (ER):** An evoked response is the recorded average of various signals.
- **Threshold:** "The minimum effective sound pressure level of an acoustic signal producing an auditory sensation within a specified section of clinical trails (ANSI, 1986), is defined as the threshold of audibility" (Yantis, 1994:97a)



1.8 Summary

This chapter aimed to provide relevant background information to introduce the focus of the current research endeavour and to provide insight on the importance of the rationale underlying the study. The importance of assessing auditory thresholds within the difficult-to-test population and especially with regard to infants, who cannot comply with behavioural test measures, was highlighted in this chapter. The influence of insert earphones and sound-field stimulation on monotic auditory steady state evoked potentials, in normal-hearing adults, as a first step towards validating the estimation of aided thresholds through sound-field stimulation was discussed. The discussion was based on a comparison with behavioural pure tone audiometry, which forms the gold standard within the clinical audiometric test arena. Attention was focused on the need for an objective test measure with the potential of bridging the gap between diagnosis and rehabilitation.

Other objective techniques that have been developed to estimate hearing thresholds within the difficult-to-test have been discussed. These included electro-physiological measures such as OAEs, ABRs and most recently ASSEPs, as well as electro-acoustic measures such as functional gain and insertion gain. Known advantages of ASSEPs were highlighted in relation to these other objective techniques, with regard to insert earphone stimulation. Finally, results of preliminary and pilot studies, with regard to sound-field stimulation and its possible application within aided threshold determination were emphasized in the light of limited research validation. Therefore, the need to determine the influence of insert earphones and sound-field stimulation on monotic auditory steady state evoked potentials was made apparent.

CHAPTER TWO: PERPSECTIVES ON SOUND-FIELD AUDIOMETRY AND POSSIBLE APPLICATION THEREOF WITHIN THE ASSEP DOMAIN

This chapter aims to provide a theoretical framework as a support for the empirical research component. It aims to specify concepts and constructs in such a way that controllable observations can be made about them. It aims, furthermore to provide a critical evaluation and interpretation of the relevant literature, so as to identify the empirical referents of theoretical terminology.

2.1 Introduction

This chapter explores the suitability of Auditory Steady State Evoked Potentials (ASSEPs) through sound-field presentation, as an objective procedure in the diagnosis of hearing impairments. It is divided into three main sections, namely perspectives on Sound-field audiometry, perspectives on ASSEP and lastly Sound-field presentation as a possible application within the ASSEP domain.

In the first section, **Perspectives on Sound-field Audiometry,** the current application of sound-field audiometry is discussed, in an attempt to delineate its scope within the field of audiology. A discussion on the advantages and limitations that apply to sound-field audiometry will introduce several comprehensive recommendations aimed at addressing the optimal characteristics for accurate threshold detection. Focus will be on stimulus related effects, optimal characteristics of such a stimulus, the relevant merits of testing in the direct field versus the reverberant field, important test room characteristics, importance of calibration, other important testing aspects and test room arrangements. This section concludes with a summary of the above-mentioned recommendations.

The second section of this chapter, **Perspectives on ASSEP,** aims to provide a logical continuation of the first. Once again, the current application of ASSEP will introduce this section. The physiological basis underlying ASSEP is discussed, in order to facilitate a functional understanding of the ASSEP definition. The audiometric variables associated with evoked potential audiometry are highlighted with specific reference to ASSEP, in an attempt to postulate recommendations, based on available literature, relating to ASSEP testing.

The last section of this chapter, **Sound-field Presentation as a Possible Application within the ASSEP Domain,** has its focus on stimulation and modulation characteristics, evoked responses and automated response detection. This section, furthermore, aims to delineate the possibilities of sound-field presentation within the ASSEP domain, as a means for objectively assessing aided thresholds and will conclude with a justification of the research question proposed in chapter one of this study.

2.2 Perspectives on Sound-field Audiometry

This section is discussed according to the application, advantages and limitations of sound-field audiometry. This section concludes with recommendations, identified from the literature, for conducting sound-field audiometry including stimulus related effects; optimal stimulus characteristics; required modulation waveform and rate for frequency modulated tones; direct versus reverberant field testing; important test room characteristics and the importance of calibration. The section will conclude with a summary of the recommendations that have been discussed (Table 2.3).

2.2.1 Application of Sound-field Audiometry

Selecting the most appropriate transducer during audiometric testing depends entirely on what the clinician or researcher wants to measure (Wilber, 2002). To ensure the appropriate selection of an air conduction transducer, certain factors pertaining to each transducer must be kept in mind. Initially, supra aural headphones appeared (until recently) to be the most popular transducer for routine pure tone testing (Arlinger & Jerlvall, 1987; Wilber 2002). The use of supra-aural headphones, however, have certain limitations, which include narrow frequency responses, leakage of sound, the possibility of collapsing ear canals, inability of reproducing extremely short duration stimuli accurately, contribution to reduced inter-aural attenuation and creating an occlusion effect (Wilber, 2002). Currently, the recommended transducer for routine behavioural testing, namely insert earphones, show the same narrow frequency response, but in comparison have less problems associated with sound leakage, collapsing ear canals, occlusion problems and reduced inter-aural attenuation is significantly decreased (Wilber, 2002). However, both insert earphones and supra-aural headphones have certain practical disadvantages within the difficult-to-test population, and specifically pertaining to the testing of infants and very young children.

Earphone placement, and maintenance of the placement, presents challenges when testing infants, very young children and uncooperative patients (Picton et al., 1998). Furthermore, some children are afraid of supra-aural headphones and/or insert earphones and will not tolerate them (Magnusson, Börjesson & Axelsson, 1997). As time is a constraining factor when testing infants and small children, it is very important to minimize all distractions that might have an influence on test time (Magnusson et al., 1997).

Due to these difficulties, the emphasis now shifts towards sound-field presentation. Although diagnostic audiometry is, in typical conditions, associated with earphones (either supra aural or insert earphones) as the transducer[6] of choice (Arlinger & Jerlvall, 1987), there are certain situations where it is impossible, or highly inconvenient, to use earphones (Wilber, 2002). The rationale for using earphones as the transducer of choice when performing audiometric test procedures is based on the fact that it eliminates all influence of the acoustic properties of the test room on the stimulus. When earphones cannot be used, however, the interaction between the test stimulus and the test room becomes critically important (Arlinger & Jerlvall, 1987).

These situations include hearing assessments in the pediatric and mentally handicapped populations where earphone testing is inappropriate, as it might lead to distraction or fear (Arlinger & Jerlvall, 1987; Beynon & Munro, 1995), and in some cases the individual simply won't tolerate them (Magnusson et al., 1997). Sound-field speaker presentation is also used when the participant will not tolerate earphones, because of fitting problems such as unusually large head size (Wilber, 2002). Furthermore, it is also used when functional gain measures of hearing aids are made (Arlinger & Jerlvall, 1987; Beynon & Munro, 1995; Wilber, 2002) and lastly the

[6] "Simply put a transducer is a device that converts input energy into output energy (or conversely output energy into input energy)" (Wilber, 2002)

evaluation of the aided thresholds (Arlinger & Jerlvall, 1987; Beynon & Munro, 1995; Walker, Dillon & Byrne, 1984). Subsequently, sound-field audiometry becomes viable when one cannot obtain measurements using earphones.

Sound-field audiometry, in itself, incurs many problems primarily because it is impractical to keep the position of the participant's ear absolutely constant. Even when testing a co-operative adult participant, it is difficult to be certain that the participant's ear remains in exactly the same position, assumed during calibration, throughout the test. The rationale behind maintaining the test position at all times stems from the fact that the sound pressure level of the stimulus varies considerably with distance from the speaker (Walker et al., 1984). In other words, in order to ensure reliable threshold estimations, the participant's head has to remain as close to the test position assumed during calibration as possible. This problem is much greater in the difficult-to-test population, due to difficulties in restraining movement without jeopardizing co-operation or inhibiting capacity to respond naturally (Walker et al., 1984).

2.2.2 Advantages of Sound-field Audiometry

Behavioural sound-field audiometry has been criticized as being an invalid and unreliable means of determining the hearing status in the difficult-to-test population and especially with reference to young children (Berlin & Hood 1993). However, awareness of the pitfalls, as well as the use of procedures that increase validity and reliability, makes the use of sound-field audiometry an efficient method for assessing hearing status within the clinical arena (Diefendorf & Gravel, 1996; Renshaw & Diefendorf, 1998). These "pitfalls" and how they have been addressed will be discussed under limitations of sound-field audiometry in 2.2.3 of this section.

There are two main advantages relating to the use of sound-field audiometry. Firstly, it provides a means of assessing hearing sensitivity for the difficult-to-test populations such as infants, very young children, mentally handicapped and others within the difficult-to-test population, when other behavioural techniques have failed (Dillon & Walker 1981; Magnusson et al., 1997; Walker et al., 1984). It also provides a measure to assess specific tasks such as hearing aid evaluations, and specifically the aided thresholds of amplification users, so as to determine functional gain for these clients

(Arlinger & Jerlvall, 1987; Beynon & Munro, 1995; Walker et al., 1984; Wilber, 2002).

2.2.3 Limitations of Sound-field Audiometry

Summarized in Table 2.1 below, are the main limitations of sound-field audiometry and how these limitations have been addressed.

Table 2.1 Limitations of Sound-field Audiometry and recommendations for addressing these limitations

Limitations	How it has been addressed
➢ **The interaction between test stimuli, the participant interface and the test room acoustics influence the accurate determination of thresholds.**	Stimuli identified to limit the influence of interaction between test stimuli, and the participant interface and test room acoustics: ➢ Use of Complex Stimuli ➢ Use of appropriate modulation of the stimulus ➢ Use of appropriate bandwidth of the modulated stimulus (Dillon & Walker, 1982a; Dillon & Walker, 1982b; Walker & Dillon, 1983; Walker et al., 1984)
	Participant characteristics identified to limit the influence of the interaction between the participant interface, and the test stimuli and test room acoustics: ➢ Limiting participant movement during threshold determination ➢ Participant placement in relation to the speaker ➢ Direct field placement versus reverberant field placement (Walker et al., 1984)
	Test room characteristics identified to limit the influence of interaction between the test room acoustics, and the test stimuli and participant interface: ➢ Absorptivity of the rooms' surfaces ➢ Placement of the speaker ➢ Dimensions of the test room ➢ Suitable seating arrangements ➢ Identifiable test position (Walker et al., 1984)
➢ **No ear specific information can be obtained.**	By making use of direct field testing the advantage of close speaker positioning seems to be that greater inter-aural attenuation values, from 10 dB at the lower frequencies to about 25 dB at the highest frequencies, are obtained. Though this is not sufficient to accurately estimate monaural thresholds, it is sufficient for providing useful hints as to monaural hearing loss. (Magnusson et al., 1997)

These recommendations are discussed in depth later on in the following sections where they will provide insight into the selection of appropriate stimulus and recording parameters discussed in chapter three of this study.

2.2.4 Recommendations when testing in the Sound-field

To ensure accurate estimation of hearing thresholds in the sound-field, it is important to determine what type of stimulus is most suitable for sound-field audiometry and, furthermore, what characteristics such a stimulus should possess. Walker et al (1984) identified four stimulus characteristics required for accurate estimation of hearing thresholds in the sound-field:

a) A stimulus should be sufficiently frequency specific to permit an accurate description of the client's hearing status.
b) The sound pressure level (SPL) should be sufficiently uniform over the whole area in which the head of the participant is liable to move during the test procedure.
c) The SPL in the sound-field should be stable for small shifts in stimulus frequency.
d) The threshold obtained in the unaided condition in the sound-field should allow for comparison to the thresholds obtained using earphones. This correlation is important, as pure tone testing, using earphones, serves as the gold standard in audiometric testing.

A comparison of different stimulus types, and specifically pure tones versus more complex stimuli, in relation to the above mentioned characteristics should highlight the appropriate stimulus type for the accurate estimation of thresholds in sound-field audiometry. Using pure tones as the stimulus of choice in the sound-field meets the first and last requirements set out in the above statement, however, standing waves are created in the reverberant field[7] (Walker et al., 1984). Standing waves, in turn, result in significant changes in SPL at the participant's ear, consequently making accurate threshold determination problematic. Previous attempts to use graphic equalizers to "flatten" the room's frequency response, in order to minimize standing waves, were limited to the use of more complex stimuli (Anderson, 1979) and did not tolerate head movement by the participant (Walker et al., 1984). Direct-field testing[8] is not greatly influenced by the acoustic characteristics of the room (Dillon & Walker, 1981; Magnusson et al., 1997; Walker et al., 1984) and therefore the use of pure tones in

[7] In most audiometric test rooms the reverberant field constitutes the space exceeding 0.6 m from the speaker.
[8] In most audiometric test rooms the direct field constitutes the first 0.6 m from the speaker.

sound-field audiometry is reasonable, provided that all testing is done in the direct field (Walker et al., 1984).

Although it is widely recognized that the traditional audiometric stimulus, the pure tone, is not optimal for testing in the reverberant field (Dillon & Walker, 1981; Walker et al., 1984; Wilber, 2002), there has been some discussion on what the optimal stimulus characteristics should be. Suggested stimuli that have come under discussion include frequency modulated (warble) tones, narrow bands of random noise, damped wavetrains (DWTs) and amplitude modulated (AM) tones.

The rationale for using more complex stimuli during sound-field presentation is based on the assumption that increased uniformity can be attributed to the averaging of intensity that occurs across the frequency range covered by the stimulus (Walker et al., 1984). Therefore, a more complex stimulus will be less affected by a null[9] in the test room's response, provided that it has sufficient energy within a frequency band, which is wider than the null (Walker et al., 1984). The variability of the reverberant field should be related to bandwidth as some stimuli create a more uniform field than others. In other words, as the bandwidth increases, the variability will decrease. In the direct field, the SPL is not influenced by the test room acoustics and thus there are no advantages for using complex rather than pure tone stimuli (Walker et al., 1984). There are, however, certain populations where the placement of the individual in relation to the speaker has an influence on placement decisions.

When speakers are placed in close proximity of the individual, and especially in the case of infants and children and others within the difficult-to-test population, the speaker can act as a distraction (Magnusson et al., 1997). It is important to note that speakers are used when testing infants and small children, who are usually afraid of earphones. When speaker placement becomes a distraction, prolonged test time and ultimately completion of the test is uncertain. It seems therefore that there are certain practical disadvantages to testing in the direct field, which have to be considered when selecting a stimulus type.

9 The aim of this procedure is to identify a listening position where the SPL within a sphere of radius 15cm does not vary by more than 2 dB from the value at the centre of the sphere. The smaller the variation (in decibel) within the sphere, the greater the accuracy of these measures will be.

The above-mentioned variables (Walker et al., 1984) and practical disadvantages (Magnusson et al., 1997) associated with the use of pure tones, combined with the fact that warble tones are more easily identifiable (Arlinger & Jerlvall, 1987), serves as rationale for the use of more complex stimuli. There are, however, various complex stimulus types, which have to be evaluated in order to determine the most appropriate stimulus type for conducting sound-field audiometry.

2.2.4.1 Optimal Stimulus Characteristics

Having established the relevance of using more complex stimuli, it is now important to evaluate the different types of stimuli available. Amplitude modulated tones create a less uniform field than any other complex stimuli (Dillon & Walker, 1982a), because of the limited advantage gained from averaging the sinusoidally amplitude modulated tone (Walker et al., 1984). Although the use of more complex amplitude modulated tones would improve uniformity in the field, the improvement in field uniformity is still inferior to that gained from the use of frequency-modulated stimuli (Walker et al., 1984). Narrow bands of noise are comparable to frequency-modulated stimuli for larger bandwidths, with reference to the resulting field uniformity.

Whilst using dampened wavetrains creates superior uniformity in the field[10] (Victoreen, 1974) the thresholds obtained using dampened wavetrains cannot be related to those obtained through pure tone testing using earphones. This is because the duration of DWT is shorter than the integration time of the normal ear and subsequently the threshold becomes a function of stimulus duration (Walker et al., 1984). Because thresholds obtained with dampened wavetrains, as stimulus presentation cannot be generalized to thresholds obtained under earphone conditions it has received little support within research and especially within the clinical arena. It seems therefore that the use of frequency modulated tones or narrow bands of noise, with appropriate bandwidths, are the most suitable stimuli for reverberant-field testing.

[10] Sound pressure levels (SPL) in a typical test room vary with distance from the speaker. Uniformity in the field, therefore, relates to a uniform SPL in the field. Field uniformity is dependent on the distance between the participant and the speaker.

The selection of suitable bandwidths for behavioural testing under sound-field conditions involves a compromise. Large bandwidths are necessary to establish uniformity in the field, and conversely small bandwidths are necessary to ensure frequency specificity (Walker et al., 1984). Furthermore, when it is not possible to restrict head-movements to a 15-cm radius sphere, as is the case when testing infants, larger bandwidths have to be employed (Walker et al., 1984) in order to minimize errors associated with field variability.

There are, however, certain disadvantages to using stimuli with broad bandwidths[11]. To reduce the errors arising from field variability, the hearing loss at a specific frequency will be underestimated to some degree unless the loss is flat along the frequency spectrum (Walker et al., 1984). Whenever there is a sloping hearing loss or decrease in sensitivity along the frequency spectrum, some of the stimulus energy will fall in regions with better hearing than the nominal frequency[12]. Substantial errors can occur since hearing loss can change rapidly from frequency to frequency, particularly in the high frequency regions (Walker et al., 1984).

In short, a stimulus with a broad bandwidth is less frequency specific. Thus to minimize this effect, the desirable bandwidth must be kept as "small" as possible, while still establishing uniformity in the field (Walker et al., 1984). This will then ensure that the obtained threshold is frequency specific and that the individual is not responding to sound energy that falls outside the nominal frequency being tested.

2.2.4.2 Required Modulation Waveform and Modulation Rate for Frequency Modulated Tones

In the clinical setup, the validation for using modulated tones is that they are more easily identifiable than steady pure tones (Arlinger & Jerlvall, 1987; Linden & Kankkunen, 1969) and furthermore less influenced by reverberation (Arlinger & Jerlvall, 1987; ISO 8253-2, 1985; Walker et al., 1984). Modulation entails altering the amplitude or frequency of a wave, by another wave of a lower frequency to convey a signal (Oxford Dictionary, 1990:763).

[11] Stimuli with a broad spectral content, or broad bandwidth, may stimulate frequencies around the nominal frequency, which leads to a decrease in frequency specificity.
[12] Nominal frequency, in the text, will indicate the intended frequency of stimulation.

The manner in which a signal sweeps back and forth around the centre/nominal frequency defines the modulation waveform (Walker et al., 1984). Dillon & Walker (1981) and Dillon & Walker (1982b) have investigated the merits of using sinusoidal, triangular, ramp and rectangular modulation. Of these, the rectangular and ramp modulation has been rejected due to considerable frequency "splatter" and a resultant decrease in frequency specificity. There has, however, been some discussion on whether to use sinusoidal or triangular modulation, as both offer certain advantages.

Sinusoidal modulation has the advantage of a more rapid falloff of energy outside the nominal band, which in turn means improved frequency specificity, whereas using triangular modulation results in a more uniform distribution of energy within the band (Walker et al., 1984). Although both sinusoidal and triangular modulation is satisfactory (Walker et al., 1984), most clinicians and researchers have definite preferences. For the current study sinusoidal modulation would provide a stronger correlate with the sinusoidal modulation used in the ASSEP technique.

Another variable that needs to be addressed is the rate of modulation, in other words the rate at which the frequency range of the stimulus is swept (specified in Hz). Care should be taken in the selection of modulation rate, as a too high rate can cause field uniformity to suffer, as there might be insufficient spectral components to ensure reasonable averaging within the band. While conversely, when the modulation rate is too low, the participants' ear will respond to intensity fluctuations (Dillon & Walker, 1982b; Walker & Dillon, 1983). This is due to its dependence on the test room acoustics (e.g. the peaks and troughs in the rooms' response). Therefore the measured threshold will depend only on the highest peak occurring within the modulation cycle (Walker et al., 1984).

Temporal integration properties of the listener's ear will influence the modulation rate at which individual peaks in the response begin to appear. Walker & Dillon (1983) have indicated that the commonly used 5 Hz modulation rate may be adequate only for the normal listener's ear and those persons with abnormal temporal integration required a rate of about 20 Hz to detect the presence of a stimulus and subsequently to respond to it.

When a single modulation frequency is required, as is mostly the case in the clinical arena, it has been recommended that a modulation rate of around 20 Hz be used (Walker et al., 1984). This relates to the fact that clinicians are bound to test both individuals with normal-hearing, as well as those with hearing impairments, within their scope of practice, and that they cannot always differentiate between these groups prior to obtaining the individuals' hearing thresholds. It is, however, important to bear in mind that, in individuals with normal integration properties, slightly better results would be obtained using a decreased modulation rate for the lower frequencies (Walker et al., 1984).

In conclusion, modulated tones for use in sound-field testing should be triangularly or sinusoidally modulated, rather than using rectangular or ramp modulation, and should have a modulation rate of around 20 Hz to ensure frequency specificity. As the focus of the current research endeavour is to provide normative data on normal-hearing sensitivity, and subsequently normal temporal integration properties, modulation rates around 5 Hz should be sufficient (Walker et al., 1984). However, as the data collection was done within a clinical setup, the stimulus, during behavioural sound-field audiometry, was modulated closer to 20 Hz.

2.2.4.3 Direct versus Reverberant-field Testing

A further consideration that needs to be addressed when conducting sound-field audiometry is the fact that the distance between the participant and the speaker takes on considerable importance (Walker et al., 1984). Sound-field audiometry can be divided into two main testing conditions, namely direct-field testing and reverberant-field testing. Distances beyond the near field and up to 0.6 m from the speaker are known as direct-field testing. For these, the sound pressure level (SPL) is influenced predominantly by the sound coming directly from the speaker. The SPL in direct-field testing varies according to the inverse square law (Walker et al, 1984). This implies that every doubling in distance from the speaker results in a 6 dB decrease in SPL (Walker et al., 1984:14). Distances that exceed 0.6 m are known as reverberant-field testing. For these, the SPL is influenced by reflected, as well as direct sound.

The main question in selecting the test position is whether the participant should be placed in the direct or the reverberant field. Various factors such as the directivity of the speaker (Walker et al., 1984), the rooms' dimensions (Anderson, 1979) and the absorptivity of its surfaces will influence the extent of the direct field (Dillon & Walker, 1981). In most audiometric test rooms, the direct field will extend only about half a metre in front of the speaker. Subsequently, when testing in the direct field, except for anechoic[13] conditions, the participant needs to be placed in close proximity to the speaker and meticulous control should be maintained over head- and body movements, in order to maintain acceptable signal stability at the level of the ear. The optimum positioning of the participant should, therefore, be as far away from the speaker as possible, while still remaining in the direct field.

There are, however, certain audiometric applications, such as testing of infants, where direct field testing is not feasible (discussed under 2.2.1) and others where the advantages of direct field testing is questionable, such as measuring real ear insertion gain (Walker et al., 1984). Although real-ear insertion gain (functional gain) of hearing aids can be measured in the direct field, the functional gain and frequency response will be influenced by the azimuth of the incident sound, because of head baffle and –shadow effects (Walker et al., 1984). When testing in the reverberant field it is of critical importance that the participants' position is chosen so as to avoid coinciding with a null at any of the audiometric frequencies. Procedural guidelines will be stipulated in the methodological chapter of this study.

Within the adult population, the main application of sound-field audiometry is to establish real ear insertion gain (Arlinger & Jerlvall, 1987; Dillon & Walker, 1981; Walker at al., 1984), which in turn is a valid tool for verification of the target gain (Mueller et al., 1992). When measuring insertion gain in the direct field, the azimuth of the incident sound, because of head baffle or shadow will influence the functional gain and frequency response (Walker et al., 1984). The choice of testing arrangement (orientation of the participant in relation to the speaker) thus becomes an important issue.

[13] Sound-field testing can be most accurately carried out in an anechoic chamber since the sound intensity varies smoothly and only gradually with distance from the speaker. Small random movements by the participant away from the calibrated test position thus have little effect on the sound intensity at the participant's ear.

For reverberant-field testing, due to the uniformity of the field, the azimuth of the sound source will not influence functional gain, unless the direct component of the field is substantial. According to Walker and colleagues (1984), a review of published studies as well as some of their own unpublished data, revealed that the functional gain and frequency response measured in the reverberant field would differ little from the measurements made in the direct field with a signal incidence of zero degrees (when the participant is directly facing the speaker). More current research (Muller et al., 1992) suggests that a 0º or 45 º speaker azimuths is the preferred measurement condition.

In conclusion, there is no simple answer when considering whether to test in the direct or reverberant field when measuring the functional gain of a hearing aid. These questions should be decided by considering the purposes of the measurement and the age of the participant being tested.

2.2.4.4 Important Test Room Considerations

When testing via a speaker there should be no reflecting surfaces in the test room and no objects between the speaker and the participants' ear (Wilber, 2002). Whenever possible, and presumably in all cases except when testing young children and neonates, a head rest should be used in order to limit or minimize head movement. Furthermore, no part of the headrest or the chair should protrude beyond the sides of the participant's head, as any such surface might disturb the sound-field. Preferably, the chair should be adjustable in height, although making use of a cushion to adjust the height of the participant is also satisfactory. The test position should be constant and accurately identifiable. The centre of the participants' head should be in line with, and at the same height as, the centre of the speakers' cone (Walker et al., 1984; Wilber, 2002). Thus, the positioning of the participant in relation to the speaker seems to be more important (Magnusson et al., 1997) than the positioning of the speaker itself (Walker et al., 1984). Within the clinical setup this implies that when testing in the direct-field, results are comparable to those obtained through testing in the reverberant field as long as a signal incidence of 0° or 45° (i.e. with the participant directly facing the speaker) is maintained (Walker et al., 1984).

2.2.4.5 Importance of calibration

The standard for audiometers (ANSI 3.6, 1996) describes the primary characteristics of sound-field testing. Special attention is paid to the test room, frequency response, method for describing the intensity of the speech signal and the location of the speaker. It also provides specific values for tonal stimuli, such as frequency-modulated tones and narrow bands of noise.

When calibrating the equipment it is important to place some sort of marker, so as to easily identify the test position where the participant will be. When calibrating for testing via a speaker there should, furthermore, be no reflecting surfaces in the room and no objects between the speaker and the participant's ear (Wilber, 2002).

Thus, when pre-test calibration is used, the selection and maintenance of the test position, as well as procedural aspects, takes on critical importance. This implies that a listening position should be identified where the SPL, within a sphere, will not vary by more than 2 dB from the value at the centre of the sphere. This criterion might have to be revised when testing infants, as their range of movement might exceed that of the identified test position. The identification of the listening position or listening sphere has an impact on the accuracy during testing. The smaller the variation, in decibels, within the sphere, the more accurate the measurement will be (Walker et al., 1984).

Calibration is important for two reasons. It establishes a relationship between the SPL, measured at the same point, and the corresponding attenuator setting on the audiometer or signal generator. Secondly, it establishes the SPL corresponding to normal thresholds (audiometric zero) so that the individual participants' hearing levels can be compared to this standard (Walker et al., 1984). The second reason for calibration is important for diagnostic audiology, but less so for hearing aid evaluation. With hearing aid evaluation the emphasis is upon the absolute level or difference in threshold brought about by the aid and upon the absolute level of sound, which can be heard through the aid (Walker et al., 1984).

Currently sound-field stimuli are **pre-calibrated** by measuring the SPL at a particular point in the sound-field for various attenuator dial settings. This technique has the advantage that head diffraction effects, caused by the introduction of the participants' head into the sound-field, are automatically taken into account whenever a threshold is determined (Walker et al., 1984). However, two potential sources of error are introduced.

Firstly, the introduced head diffraction effects are, to some extent, dependant on the particular test position, whereas one would preferably include only those systematic components of head diffraction which the participant experiences in diverse acoustic environments. Secondly, any movements by the participant (e.g. head movement) from the pre-calibrated point cause a measurement error. Although stimuli are chosen so that this error is acceptably small within a sphere radius of 15 cm, it may not always be possible to ensure that the movement is restricted to this extent.

An alternative calibration technique involves the use of a microphone to **continuously monitor the SPL** near the participants' head. The output of the microphone is used to automatically control the attenuator of the signal generator to maintain an invariant signal level at the microphone (Walker et al. 1984). This technique has the advantage that if the control microphone is attached to the participants' head, the calibrated position moves whenever he/she does. The major disadvantage associated with this technique is that the SPL at the control microphone is not exactly that of the position of interest (the hearing aid microphone or ear drum for aided and unaided assessment, respectively). This discrepancy is both person and environment dependent.

Because the current study was performed within a clinical set up, the calibration method employed was pre-calibration. Control microphone calibration has the advantage of greater accuracy, especially within the infantile population, due to the likelihood of considerable and unavoidable head movement (Walker et al., 1984). Furthermore, when using any type of complex stimuli, the intensity at the participant's ear will vary with time. Although frequency modulated (FM) tones, unlike other stimulus types, do not contain inherit intensity fluctuations the intensity at the ear varies (in the reverberant field) because the peaks and troughs in the room's frequency response are sequentially excited, as the tone sweeps the frequency (Walker et al., 1984).

Previous research (Dillon & Walker, 1980) evaluated the measurement of intensity fluctuating stimuli. Findings indicated that similar calibration figures of acceptable accuracy can be obtained by reading peak deflections off a sound level meter set to "route mean square-fast" mode. When calibration is done as indicated above, thresholds obtained in the sound-field can be related to thresholds that would be obtained by testing under earphones with pure tone stimuli. This is therefore the method of calibration used during the current research endeavour.

The following summary of conclusions (Table 2.2) represents a reasonable set of comprehensive recommendations based on the discussion provided so far.

Table 2.2 Summary of the Limitations of Sound-field Audiometry and Recommendations for addressing these Limitations

Literature	Goal of Research Endeavour	Recommendation	Implication for Current Study
1. Dillon & Walker, 1982 2. Walker et al., 1984 3. Dillon & Walker, 1982 4. Dillon & Walker 1982	Comparing stimuli used in sound-field audiometric testing Recommendations for stimuli and procedures in sound-field testing Comparison of stimuli used in sound-field audiometric testing The selection of modulation wave form for frequency modulated sound-field stimuli	Complex stimuli, and not pure tone stimuli, should be used, as the **type of stimulus**, for testing in the reverberant field. In most audiometric test rooms this means any distance that extends beyond about half a metre from the speaker. FM Tones have been identified as the best type of stimulus, according to its **stimulus characteristics,** for sound-field testing, having suitable characteristics.	Complex stimuli with large bandwidths ensure uniformity in the field, but have to be kept as small as possible to ensure **frequency specificity**.
5. Walker et al., 1984 6. Dillon & Walker, 1982	Recommendations for stimuli and procedures in sound-field testing The selection of modulation wave form for frequency modulated sound-field stimuli	FM tones should be **sinusoidally or triangularly modulated**. For this particular study, and specifically the comparison between sound-field and ASSEP, sinusoidally modulated tones were selected at a modulation rate of around 20Hz. The modulation rate selected is sufficient for normal and abnormal temporal integration.	Sinusoidal modulation ensures improved **frequency specificity**, whereas a modulation rate of around 20 Hz will be sufficient for normal and abnormal individuals integration properties.
7. Dillon & Walker 1981 8. Beynon & Munro, 1995 9. Walker et al., 1984	The effect of the acoustic environment on the reliability of sound-field audiometry Measuring variability in sound-field audiometry due to subject movement Recommendations for stimuli and procedures in sound-field testing	**Test room considerations:** ➢ A height adjustable chair should be used whenever feasible. ➢ The test room should be as non-reverberant as possible. ➢ There should be no reflecting surfaces in the test room and no objects between the speaker and the participants' ear. ➢ The test position should be constant and accurately identifiable. ➢ The centre of the participants' head should be in line with, and at the same height as, the centre of the speakers' cone.	These considerations ensure that the **thresholds** obtained **are accurate** and that the influence of the acoustic environment is kept to a minimum.
10. ANSI 3.6, 1996 11. Dillon & Walker, 1980 12. Arlinger & Jerlvall, 1987	Specifications for audiometers. ANSI 3.6-1996 The perceptions of normal-hearing persons of intensity fluctuations in narrow band stimuli and its implications for sound-field calibration procedures Reliability in warble tone sound-field audiometry	**Other important factors:** ➢ Traditional pre-calibration was chosen as a satisfactory method of calibration. ➢ Presentation level of a complex sound can be determined by reading the peak deflection off the "route-mean-square- fast mode" on a sound level meter. Therefore, sound-field measures can be described as dB HL.	Calibration of the equipment ensures that the thresholds obtained under **sound-field conditions are comparable with those obtained under earphone testing.**

The final goal of the current research endeavour entails a more advanced application of ASSEP, namely the estimation of hearing thresholds through sound-field presentation. ASSEPs is a relatively new, objective technique in the AEP arsenal, that has until recently been investigated as the method of choice in diagnostic hearing threshold estimation. In an attempt to validate the possible application of ASSEPs through sound-field presentation, it is necessary to discuss the current application of steady state in order to delineate the current application status.

2.3 Perspectives on Auditory Steady State Evoked Potentials

The following section aims to provide the reader with information related to the current application of ASSEPs, and argues for the use of sound-field speaker presentation. The information is structured to provide a definition of auditory steady state evoked potentials, followed by the current clinical applications as well as current research applications. Thereafter the audiometric variables are discussed in depth, according to transducer-, stimulus-, intensity- and latency-related variables. Attention is paid to the influence of participant related variables, such as stimulus and response characteristics, transducer influence, as well as the state of consciousness of the individual. This section concludes with the possible advantages of ASSEP over other techniques in the estimation of aided thresholds.

2.3.1 Definition of Auditory Steady State Evoked Potentials

ASSEPs are evoked by continuous tones (Lins et al., 1996). They are sinusoidally amplitude and/or frequency modulated at frequencies between 3 and 200 Hz (Lins et al., 1996), of which the best modulation rates for audiometric purposes appear to be around 40 Hz and between 75-110 Hz (John et al., 1998). And, finally, they are detectable at the frequency of modulation (Rance et al., 1998). This periodically changing stimulus, although continuous in presentation, causes a shortened inter-stimulus interval. The resultant response detected is a compound response, of several “overlapping” transient responses, and is referred to as Auditory Steady State Evoked Potential for the purpose of this research.

2.3.1.1 The Physiology underlying ASSEPs

ASSEPs can better be understood when considering the functioning of the cochlear transducer (Lins & Picton, 1995). An auditory stimulus consists of acoustic energy distributed over a frequency spectrum that can be processed by the cochlea (Dimitrijevic et al., 2001). The basilar membrane and outer hair cells act as *frequency-place analyzers* for the specific frequencies contained in incoming sound signals, where higher frequencies activate the region of the basal membrane closer to the oval window and lower frequencies activate regions further along the membrane (Lins & Picton, 1995).

Any incoming auditory signal creates a "wave/traveling wave" that moves along the basilar membrane of the cochlea. While mediating a frequency-to-place coding in the auditory system (John & Picton, 2000), it also involves a delay since time is taken to move along the basilar membrane. This serves as a possible explanation as to the fact that physiological responses to auditory stimulation, generally occur at earlier latencies for high frequencies, than responses to low frequency stimulation

The *transducer function*, associated with the depolarization of inner hair cells, is asymmetric and non-linear, since larger potentials are evoked when the inner hair cells are bent away from, rather than towards, the basal body (Lins & Picton, 1995). Therefore the non-linear functioning of the cochlea can be attributed to the preferential response of hair cell movement in one specific direction, namely away from the basal body (John et al., 1998). In addition to the non-linear functioning, the responsiveness of the cochlea saturates with increasing amplitude of the stimulus (John et al., 1998), this in turn can be attributed to high levels of depolarization of the inner hair cells (Lins & Picton, 2000).

Inner hair cells, then, synaptically activate dendrites of the ganglion cells that compose the afferent fibers of the auditory nerve. Rectification of the signal occurs, since only depolarization of the inner hair cells causes action potentials in the ganglion cells. Larger depolarization's causes faster firing rates in ganglion cells (Lins & Picton, 2000). The cochlear transfer function can therefore be described as a compressive rectification (John et al., 1998).

A sinusoidal amplitude-modulated (AM) pure tone contains energy at three frequencies (the carrier and two other frequencies separated from the carrier by the modulation frequency). It is important to note that the signal contains no energy at the modulation frequency. However when the signal undergoes non-linear distortion resultant energy will by present at certain frequencies, and foremost among these combined tones will be the modulation frequency (John et al., 1998).

Non-linearity's in the output of the cochlea thus provide the basis for the detection of responses (John et al., 1998). In other words the cochlea contains a rectified version of the acoustic signal, which subsequently causes the output of the cochlea to contain a spectral component at the frequency where the carrier signal was modulated. This component, which is not present in the spectrum of the signal, can be used to assess the response of the cochlea to the frequency of the carrier (Lins et al., 1996).

2.3.1.2 The Anatomy underlying ASSEPs

ASSEPs can be recorded by stimulus rates of up to several hundred hertz (Rickards & Clark, 1984). The amplitude of these responses are larger at rates near 40 Hz (Galambos et al., 1981) and 80 Hz (Lins et al., 1995). The nature of these potentials has been studied with responses evoked with stimulus rates near 40 Hz (Galambos et al., 1981; Stapells et al., 1984). Should these responses arise from the same neurons that generate transiently evoked responses, then ASSEP could be predicted from the super-positioning of multiple overlapping transient responses (Hari et al., 1989). It is, however, also possible that the rapid stimulation might elicit a separate response from neurons that are specifically responsible for rhythmic activity and that resonate at the frequency of stimulation (Basar et al., 1987). These generators might also be responsible for spontaneous cortical gamma rhythms (John & Picton, 2000).

Discrepancies between ASSEP responses and those predicted by super positioning (Azzena et al., 1995) and the persistence of the response the time when the stimuli are presented (Santarelli et al., 1995) support the idea of resonance. However by modeling the refractory effects and considering the multiple generators, one can still explain the most of the 40 Hz response findings on the basis of transient response waveforms (Gutschalk, et al., 1999). It is therefore unlikely that independent rhythmic generators would account for the 40 Hz ASSEP, and more so for the 80 Hz response (John & Picton, 2000). It seems more likely that these responses are generated by neurons in the brainstem, and possibly the cortex, which respond to both transient stimuli and become "locked" to the envelopes of amplitude modulated tones (John & Picton 2000). The longer latencies of 80-110 Hz responses suggest either a generator further along the auditory pathway or one lower in the auditory pathway, activated by a multi-synaptic circuit (John & Picton, 2000).

To summarize it seems that many different regions of the auditory nervous system from the auditory nerve to the auditory cortex generate responses that follow the modulation signal of an amplitude-modulated tone. Each of these regions can create a response that has a specific phase and latency relationship to the stimulus. All these responses will overlap to make up the response recorded from the scalp (John & Picton, 2000). Therefore the dominant response in an "awake" subject, at 40 Hz probably derives from the auditory cortex, with the brainstem contributing only a little. With sleep the cortical responses may attenuate and the scalp recorded response may mainly reflect those potentials generated by the brainstem (John & Picton, 2000). It seems that scalp recorded potentials in response to tones modulated around 80-110 Hz derives from a generator high in the brainstem (John & Picton, 2000).

2.3.2 Current Clinical Applications of ASSEP

The ultimate goal of objective audiometry is to generate a frequency specific audiogram (Aoyagi et al., 1996), without any behavioural response from the participant or subjective interpretation of the results by a clinician. ASSEP has recently become available as an objective hearing test option (Rance et al., 1998). This statement was confirmed by various researchers (Aoyagi et al., 1994; Cohen et al., 1991; Lins et al., 1996; Rickards et al., 1994), having obtained reliable, and frequency specific estimates of behavioural pure tone thresholds in adults, well babies and hearing-impaired participants. Currently the ASSEP techniques have two major applications within the clinical arena, namely **detection** (of hearing loss) and **diagnosis** (characterization of the hearing impairment).

With the current focus on neonatal hearing screening (NIH Consensus Committee, 1993; Joint Committee on Infant Hearing, 1994), and identification and treatment of those infants with hearing impairments before the age of 6 months (Picton et al., 1998), there has been an increase in the difficult-to-test populations. Researchers (Perez-Abalo, Savio, Torres, Martin, Rodriguez & Galan, 2001; Picton et al., 1998; Rance et al., 1998; Stürzebecher et al., 2001) have documented several advantages of ASSEP, over other AEP techniques such as the ABR, as an objective screening measure. The ASSEP technique is more time efficient, when the dichotic multiple stimuli technique is used (Picton et al., 1998) and it has commercially available response detection techniques, which allows for objective response detection (Stürzebecher et al., 2001) not yet available in commercial Auditory Brainstem Response (ABR) equipment. Furthermore, the technique is able to identify reliable frequency specific thresholds in infants, regardless of the state of consciousness (Aoyagi et al., 1993; Cohen et al., 1991; Lins & Picton, 1995; Rickards et al., 1994).

Recently, researchers (Picton et al., 2002a; Stürzebecher et al., 2001) have cautioned against using the multiple stimuli technique at high intensities, as frequency specificity might suffer due to overlapping of responses at high intensities. Picton and colleagues (2002b) explained that at high intensities each stimulus would activate a broader region of the basilar membrane than at lower intensities, causing subsequent overlapping in the activation patterns of the different stimuli. Researchers (Perez-Abalo et al., 2001) were, however, able to show that overlapping of responses and subsequent decreased frequency specificity did not occur even at intensities around 110 dB. There are, however, still research questions regarding dichotic multiple-stimulation at high intensities and the effect thereof on frequency specificity, the effects of multiple stimuli on the maturation of infantile nervous systems and the improved performance of statistical tests used for objective response detection to minimize false-negative decisions.

The second, and most widely used, application of the ASSEP technique has its focus on the **diagnosis** or characterization of the hearing impairment, especially within the difficult-to-test population. As research improves the objective response detection techniques available (Cebulla, Stürzebecher & Wernecke, 2001; John et al., 2001), exciting possibilities arise in terms of improved objectivity and frequency specificity.

Furthermore, the ability to employ increased signal presentation levels means that residual hearing sensitivity, even in the severe to profound regions, can be accurately estimated (Rance et al., 1995; Rickards et al., 1994). The accurate estimation of residual hearing is crucial, especially with cochlear implant candidates (Rance et al., 1994), and because ASSEP can be presented at high intensity levels without the artifact complications associated with the ABR (discussed later on in this chapter), its application within this population has been highly successful.

The ASSEP technique complies with all the requirements to allow for complete characterization of the hearing impairment. The technique is able to accurately determine degree of loss, predict the configuration of the loss and determine frequency specific thresholds (Kuwada, Batra & Maher, 1986; Lins & Picton, 1995; Lins et al., 1996; Picton et al., 1998). Results obtained can be presented as an audiogram and the technique is, furthermore also time efficient (Rance et al., 1995; Rickards et al., 1994).

2.3.3 Research Applications

Although the ASSEP technique has become available as an objective hearing test option for infants and others in the difficult-to-test population (Rance et al., 1998), there are still various possibilities regarding application within the clinical arena that are yet to be established, through research. Research is still required to establish whether single modulated tones offer higher frequency specificity at high stimulation intensities. These results will offer insight into the application of ASSEP in cochlear candidacy. Research is also required to establish whether aided thresholds can be obtained from cochlear implant users, using an adapter cable, to maximize usage of electrode configurations in the maps of difficult-to-test patients.

Although the current applications of ASSEP are aimed at providing the clinician with an electro-physiological audiogram, to assess the hearing impairment, more information is needed regarding supra-threshold discrimination (Picton et al., 2002a). Although the ASSEP at this stage cannot directly evaluate speech perception it is able to evaluate small changes in intensity and frequency, which provide the cortical regions with information regarding speech perception. Further research is required, where a single carrier is independently modulated through AM and FM, and with various combinations of AM/FM modulation (e.g. 50% AM and 25 % FM), to establish how the cochlea processes information needed for speech perception.

Recently researchers (Lins & Picton, 1995) have endeavoured to further investigate the physiology underlying ASSEP, using modulation rates between 150-190 Hz. At these higher modulation rates equal contributions between the brainstem and cortical areas were noted. With variation in modulation rate, insight might be gained into pathology of the auditory system up to cortical level (Regan, 1989; Regan & Regan, 1993; Lins & Picton, 1995). Research in this regard has "not extended beyond hypothesis in most instances" (Schmulian, 2002: 69).

2.3.4 Current Research Available

To date only two studies have investigated the objective evaluation of aided thresholds using ASSEP. The first, a study by Picton et al (1998) used three different groups of subjects. A normal hearing group of 10 subjects (6 female) with thresholds less than 20 dB HL at frequencies between 0.5 and 4 kHz were selected. Subject age varied between 13 and 40 (mean 29) years of age. The other normal hearing group consisted of 10 female subjects aged between 23 and 43 (mean 31) years of age.

The second grouping consisted of 35 hearing-impaired children with moderate hearing impairment. These children were using hearing aids, and were aged between 11 and 17 (mean 15) years of age. Only one ear of each subject was tested. The test ear was the one with the best pure tone average, while random selection was carried out for the children with symmetric hearing losses. The non-test was occluded. In all 15 left and 20 right ears were tested.

A small third group of subjects included 3 children who were being fitted with hearing aids and who were unable to provide reliable responses to sound. Two of these children were newly identified infants under 1 year of age. The first was assessed at 9 months of age (X1), while the second was assessed at 8 months of age (x2). The 8 month old was premature and developed respiratory distress syndrome. The last child was a 9-year-old girl with severe developmental delays (x3).

Picton and his colleagues (1998) used sinusoidally amplitude-modulated tones, with the depth of modulation at 100% for each stimulus. The carrier frequencies included were 0.5, 1, 2 and 4 kHz. These frequencies were modulated using 80.9, 88.9, 96.9 and 104.8 Hz respectively over the carrier frequencies 0.5-4 kHz. Simultaneous presentation of stimulus was used in all cases, except in for some instances where the normal hearing group was tested.

The timing of the stimulus and the recording was exactly synchronized for frequency analysis to detect responses. The stimuli were therefore adjusted is that there was an integer number of both the carrier frequency and the modulation frequency within the 754-msec buffer. A Madsen Micro 5 audiometer equipped with both TDH 39 supra aural headphones and a Madsen FF-73 sound field speaker was used to present stimuli. All subjects were tested in a single walled audiometric test room were ambient noise levels complied with ANSI standards of 1991. Subjects were seated in an armchair in the center of the room 1.25 meters away from the speaker at an azimuth of 0º. The head position was in the center of the speaker axis. Stimuli were calibrated according to the recommendations of Walker et al. (1984) and Beynon and Munro (1995) as well as the ANSI S3.6 (1996).

Subjects were mostly asleep during recording of responses, with the exception of the 9-year-old girl in the third group. Ground electrode was connected to the lateral neck, while reference electrodes were placed between the vertex and the posterior midline neck, half way between the inion and the vertebra prominens. While infants presented difficulties with electrode placement and maintenance and the reference electrode was therefore placed on the ipsilateral mastoid to the test ear and the ground on the forehead. Responses were amplified and filtered with a band pass of between 10 and 300 Hz. The signal was then converted from analogue to digital. Each recording section included 512 samples and 16 sections were concatenated to form a full recording sweep of 12.06 seconds. The amount of sweeps required was dependant on the signal-to-noise ratio. This lasted between 6 and 15 minutes. The use of recording sections allowed Picton and colleagues (1998) to reject artifacts over the section rather than over the entire sweep. Artifact rejection was set at 40 μV for most subjects, but where the artifacts were more frequent the rejection criteria was raised to 50 or 60 μV (depending on the subjects' alpha rhythm). The average 12-second sweep was transformed to the frequency domain using a Fast Fourier Transform. The amplitudes reported in their paper were baseline-to- peak amplitudes and the phases, cosine-onset phase.

Threshold estimation for pure tones was using conventional audiometric techniques (Carhart & Jerger, 1959). Stimuli were presented singly rather than in combination. The voltage of the batteries of all hearing aid users was checked prior to the threshold estimations. Physiological thresholds were determined by the presence or absence of recognizable ASSEP responses.

In the normal hearing group the aim was twofold, namely to determine the influence, if any of transducers and stimulus presentation. No significant difference was observed when stimulus presentation was varied between single and multiple conditions. However for both conditions physiological thresholds was 10 –20 dB above behavioural threshold. When the influence of transducers was investigated there was no significant difference between SPL thresholds obtained under earphones and those obtained under sound field speakers.

The responses obtained from the second group (hearing aid users) revealed a significant correlation between behavioural thresholds and ASSEP thresholds. In the group with profound hearing losses aided thresholds were obtained at threshold levels with the exception of 4 kHz where no responses were obtained even when the stimulus was presented at levels that exceeded threshold level. A clear response was obtained at 4 kHz when the stimulus presented singly instead of in combination.

The first experiment has significant influence on the current study, as it indicates that reliable responses could be recorded close to behavioural thresholds (13-16 dB), irrespective of the transducer used. Therefore it seems logical that should the transducers be calibrated to present the same dB SPL at the eardrum for the different stimuli used, the transducer effect will be negligible. A pilot study by Cone Wesson and colleagues (2001) using 4 adult hearing aid users presented similar findings.

2.3.5 Audiometric Variables

- **Transducer related variables**

There is, currently, limited research available to document the influence of using speakers as a transducer when recording ASSEP. Taking into account that an ASSEP is evoked by regularly repeating stimuli, the response should stabilize after the initial few stimuli (Picton et al., 1998). Furthermore, it should thereafter contain constituent frequency components that remain constant in amplitude and phase over time (Regan, 1989). When these responses are evoked, by amplitude-modulated tones, in the auditory nervous system, they are frequency specific and stable over time. They should therefore not distort in the sound-field speaker or the hearing aid (Picton et al., 1998).

- **Stimulus related variables**

It is important to pay attention to the stimulus rate used to evoke these responses, as the stimulation rates are influenced by the various factors (e.g. state of consciousness) that will impact on the responses recorded. The 40 Hz potential, initially described by Chatrian, Petersen and Lazarte (1960), as well as Schimmel, Rapin and Cohen (1975), was first detailed according to its general characteristics by Galambos and colleagues (1981). Although the 40 Hz potential has application value to this day, the best modulation rates for audiometric purposes may be between 70-110 Hz (Picton et al., 1998). The reason for this is that responses evoked at these modulation rates are not significantly effected by state of consciousness, or state of arousal (Cohen et al., 1991), and can be reliably recorded in infants (Aoyagi et al., 1993; Rickards et al., 1994; Lins et al., 1996).

- **Intensity Effects of the Stimulus**

Intensity is a well-documented variable in relation to other AEP measurements such as the ABR and has an effect on the latency of evoked potential measures. With a decrease in intensity the latency tends to increase (John & Picton, 2000). John & Picton (2000) hypothesized that a shift in the cochlea, related to intensity variations, contributes significantly to a change in latency. They also mentioned that short duration stimuli at high intensities evoke responses earlier on the rise time of the synaptic activation pattern.

It is important, however, to remember that intensity fluctuations will have a more adverse effect on transient stimulation. This is due to the short stimulus duration and the subsequent silence following the stimulus, as the postsynaptic membrane returns to a resting position (John & Picton, 2000). Although intensity variation might have smaller latency effects on sustained stimulation, such as the ASSEP, there might still be an influence, depending on the frequency of stimulation. This is because low frequency carriers evoke an activation pattern on the basilar membrane that covers a greater spatial extent than higher carrier frequencies. According to John & Picton (2000) there might be a resultant latency jitter of the responses, which in turn might attenuate the amplitude of the compound response. This can be attributed to the fact that neurons along a broad area of the basilar membrane all respond to the same low frequency carrier and some of these responding neurons might be activated significantly earlier than others, and especially at higher intensities (John & Picton, 2000).

Experiments that focused on the effect of stimulus intensity (Lins et al., 1995) have indicated that for stimulus intensities above 70 dB SPL the amplitude of the response grows much more rapidly than for stimulus intensities below 70 dB SPL. Furthermore it also indicated that the difference in amplitude was attenuated for lower frequencies, when compared to higher frequencies. Therefore, at threshold levels only the fibers with characteristic frequencies near the carrier frequency seems to be activated, whereas a larger number of fibers, with higher characteristic frequencies, are activated when the intensity is increased above 60-70 dB SPL. It seems that the intensity of the stimulus presented could possibly impact on the estimation of lower frequencies, and more so for moderate to high intensity presentation levels.

- **Latency Effects**

The physiological interpretation of latencies of scalp-recorded ASSEP remains difficult, as the responses evoked do not derive from a single generator. Because of the periodic nature of ASSEPs, however, the conventional measurement of latency is prohibited in the frequency domain (Rickards et al., 1994). This becomes evident when considering that there are several different regions of the auditory nervous system that generate responses following the modulation signal of an amplitude modulated tone. The compound responses recorded at the scalp are made up of several individual responses along the auditory nervous system. Each of these individual responses has their own phase- and latency-relationship to the stimulus (John & Picton, 2000). There seems to be an indefinite relationship between phase and latency, as phase cannot be directly translated to latency. According to Regan (1966) this problem can be resolved through assessing phase at different stimulus rates to arrive at clear estimates of apparent latencies, or "group delay" as Goldstein, Baer and Kiang (1971) termed this phenomenon.

Frequency or latency related delays are an important consideration when measurements are made in the frequency domain or in the time domain. These latency-related delays have a definite influence on measurements that are obtained in the frequency domain. There are five main contributors to the latency of neuro-physiological responses to auditory stimulation, and each of these will be discussed.

The acoustical delay relates to the delay between the stimulus being produced and the stimulus arriving at the oval window after transmission through the air to the tympanic membrane and through the middle ear (John & Picton, 2000). The second contributor is related to transport time delays. This simply means that the travelling wave takes time to move along the basilar membrane, and refers to the amount of elapsed time between the arrival of the sound energy at the oval window and the beginning of activity at the location on the basilar membrane. Although most evidence suggests that the delay is in the millisecond range, and that it increases exponentially with increasing distance along the basilar membrane (John & Picton, 2000), there is still a lot of controversy surrounding transport delays.

The third contributor is related to transduction or filter delays. This has to do with the filtering of acoustic energy into electrical impulses, in other words, the time the acoustic energy takes to pass through the active filtering process of the cochlear hair cells that are sensitive to the frequencies of sound in the stimulus. The more sharply the filter is tuned, the longer it will take for the output of the filter to reach maximum amplitude (John & Picton, 2000). This filter delay, together with the transport delay, contributes within the normal cochlea, to the frequency related delays of physiological responses.

Synaptic and conduction delays are the last two contributors to frequency delays. It simply infers that there is a time delay as the sound energy is transmitted between the inner hair cell and the afferent nerve fibre as well as the time it takes to conduct the potential between the cochlea and the neural generator (of the response). There seems to be no significant affects created by the frequency of the signal (John & Picton, 2000). These delays could possibly create significant differences between the responses obtained from male and female individuals being tested, due to the difference in the length of their basilar membranes.

When stimulation rates around 70 Hz are used, apparent latencies ranging between 11 and 14 ms are detected (Cohen et al., 1991; Lins & Picton, 1995; Rickards et al., 1994) depending on the carrier frequency. Rickards et al (1994) suggests that the use of ASSEPs in the assessment of the hearing sensitivity of infants and young children is most successful when responses with latencies of about 10 ms are used.

2.3.6 Participant Related Variables

Participant related variables are discussed according to age, gender and hearing sensitivity:

2.3.6.1 Influence of Age

Although age seems to be a significant contributor to variability, research has shown that when stimulation rates around 40 Hz are used, responses can be consistently recorded (in the neonatal population) when modulation rates in excess of 70 Hz are used (Rickards et al., 1994). Other related studies by Boetcher, Madhotra, Poth and Mills (2002a) as well as Boetcher, Poth, Mills and Dubno (2002b) on ASSEP have predicted that reduced amplitudes would be obtained for aged participants. This prediction is based on two main factors, namely reduced frequency discrimination in geriatric participants, possibly due to changes within the auditory system (including the effects of presbycusis). The second factor relates to the fact that other AEPs (like the ABR) have reduced amplitudes in geriatric participants.

2.3.6.2 Influence of State of Consciousness

Earlier studies (Galambos et al., 1981; Maurizi et al., 1990) have investigated the reliability of the 40 Hz ASSEP, in the accurate estimation of frequency specific hearing thresholds, in infants and other difficult-to-test populations. The robust amplitudes observed near threshold level as well as their established relationship to behavioural responses motivated these investigations. These investigators as well as others have since established that the amplitudes, and subsequently accurate threshold estimation capability, of the 40 Hz response are severely affected by state of consciousness (Brown & Shallop, 1982; Linden, Campbell, Hamel & Picton, 1985; Osterhammel, Shallop & Trkildsen, 1985; Plourde, Stapells & Picton, 1991; Suzuki et al., 1994) and state of arousal (Plourde & Picton, 1990). Thus, behavioural thresholds are over estimated.

Later research (Cohen et al., 1991) determined that when higher modulation rates are employed, responses down to near-threshold levels could be recorded reliably in infants regardless of state of consciousness (Aoyagi et al., 1993; Lins et al., 1996; Rickards et al., 1994). This phenomenon is probably related to the neural generators responsible for the evoked responses.

The 40 Hz ASSEP is thought to be generated by contributors from the ascending auditory brainstem pathways and auditory regions of the thalamus and auditory cortex (Pratt, Mittelman, Bleich & Zaaroor, 2002). According to these researchers the relative contributions of cortical and sub-cortical regions are still unclear, but appear to be modified by sleep (Makela & Hari, 1987; Spydell, Pattee & Goldie, 1985; Suzuki et al., 1994). John and Picton (2000) have hypothesized that the dominant response at 40 Hz derives from the auditory cortex, with the brainstem contributing only a little. This would explain the effect of state of consciousness, as the cortical contribution may attenuate. This would mean that the scalp-recorded response would mainly reflect those potentials generated in the brainstem. Thus there is a significant influence by state of consciousness on the estimation of hearing sensitivity, when using the 40 Hz ASSEP. Therefore, as long as strict control is exercised when monitoring the adult participants' state of arousal, accurate and reliable responses can be evoked by the 40 Hz ASSEP, due to the larger response amplitudes.

Scalp potentials recorded in response to tones amplitude modulated at frequencies between 80 and 110 Hz probably derives mainly from a generator in the high brainstem (John & Picton, 2000; Mauer & Döring, 1999). The use of ASSEP in the assessment of hearing in sleeping participants has shown to be most effective when employing responses with latencies of around 10 ms (Rickards et al., 1994). Results from a study done by Cohen and colleagues (1991) indicate that rates in excess of 70 Hz are required in order to produce these latencies.

2.3.6.3 Influence of Gender

Don, Ponton, Eggermont and Masuda (1993) interpreted the distinct gender-related latency differences in terms of two effects, firstly the faster cochlea delay times (associated with the shortened length, and greater stiffness of the female basilar membrane) and secondly the length of the cochlear nerve. There might, however, be a third contributing factor relating to the gender differences. According to Goldstein and Aldrich (1999) the inherit degree of variability in head size, found between the genders, could possibly contribute to gender-related latency effects. No conclusive evidence (to the knowledge of the researcher, at date of publication) across different carrier frequencies, have been established to confirm any of these hypotheses, as very limited research is available on the effect of gender on ASSEPs.

2.3.6.4 Hearing Sensitivity

The 40 Hz response has been used to obtain reliable frequency specific measures that correlate well with thresholds obtained through behavioural audiometry, in normal-hearing and hearing-impaired adults (Lynn, Lesner, Sandridge & Daddario, 1984). These responses can be obtained across the frequency range (Lynn et al., 1984; Stapells et al, 1984). The response, however, is considerably affected by state of arousal and state of consciousness (Brown & Shallop, 1982; Osterhammel et al., 1985).

One of the most comprehensive studies on frequency specificity of the ASSEP in estimating hearing thresholds in both normal and hearing-impaired participants, highlighted the variability related to the hearing sensitivity in threshold estimation (Rance et al., 1995). Threshold estimation in normal-hearing adults were about 10 dB higher than the ANSI standards for pure tones (on average 12 dB), whereas thresholds in “well” babies have been estimated to be 10-15 dB higher than for the normal-hearing adults (with the difference being greater at lower frequencies). They (Rance et al., 1995) related these smaller responses at lower frequencies to inadequate coupling between the earphone and the infants’ ear.

Thresholds in the adult hearing-impaired population showed smaller discrepancies between physiological and behavioural responses, than those of the normal-hearing population, and furthermore, showed improved threshold detection when compared to transiently evoked ABR elicited by 1 kHz tone pips. Thus it can be postulated that ASSEP responses accurately reflect behavioural audiograms in normal-hearing and hearing-impaired participants, although it seems that the technique favors pathology (Rance et al., 1995). Later studies by Rance et al (1998) indicated that there is a close relationship between the responses obtained during behavioural and physiological testing, and more importantly, that this relationship is consistent across the frequency range.

According to Picton and colleagues (1998) as well as Rance and colleagues (1998) this effect is probably related to recruitment. Due to the effects of recruitment in the hearing-impaired population, the responses are likely to reach a level where it is recognizable at a specific intensity closer to threshold than in normal-hearing participants. In other words, hearing-impaired participants with severe sensory-neural impairments can have a more pronounced increase in ASSEP amplitudes near minimum response levels (Rance et al., 1998).

A recent study (Picton et al., 2002a) has concluded that physiological responses are usually between 10-20 dB above behavioural thresholds (Herdman & Stapells, 2001; Lins et al., 1996; Perez-Abalo et al., 2001), and that these figures are representative of both normal-hearing and hearing-impaired participants.

Having established the application of ASSEP as a reliable and valid tool in the accurate estimation of frequency specific hearing thresholds, within a population who cannot comply with behavioural testing, the focus now shifts to a more advanced application within the ASSEP arsenal. Subsequently the suitability of sound-field presentation as a method for obtaining objective, frequency specific hearing thresholds, will be argued.

2.3.7 Calibration

Calibration is carried out for two reasons. First, it establishes the relationship between the sound pressure level (measured at some point) and the corresponding attenuator setting on the signal generator. Secondly, it establishes the sound pressure level corresponding to normal thresholds (audiometric zero) so that an individual clients' hearing levels may be compared to this standard.

For all complex stimuli, when use in the sound field, the intensity at the subjects ear will vary with time (Walker et al., 1984), because peaks and troughs in the room's frequency response are sequentially excited as the tone sweeps across the frequency. Calibration levels of acceptable accuracy by the simple method of reading peak deflections of a sound level meter set to "route mean square-fast" mode. When calibration is performed in this way thresholds/responses obtained in the sound field, with any type of complex stimulus, can be related to stimulus levels obtained under earphone presentation with pure tones (Walker et al., 1984). This eliminates the need to establish normative data for individual test environments (Walker et al., 1984). It is, however necessary to use conversion figures when comparing thresholds or responses obtained under different transducers. Therefore thresholds obtained under sound field conditions should correspond to thresholds obtained under earphone conditions.

2.3.8 Possible Advantages of ASSEP over other Techniques in the Estimation of Aided Thresholds

After the Second World War, Carhart (1946) described and applied a so-called objective technique for hearing aid selection (Hall & Ruth, 1985). According to his technique four parameters, namely effective hearing aid gain, tolerance for amplified sound, speech discrimination in quiet as well as in background noise had to be measured. According to Hall & Ruth (1985) his method can be described as objective because it relies on quantitative audiometric data rather than depending entirely on subjective impressions from the patient.

Various procedures have been developed to ensure appropriate selection and fitting of amplification. As these procedures have been extensively reviewed by previous studies (Harford, 1979; Libby, 1985), they will not be discussed in depth in the current study. Rather, the current study will discuss the advantages and disadvantages of these techniques and compare them with the characteristics of the ASSEP technique in an attempt to highlight possible advantages.

Several fitting formulas (Berger, 1976; Fletcher, 1952), such as the half-gain rule and Bragg converter (Bragg, 1977) and the selective amplification technique (Victoreen, 1973; Watson & Knudson, 1940) have been used in the past. Since the $2cm^3$ coupler and the modified Kemar coupler (Romanov, 1942; Wisniewsky, 1970) only offers approximate real-ear conditions (Hall & Ruth, 1985), hearing aid performance often differs substantially from these measures.

Even functional gain measures, obtained under sound-field conditions, incur certain problematic influences. The characteristics of the sound differ substantially due to individual differences in head diffraction, head shadow effect (Hall & Mueller, 1997) and “body baffle” (Hall & Ruth, 1985). These individual differences, with specific reference to the ear canal volume, diameter and length of the canal, are unique for each person and are markedly different between adults and infants (Hall & Ruth, 1985). Therefore, valid and reliable measurement of hearing aid function is dependent on the specific amplification device being fitted, the specific mould attached to the aid and the specific hearing-impaired individual being fitted. Although most hearing aid fitting procedures take this factor into account (McCandless & Lyregaard, 1983; Moodie et al, 1994; Seewald et al., 1985), this process is demanding even when testing co-operative individuals. However, when infants and others within the difficult-to-test population undergo fitting procedures these demands are aggravated (Seewald et al., 1985).

Taking into account that these measures are reliant on accurate behavioural thresholds (Stelmachowicz & Lewis, 1988) and that behavioural results obtained from infants and other individuals, of all ages, within the difficult-to-test population are often unreliable (Picton et al., 1998) it becomes evident why this process has been described as "a matter of luck and intuition" (Picton et al., 1998:329). When considering that early identification of hearing loss is only valuable if it leads to aggressive (Hall & Ruth, 1985) and appropriate management, it seems that an objective technique that is able to measure the benefits of appropriate hearing aid fitting is required.

Subsequently the use of auditory brainstem responses, as well as the possible application of ASSEPs will be evaluated, on a comparative basis, to establish the most appropriate "objective" technique for the selection and fitting of amplification devices. The comparison will be based on the stimulus used, the response obtained, the transducer employed and the state of consciousness of the individual.

- **Stimulus Characteristics:**

As mentioned earlier, the use of real-ear measures is reliant on accurate behavioural thresholds. However, this is not the only complication that inhibits the use of real ear measures, and especially in the difficult-to-test population. Probe tube placement and the maintenance thereof in infants and uncooperative patients can be extremely challenging (Picton et al., 1998). Thus, other factors rather than the broadband stimulation employed during the recording of real ear measures precludes these measures from providing reliable data within the clinical setup.

While subjective measures such as functional gain are reliant on behavioural responses for both unaided and aided measures, objective measures such as, for example the auditory brainstem response are reliant on aided and unaided electro-physiological thresholds that do not require any behavioural responses from the individual (Beauchaine & Gorga, 1988). Previous investigations (Beauchaine & Gorga, 1988; Cox & Metz, 1980), using the auditory brainstem response (ABR) employed click and tone burst stimulation and evaluated component latencies, thresholds and slope of latency-intensity functions under aided and unaided conditions.

According to Cox & Metz (1980) the latency shift of wave V, of the ABR, could be used to select appropriate amplification. Their results indicated that the hearing aid response that produced the shortest wave V latency also provided the best speech discrimination score. However, in order to evaluate the validation of this statement it is necessary to critically evaluate the type of stimulus used by the ABR.

Because click-evoked ABRs originate from the basal regions of the cochlea, it is highly unlikely that the technique would be able to differentiate between aids that employ various amounts of low frequency gain (Beauchaine & Gorga, 1988). Also low frequency stimulation may cause artifacts that prevent frequency specific measurements (Hall & Ruth, 1985; Kileny, 1982; Mahoney, 1985). Both click- and tone burst stimulation, because of their short duration, is more likely to distort in both the sound-field speaker and the hearing aid amplifier (Picton et al., 1998).

Other studies investigating the appropriateness of tone burst stimulation (Stapells et al., 1995; Stapells et al., 1990) have indicated that although this technique shows some ability to investigate low frequency hearing, it is also restricted due to its maximum presentation levels (Rance et al., 1998). Thus, hearing losses that exceed 105 dB nHL cannot be investigated with tone burst ABR measures (Rance et al., 1998) and in cases of severe to profound losses the absence of ABR responses at high intensities cannot exclude hearing aid benefit (Beauchaine & Gorga, 1988).

Furthermore, click stimulation is dependant on the integrity of the basal regions of the cochlea, thus implying that hearing sensitivity can only be estimated for the higher frequency region (Beauchaine & Gorga, 1988). While tone burst stimulation provides more frequency specific measurements, these measurements can be rather time consuming (Beauchaine & Gorga, 1988) and may cause feedback that may last as long as 20 milliseconds after stimulus onset (Kileny, 1982). Subsequent research by Serpanos, O'Malley and Gravel (1997) demonstrated that the correlation between wave V latency and loudness appears to be low. Lastly, hearing aids handle rapidly changing stimuli (such as click and tone burst stimulation) differently from more continuous stimuli (such as speech) and it is difficult, therefore, to predict the steady state characteristics of hearing aids from responses evoked by short duration stimuli (Gorga, Beauchaine & Reiland, 1987).

In contrast, ASSEP testing using modulated tones offers significant advantages over techniques that employ brief duration stimuli. Because the tones are continuous they do not suffer from spectral distortion associated with brief duration stimuli such as the click stimuli employed by the ABR (Rance et al., 1998). The ASSEP offers frequency specificity (Rance et al., 1998), which allows for the generation of evoked potential audiograms, accurately reflecting the configuration of the hearing loss (Lins et al., 1996; Rance et al., 1995). The continuous nature of the stimuli also offers presentation level advantages, which relates to presentation levels as high as 120 dB HL. Thus, even minimal amounts of residual hearing can be investigated with the ASSEP technique (Rance et al., 1995). Various studies (Herdman & Stapells, 2000; Perez-Abalo et al., 2001; Picton et al., 1998) have found a close relation between the actual hearing thresholds and the threshold estimations obtained through ASSEP testing.

In summary, electro-physiological measures provide information regarding the perception of sound (HL) and not only regarding the signal at the eardrum (SPL). ASSEP, furthermore, provides several advantages over other evoked potential techniques such as the ABR, limiting the amount of useless responses (Rance et al., 1998).

- **Response Characteristics:**

Auditory brainstem responses are measured in the time domain. Recording of responses incurs some problems because the hearing aid acts as a filter or amplifier and will thus alter the time waveform and amplitude spectra of the stimulus (Beauchaine & Gorga, 1985). As mentioned earlier in this section the hearing aid might introduce electro-magnetic artifacts that can distort the response waveform.

This phenomenon will be aggravated if the hearing aid is in close proximity to the recording electrode (Beauchaine & Gorga, 1985).

As regular repeating stimuli evoke the ASSEP the response stabilizes after the initial few stimuli (Picton et al., 1998). Thereafter the response contains constituent frequency components that remain constant in amplitude and phase over time (Regan, 1989). It logically follows then that when these responses are evoked by amplitude modulated tones that are frequency specific and stable over time, the likelihood of distortion in either the sound-field speaker or the hearing aid amplifier is limited (Picton et al., 1998). Also, the modulated tones used to elicit ASSEPs are similar to the warble tones use in behavioural assessment (Rance et al., 1995).

Again, the ASSEP offers some advantages over the ABR technique, in that response detection is "double" objective. In other words no response is required from the individual being tested and, no interpretation is required from the clinician conducting the test (Rickards et al., 1994). Responses are measured in the frequency domain at the frequency of modulation and some of its harmonics (Lins & Picton, 1995). Response detection is done mathematically through either an f-test or t-test. ASSEP is limited in its application to hearing sensitivity assessment, as there are no latency measures to indicate retro-cochlear lesions. Nevertheless, the application of ABR for the investigation of retro-cochlear pathology is becoming less viable due to the introduction of CT- and MRI-Scans (Jerger, Grimes, Jacobson, Albright & Moncrieff, 2000).

- **Transducer Influence:**

As discussed previously the brief nature of the stimulus employed during ABR testing show a high susceptibility to distortion in both the sound-field speaker and the hearing aid amplifier (Hall & Ruth, 1985; Kileny, 1982). Picton and colleagues (1998) hypothesized that the likelihood of distortion in either the sound-field speaker or the hearing aid amplifier is limited due to the continuous nature of the stimuli used to evoke ASSEPs. This theory has since been substantiated by preliminary research (Cone-Wesson et al., 2001; Picton et al., 2002a).

- **State of Consciousness of the Individual:**

Probe tube placement and maintenance thereof, associated with electro-acoustic measures (e.g. real-ear measures), is challenging in infants and uncooperative patients (Picton et al., 1998). Electro-physiological measures allow for assessment regardless of the state of consciousness of the individual (Aoyagi et al., 1994; Cohen et al., 1991; Lins & Picton, 1995; Rickards et al., 1994). The ASSEP therefore apply to difficult-to-test populations as it provides recordable responses at low sensation levels in sleeping and sedated subjects when modulation rates in excess of 70 Hz are used (Cohen et al., 1991; Lins & Picton, 1995). It is also reliably present in children of all ages including the neonatal population (Aoyagi et al 1993; Rickards et al., 1994). Finally, preliminary research (Cone-Wesson et al., 2001; Picton et al., 1998) has thus far supported the advantages over other techniques that have been highlighted in this section.

2.4 Sound-field as a Possible Application within the ASSEP Domain

As previously mentioned in the introduction of this study, the initial treatment of a hearing-impaired individual will typically involve the fitting of appropriate amplification (i.e. hearing aids). In adults as well as in older children amplification can be selected and adjusted according to the participants' subjective responses, as they are able to comply with audiometric testing. One of the most important factors to consider when fitting an amplification device is what gain is derived from the device. The term functional gain can be defined as the difference between audiometric thresholds with and without the device (Hawkins & Haskell, 1982). When testing infants, very young children and others within the difficult-to-test population the clinician is faced with several challenges. The most prominent of these challenges seems to be how to obtain aided and unaided thresholds when the population that is being testing, is unable to provide reliable behavioural responses to auditory stimulation.

Objective techniques such as real-ear coupler differences (RECD) and real ear insertion gain (REIG) have been employed in order to obtain measures that are equivalent to functional gain (Dillon & Murray, 1987). It is important to mention that these measurements are only of value when the actual unaided responses of the participant are known (Picton et al., 1998). There are further practical challenges when using these techniques. Probe-tube placement and low noise levels, necessary for the measurement of Real Ear Insertion Gain (REIG), is very difficult to sustain in uncooperative and very young participants (Picton et al., 1998). Thus, an objective method to measure the benefits of amplification in participants with a hearing impairment, who are unable to reliably respond to behavioural audiometry, would be of great value.

2.4.1 Stimulus Characteristics

The stimulus characteristics of amplitude modulated tones, which are frequency specific and stable over time, seems to be much less likely to be distorted during amplification in either the sound-field speaker or the hearing aid (Picton et al., 1998; Picton et al., 2002a). Results from the aforementioned studies revealed that ASSEP responses to amplitude modulated tones with modulation frequencies between 80 and 105 Hz can be recorded when stimuli are presented through a sound-field speaker and amplified by a hearing aid (Picton et al., 2002a).

The complex nature of stimuli used during ASSEP testing allows frequency specific description of the client's hearing loss, while its bandwidth allows for sufficient uniformity when testing in the reverberant field. Results obtained through preliminary research on the topic furthermore indicates that responses obtained during the unaided condition in the sound-field allows for a close comparison to behavioural thresholds obtained using earphones (Picton et al., 2002a)

2.4.2 Modulation Characteristics

Initial interest around Steady State Responses (SSR) centered on amplitude modulation rates of 40/sec (40 Hz) responses, since Galambos et al (1981) demonstrated increased amplitudes (two to three times greater), of responses, when modulation rates of 30-50/second were used instead of 10/second (Linden et al., 1985; Stapells et al., 1984). Various researchers (Dauman, Szyfter, De Sauvage & Cazals, 1984; Kankkunen & Rosenhall, 1985; Lynn et al., 1984; Sammeth & Barry, 1985; Stürzebecher, Kuhne & Berndt, 1985; Szyfter, Dauman & De Sauvage, 1984) obtained threshold determinations, using the 40 Hz technique, which were in concordance with pure tone audiometry thresholds. When comparing physiological with behavioural responses, thresholds varied between 9-35 dB (Rodriguez et al., 1986).

There was however some problems associated with the use of the 40 Hz potential, of which the greatest seemed to be that response amplitudes decreased dramatically when participants drifted into sleep (Cohen et al., 1991). The 80 Hz response, in contrast to the 40 Hz response, is not significantly affected by the participants' state of arousal (Aoyagi et al., 1993; Cohen et al., 1991; Lins & Picton, 1995), and has short apparent latencies in both sleeping and awake participants (Lins & Picton, 1995). Research (Stapells et al., 1984; Lins & Picton, 1995) has noted the differential effect of sleep on latencies as well as amplitude changes, when using the 40 Hz response compared to the 80 Hz response. These differences seem to indicate that the two responses have two distinct neural generators.

The 40 Hz Steady State still has its applications within the clinical setup. It can be used successfully for objective audiometry (Rance et al., 1995) in "awake" adults and serves as a method to monitor state of arousal during general anesthesia (Plourde & Picton, 1990). Furthermore, the involvement of the auditory corti holds exiting research possibilities (Schmulian, 2002), focused on the auditory processing of sound rather than hearing (supra-threshold levels rather than threshold levels).

Various researchers (Regan, 1989; Regan & Regan, 1993; Rickards et al., 1994) have done comparative studies on the effects of a lower versus higher modulation rate. Clinical utility of the 80 Hz ASSEP grew due to several factors. It can be reliably recorded in most populations, including infants (Rickards et al., 1994) and the response does not significantly change with changes in state of arousal or level of consciousness (Aoyagi et al., 1993). It, furthermore, offers frequency specificity (Lins et al., 1996) and easy, objective response detection above 70 Hz (Cebulla et al., 2001; Cohen et al., 1991).

Although reliable responses have been recorded when modulation rates ranging between 85 Hz and 105 Hz were used, when stimuli are presented through a sound-field speaker (Picton, 2002a), it is uncertain whether reliable responses could be obtained using modulation rates around 40 Hz. However, if responses could be evoked from 40 Hz stimulation, these responses due to their increased amplitudes and subsequent easy detection offer advantages in "awake" adult patients within the difficult-to-test populations.

2.4.3 Evoked Responses

According to Lins et al. (1996) the transduction process of the hair cells and auditory nerve fibers involves compressive rectification of the signal waveform. Therefore the compound electrical activity recorded from the cochlear nerve contains a spectral component at the rate of modulation (Lins et al., 1996), and at two side bands separated from this frequency by the frequency of the modulation signal.

It is furthermore important to remember that auditory neurons do not fire synchronously in response to high frequency sounds, as is the case with low frequency sounds (Kuwada et al., 1986). Auditory neurons do, however, fire synchronously to low frequency envelopes of high frequency signals that are amplitude modulated (Rees & Moller, 1983).

The evoked response (scalp-recorded response) reflects a combination of activity of the Steady State Response (SSR), at the modulation rate, and electrical noise produced by the brain and scalp muscles (Lins et al., 1996). A visual representation of the compound electrical activity recorded is provided in Figure 2.1.

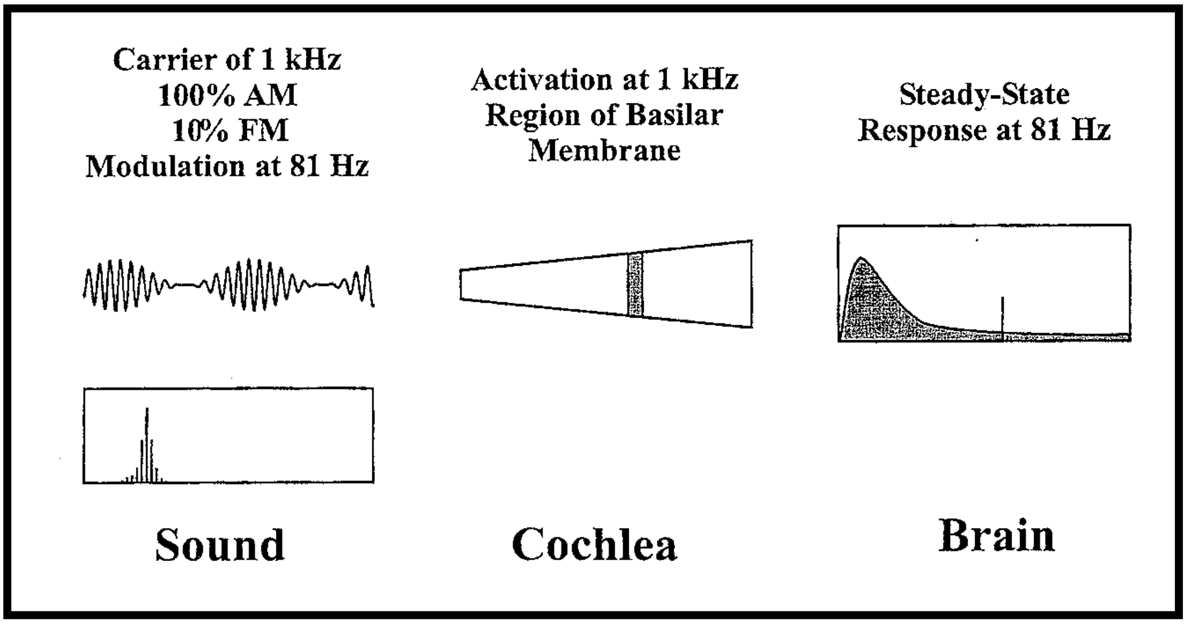


Figure 2.1 Illustration of the Electrical Activity involved in Evoked Responses (Adapted from Picton, Dimitrijevic & John, 2002c)

Because of the distinct energy displacement at the modulation frequency, and its first and second harmonics, response detection can be analyzed accurately, objectively and rapidly.

2.4.4 Automated Response Detection

Steady state evoked potentials are essentially sinusoidal responses to auditory stimuli. When the evoking stimuli are reduced in intensity or when the participants' hearing is impaired, or when the background noise (electrical or acoustical) increases, these responses become difficult to detect. Subjective analysis, by examiners, of waveform and spectrum may lead to confusion regarding the presence or absence of a response (Dobie & Wilson, 1996). Truly objective methods of response detection, with known statistical power and false-positive rates, then attain critical importance.

Evoked responses are converted from the time domain to the frequency domain through Fast Fourier Transform and are automatically detected in the frequency domain by the F-test (Schmulian, 2002). Previous research (Dobie & Wilson, 1996) has indicated that F-test is preferable to t-tests based on either root-mean-square amplitudes or dB values. When a Fast Fourier Transform (FFT) is employed it allows for the conversion of amplitude-time domain waveforms to the frequency domain, as a series of cosine waves. These waveforms are represented as a vector on a two dimensional plane (John & Picton, 2000). The responses to each carrier frequency can be assessed by the amplitude and phase of the FFT component and its correspondence to the frequency of modulation of the carrier.

Amplitudes are calculated as baseline to peak, whereas the phase of the responses was measured as the cosine onset phase of the recorded wave (Herdman & Stapells, 2001; Lins et al., 1996) when analyzing responses. The F-technique allows for objective response detection as it evaluates whether a response at a specific frequency of stimulation can be differentiated from the noise in the adjacent frequencies (Wei, 1990; Zurek, 1992). Response detection criteria are based on the "phase coherence" technique employed by Galambos et al (1981), Jerger, Chmiel, Frost & Coker (1986) and Stapells, Makeig and Galambos (1987).

Also, because the energy of the responses are found at the modulation frequency and two of its harmonics, instantaneous response detection is possible (Levi, Folsom & Dobie, 1993; Lins & Picton, 1995; Lins et al., 1996. Figure 2.2 provides a diagrammatical representation of automated response detection.

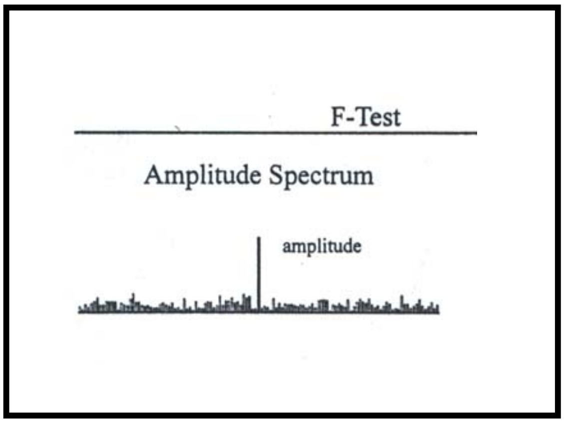


Figure 2.2 Representation of Automated Response Detection using the F-Test (Adapted from Lins et al., 1996)

2.5 Conclusion

The need for a technique that can bridge the gap between diagnosis and rehabilitation, especially within the difficult-to-test population becomes increasingly evident as the global trend towards earlier identification and rehabilitation intensifies. Although the exploration of other AEP techniques has made several advances in addressing this need, their implementation into the clinical arena has been unsuccessful due to inherent limitations.

Sound-field presentation as a possible application within the ASSEP domain, offers several advantages over other techniques previously explored, which holds the promise of finally addressing this crucial need. A summary of the advantages discussed is presented in Table 2.3

Table 2.3 A Summary of the advantages of ASSEP over other techniques

Characteristics of:	Electro-Acoustic Techniques			Implications for clinical Hearing testing
	1. Real ear insertion gain	**2. ABR**	**3. ASSEP**	
a.) Stimulus	Broad band noise	Transient: Click or Tone pips	Sustained: Sinusoidal Mixed Modulated tones	Electrophysiological measures provide information regarding perception of sound (HL) and not only regarding the signal at the eardrum (SPL). The spectral jitter associated with brief duration stimuli (ABR) is eliminated with the use of more complex stimuli (ASSEP), limiting the amount of useless responses (Rance et al., 1998).
b.) Response	Frequency domain	Time domain	Frequency domain	Response detection is double objective (ASSEP) as no response is required from the participant and no interpretation by the clinician (Rickards et al., 1994), and may be observed at the frequency of modulation and its harmonics (Lins & Picton, 1995). Subsequently no subjective interpretation required as with ABR. ASSEP provides information regarding perception and not only SPL values at the eardrum.
	Amplitude and frequency measurements	Latency and amplitude measurements	Amplitude and Phase measurements	ASSEP application is limited to hearing assessment, as there are no latency measures to indicate retro-cochlear lesions. ABR application for retro-cochlear lesions is becoming less viable due to CT- and MRI-Scans (Jerger, 2000).
c.) Transducer	Sound-field Speaker	Sound-field Speaker	Sound-field Speaker	Brief nature of the ABR stimuli shos high susceptibility to distortion in the sound-field speaker and the hearing aid (Kileny, 1982; Hall & Ruth, 1985). Complex stimuli of the ASSEP do not distort in the sound-field speaker or hearing aid (Picton et al., 2002a).
d.) Participant state of consciousness	Awake/ Asleep in infants	Awake/Asleep	Awake/Asleep	Probe tube placement and maintenance of its position, associated with REIG, is challenging in infants and uncooperative participants (Picton et al., 1998). Electro-physiological measures allow for assessment regardless of state of consciousness (Aoyagi et al., 1994; Cohen et al., 1991; Lins & Picton, 1995; Rickards et al., 1994)

2.6 Summary

This chapter aimed to provide a theoretical framework as support for the empirical research component. To achieve this aim the chapter was subdivided into three sections. The first section focused on the application of Sound-field Audiometry and its advantages and limitations. Comprehensive recommendations for conducting Sound-field Audiometry were described, critically evaluated and discussed. These recommendations have their foundation based on research data available and highlight the most appropriate method for conducting Sound-field Audiometry.

The second section focused on ASSEPs. Although the final goal of the current research endeavour has its focus on a more advanced application of ASSEPs, it remains important to delineate the current application value thereof. The technique was defined and discussed according to its physiological basis. A brief description of its stimulation and modulation characteristics, as well as evoked responses and the automated detection thereof, was provided. These discussions formed the basis for the critical evaluation of Sound-field Audiometry as a possible application within the ASSEP domain, which formed the last section of this chapter.

Finally the application of Sound-field Audiometry within the ASSEP domain was critically evaluated. The focus was on audiometric variables that apply to ASSEP testing, the current clinical application of ASSEPs, research applications, current research available regarding the application of Sound-field Audiometry within the ASSEP domain and the advantages over other techniques currently available.

CHAPTER THREE: Research Methodology

Aim: To provide the method used to conduct the empirical research component of this study.

3.1 Introduction

In chapter one the problem surrounding the current research endeavour was introduced. It provided an orientation, described the terminology and presented an overview of the content and organization of the study. Chapter two aimed to provide a theoretical framework, as a support for the empirical research component. It specified concepts and constructs and furthermore provided a critical evaluation and interpretation of the relevant literature available.

This chapter provides the methodological approach implemented in conducting the empirical component of the current study. The chapter is discussed according to the synopsis presented in figure 3.1 below.

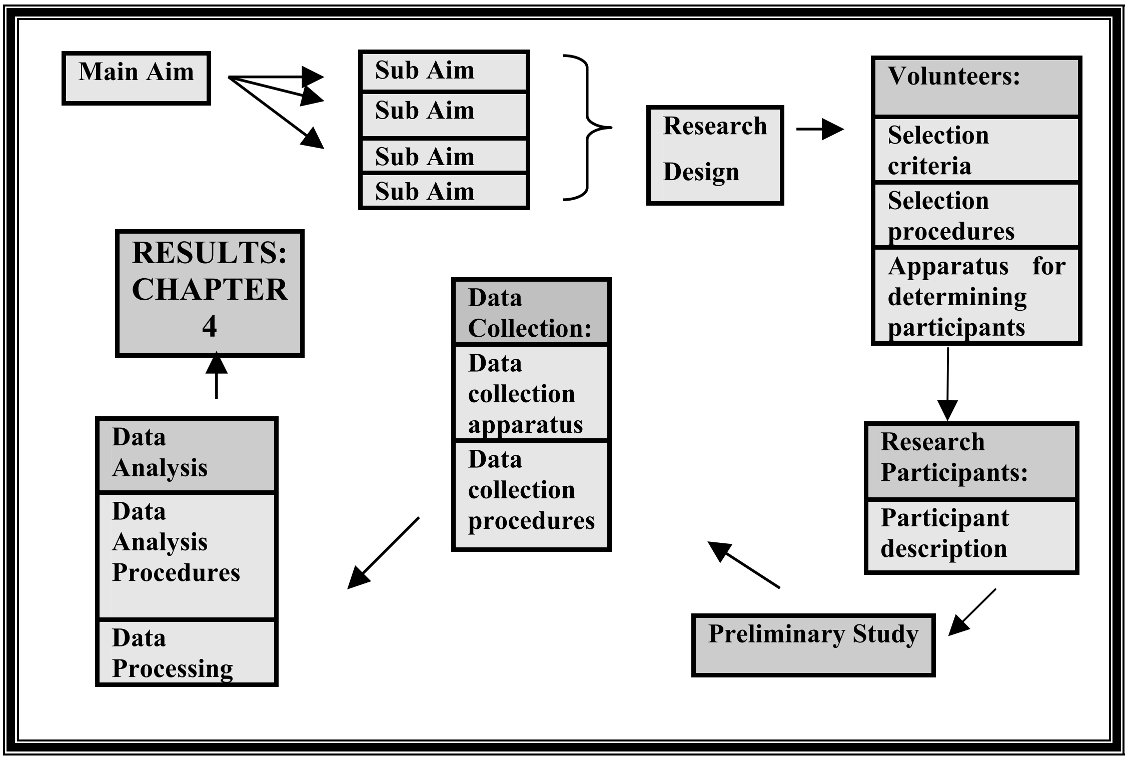


Figure 3.1 Chapter Outline

3.2 Aims of Research

Although previous studies (Aoyagi et al., 1996; Lins et al., 1995; Perez-Abalo et al., 2001; Rance et al., 1998) have already established ASSEP as an objective clinical procedure for hearing threshold estimation, across a range of frequencies, less attention has been paid to aided threshold estimation in the difficult-to-test populations. Preliminary studies (Picton et al., 1998; Cone-Wesson et al., 2001) have shown promising initial results, when recording ASSEP using sound-field stimulation.

The need now arises to validate these preliminary findings as accurate and reliable. Validation of these preliminary findings depends on further investigation of threshold estimation through sound-field stimulation using a monotic ASSEP technique. The current study centered on normal-hearing adults in an attempt to provide normative data for the monotic ASSEP technique, through sound-field stimulation. The importance of this technique, should it gain clinical application, becomes evident when we consider the advantage for assessment of amplification, in the difficult-to-test population (Picton et al., 2002a). For this purpose it is of critical importance that the technique has to be standardized. Standardization of any technique is dependent on normative data as the validation thereof. Therefore the main aim of the current study is:

3.2.1 Main Aim

To compare minimum response levels obtained from the monotic ASSEP technique using insert earphones and sound-field speaker presentation, in a group of normal-hearing adults.

The following sub-aims were formulated in order to realize the main aim of the study:

3.2.2 Sub-aims

- ✓ To compare pure tone-, frequency modulated (FM) and mixed modulated (AM/FM) tone behavioural thresholds at 0.5, 1, 2 & 4 kHz under insert earphone and sound-field speaker conditions.

- ✓ To compare minimum response levels at 0.5, 1, 2 and 4 kHz obtained with a monotic ASSEP technique under insert earphone and sound-field speaker conditions.
- ✓ To compare the actual behavioural thresholds (for pure tone, FM and mixed modulated tone stimulation) with the GSI AUDERA system's accuracy in predicting these thresholds by means of an algorithm for insert earphone and sound-field conditions.

3.3 Research Design

In order to achieve the aims of the study, a comparative, within-group experimental design (Graziano & Raulin, 2000) was selected. Within-group designs are true experimental designs and are quite similar to the more common pretest-posttest control group design (Graziano & Raulin, 2000; Leedy, 1997). The within-group design has three basic characteristics: each participant is tested under each experimental condition, scores in each condition is correlated with scores in other conditions and the critical comparison is the difference between correlated groups on the dependant variable (Graziano & Raulin, 2000). For within participant designs, participants are sampled from a target or accessible population, and each participant is exposed to all the experimental conditions: "In essence, each participant serves as his or her own control" (Graziano & Raulin, 2000; 248). Therefore, sampling errors are eliminated, as all participants are tested under all conditions. Hence, the suitability of this specific research design for the current study is emphasized.

<u>Strengths and weaknesses of the design:</u>

There is a similarity between within-participant designs and single group pretest-posttest designs, in that the same participant is tested under each condition (Graziano & Raulin, 2000). However in the pretest-posttest design, participants respond first to the pretest and then the posttest. The within-group designs, in contrast, allow for participants to be tested under each condition but with no fixed order of presentation (Graziano & Raulin, 2000). This order effect is particularly important and it contributes to reducing the possibility of a practice effect occurring (Graziano & Raulin, 2000).

This design also holds important advantages as the same participants are tested in each condition and subsequently there can be no group differences due to sampling errors. This suggests that participants are equal at the start of the study. If participants were not equal to start with it would be impossible to deduce whether the differences were due to the experimental manipulation or to the pre-existing differences within the group (Graziano & Raulin, 2000). Therefore, the larger the individual differences between participants, the greater the benefit derived from within-participant designs, as a within-participant design not only controls, but also eliminates the variance due to individual differences, thereby reducing error variance (Graziano & Raulin, 2000). Because research participants in the current study were selected from a predetermined “quota” (discussed under 3.4.2), and not through random selection, this design holds an important advantage as it eliminates individual differences, thereby relating the deductions to experimental manipulation rather than inter-participant variability.

Another advantage of this type of design further contributes to efficiency. Because the same participants are tested under several conditions instructions can be given once instead of at the beginning of each condition, or at least will require only slight modification for each condition. When instructions are complicated or when a practice period is part of the instructions, timesaving could be considerable (Graziano & Raulin, 2000). As research participants will be tested with both behavioural, as well as electro-physiological techniques, and under both insert earphone- and sound-field conditions, the expected test time will be considerable. As a result, increased efficiency will contribute to minimizing participant fatigue, as well as test time.

Despite the advantages offered by this design, there are also disadvantages relating to the within-group design. For example, with regard to the sequence effect, the same participants are exposed to a number of different conditions. Thus, the experience participants have in one condition might affect how they respond to the subsequent conditions (Graziano & Raulin, 2000). Hence, if differences were found between the conditions of an experiment, they may not be due to the manipulation of the independent variable but to the compounding effects of one condition on later conditions (Graziano & Raulin, 2000).

Sequence effects can occur in within-participant designs and should be controlled by varying the presentation of conditions (Graziano & Raulin, 2000). There are two important types of sequence effects that are relevant to this study, namely practice effects and carry-over effects.

Practice effects are caused by participants' practice and growing experience as they move through the successive conditions. Disadvantages because of practice effects are not related to any particular condition, but rather to the participants' growing familiarity with the conditions. Practice effects can be either negative (e.g. due to fatigue) or positive (due to familiarity). **Carry-over effects** are sequence effects due to the influence of a particular condition, or combination of conditions, on the responses following in subsequent conditions. Presentations of conditions were varied so that each condition was represented in all of the possible orders of presentation, the same amount of times.

This random order of presentation constitutes the only sure way to counteract for practice- and carry-over effects. Table 3.1 below provides a visual representation of how practice and carry-over effects were counterbalanced. Letters of the alphabet (e.g. A, B, C etc.) represent various conditions. Thus, each participant (e.g. 1,2,3 etc.) was tested with conditions presented in a different order, as represented in Table 3.1 below.

Table 3.1 Counterbalancing of Practice- and Carry-over effects

Participants	Order of Presentation: →						
1.	A	B	C	D	E	F	G
2.	B	C	D	E	F	G	A
3.	C	D	E	F	G	A	B
4.	D	E	F	G	A	B	C
5.	E	F	G	A	B	C	D
6.	F	G	A	B	C	D	E
7.	G	A	B	C	D	E	F
8.	F	E	D	C	B	A	G
9.	E	D	C	B	A	G	F
10.	D	C	B	A	G	F	E
11.	C	B	A	G	F	E	D
12.	B	A	G	F	E	D	C
13.	A	G	F	E	D	C	B
14.	G	F	E	D	C	B	A

Fundamental to the experimental design is the nature of the relationship between the dependent and independent variables. It is important to be aware of the variables in a particular experiment as they may impact on the results of a study.

Figure 3.2 below, provides a schematic representation of the relationship between the Independent-, the Dependent- and the Controlled variables within the experimental setting in this study.

Key for Figure 3.2:

➢ **Independent Variables:**

i. Behavioural pure tone testing under insert earphones
ii. Behavioural frequency modulated (FM) tones testing under sound-field speakers
iii. Behavioural mixed modulated (AM/FM) tone testing under insert earphones
iv. Behavioral mixed modulated (AM/FM) tone testing under sound field speakers
v. A monotic auditory steady state evoked potential technique under insert earphones
vi. A monotic auditory steady state evoked potential technique under sound-field speakers

➢ **Measured or dependent variables:**

a. Pure tone thresholds obtained at 0.5, 1, 2 and 4 kHz during behavioural pure tone testing under insert earphones
b. FM tone thresholds obtained at 0.5, 1, 2 and 4 kHz during behavioural pure tone testing under sound-field speakers
c. Thresholds obtained at 0.5, 1, 2 and 4 kHz during behavioural mixed modulated tone testing under insert earphones
d. Thresholds obtained at 0.5, 1, 2 and $ kHz during behavioural mixed modulated tone testing under sound-field speakers
e. Minimum response levels obtained at 0.5, 1, 2 and 4 kHz during monotic ASSEP recordings under insert earphones
f. Minimum response levels obtained at 0.5, 1, 2 and 4 kHz during monotic ASSEP recordings under sound-field speakers

➢ **Controlled variables:**

I. Test environment
II. Hearing ability of the participants
III. Age of the participants
IV. Gender of the participants

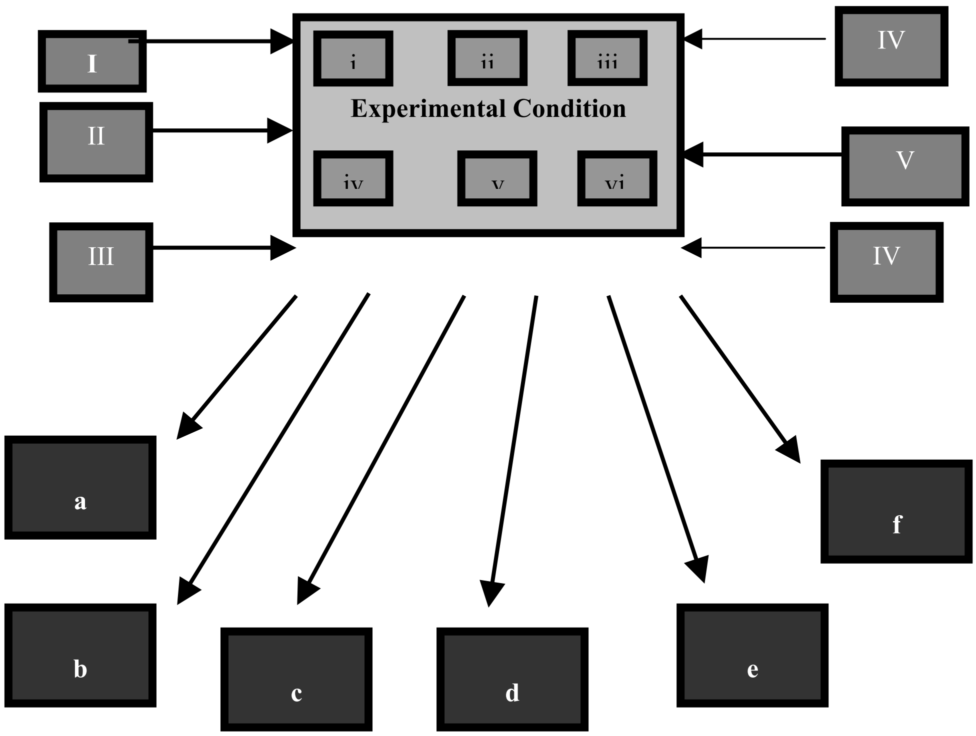


Figure 3.2 Relationship between Independent-, Dependent- and Controlled Variables

As can be seen from Figure 3.2 there are 4 co-variables (age, gender, hearing ability and test environment) that have an influence on the experimental setting. Within the experimental setting there are also 6 independent variables (behavioural pure tone testing under insert earphones, behavioural FM tone testing under sound-field speaker presentation, behavioural modulated tone testing under both insert earphone and sound field speaker conditions, and the monotic ASSEP technique, under insert earphone and sound-field speaker conditions). And, finally, there are 6 dependant variables (the thresholds relating to pure tone audiometry and the behavioural thresholds and minimal response levels relating to monotic ASSEP technique) that result from the experimental setting.

3.4 Volunteers

A total of 35 people volunteered to take part in the current study. Selection criteria were stipulated for the selection of participants. These criteria will be discussed below with specific reference to: informed consent, otoscopic examination, middle ear functioning and behavioural pure tone results.

3.4.1 Selection Criteria:

The University of Pretoria's Research and Ethics Committee was approached for permission to conduct this study. (Appendix A). Once permission was obtained certain selection criteria was set for participant selection. These criteria are discussed with reference to the rationale behind each.

3.4.1.1 Normal-hearing

Firstly, all participants were required to have hearing thresholds within the normal range (0-25dB HL) across all the frequencies tested, namely 0.5, 1, 2 & 4 kHz (Roeser, Valente & Hosford-Dunn, 2000b). This criterion was stipulated, as the aim of the current research was to collect normative data.

3.4.1.2 Normal Middle Ear Functioning

Participants were required to have normal middle ear functioning. Conductive hearing losses and/or components have an influence on the peripheral hearing (Hall & Mueller, 1997) and thus also indirectly on the results obtained from ASSEP, specifically the amplitude of the steady state response (Yantis, 1994a; Yantis, 1994b; Hall & Mueller, 1997). Furthermore, normal-hearing sensitivity does not exclude the presence of middle ear pathology (Martin, 1997; Stach, 1998). Participants were subsequently required to have normal otoscopic results as well as normal middle ear functioning.

3.4.1.3 Age Distribution

Participants were required to be between the ages of 15 and 40 years of age. This stipulation was made even though auditory evoked potentials can be elicited from persons of any age, from neonates through to people in their ninth decade (Abramovich, 1990; Hecox & Galambos, 1974). There are however some characteristics that do change with age such as latencies, amplitudes and general configuration (Goldstein & Aldrich, 1999). The lower age range was selected, as there are certain differences between neonatal and adult AEPs, especially concerning low and high frequency sensitivity (Wolf & Goldstein, 1980).

3.4.1.4 Gender Distribution

The last criterion was that equal numbers of male and female volunteer participants were selected. This criterion was considered important as head size may affect latencies and amplitudes recorded for evoked responses (Watson, 1996; Goldstein & Aldrich, 1999). Some researchers believe that head size rather than intrinsic gender differences account for the different latency values in men and women (Dempsey, Censoprano and Mazor, 1986). Thus, in order to counteract the possibility of differences due to head size (in particular, in women), participants were selected to reflect a relatively even gender distribution.

3.4.2 Selection Procedures

Volunteer participants were selected, through non-probability quota sampling (Moore, 2000; Neuman, 1997). According to Moore (2000) quota sampling implies that people will not have an equal chance at being selected, but instead that the researcher decides which types of people he/she would like to select (Moore, 2000). Participants were selected according to the selection criteria, as well as their availability (time constraints on the part of the volunteers). All volunteer participants underwent the following participant selection procedures in order to establish their suitability for participation in the study.

The researcher telephonically contacted participants volunteering for the project and a suitable time was arranged for discussion of informed consent. All volunteers were briefed on the non-invasive nature of the procedures and the time involved in the execution of the procedure. The objective of the study was highlighted and volunteers were assured that all biographical information would be treated confidentially. Volunteers were furthermore informed that they would be able to obtain copies of the results should they request them. Once informed consent was obtained, a suitable time was made for the selection criteria testing, in order to establish which of the volunteers would be selected as participants during the study itself. A copy of the informed consent form can be found in Appendix B.

The first examination for participant selection criteria was an otoscopic examination of the external meatus. This examination was conducted to identify any possible pathology that could cause a conductive hearing loss (Ginsberg & White, 1994). In order to pass the otoscopic examination all participants were required to have at least an identifiable light reflex, while position, color and transparency of the tympanic membrane was also taken into consideration (Silman & Silverman, 1991).

Immediately after meeting the minimum criteria for the otoscopic examination, estimation of acoustic immittance at the tympanic membrane as a function of air pressure was investigated. This procedure is known as tympanometry. Participants were required to have type A tympanogram (Martin, 1994). The normative data for type A Tympanograms can be found in Appendix C.

Finally, pure tone audiograms were obtained form all volunteers to determine whether they had hearing sensitivity within the normal range. The normative data relating to hearing sensitivity can also be found in Appendix C. Those volunteers that did not meet the selection criteria were debriefed and referrals were made where appropriate.

3.4.3 Selection Apparatus

- The otoscopic examination of the external meatus and tympanic membrane was performed with a **Heine Minilux 2000** otoscope.
- A tympanometric evaluation of the middle ear was performed using the **GSI-33 Middle Ear Analyzer**. The apparatus met the requirements set out by the South African Buro of Standards (SABS) and was calibrated in January 2002.
- Pure tone behavioural thresholds were obtained using the **GSI-61 Clinical Audiometer**. The audiometer is fitted with **Bio-Logic Earlink Foam Eartips for insert earphones**. Behavioural pure tone stimuli were available in steady tones for the insert earphones and in warble tones for the sound-field speaker stimulation. The apparatus meets with the requirements set out by the SABS and was calibrated in January 2002. The audiometer is housed in a single-walled soundproof booth.

3.5 Participants

Following the selection criteria, 25 participants were selected according to non-probability quota sampling. These participants took part in the research endeavour and their behavioural pure tone thresholds, behavioural FM thresholds, behavioural mixed modulated thresholds as well as their minimum response levels formed the data basis of the current study. A description of the participants selected will subsequently follow.

3.5.1 Description of Participants

The total sample (25 participants/50 ears) consisted of 13 females (52%) and 12 males (48%). Participant age ranged between 15 and 36 with a mean of 23.4. The median was 22.5 and the mode 22. The standard deviation was 4.3. All of the participants met the requirements stipulated in the 3.4.1 (criteria for the selection of participants). All the participants were selected according to non-probability quota sampling. Participants were coded as N1-N25. In all 50 ears were tested in each of the test conditions. A graphical representation of age distribution is provided in 3.3 below.

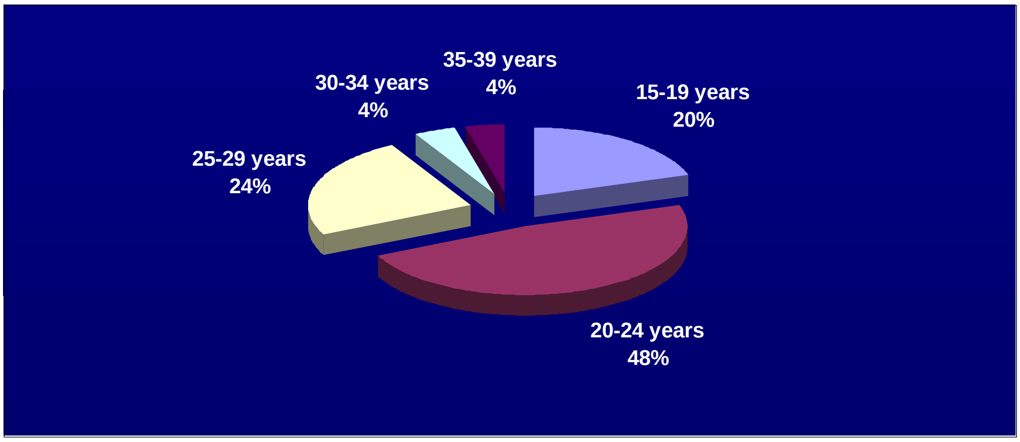


Figure 3.3 Age Distribution of the Participants according to age intervals (in years) and percentages

3.6 Preliminary Study

Before the data for the current research endeavour was collected, a preliminary study was performed in order to determine clinical accountability of the stimulus parameters. Two participants volunteered to be part of the preliminary study. Both of these participants met the criteria stipulated under criteria for the selection of participants (3.4.1).

3.6.1 Aim:

- To determine the appropriate stimulus parameters for the monotic ASSEP technique
- To determine the threshold criteria for electro-physiological testing
- To determine the required time for the completion of the test procedures for a single participant, in order to plan the data collection procedures.
- To determine the appropriate placement of the test equipment and positioning of the participants

3.6.2 Procedures

- **Determination of the Stimulus Parameters for the ASSEP Technique**
  Electrodes were fixed with electrolytic paste to the scalp at Fz (positive), Test ear (negative) and non-test ear (ground). Impedance levels were maintained below 7000 Ohms. The bio-electric activity was amplified with a gain of 100 000 and analogue filtered between 30 and 300 Hz. The notch filter was activated at 50 Hz to avoid line interference. Sixty-four samples were

averaged in a response, as per manufacturer specification. Response significance was monitored with the vector view window and the probability curve window. The presence of a response was determined using the F-test for hidden periodicity in order to test the amplitude of the spectrum at each modulation frequency against the 120 adjacent bins for significant amplitude difference. Artifact rejection was performed with shorter epoch sections of 512 points. Amplitude was used as the criterion for rejection. A rejection level of 50 micro Volts was specified to reject any responses with amplitudes greater than the specified value. A no-response was annotated after 40 epochs while the minimum response level for each frequency in each ear was taken as the threshold.

The recordings for both volunteers revealed minimum response levels that closely approximated their behavioural thresholds (20-30 dB HL mean difference to the behavioural threshold). Responses were readily identifiable with both the 40 Hz and 80-110 Hz modulation techniques, when these techniques were appropriately varied (depending on the volunteers' state of consciousness). No modifications were made to these parameters during the data collection of the current study.

- **Determination of Threshold Criteria for Electro-Physiological Testing**

All stimulation commenced at supra threshold level. Initial intensity was presented at 50 dB HL, as prescribed by Swanepoel (2001). A descending threshold seeking procedure was implemented, and intensities were decreased in 10 dB steps. When a no-response was recorded the intensity level was raised in 5 dB steps, until a response was recorded. The minimum response level was taken as the intensity level where the last response was recorded. Due to time constraints the lowest intensity level where a minimum response level was recorded, was accepted as the electro-physiological threshold, regardless of whether testing at lower intensity levels revealed a no-response or a noise response, during the data collection of the current study. Also, instead of commencing with stimulation at 50 dB HL, electro-physiological testing commenced at 20 dB HL above the behavioural pure tone threshold (obtained for the specific transducer), during the data collection of the current study.

➢ **Determination of the Time required for the Completion of all the Test Procedures**

In order to schedule appointments with the future participants a test battery was performed during the preliminary study to determine the amount of time that will be required for the assessment of each participant. As seen in Table 3.2 the complete assessment lasted for approximately two hours for each participant.

Table 3.2 Approximate time required for the assessment of a single participant

Test Procedure	Test time
Otoscopic examination and Tympanometry	5 minutes
Behavioural pure tone Audiometry (using insert earphones and sound-field speaker presentation)	15 minutes
Behavioural monotic ASSEP thresholds (using insert earphones and sound-field speaker presentation)	15 minutes
Monotic ASSEP minimum response levels (using insert earphones)	40 minutes
Monotic ASSEP minimum response levels (using sound-field speaker presentation)	40 minutes
TOTAL TESTING TIME	1 Hour and 55 minutes

From the above table (3.2) it is clear that the otoscopic examination, tympanometry and all the behavioural thresholds were obtained in approximately 35 minutes. The researcher recorded these times. Minimum response levels obtained with the monotic ASSEP technique took approximately 40 minutes when the insert earphones were used, as well as when the sound-field speaker was used. The software recorded the time of the recording (although not the time involved in participant preparation).

➢ **Determination of appropriate placement of the test equipment and positioning of the participants**

The preliminary study was conducted in an audiometric test room (the same audiometric room was later used for the data collection). Figure 3.4 shows the plan of the test room, the placement of the speakers as well as the test positions for both the behavioural measures and the electro-physiological measures.

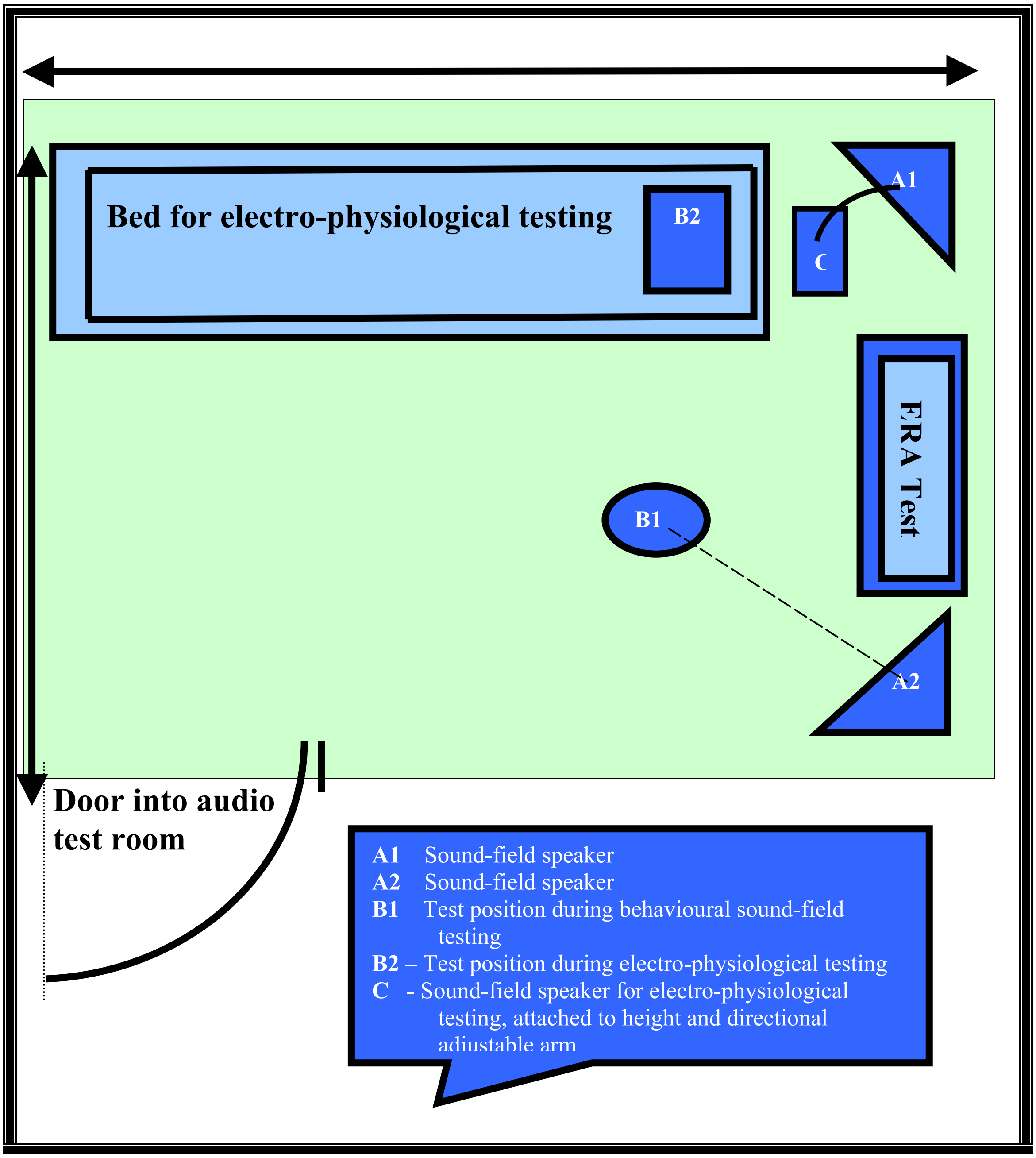


Figure 3.4 Plan of the test room showing the lay out of the room, the position of the speakers as well as the test positions for behavioural and electro-physiological measures

The test room was an audiometric test booth, "Controlled Acoustics Environment" with internal floor dimensions 2.55m x 2.75m and height 2m. The booth is equipped with two sound-field speakers attached to the wall. The speakers are positioned at 45º angles from the wall, facing the test position. The cone of each speaker is roughly at head level of a seated adult, 1.2 m from the floor (Walker et al., 1984). The test position during behavioural sound-field measures was exactly 1 m away from the speaker. The position was identified for each participant individually, so that the test point was at the centre of the participants' head (Beynon & Munro, 1995). Participants were required to minimize their head-movements as far as possible (Walker et al., 1984) and these movements, if present, were monitored by the audiologist. If there was any concern that the positioning of the participants' head was altered the test point was re-identified. The seat used, was height adjustable, to ensure that the participants head was at the centre of the speakers' cone.

Simple control measurements were made of the sound level of the FM tones at the reference point and at points 10 cm from the reference point along longitudinal, transverse and vertical lines at all test frequencies (0.5, 1, 2 & 4 kHz). The measurements were made with a modulation frequency of 20 Hz and frequency deviations 4 and 25%. The non-test ear was fitted with a wax plug during measurements (Picton et al., 1998). Hearing thresholds were determined using an ascending method of testing, with 10 dB increments until a response from the participant was obtained and then decreased in a 5 dB increment. This procedure was followed until a minimum response level was obtained 50% of the time. This level was taken as the audiometric threshold for that specific frequency.

Electro-physiological measurements were made while the participant was lying, comfortably on a bed. The sound-field speaker was mounted on a movable, height-adjustable arm. The speaker was placed directly in line with the centre of the participants' head, at exactly 0.5 m away. The speaker was then secured in place. Participants were instructed to try and minimize head-movements (Walker et al., 1984). The audiologist monitored the participant throughout the measurements to ensure that the test position was accurately maintained.

- **Determination of appropriate calibration**

Test stimuli were calibrated using procedures outlined by Walker et al. (1984), ISO DP 8253/2 (1989), Beynon and Munro (1995), ANSI S3.6 and Picton et al. (1998) for quasi free field conditions. The sound field was determined for each FM stimulus with the research participant and chair absent. The sound pressure level (SPL) was measured at the reference test point and at six neighboring positions (15cm anterior, posterior, to the left, to the right, above and below the test point). The stimuli was measured using a Brüel and Kjaer Model 2209 sound level meter with a 1 inch Model 4145 condenser microphone. The mean of the seven SPL measurements was used as the calibrated level of each stimulus. The 1 kHz and 2 kHz stimuli showed a level 5 dB greater than that of the 0.5 kHz and 4 kHz stimuli, for equivalent electrical input to the speaker, as was the case in the study conducted by Picton et al. (1998).

The standard deviation values of the seven SPL measurements were used to estimate the spatial variability of the sound field for each stimulus. Standard deviations were similar to those obtained by Picton et al. (1998) and Beynon and Munro (1995). For the stimuli used during the current research project standard deviations, as an estimate of the error in the threshold measurement arising from the sound field variability was +/- 3.9 dB (0.5 kHz), 3.8 dB (1 kHz), 2.5 dB (2 kHz) and 2.4 dB (4 kHz).

3.7 Data Collection

3.7.1 Data Collection Apparatus

- Pure tone thresholds were obtained from the participants using a **GSI 61 Clinical Audiometer**, calibrated January 2002. Pure tone stimuli were presented in steady tones through **Bio-Logic Earlink Foam Eartips for insert earphones** and FM (warble) tones for sound-field presentation, in **a single- walled soundproof booth**.
- Monotic ASSEP recordings were obtained with the **GSI AUDERA** system (School of Audiology, University of Melbourne, Australia), an AUDERA prototype. The equipment consists of a specialized Software component connected to a Pentium Laptop Computer, a serial cable, an GSI AUDERA system Unit, a fiber-optic cable, an EEG amplifier, tube phones and electrodes. The system is operated by a software package specifically designed for the acquisition and analysis of auditory evoked responses (AER) at varying frequencies and sound levels as well as simultaneous analysis of patient EEG activity for evidence that an

evoked potential has occurred. Calibration of the GSI AUDERA system was performed in January 2002.

- The AER measurements were obtained in a **single-walled soundproof booth** using **Bio-Logic Earlink Foam Eartips for insert earphones** and a **MS-697 BASS speaker** for sound-field presentation to present acoustic signals while participants were lying on a bed.

3.7.2 Data Collection Procedures

Six sets of data were collected from each participant, behavioural pure tone and mixed modulated (AM/FM) tone thresholds under insert earphones, behavioural frequency modulated (FM) tone and mixed modulated (AM/FM) tone thresholds under sound-field speakers, monotic ASSEP minimum response levels under insert earphones, and lastly monotic ASSEP minimum response levels under sound-field speakers. Data for each participant was collected on the same day. Behavioural pure tone thresholds were obtained first, as part of the selection criteria, followed by the various ASSEP recordings. Data collection was performed at the Department of Communication Pathology at University of Pretoria.

- **Data Collection using Behavioural Pure and Behavioural FM Tone Audiometry**

These tests were conducted to determine the peripheral hearing acuity. The pure tone and FM tone thresholds were used as a basis for comparison with the thresholds obtained from mixed modulated stimuli. The comparison between thresholds obtained under different stimulus presentations ultimately served as the basis for the determination of the influence of insert earphones compared to sound-field presentation on threshold estimation, when using a monotic ASSEP technique. Thresholds were obtained for 0.5, 1, 2 and 4 kHz in each individual ear, once normal middle ear functioning had been established through otoscopy and tympanometry.

The frequencies were chosen to provide correlation with the monotic ASSEP data, obtained at the same frequencies, and ultimately for data analysis. Participants were classified as normal-hearing when all the thresholds at 0.5, 1, 2 and 4 kHz were equal to or less than 25 dB HL (Roeser et al., 2000a). Thresholds were obtained using an ascending intensity step, starting at –10 dB, of 10 dB and a descending step of 5 dB until 50% accurate responses were obtained. This procedure was followed for insert earphone presentation as well as sound-field conditions.

Thresholds obtained through insert earphone presentation were obtained using steady tones, while thresholds obtained through sound-field presentation were obtained using FM (warble) tones, with the participant at 100 cm from the speaker at an angle of zero degrees (0˚). The use of FM tones during sound-field presentation limits the chance of free standing waves having an influence on the results obtained.

- **Data Collection using Behavioural Mixed Modulated Tones**

Mixed modulated (AM/FM) thresholds were obtained from the participants using the GSI AUDERA (AUDERA prototype) system, calibrated in January 2002. Stimuli were presented through insert earphones and a height adjustable sound field speaker, in a single- walled soundproof booth. This test was conducted to determine the peripheral acuity for modulated stimuli. The peripheral hearing acuity for mixed modulated stimuli together with the peripheral hearing acuity for pure tones and FM tones forms the basis of comparison form where the influence of insert earphones compared to sound field presentation on threshold estimation can be argued.

Thresholds were obtained at 0.5, 1, 2 and 4 kHz in each ear individually. Thresholds were again obtained using an ascending intensity step method, starting at -10 dB HL, in increments of 10 dB ascending and 5dB descending until 50% accurate responses were present. This procedure was again followed for insert earphone as well as sound field conditions.

- **Data Collection using the monotic ASSEP**

Research participants who passed all the selection criteria were orientated as to the procedure of the monotic ASSEP testing for this specific study. Definite instructions as to the required behaviour during testing were discussed with each participant.

Preparation of participants involved cleaning the skin surface with **NuPrep ECG & EEG Abrasive Skin Prepping Gel**, in order to clean the areas that was used for placement of the electrodes (Mastoid and different scalp areas). A 15cm cotton bud was used to apply the Nuprep. The skin was thereafter wiped with gauze, after which **Preptic-isopropyl-alchohol-blotters** were applied, to clean the skin areas again.

A conductive medium, namely **Electro Gel, ECG Conductive Electrode Gel**, will be applied to the **silver-chloride disk electrodes** before application to the scalp. After the placement of the electrodes, both ears were fitted with insert earphones, namely **Bio-Logic E-A-R Link Foam Ear Tips for 3A Insert Earphones**. These earphones served as the transducer through which the sound stimuli will be presented. The responses were elicited by using a Monotic ASSEP technique, which incorporates the use of mixed modulated (AM/FM) tones.

Once results were obtained for the monotic ASSEP technique using insert earphone presentation, they were removed. The non-test ear was occluded and sound- field presentation commenced with the speaker 50 cm from the participants face at an azimuth of zero degrees (0˚). The same procedure was followed in order to determine minimum response levels for both ears under sound field conditions.

- **Determination of Stimulus Parameters for Pure tone and FM tone Behavioural Audiometry**

Four frequencies will be used as comparative reference points between the pure tone behavioural data (insert earphone thresholds and sound-field thresholds) and the monotic ASSEP estimated thresholds (for insert earphones and sound-field presentation). Test stimuli included pure tones and FM tones for the behavioural thresholds as well as for the carrier frequencies of the ASSEP at 0.5, 1, 2 and 4 kHz. These frequencies were chosen to ensure that the responses obtained from the ASSEP testing, as well as the conclusions drawn from this study, had clinical value and were comparable, as they provide both high- and low frequency information central to speech discrimination.

- **Specification of Stimulus Parameters for the Monotic Sequential Frequency Auditory Steady State Response**

The specifications of the stimulus parameters for the Monotic Sequential Frequency Auditory Steady State Evoked potential technique will be discussed below.

a.) Selection of carrier and modulation frequencies

Mixed-modulated tones with selected carrier frequencies, 0.5, 1, 2, and 4 kHz were modulated at 40 Hz for "awake" and at 80-110 Hz for "sleeping" participants. Multiple carrier frequencies were selected in order to provide, low- and high frequency information, central to speech discrimination, and also to enable comparison between the ASSEP and the pure tone behavioural audiogram.

Carrier frequencies will be 100% amplitude modulated and 10% frequency modulated at 40 Hz or between 80-110 Hz, depending on the state of consciousness of the participant. Faster modulation rates were used for participants that were awake, because of their resilience towards state of consciousness (Lins et al., 1995).

b.) Selection of the stimulus intensity and threshold criteria

All stimulation for the estimation of behavioural thresholds commenced at –10 dB HL, while the estimation of monotic ASSEP commenced at 20 dB HL above the behavioural threshold for that specific frequency. Steady state stimulus intensity for the experimental study commenced at 20 dB HL above the behavioural thresholds obtained during behavioural pure tone tests, as previous research (Swanepoel, 2002), as well as subjective feedback from participant during the execution of the preliminary study, showed uncomfortable loudness levels at 70 dB HL. According to Rickards (2001) uncomfortable sound intensity levels increase the EEG noise in the recording, probably due to muscle artifacts.

An ascending threshold seeking procedure was used, during behavioural testing, in steps of 10dB HL until a response was present; the intensity was then lowered in steps of 5dB HL, until no response is present.

During electro-physiological testing, stimulation commenced at 20 dB HL above the estimated behavioural threshold for that specific frequency. Stimulus intensity was decreased in steps of 10 dB HL if a response to stimulation was recorded. If a response to stimulation was not recorded, however, the intensity was increased with 5 dB HL until a response to stimulation was present. The minimum response level was identified as the lowest intensity where a response was recorded, irrespective of whether a decrease in intensity revealed a no-response or a noise-response.

Table 3.3, below, contains a summary of the recording procedures for monotic ASSEP through both sound-field speaker and insert earphone presentation.

Table 3.3 Monotic ASSEP Recording Procedure

Recording procedure for the determination of minimum response levels		
	Using Insert Ear Phones	**Using Sound-field Speaker Presentation**
Electrode Placement	Electrode discs of Ag/AgCI will be fixed with electrolytic paste to the scalp at Fz (positive), Test ear (negative) and Non-test ear (ground)	
Impedance Values	Impedance values were kept below 7000 Ohms	
Transducer Type	Bio-Logic Earlink Foam Eartips for 3A insert earphones will be used to present the stimuli	Multi Media Sound-field Speakers MS-697 was used to present stimuli
Participant Positioning	Participants will be asked to lie in a bed in a single walled soundproof booth and will be encouraged to relax.	Participants were asked to lie on a bed, in a single walled soundproof booth. The sound-field speaker was positioned 50cm away from the participant at 0º azimuth.
Initial Stimulus Intensity	Stimuli were presented monotically and sequentially at supra threshold intensities, as determined in the preliminary study.	
Amplification and Filtering	Bio-electric activity will be amplified at a gain of 100 000 and analogue filtered between 30-300 Hz	
Filter	The notch filter will be switched on at 50 Hz to eliminate line interference	
Averaging	Sixty-four samples were averaged in a response. No less than 10, and no more than 40 epochs of 8 192 samples (digitized with a sampling period of 1.37 ms) each, will be averaged in a response	
Response Detection	A Fast Fourier Transformer (FFT) was calculated "online" for each long epoch averaging the response spectra continuously. The presence of a response was determined by using the F-test for hidden periodicity in order to test the amplitude of the spectrum at each modulation frequency against the 120 neighbouring bins of significant amplitude difference	
Artifact Rejection	Artifact rejection was carried out with shorter epoch sections of 512 points. A rejection level of 50 mV was specified to reject any response with amplitudes greater than the specified value	
Minimum Response Level	Minimum response levels were established in descending intensity steps of 10 dB, until no response was present. A no-response, however, could only be determined after 40 epochs had been collected and averaged.	

3.8 Data Analysis Procedures

The raw quantitative data was prepared and organized into a data set. All measures will reflect results in dB HL. A statistician at the department of Information Sciences analyzed the results. Data analysis procedures and the rationale for the analysis method of choice are presented in Table 3.4 and 3.5 below.

Table3.4 Data Analysis Procedures and the Rationale for Analysis Method of Choice

MAIN AIM OF THE RESEARCH ENDEAVOUR			
The aim of this study was to determine the influence of insert earphones and sound-field speaker presentation on minimum response level detection using a monotic steady state evoked potential technique, in a group of normal-hearing adults.			
Sub-aims	**Nature of the Data**	**Analysis Method**	**Literature** (http://ubmail.ubalt.edu/~harsham/stat-data/opre330.htm; http://www.collegeboard.com/about/news_info/cbsenior/yr2002/htlm/define.html) (*Oxford Dictionary, 1990:737)
1.) To determine pure tone and amplitude modulated behavioural thresholds at 0.5, 1, 2 and 4 kHz using insert earphone and sound-field speaker presentation.	Numerical values in dB	a.) Determine means, medians, percentile ranks and normal curves for each technique at each frequency. b.) Perform ANOVA analysis on data obtained through both techniques.	a.) Means provide the arithmetic averages, while the median value indicates the middle value of a series of values arranged in order of size *. The percentile rank indicates the number of participants who fall below a particular scaled score. All these analysis methods together provide information regarding the distribution. b.) Analysis of variance allows the researcher to test the difference between two or more means, by examining the ratio of variability between conditions as well as within conditions
2.) To determine minimum response level detection at 0.5, 1, 2 and 4 kHz using a monotic ASSEP technique using insert earphone and sound-field speaker presentation.	Numerical values in dB	a.) Determine means, medians, percentile ranks and normal curves for each frequency. b.) Perform ANOVA analysis on data obtained through both techniques. c.) Perform paired t-tests and Pearson Correlation on data obtained from both techniques	a.) Means provide the arithmetic averages, while the median value indicates the middle value of a series of values arranged in order of size *. The percentile rank indicates the number of participants who fall below a particular scaled score. All these analysis methods together provide information regarding the distribution. b.) Analysis of variance allows the researcher to test the difference between two or more means, by examining the ratio of variability between conditions as well as within conditions c.) The t-test indicates whether the means are different while the Pearson correlation indicates whether the judgments are otherwise consistent

Table 3.5 Data Preparation, -Analysis and the Rationale for Analysis Method of Choice

MAIN AIM OF THE RESEARCH ENDEAVOUR			
The aim of this study was to determine the influence of insert earphones and sound-field speaker presentation on minimum response level detection using a monotic steady state evoked potential technique, in a group of normal-hearing adults.			
Sub-aims	**Nature of the Data**	**Analysis Method**	**Literature** (**http://ubmail.ubalt.edu/~harsham/stat-data/opre330.htm; http://www.collegeboard.com/about/news_info/cbsenior/yr2002/htlm/define.html**) (*Oxford Dictionary, 1990:737)
3.) To determine the accuracy of the GSI AUDERA system in predicting the pure tone thresholds obtained from the participants	Numerical values in dB	a) Determine means, medians, percentile ranks and normal curves for each frequency. b) Perform ANOVA analysis on data obtained through both techniques. c) Perform paired t-tests and Pearson Correlation on data obtained from both techniques	a) Means provide the arithmetic averages, while the median value indicates the middle value of a series of values arranged in order of size*. The percentile rank indicates the number of participants who fall below a particular scaled score. All these analysis methods together provide information regarding the distribution. b) Analysis of variance allows the researcher to test the difference between two or more means, by examining the ratio of variability between conditions as well as within conditions c) The t-test indicates whether the means are different while the Pearson correlation indicates whether the judgments are otherwise consistent

3.9 Data Processing Procedures

A statistician at the Department Information Management of the University of Pretoria was consulted during the planning of this study. Collected data was tabulated and was made available to the statistician in the form of raw data. The following procedure was followed:

- Results from the audiological test battery was analyzed and interpreted as normal or abnormal, so as to fit in with the selection criteria.
- The results from the monotic sequential ASSEP was analyzed by the GSI AUDERA system's algorithm.
- Data was summarized in a table, specifying participant numbers, ear tested, and gender of the participant. Also included were the technique used, the frequency tested and the thresholds and/or minimum response level obtained.
- Data was delivered to the statistician, results were discussed and objectives for the analysis of data were determined.

3.10 Summary

This chapter provided a description of the procedures implemented in the research methodology to obtain the data according to the sub-aims of the current study. This was done in order to achieve the main aim of the study. The need for a normative data basis regarding the influence, if any, of insert earphones and sound-field speaker presentation on threshold estimation when using a monotic ASSEP technique, was the motivation behind the current study. The volunteers were discussed in terms of criteria for selection, procedures involved in the selection and apparatus used for the selection of participants. Subsequently a description of the selected participants was provided. A discussion surrounding the preliminary study provided insight into the data collection section of this chapter. Data collection was discussed in terms of the apparatus used and the collection procedures used. The chapter concluded with an overview of the data analysis and the processing thereof.

FOUR: Results and Discussions

This chapter aims to create and present new meaning as a contribution to the field of audiology. Meaning is derived from findings through a process of interpretations. It furthermore aims to establish validity of the findings, by relating them to theoretical principles.

4.1 Introduction

In this chapter the results of the current study are presented and discussed. The main aim of this study was to determine the influence of insert earphones and sound-field speaker presentation on threshold estimations using a monotic auditory steady state evoked potential technique, in a group of normal-hearing adults. In order to address the main aim of this study, three closely related sub-aims were formulated. These aims and their relation to the main aim of the study are represented in figure 4.1.

Presentation of these results addresses the main aim of this study. Results are discussed based on the current body of knowledge (data obtained through the current study) and the integration of this knowledge into the literature currently available. The results are presented according to the three sub-aims and a discussion of these results, alongside relevant literature, follows.

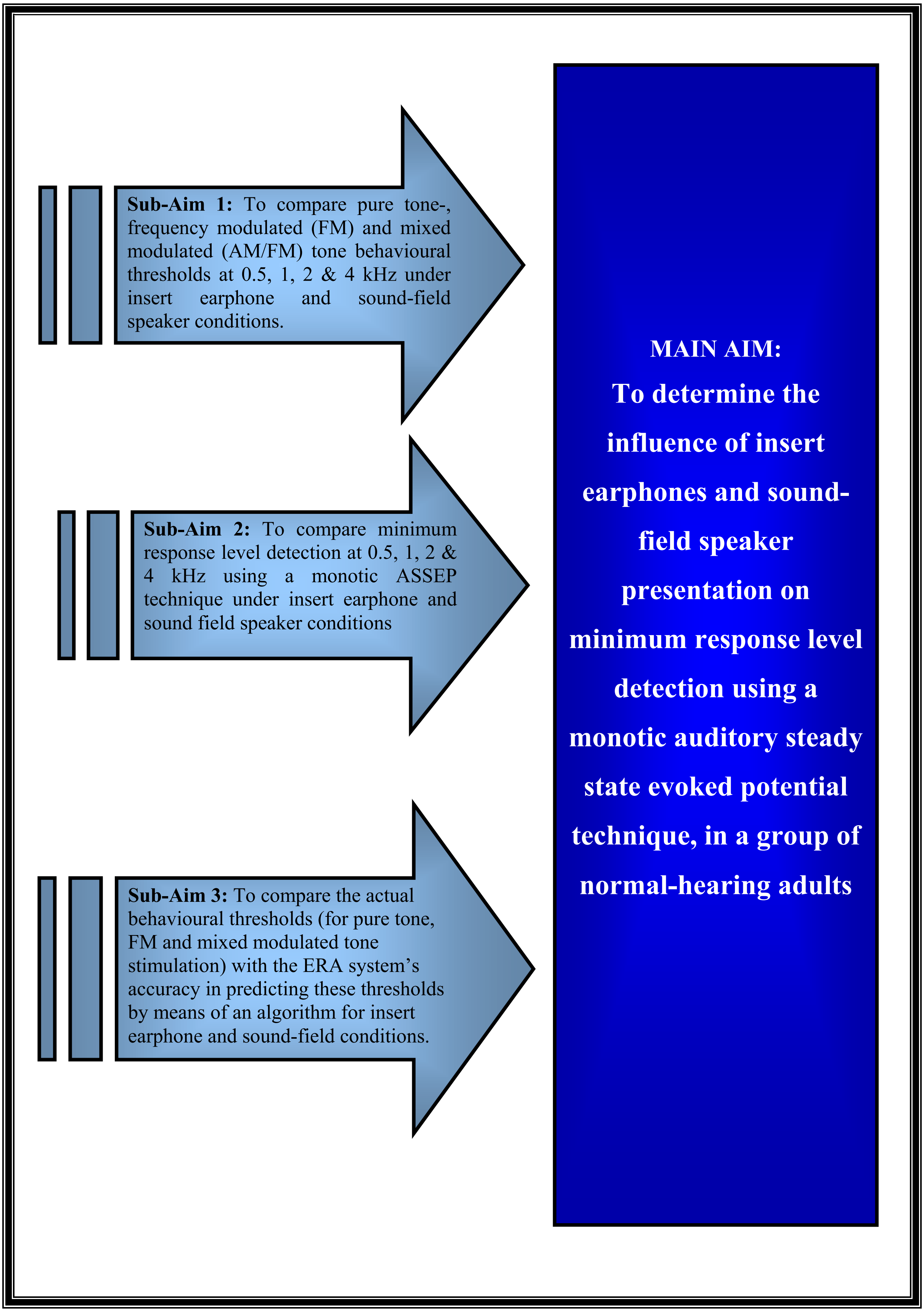


Figure 4.1 Research Process: The sub-aims and their relation to the main aim of the research project

Figure 4.1, above, provides a visual representation of how each sub-aim, independently relates to the main aim. The three sub-aims are discussed separately in an attempt to address the main aim of the current study.

4.2 A comparison between pure tone-, frequency modulated (FM) and mixed modulated (AM/FM) tone behavioural thresholds at 0.5, 1, 2 & 4 kHz under insert earphone and sound-field speaker conditions

Results are presented in relation to two comparisons, namely a comparison across **stimulus presentation**, and one across **transducers.** Both of these comparisons were controlled for gender and ear effects. Following the presentation of results, a discussion relating to current literature follows.

A comparison of the behavioural thresholds using the two different stimulus presentations, for both insert earphones and sound-field speaker presentation, establish a basis from where the accuracy of the calibration of the different stimulus presentations and transducers can be argued. These comparisons also establish a basis from which the accuracy of the minimum response levels obtained using the monotic ASSEP technique under both insert earphone and sound-field conditions can be argued.

4.2.1 A Comparison across Stimulus Presentations:

The comparison across stimulus presentation details the discussion of thresholds obtained through behavioural pure tone, behavioural FM tone and behavioural mixed modulated tone presentation, subdivided into insert earphone and sound-field conditions.

4.2.1.1 Thresholds obtained under Insert Earphone Conditions

Table 4.1 below provides a summary of the mean values (in dB HL), and standard deviations, obtained from the participants during behavioural pure tone and mixed modulated tone presentations (using the GSI AUDERA equipment), at 0.5, 1, 2 & 4 kHz, when insert earphone presentation was used.

Table 4.1 Mean and Standard Deviation Values for Behavioural Pure Tone and Behavioural Mixed Modulated Tone thresholds under insert earphone conditions (n = 50)

Thresholds obtained under Insert Earphone Conditions (in dB HL)		500 Hz	1000 Hz	2000 Hz	4000 Hz
Pure Tone Thresholds	**Mean (*SD*)**	7 (+/-7)	1 (+/-5)	1 (+/-6)	1 (+/-7)
Mixed Modulated Tone Thresholds	**Mean (*SD*)**	7 (+/-7)	3 (+/-5)	2 (+/-5)	3 (+/-7)

Behavioural pure tone thresholds, as well as behavioural mixed modulated thresholds, were within 5 dB from one another when insert earphones were used. No difference was found between the techniques at 0.5 kHz where the mean value for both techniques was 7 dB.

The standard deviation for the behavioural pure tone thresholds varied between 5 dB and 7 dB for all the frequencies tested. The standard deviation for the behavioural mixed modulated tone thresholds, were exactly the same except at 2 kHz where there was a 1 dB difference in standard deviation. Bearing in mind that behavioural thresholds are estimated using 5 dB increments, these standard deviations were almost identical. For both techniques the greatest standard deviations were present at 0.5 and 4 kHz, namely 7 dB.

Statistical analysis of the behavioural pure tone thresholds compared to the behavioural mixed modulated tone thresholds, under insert earphone conditions revealed no significant differences for any of the frequencies tested ($p < 0.05$). It is clear from this analysis that the behavioural thresholds obtained from the different stimulus presentations, under insert earphone conditions, are comparable based on a 5% level of significance. The numerical data obtained from the statistical analyses are available in Appendix D.

This experiment was controlled for both gender- and ear effects. When the results were analyzed using the Mann-Whitney paired T-Test with $p < 0.01$ no statistical differences, for behavioural pure tone thresholds, were noted between male and female research participants. The only statistical difference was obtained at 2 kHz when p< 0.05 was used to analyze the results. No statistical differences were obtained between male and female research participants for either p< 0.01 or p<0.05 when the behavioural modulated tone thresholds were analyzed. Statistical analyses of ear effects revealed no significant differences between the left and right ears analyzed for both p<0.01 and p<0.05, regardless of the stimulus presentation employed in obtaining the thresholds. The numerical data obtained from the statistical analyses for both the gender and ear analyses are presented in Appendix E.

4.2.1.2 Thresholds obtained under Sound-field Conditions

Table 4.2 below provides a summary of the mean values and standard deviations (in dB HL) obtained from the participants during behavioural pure tone and behavioural modulated tone (using the GSI AUDERA equipment), at 0.5, 1, 2 & 4 kHz, when sound-field speaker presentation was used.

Table 4.2 Mean and Standard Deviation Values for Behavioural FM Tone and -Mixed Modulated Tone thresholds under sound-field conditions (n = 50)

Thresholds obtained under Sound-field Conditions (in dB HL)		**500 Hz**	**1000 Hz**	**2000Hz**	**4000 Hz**
Behavioural FM Tone Thresholds	**Mean (*SD*)**	4 (+/-6)	-2 (+/-4)	-1 (+/-5)	3 (+/-5)
Behavioural Mixed Modulated Tone Thresholds	**Mean (*SD*)**	1 (+/-6)	0 (+/-5)	0 (+/-4)	7 (+/-7)

Thresholds obtained through behavioural FM tone testing, as well as behavioural mixed modulated tone testing, were again within 5 dB from each other, when sound-field speaker presentation was used. The smallest difference with regard to the mean dB values was at 2 kHz where the behavioural FM tone stimulation showed –1dB, whereas the mixed modulated tone stimulation showed a mean value of 0 dB. The greatest difference in mean values was found at 4 kHz with a difference of 4 dB. The standard deviations for the behavioural pure tones varied between 4 dB and 6 dB, whereas the standard deviations for the behavioural mixed modulated tones varied between 4 dB and 7 dB. The behavioural mixed modulated tones showed the greatest standard deviation (at 4 kHz), namely 7 dB.

The greatest difference between the two stimulus presentations (FM tone -versus modulated tone presentation) is found at 4 kHz. The greater mean values as well as the greater standard deviations at 4 kHz shown for the mixed modulated tones when sound-field speaker presentation is used could probably be explained by the fact that the field is less uniform for higher frequencies (Dillon & Walker, 1981). Furthermore thresholds obtained at 4 kHz are more susceptible to head-movements (directionality), as well as the head shadow effect (Dillon & Walker, 1981; Hall & Mueller, 1997).

Statistical analysis of the behavioural FM tone thresholds compared to the behavioural mixed modulated tone thresholds, under sound-field conditions revealed no significant differences for any of the frequencies tested ($p < 0.05$). It is clear from this analysis that the behavioural thresholds obtained from the different stimulus presentations, under sound-field conditions, are comparable based on a 5% level of significance. The numerical data from the statistical analyses are available in Appendix D.

This experiment was again controlled for gender and ear effects. Gender effects were analyzed using the Mann-Whitney test and showed no significant differences between male and female research participants for $p < 0.05$ or $p < 0.01$, regardless of the transducer used. The numerical data from the statistical analyses are available in Appendix F. There was a significant difference between left and right ears at 0.5 kHz, when the FM tones were analyzed, with a $p < 0.05$, while analysis with a $p < 0.01$ did not reveal a significant difference. For all the other frequencies tested with the behavioural FM tones, namely 1, 2 & 4 kHz, there were no significant differences between left and right ears. The numerical data from the statistical analyses are available in Appendix F. With regard to ear effects, no significant differences were noted at any of the frequencies tested (0.5 - 4 kHz) with the behavioural mixed modulated tones regardless of which p-value was used. The results from the statistical analysis are available in Appendix F.

4.2.2 Comparison across Transducers

The comparison across transducers will detail the discussion of thresholds obtained under insert earphone and sound-field conditions. The discussion across transducers will be subdivided for thresholds obtained through behavioural pure tone, behavioural FM tone and behavioural mixed modulated tone testing.

4.2.2.1 Thresholds obtained through Behavioural Pure Tone and Behavioural FM Tone Testing

Table 4.3 provides a summary of the mean values and standard deviations (in dB HL) obtained from the participants during behavioural pure tone and behavioural FM tone testing, at 0.5, 1, 2 & 4 kHz, when insert earphones and sound-field speaker presentation were used.

Table 4.3 Mean and Standard Deviation Values for Behavioural Pure Tone and Behavioural FM Tone thresholds under insert earphone and sound-field conditions (n = 50)

Pure Tone and FM Tone Techniques (in dB HL)		500 Hz	1000 Hz	2000Hz	4000 Hz
Insert Earphone Presentation (Pure Tone)	**Mean (*SD*)**	7 (+/-7)	1 (+/-5)	1 (+/-6)	1 (+/-7)
Sound-field Speaker Presentation (FM)	**Mean (*SD*)**	4 (+/-6)	-1 (+/-4)	-1 (+/-5)	3 (+/-5)

The thresholds obtained through behavioural pure tone and FM tone testing, using insert earphones and sound-field speaker presentation, were within 5 dB from one another, across transducers. The greatest mean difference is found at 0.5 kHz where the mean difference was 3 dB. The standard deviations for the pure tone behavioural technique, using insert earphones, varied between 5 dB and 7 dB for all the frequencies tested. Standard deviations for the behavioural FM tone technique, using sound-field speaker presentation varied between 4 dB and 6 dB.

Statistical analysis of the behavioural pure tone and FM tone thresholds obtained under insert earphone and sound-field conditions revealed significant differences for all of the frequencies tested ($p < 0.05$). It is clear from this analysis that the behavioural thresholds obtained from the different stimulus presentations, under insert earphone and sound-field conditions, are not comparable based on a 5% level of significance. When the thresholds were analyzed on a 1% level of significance there was no significant difference at 4 kHz between the thresholds obtained under insert earphone and sound-field conditions. The numerical data obtained from the statistical analyses are available in Appendix G.

This experiment was controlled for gender- and ear effects. Gender effects were analyzed using the Mann-Whitney test and showed no significant differences between male and female research participants for $p < 0.05$, for all frequencies tested except 2 kHz, regardless of the transducer used. Measured against $p < 0.01$, there were no significant differences between genders. There was a significant difference between left and right ears at 0.5 kHz, when the FM tones were analyzed, with $p < 0.05$, while analysis with $p < 0.01$ did not reveal a significant difference. The results are tabulated in Appendix E and F.

4.2.2.2 Thresholds obtained through Behavioural Mixed Modulated Tone Testing

Table 4.4 provides the summary of the mean values and standard deviations obtained (in dB HL) from the participants during behavioural mixed modulated tone testing, at 0.5, 1, 2 & 4 kHz, when insert earphones and sound-field speaker presentation were used.

Table 4.4 Mean and Standard Deviation Values for Behavioural Mixed Modulated Tone thresholds under insert earphone and sound-field conditions (n = 50)

Behavioural Mixed Modulated Tone Thresholds (in dB HL)		**500 Hz**	**1000 Hz**	**2000Hz**	**4000 Hz**
Insert Earphone Presentation	**Mean (*SD*)**	7 (+/-7)	3 (+/-5)	2 (+/-5)	3 (+/-7)
Sound-field Speaker Presentation	**Mean (*SD*)**	1 (+/-6)	0 (+/-5)	-1 (+/-4)	7 (+/-7)

The thresholds obtained through behavioural mixed modulated testing, across transducers, was within 5 dB from one another, except at 0.5 kHz (highlighted in the Table) where there is a mean difference of 6 dB. The data contained in Table 4.5 will subsequently also be presented in Figure 4.2 to highlight the difference. The smallest difference, in mean value, was found at 2 kHz were the mean difference was 2 dB. The standard deviations for the behavioural mixed modulated technique, using insert earphones, varied between 5 dB and 7 dB for all the frequencies tested. Standard deviations for the same technique, using sound-field speaker presentation varied between 4 dB and 7 dB.

Statistical analysis of the behavioural mixed modulated tone thresholds obtained under insert earphone and sound-field conditions revealed significant differences for all of the frequencies tested (p < 0.05/ p < 0.01), except at 2 kHz for p < 0.01. It is clear from this analysis that the behavioural thresholds obtained from the modulated tone presentations, under insert earphone and sound-field conditions, are not comparable based on a 5% level of significance. The numerical data obtained from the statistical analyses are available in Appendix G.

This experiment was again controlled for gender- and ear effects. No statistical differences were obtained between male and female research participants for either a p value of < 0.01 or 0.05 when the behavioural modulated tone thresholds were analyzed, regardless of which transducer was used. With regard to ear effects, there were no significant differences were noted at any of the frequencies tested (0.5 - 4 kHz) with the behavioural modulated tones regardless of which p-value was used, regardless of which transducer was used. The numerical data obtained from the statistical analyses are tabulated in Appendix E and F.

Figure 4.2, below, provides a visual interpretation of the behavioural mixed modulated tone thresholds obtained using insert earphone- and sound-field speaker presentation at 0.5, 1, 2 & 4 kHz.

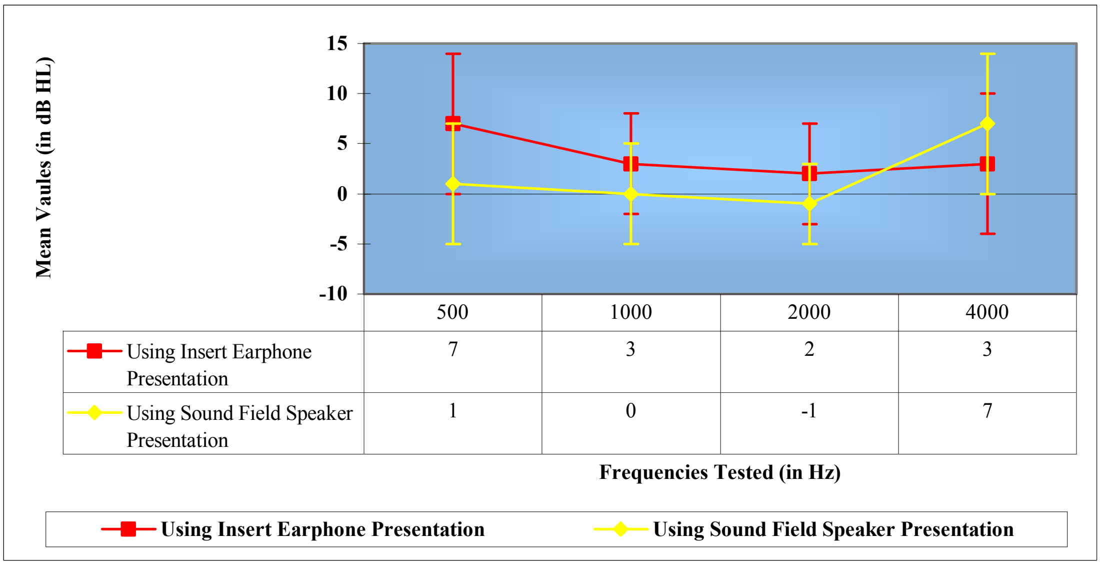


Figure 4.2 Behavioural Mixed Modulated Tone Thresholds, obtained under Insert Earphone and Sound-field conditions

Mean thresholds obtained through behavioural testing across transducers, when using a mixed modulated (AM/FM) stimulus, revealed no greater than 5 dB differences across 1, 2 & 4 kHz. At 0.5 kHz a mean difference of 6 dB can be observed which is marginally larger than the minimum standard error (5 dB) introduced for behavioural testing. A statistical difference is noted for all the frequencies tested (0.5, 1, 2 & 4 kHz) for the comparison across transducers and is tabulated in Appendix G. In light of the above, and especially at 0.5 kHz, it will therefore be pertinent to compare across stimulus presentation rather than across transducer. This implies that, for this particular study, behavioural data specific to the type of transducer employed will have to be used as a baseline. Therefore, behavioural thresholds obtained through mixed modulated stimuli (tones), using insert earphone presentation, will not suffice as a baseline measure against which monotic ASSEP minimum response levels, using sound-field speaker presentation, can be compared. The same principle applies to behavioural thresholds obtained through mixed modulated stimuli (tones) under sound-field conditions when compared with monotic ASSEP minimum response levels obtained under insert earphone conditions.

4.2.3 Discussion of Behavioural Thresholds obtained, when compared across Stimulus Presentations and Transducers

The results of the current study indicate that no greater than 5 dB mean differences were obtained for the comparison across stimulus presentations (regardless of the transducer used). However for the comparison across transducers, and specifically relating to the behavioural thresholds obtained through mixed modulated stimulation (modulated tones) at 0.5 kHz, a difference in excess of 5 dB was recorded. According to Katz (1985) extrinsic factors (temperature, light and ambient noise) as well as intrinsic factors (motivation, attention and familiarity with the listening task), within the test environment play a significant role when the audibility thresholds of average listeners are estimated.

Within the clinical setting this implies that certain compromises have to be made in order to obtain hearing thresholds within a relatively short period of time (Katz, 1985). Because attenuator steps of 5 dB are employed, a minimum standard error of +/- 5 dB is introduced (Katz, 1985) for behavioural testing of any individual. These minimum standard errors together with the statistical analysis of the results form the basis from which the accurate calibration of the equipment is argued. Furthermore, sets the basis for appropriate comparisons of the monotic ASSEP thresholds with behavioural thresholds. Table 4.5, below provides a summary of the results presented, when compared across stimulus presentations and transducers.

Table 4.5 Summary of the Mean and Standard Deviation values across Stimulus Presentations and Transducers (n = 50)

Thresholds Obtained Under Behavioural Testing		**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
Behavioural Pure Tone Thresholds under Insert Earphone conditions	**Mean (*SD*)**	7 (+/-7)	1 (+/-5)	1 (+/-6)	1 (+/-7)
Behavioural FM Tone Thresholds under Sound-field conditions	**Mean (*SD*)**	4 (+/6)	-2 (+/-4)	-1 (+/-5)	3 (+/-5)
Behavioural Mixed Modulated Tone Thresholds under Insert Earphone conditions	**Mean (*SD*)**	7 (+/- 7)	3 (+/-5)	2 (+/-5)	3 (+/-7)
Behavioural Mixed Modulated Tone Thresholds under Sound-field conditions	**Mean (*SD*)**	1 (+/-6)	0 (+/-5)	0 (+/-4)	7 (+/-7)

4.2.3.1 Discussion of the Comparison across Stimulus Presentation (controlled for Transducers)

It is therefore clear that for the comparison across stimulus presentation (regardless of the transducer used) there were no mean differences that exceeded the minimum standard error. Also, no statistical differences were obtained between the techniques (within each specific transducer used). Therefore, the calibration of the equipment relating to the comparison across stimulus presentations seems to be comparable. The numerical data from the comparison across stimulus presentation is available in Appendix D.

The results, relating to the comparison across technique, revealed pure tone behavioural thresholds that closely approximated 0 dB HL, which according to Roeser and colleagues (2001) represents the “perfect” normal-hearing sensitivity standard. Mean thresholds were between 1 and 7 dB HL. A large percentage (78%) of the behavioural pure tone thresholds was equal to or less than 5 dB HL and this increased to 91% if 10 dB HL is included. Therefore the great majority of the behavioural pure tone responses were less than 10 dB HL, even though the normal cut-off of 25 dB HL was used during research participant selection. The standard deviations observed for the pure tone behavioural technique varied between 5-7 dB, which closely approximates the prescribed standard variation of 6 dB across all the frequencies tested (Haugton, 1980).

Although there is very little literature available to compare the behavioural mixed modulated thresholds, using insert earphone presentation, Picton and colleagues (1998) reported that a 100% modulated tone is clearly distinguishable from an un-modulated tone at 5 dB above the hearing threshold for the particular tone. This is corroborated by earlier research (Bacon & Viemeister, 1985) reporting that modulations of –6 dB (equivalent to 50%) can be detected at 5 dB above hearing threshold, at modulation frequencies between 64-128 Hz. The mean thresholds obtained closely approximated 0 dB HL and ranged between 1 and 7 dB HL. Of the behavioural thresholds obtained through mixed modulated stimuli under insert earphone conditions, 78% were equal to or less than 5 dB HL. This figure increased to 92% if 10 dB HL was included. Again the great majority of the behavioural mixed modulated thresholds were less than 10 dB HL. Standard deviations observed for the behavioural thresholds obtained through modulated stimuli under insert earphone conditions were identical to the standard deviations for the behavioural pure tone technique, and varied between 5 and 7 dB.

The same pattern emerged when the results relating to the comparison across technique for behavioural FM tone and behavioural mixed modulated thresholds, using sound-field speaker presentation, were evaluated. The thresholds obtained closely approximated 0 dB HL. Of all the ears tested behaviourally under the sound-field conditions, 89 % revealed thresholds of 5 dB HL or less, while this figure grew to 95% if 10 dB HL was included. Once again it is clear that for the majority of the ears tested, thresholds were 10 dB HL or less. Standard deviations for the behavioural pure tone technique, using sound-field speaker presentation, varied between 4 and 6 dB, which is slightly higher than those obtained by Arlinger & Jerlvall (1987), namely 2.5-3.4 dB, also obtained from adult research participants.

The higher standard deviations obtained in the current study can possibly be attributed to the stipulated range of normality. In the study done by Arlinger & Jerlvall (1987) research participants were required to have hearing thresholds that ranged between 0-20 dB HL, whereas the current study stipulated normal-hearing as ranging between

0-25dB HL. Thus, the greater range (of normality) analyzed could have slightly elevated the standard deviations obtained during the current study. However, in light of the fact that 95% of the behavioural thresholds obtained under sound-field conditions (in the current study) were equal to or less than 10 dB HL, this explanation seems highly unlikely.

Another difference between the current study and that of Arlinger & Jerlvall (1987) is that the modulation frequencies employed differed substantially. For their study, Arlinger & Jerlvall (1987) used a modulation frequency of 5 and 20 Hz, whereas the current study employed modulation frequencies that varied between 80 and 110Hz depending on the carrier frequency being modulated. Further investigation is required, as other variables (e.g. ambient noise levels in the test room) could also possibly have attributed to the higher than reported standard deviations.

Again, there is limited literature available to serve as comparison between the behavioural modulated thresholds obtained under sound-field conditions. Mean thresholds varied between –1 and 4 dB HL and yet again closely approximated 0 dB HL. Of these thresholds 85% were equal to or less than 5 dB HL. This figure grew to 93% when 10 dB HL was included. Once again the majority of the thresholds were obtained at 10 dB HL or less. Standard deviations for the thresholds obtained with modulated tones, under sound-field conditions, were similar to those obtained using the behavioural FM tone technique, and varied between 4 and 7 dB. These results correlate well in light of the range of normality (0-25 dB HL) of the research participants involved.

4.2.3.2 Discussion of the Comparison across Transducers (controlled for Stimulus Presentation):

As with the comparison across stimulus presentations, the comparison across transducers with specific reference to the behavioural pure and –FM tone technique again revealed no greater mean differences than 5 dB. However statistical analysis of these thresholds revealed significant differences for all the frequencies tested using a $p < 0.05$, thus compromising the comparison across transducers. When considering, the comparison across transducers, specifically related to the behavioural thresholds obtained when mixed modulated (AM/FM) stimuli were used, are considered, the mean difference at 0.5 kHz exceeds the minimum standard error of 5 dB and furthermore shows statistical differences for all the frequencies tested. The numerical data obtained from the comparison across transducers are available in Appendix G. Thereby compromising the comparison based on the assumption of accurate calibration.

In light of this phenomenon, further comparisons with behavioural modulated thresholds will have to be considered on a transducer-specific basis. Stated differently, behavioural mixed modulated thresholds obtained under insert earphone conditions will have to serve as the basis for comparison with monotic ASSEP minimum response levels obtained under the same conditions, and likewise with the comparison obtained under sound-field conditions.

Both behavioural pure tone and behavioural FM tone data closely approximated 0 dB HL. Of the pure tone thresholds obtained using insert earphone presentation, 91% were equal to or less than 10 dB HL while 89% of the FM tone thresholds obtained, using sound-field speaker presentation, were equal to or below 10 dB HL. The standard deviations for the technique while using insert earphone presentation varied between 5 and 7 dB, while the standard deviations for the same technique using sound-field speaker presentation, varied between 4 and 6 dB HL. Furthermore there were significant differences when non-parametric statistics (Wilcoxon Paired T-Test) were investigated ($p < 0.05$). Therefore, the results obtained for behavioural pure tone testing are not comparable across the transducer used. These numerical data from the statistical analyses are tabulated in Appendix G.

The comparison across transducers, specifically related to the behavioural thresholds obtained when mixed modulated tones were employed, revealed a greater than expected variance (> 5 dB) of 6 dB at 0.5 kHz, bearing in mind the +/- 5 dB minimum standard error introduced for behavioural testing. For all the other frequencies tested (1, 2 & 4 kHz) the variance was no greater than 5 dB, and calibration of the equipment for these frequencies can therefore be seen as accurate. The Wilcoxon Paired T-Test revealed significant differences between these transducers for all the frequencies when $p < 0.05$ was implemented and is tabulated in Appendix G.

There are several factors that could have influenced the results obtained. Participants were tested in the reverberant field for behavioural FM tone testing and in the direct field for behavioural mixed modulated tone ASSEP testing. According to Walker et al. (1984) the sound pressure level in the reverberant field is influenced by reflected as well as direct sound. Mixed modulated thresholds, in the current study, were obtained in the direct field and therefore there was less interaction of the acoustic environment, while the behavioural pure tones were obtained in the reverberant field. Thus the influence of the acoustic environment could possibly have affected the thresholds obtained to a greater degree.

Other factors such as directivity of the speaker (Walker et al., 1984), the rooms' dimensions (Anderson, 1979) and absorptivity of its surfaces will influence the extent of the direct field. In the current study participants were positioned according to a zero degree azimuth in relation to the speaker. It is possible that absorptivity of the surfaces influenced the results obtained at least to a certain extent seeing as the behavioural pure tone testing was done while participants were seated in a chair, whereas the behavioural mixed modulated testing was done with participants lying on a bed. The absorptivity of the bed would be significantly different from the absorptivity of the room behind the seated participant. Also the dimensions of the test room (discussed in the methodological chapter of this study) are not constant for the two conditions.

Positioning of the participants as well as their head movements also influence the thresholds obtained (Magnusson et al., 1997). Positioning of participants was correlated with a marker at the position identified during calibration. The researcher and another qualified audiologist, throughout the recording of thresholds and minimum response levels, checked the maintenance of the test position. It is possible, however, that small head movements could have been overseen and that these movements subsequently had an effect on the results obtained.

Lastly, where sound-field presentation was the last presented condition, fatigue of the participants could also have impacted on the results. As discussed in the methodological chapter of this study the test conditions were randomized so that each condition accounted for practice and carry-over effects. It is unlikely therefore that fatigue would have adversely affected the results obtained, however the possibility still exists. Although it is seemingly impossible to pinpoint the direct cause of the greater than expected variance and statistical differences, it is more likely than not a combination of these variables that have contributed to the results obtained.

4.3 A comparison between minimum response level detection at 0.5, 1, 2 & 4 kHz using a monotic ASSEP technique under insert earphone and sound field speaker conditions

This sub-aim details and discusses the results from four related groups of data pertaining to its focus. Three comparisons were analyzed, namely a comparison across techniques, one across transducers and the last across both technique and transducer.

The comparison across techniques provides the basis from where the accuracy of the threshold estimations using the different transducers can be argued. For this comparison behavioural data are compared, as a basis, against the electro-physiological data to establish how closely the electro-physiological minimum response levels approximate the actual behavioural thresholds. The same comparison was made between behavioural mixed modulated tone thresholds and electro-physiological data to establish whether the electro-physiological minimum response levels are more closely related to the behavioural pure tone thresholds or the behavioural modulated tone thresholds.

The comparison across transducer provides critical information regarding the influence of the different transducers on ASSEP minimum response level detection. Lastly, the comparison across technique and transducer provides critical information relating to whether minimum response levels, using sound-field speaker presentation can be used, with normative data from both pure tone thresholds using insert earphone presentation and pure tone thresholds using sound-field speaker presentation.

4.3.1 A Comparison across Stimulus Presentations:

The comparison across stimulus presentation will detail the discussion of thresholds obtained through behavioural testing and ASSEP testing. The discussion of stimulus presentations will be subdivided for thresholds obtained under insert earphone- and sound-field conditions.

4.3.1.1 Thresholds an Minimum Response Levels obtained under Insert Earphone Conditions

Table 4.6 provides a summary of the comparison between the mean behavioural thresholds, for both pure tone stimulation and modulated tone stimulation, and the mean ASSEP minimum response levels at 0.5, 1, 2 and 4 kHz, using insert-earphone presentation.

Table 4.6 Mean and Standard Deviation Values for Behavioural Pure Tone thresholds and ASSEP minimum response levels under insert earphone conditions (n = 50)

Thresholds obtained under Insert Earphone conditions (in dB HL)		500 Hz	1000 Hz	2000Hz	4000 Hz
Behavioural Pure Tone Thresholds	**Mean (*SD*)**	7 (+/-*7*)	1 (+/-*5*)	1 (+/-*6*)	1 (+/-*7*)
Behavioural Mixed Modulated Thresholds	**Mean (*SD*)**	7 (+/-*7*)	3 (+/-*5*)	2 (+/-*5*)	3 (+/-*7*)
ASSEP Minimum Response Levels	**Mean (*SD*)**	35 (+/-*12*)	25 (+/-*10*)	26 (+/-*9*)	27 (+/-*11*)

The thresholds obtained through behavioural pure tone testing differ substantially from the ASSEP minimum response levels obtained under insert earphone conditions. The greatest mean difference for the comparison of ASSEP minimum response levels with behavioural pure tones (28 dB) is found at 0.5 kHz where the mean value for the electro-physiological threshold was 35 dB HL compared to the mean pure tone threshold of 7 dB HL. The smallest difference (24 dB) in mean values was found at 1 kHz where the mean value for the ASSEP minimum response level was 25 dB HL compared to the mean behavioural threshold of 1dB HL. The difference in mean values between the behavioural thresholds and the electro-physiological minimum response levels for 2 kHz was 25 dB, and 26 dB at 4 kHz.

Although elevated, these figures correlate well with previous studies investigating the threshold estimation of the monotic ASSEP technique in normal-hearing adults. Picton and colleagues (1998) reports a mean minimum response level, for monotic ASSEP, of 34 dB SPL at **0.5 kHz** compared to the 44 dB SPL (35 dB HL), corrected for ER-3A insert earphones, of the current study. The 25 dB HL obtained at **1 kHz** is slightly better than the 29 dB HL reported by Aoyagi and colleagues (1994) at the same frequency. This figure when corrected for supra aural headphones relates to 37 dB SPL, which is higher than 34 dB SPL, again corrected for insert earphones, obtained in the current study. Research by Herdman & Stapells (2001) on monotic ASSEP revealed significantly lower MRLs of 20 dB SPL compared to the 33dB SPL (26 dB HL), corrected for insert earphones, at **2 kHz**. Again at **4 kHz** the current study revealed a generally lower minimum response level of 29 dB SPL (27 dB HL), again corrected for insert earphones, compared to the 41dB SPL (30 dB HL), corrected for TDH 49 supra-aural headphones obtained by Aoyagi et al (1994). However, a very close similarity is obtained with the results that Picton and colleagues (1998) obtained, namely 33 dB SPL.

Research done by Herdman & Stapells (2001) reported ASSEP minimum response levels that ranged between 18 and 20 dB SPL across 0.5-4 kHz, which is significantly better than the 29-44 dB SPL obtained in the current study. However when viewed in the light of other studies the range obtained in the current study (29-44 dB SPL) compares well with the 36-41 dB SPL (29-30 dB HL), corrected for TDH 49 supra-aural headphones, obtained by Aoyagi and colleagues (1994), and the 33-34 dB SPL obtained by Picton and colleagues (1998). Although the minimum response levels obtained in the current study compare well with other literature, it is important to mention that at present no universal criteria exists to define "acceptable difference in threshold".

When the ASSEP minimum response levels, obtained in the current study, are compared with the behavioural thresholds obtained from modulated stimuli (modulated tones), also obtained in the current study, slightly smaller differences were observed between 1 and 4 kHz, while the mean difference at 0.5 kHz was exactly the same. Both comparisons revealed a mean difference of 28 dB at 0.5 kHz, while the mean difference between the behavioural modulated tone threshold and ASSEP minimum response level was 22 dB at 1 kHz and 24 dB at 2 and 4 kHz.

There is limited literature available to compare these behavioural modulated tone thresholds against. As discussed earlier, a 100% modulated tone is distinguishable from a pure tone at 5 dB above hearing threshold (Bacon & Viemeister, 1985; Picton et al., 1998). Furthermore, there were no significant statistical differences between the behavioural pure tone and behavioural modulated tone data (discussed earlier in this chapter). Finally these sets revealed no greater than 5 dB difference (minimum standard error) between them. Therefore in light of the aforementioned factors, these differences seem marginal.

The standard deviations for the behavioural pure tone technique, using insert earphones varied between 5 dB and 7 dB for all the frequencies tested. Standard deviations for the ASSEP technique, using insert earphones, varied between 9 dB and 12 dB. The greatest standard deviation for the ASSEP technique was found at 0.5 kHz, namely 12 dB, while the smallest standard deviation was observed at 2 kHz, namely 9 dB.

The standard deviations for both the behavioural pure tone thresholds as well as the ASSEP minimum response levels were within 5 dB HL from each other for 0.5 & 4 kHz with a difference of 5 dB HL at 1 & 2 kHz. These standard deviations, obtained in the current study, are marginally better than those obtained by Aoyagi and colleagues (1994). The standard deviation at 1 kHz was 10 dB (current study) compared with the 14 dB, obtained by Aoyagi and colleagues (1994), and 11 dB (current study) compared with the 15 dB at 4 kHz. The greater standard deviations obtained by Aoyagi and colleagues (1994) could possibly be attributed to the transducers used for presentation of stimuli. According to Lins and colleagues (1996), supra aural headphones attenuate ambient noise levels by approximately 10 dB for the lower frequencies, while higher frequencies are attenuated by as much as 20 dB. Additionally, the smaller standard deviations obtained in the current study can possibly be attributed to the use of insert earphone stimulation, which has less problems with sound leakage (Wilber, 2002).

It seems therefore that the ASSEP minimum response levels, under insert earphone conditions, compare well with those reported in the literature (Aoyagi et al., 1994; Picton et al., 1998), except possibly for those reported in a study by Herman & Stapells (2001). The average SPL thresholds varied between 29 and 44 dB SPL compared with the 36-40 dB SPL reported by Aoyagi and colleagues (1994), with values converted from HL (at 1 & 4 kHz) and those obtained by Lins and colleagues (1996), namely 29-36 dB SPL.

Statistical analyses of the thresholds obtained under behavioural testing (both pure tone- and modulated tone) and those obtained under ASSEP testing differ significantly from each other, controlled for insert earphone presentation. For all the frequencies tested (0.5-4kHz) both sets of behavioural data showed greater than 0.05 p-values when compared to the ASSEP minimum response levels. These sets of data, therefore, differ significantly from each other on a 5% significance level. The results of this analysis are available in Appendix D.

This experiment was, again, controlled for gender- and ear effects. On a 5% level of significance the minimum response levels obtained from male and female research participants did not show significant differences. However, at 2 kHz there was a significant difference relating to the gender effect. When these results are viewed on a 1% level of significance there is no statistical difference between the genders. For all the other frequencies there were no statistical differences on either a 1% or a 5% level of significance. The numerical data from the statistical analyses are available in Appendix H.

The statistical difference obtained between genders could possibly be attributed to a difference in the length of the basilar membrane, between males and females. According to John & Picton (2000) the representation of frequencies along the basilar membrane are not accurately known. The length of the membrane differs from person to person, and is longer for males compared to females (John & Picton, 2000). Thus, longer traveling time associated with the increased length of the basilar membrane, may account for the difference observed for male participants (when compared to female research participants).

Goldstein & Aldrich (1999) reported that the differences in head size between genders could create gender related latency delays. Although this statement refers to auditory evoked potentials in general, the latency effects will almost certainly affect the phase measures of the ASSEP. Thus, there is some support in literature to corroborate the findings obtained in the current study, but more research is required before any definite conclusions can be drawn. In light of the fact that the difference was not noted when a stricter ($p < 0.01$) analysis was made, the influence of gender did not seem to significantly affect the results obtained from the research participants. The numerical data from the analysis is available in Appendix H.

When the same comparison was made for ear effects there were no statistical differences between the ears for either a 1% or 5% level of significance. These results are available in Appendix I.

4.3.1.2 Thresholds and Minimum Response Levels obtained under Sound-field Conditions

Table 4.7 below, again provides a summary of the behavioural FM tone technique's mean thresholds compared to the ASSEP techniques' mean thresholds, using sound-field speaker presentation.

Table 4.7 Mean and Standard Deviation values for Behavioural FM Tone thresholds and ASSEP minimum response levels under sound-field conditions (n = 50)

Thresholds obtained under Sound-field conditions (in dB HL)		500 Hz	1000 Hz	2000Hz	4000 Hz
Behavioural FM Tone Thresholds	Mean (*SD*)	4 (+/-*6*)	-2 (+/-*4*)	-1 (+/-*5*)	3 (+/-*5*)
Behavioural Mixed Modulated Tone Thresholds	Mean (*SD*)	1 (+/-*6*)	0 (+/-*5*)	-1 (+/-*4*)	7 (+/-*7*)
ASSEP Minimum Response Levels	Mean (*SD*)	26 (+/-*12*)	18 (+/-*10*)	21 (+/-*10*)	36 (+/-*11*)

Thresholds obtained, under sound-field conditions, through behavioural FM tone testing, as well as those for behavioural mixed modulated tone testing, differ substantially from the ASSEP minimum response levels. The comparison between ASSSEP minimum response levels and behavioural FM tones, the greatest difference (33 dB) is found at 4 kHz. The mean value for the electro-physiological minimum response level was 36 dB HL, while the FM tone threshold mean was 3 dB HL. The smallest difference (20 dB) in mean values was found at 1 kHz where the mean value for the electro-physiological minimum response level was 18 dB HL compared to the mean behavioural threshold of –2 dB HL. The difference in mean values between the behavioural and electro-physiological minimum response levels was 22 dB both at 2 & 4 kHz.

These figures are compared to those obtained by Picton and colleagues (1998) as there is very limited published literature available. Similarities as well as differences between the current study and that of Picton and colleagues (1998) will be highlighted during the description of results as well as in the subsequent discussion. The ASSEP minimum response level obtained at **0.5 kHz** in the current study is 35 dB SPL (26 dB HL), corrected for sound-field speaker presentation, which closely correlates to the 31dB SPL obtained by Picton and colleagues (1998) for the same frequency. The 24 dB SPL (18dB HL) again corrected for sound-field conditions, obtained in the current study at **1 kHz** is significantly lower than the 36 dB SPL obtained by Picton and colleagues (1998). However, at **2 kHz** Picton and colleagues (1998) reported an ASSEP minimum response level of 26 dB SPL, which is lower than the 33 dB SPL (21 dB HL) obtained in the current study. For the comparison at **4 kHz** Picton and colleagues (1998) obtained a mean ASSEP minimum response level of 26dB SPL, which is significantly lower than the 51 dB SPL (36 dB HL) obtained in the current study. This relates to a mean difference of 20 dB between behavioural thresholds and electro-physiological minimum response levels obtained by Picton and colleagues (1998) compared to a mean difference of 33 dB in the current study. The mean values for both 2 and 4 kHz are highlighted in Table 4.7, above, in order to emphasize the higher than reported ASSEP minimum response levels obtained in the current study.

As with the comparison between behavioural pure tone testing and ASSEP minimum response levels, certain patterns emerged. Slightly smaller mean differences were obtained at 2 kHz (22 dB) and 4 kHz (29 dB), while the mean differences at 1 kHz were equal (18 dB) and the mean difference at 0.5 kHz was slightly bigger (25 dB) when the behavioural modulated tone thresholds were compared to the ASSEP minimum response levels.

As mentioned earlier in this section, there is very little literature available to compare the behavioural mixed modulated tone thresholds against, whether it is under insert earphone- or sound-field conditions. As with the behavioural ASSEP minimum response levels obtained under insert earphone conditions, there were no greater than 5 dB differences between the behavioural pure tone thresholds and those behavioural thresholds obtained with a modulated stimulus (modulated tone). Although for most frequencies, the mean difference between the behavioural FM tones and the ASSEP minimum response levels compared to the mean difference between the behavioural mixed modulated tone thresholds and the ASSEP minimum response levels, seem marginal there are certain discrepancies.

The standard deviations for the behavioural FM tone technique, using sound-field speaker presentation varied between 4 dB and 6 dB for all the frequencies tested. Standard deviations for the ASSEP technique, using insert earphones, varied between 10 dB and 12 dB. The greatest standard deviation for the ASSEP technique was found at 0.5 kHz, namely 12 dB, while the smallest difference was found at 1 and 2 kHz, namely 10 dB.

Statistical analyses of the thresholds obtained under sound-field conditions, for behavioural testing (both FM tone- and mixed modulated tone and those obtained under ASSEP testing differ significantly from each other. For all the frequencies tested (0.5 - 4 kHz) both sets of behavioural data showed greater than 0.05 p-values when compared to the ASSEP minimum response levels. These sets of data, therefore, differ significantly from each other on a 5% significance level. The numerical data from the statistical analysis is available in Appendix D.

This experiment was, again, controlled for gender- and ear effects. At 5 kHz there was a significant difference relating to gender effects between male and female research participants, when ASSEP minimum response levels were analyzed. Therefore, on a 5% level of significance the minimum response levels obtained from male and female research participants differed significantly from each other. However, when these results are viewed on a 1% level of significance there is no statistical difference between the genders. Although gender might have some influence on the results obtained (discussed earlier in this section), the influence does not seem to be related to specific frequencies. Stricter analysis ($p < 0.01$) again revealed no significant difference, and further studies are required to address the possible influence of gender on the minimum response levels obtained from ASSEP testing. For all the other frequencies there were no statistical differences on either a 1% or a 5% level of significance. These results are available in Appendix J.

When the same comparison was made for ear effects there were no statistical differences between the ears for either a 1% or 5% level of significance. These results are available in Appendix K.

4.3.2 Comparison across transducers

The comparison across transducers will detail the discussion of thresholds obtained through behavioural testing and ASSEP testing. The discussion of transducers will be subdivided for thresholds obtained with pure tone stimulation and those obtained with modulated tone stimulation.

4.3.2.1 ASSEP Minimum Response Levels obtained at 0.5, 1, 2 and 4 kHz, under Insert Earphone and Sound-field Conditions

Table 4.10 provides a summary of the comparison between the mean ASSEP minimum response levels obtained from the monotic ASSEP technique, using insert earphones and sound-field speaker presentation at 0.5, 1, 2 & 4 kHz.

Table 4.8 Mean and Standard Deviation values for ASSEP minimum response levels under insert earphone and sound-field conditions (n = 50)

ASSEP Minimum Response Levels (in dB SPL)		500 Hz	1000 Hz	2000Hz	4000 Hz
Using Insert Earphone Presentation	**Mean (*SD*)**	44 (*+/-12*)	29 (*+/-10*)	34 (*+/-10*)	29 (*+/-11*)
Using Sound-field Speaker Presentation	**Mean (*SD*)**	35 (*+/-12*)	24 (*+/-10*)	32 (*+/-10*)	51 (*+/-11*)

ASSEP minimum response levels obtained, under insert earphone conditions, as well as those obtained under sound-field conditions, differ substantially from one another at 4 kHz while the mean differences across 0.5-2 kHz were marginal. The greatest difference (22 dB) for the comparison was found at 4 kHz where the mean value for the electro-physiological minimum response level, using insert earphones, was 29 dB SPL, compared to the electro-physiological minimum response levels, using sound-field speaker presentation, of 51 dB SPL. The smallest difference (2 dB) in mean values was found at 2 kHz where the mean value for the ASSEP minimum response level using insert earphones was 34 dB SPL compared to the mean ASSEP minimum response level value of 32 dB SPL obtained under sound-field conditions. The difference in mean values across the transducers was 9 dB at 0.5 kHz and 5 dB at 1 kHz.

Picton and colleagues (1998) found no significant differences between the SPL minimum response levels with insert earphones or sound-field speakers. It is important to note however that their study did not make use of repeated measures since the subjects were different for the two measures (Picton et al., 1998). The current study did make use of repeated measures within the same group of research participants. There are however certain similarities when the two studies are compared. As is the case with the current study, Picton and colleagues (1998) also found the smallest mean difference across transducers to be at **2 kHz**. Both studies obtained a mean difference of 2 dB SPL across the transducers.

The 9 dB mean difference obtained in the current study at **0.5 kHz** is marginally higher than the 6 dB mean difference obtained by Picton and colleagues (1998). Picton and colleagues (1998) obtained a mean difference of 4 dB across the transducers at **1 kHz**, which correlates very well with the 5 dB obtained in the current study for the same comparison. For the comparison at **4 kHz**, however, the study done by Picton and colleagues revealed a mean difference of 4 dB across the transducers, which is significantly lower than the 22 dB obtained during the current study. It is important to note that multiple simultaneous stimuli were used during the data collection of the study done by Picton and colleagues (1998), while the present study employed single sequential stimuli.

Figure 4.3, below, provides a visual interpretation of the results obtained across transducers (in dB SPL) at 0.5, 1, 2 & 4 kHz, in an attempt to clarify the subsequent interpretation of the results.

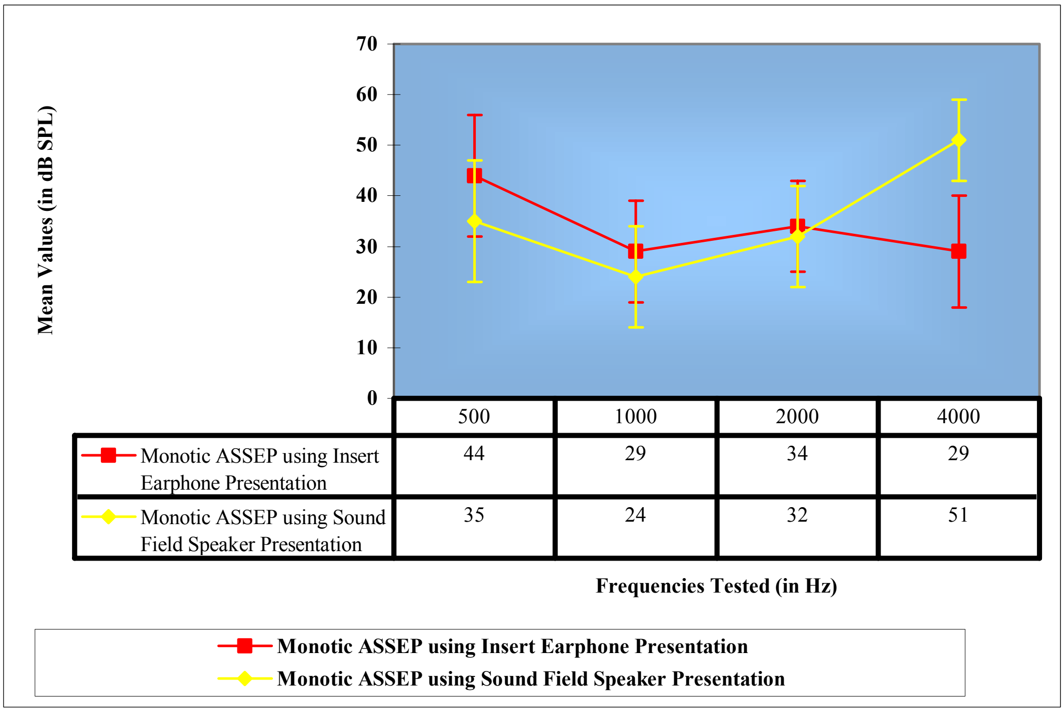


Figure 4.3 Electro-physiological Data, obtained using the ASSEP Technique across Transducers

Mean minimum response levels obtained through electro-physiological testing across transducers, when using a monotic ASSEP stimulus, revealed no greater than 5 dB differences for 1 or 2 kHz. At 0.5 kHz a mean difference of 9 dB can be observed, while the mean difference obtained at 4 kHz was 22 dB. The electro-physiological data obtained using the different transducers seem to have a close resemblance, with the exception at 4 kHz.

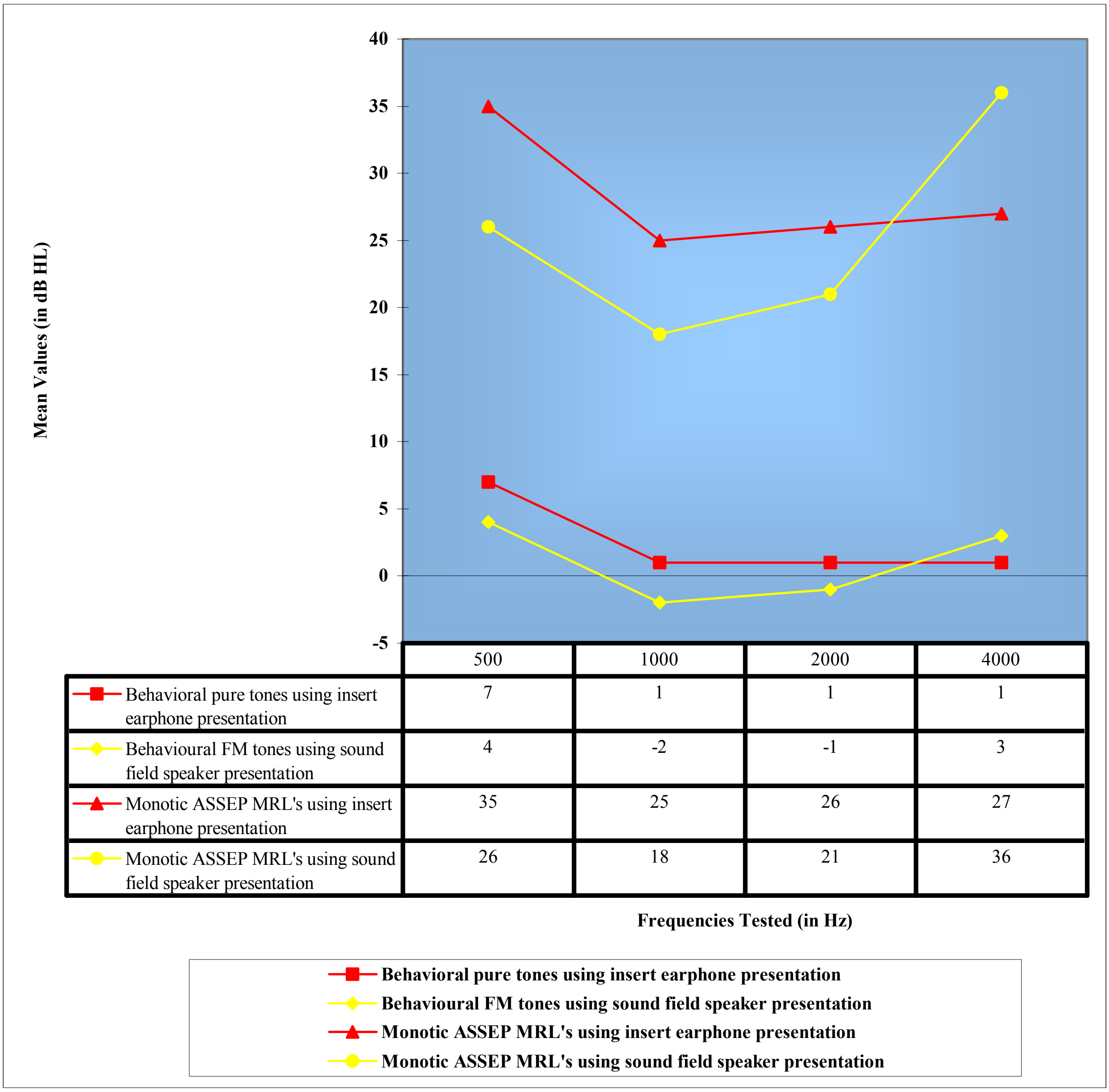
However, when the mean ASSEP minimum response levels obtained using the different transducers were analyzed statistically certain statistical differences were noted. All the frequencies tested did show significant differences for both $p < 0.05$ and $p < 0.01$, with the exception of 2 kHz which showed no significant difference for $p < 0.05$. The results from the statistical analysis are presented in Appendix G. Therefore, only the minimum response levels obtained at 2 kHz are comparable on a 5% level of significance.

4.3.3 Comparison across Stimulus Presentations and Transducers

The comparison across stimulus presentations and transducers will detail the discussion of thresholds obtained through behavioural testing and the minimum response levels obtained through monotic ASSEP testing.

- **ASSEP Minimum Response Levels at 0.5, 1, 2 and 4 kHz compared to behavioural thresholds, under Insert Earphone Presentation as well as Sound-field Speaker Presentation**

  Figure 4.4, below provides a visual interpretation of the behavioural thresholds and ASSEP minimum response levels obtained with the different transducers at 0.5, 1, 2 & 4 kHz.



	500	1000	2000	4000
Behavioral pure tones using insert earphone presentation	7	1	1	1
Behavioural FM tones using sound field speaker presentation	4	-2	-1	3
Monotic ASSEP MRL's using insert earphone presentation	35	25	26	27
Monotic ASSEP MRL's using sound field speaker presentation	26	18	21	36

Figure 4.4 Mean Pure Tone, FM Tone Thresholds and Mean ASSEP Minimum Response Levels obtained using both Insert Earphone and Sound-field Speaker Presentation

When the mean differences between the thresholds and minimum response levels are compared, within the same transducer, the following figures are noted: At **0.5 kHz** the mean difference for insert earphone conditions was 28 dB compared to the 22 dB difference for the sound-field conditions. Mean differences obtained at **1 kHz** revealed a 24 dB difference for the insert earphone conditions, while the sound-field conditions revealed a difference of 20 dB. Insert earphone conditions revealed a 25 dB a mean difference at **2 kHz**, while sound-field conditions revealed a mean difference of 22 dB for the same frequency. The greatest mean differences were recorded at **4 kHz** where a value of 26 dB HL was obtained for the insert earphone conditions and a value of 33 dB HL for the sound-field speaker presentation.

As discussed earlier in this chapter, there were no greater than 5 dB differences between the behavioural thresholds (across transducers) however statistical differences (Appendix G) were noted for all the frequencies tested ($p < 0.05$). Statistical analyses of the ASSEP minimum response levels obtained under insert earphone- and sound-field conditions revealed significant differences (Appendix G) for all the frequencies tested except 2 kHz.

Other researchers (Picton et al., 1998) have reported no significant differences between results obtained under insert earphone conditions and those obtained under sound-field conditions. However, in light of the aforementioned variation in mean differences, as well as the fact that statistical analyses highlighted several significant differences between the results obtained using the monotic ASSEP technique with different transducers, the current study cautions against comparison across transducers.

Figure 4.5 and 4.6 below provides a visual representation of the frequency distribution. It represents the percentage of ASSEP minimum response levels acquired at different intensity levels.

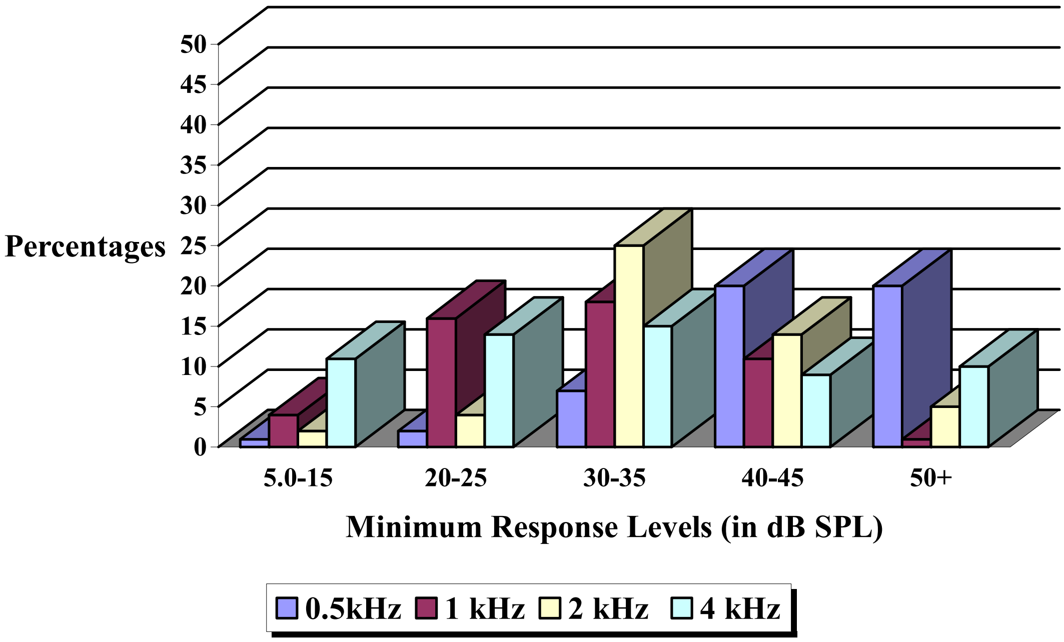


Figure 4.5 Frequency Distribution of Minimum Response Levels (in dB SPL), under Insert Earphone Conditions

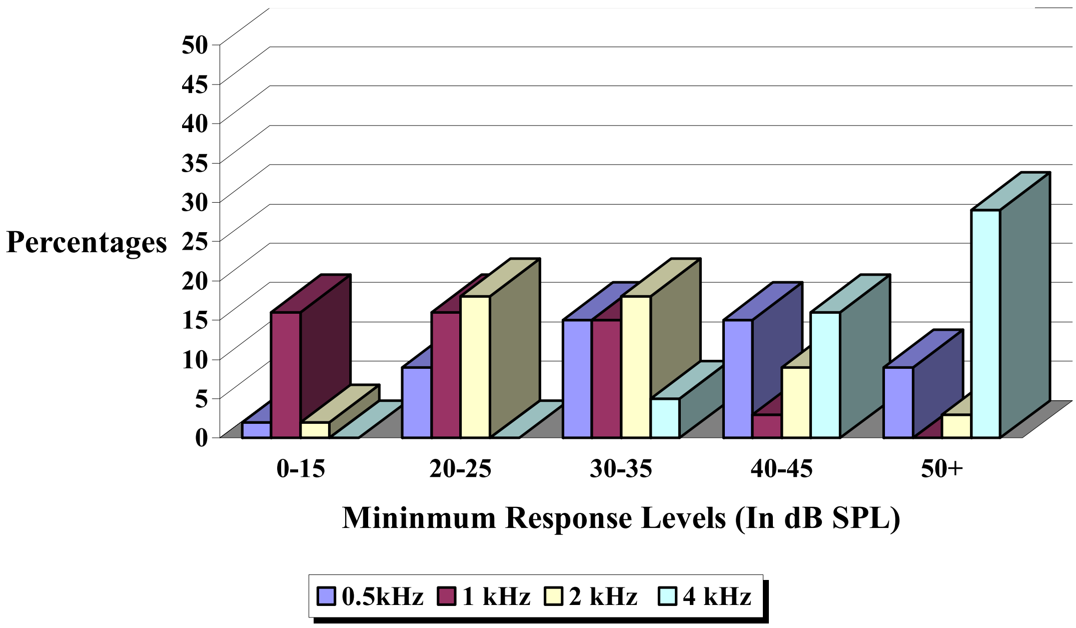


Figure 4.6 Frequency Distribution of Minimum Response Levels (in dB SPL, under Sound-field conditions

All the minimum response levels presented in Figure 4.5 and Figure 4.6 are expressed in dB SPL. The correction factors for the conversion of minimum response levels from dB HL to dB SPL, under insert earphone and sound field conditions are available in Appendix L. The majority of minimum response levels, obtained under insert earphone conditions (figure 4.5), were recorded at 30-35 dB SPL, across 1-4 kHz. However, the percentage of minimum response levels for 0.5 kHz, where the equal percentages of the minimum response levels were recorded at 40-45 dB SPL and 50+ dB SPL.

The minimum response levels obtained under sound-field conditions (Figure 4.6) did not show a uniform distribution for all the frequencies tested (0.5-4 kHz). The majority of the minimum response levels recorded for 0.5 kHz was between 30-45 dB SPL. The minimum response levels recorded for 1 kHz revealed that the greatest percentage of MRLs was recorded between 0-25 dB SPL. Thirty two percent of the minimum response levels, recorded for 1 kHz were recorded between 0-15 dB SPL, which was exactly the same as the percentage recorded for 20-25 dB SPL. The greatest percentage of the minimum response levels recorded for 2 kHz were between 20-35 dB SPL (with equal percentages, namely 36% were recorded between 20-25 and 30-35 dB SPL). The analysis of the minimum response levels recorded at 4 kHz revealed that the greatest percentage was recorded at 50+ dB SPL.

4.3.4 Discussion of the Comparison across Stimulus Presentation, Transducer and a combination of Stimulus Presentation and Transducer

The comparison across stimulus presentation, transducer and the combination of stimulus presentation and transducer will be discussed in terms of the influence of certain variables, and not separately as was the case with the discussion of the first sub aim. The variables that will be discussed are the influence of noise, the influence of amplitude modulation on frequency specificity, the physiological influence on response estimation and the influence of the acoustic environment.

- **Influence of noise:**

The technique implemented in determining whether a response was present or not, in this case the Fast Fourier Transform (FFT), might provide insight regarding the influence of noise. The signal-to-noise ratio in the frequency domain depends equally on the variability and the amplitude of the response in the FFT bins adjacent to the signal (Regan and Regan, 1989; Regan 1989). Furthermore the ASSEP signal has its "power" concentrated on the modulation frequency or some harmonics thereof (Lins et al., 1995). Because of the high resolution of the FFT, the power of the signal is greatly confined to a single FFT bin, while the noise is distributed across a wider frequency spectrum (Lins et al., 1995). By increasing the resolution of the FFT, the signal-to-noise ratio also increases. According to Lins and colleagues (1995) the noise levels can be decreased through both averaging and decreasing the width of the frequency bin. However in the current study the researcher did not have the option to alter the prescribed parameters and therefore it is necessary to further investigate the influence of noise on the ASSEP minimum response levels that were obtained.

It is possible though that the presence of ambient noise levels within the test environment could have acted as a background masking noise (Perez-Abalo et al., 2001), thereby elevating the pure tone thresholds without affecting the ASSEP minimum response levels (Picton et al., 1998). This phenomenon could possibly have a more pronounced effect on the behavioural thresholds obtained under sound-field conditions as these thresholds are also influenced by other factors within the acoustic environment, such as direct versus reverberant field testing, absorptivity of the rooms' surfaces, directivity of the speakers used and head movements of the participants being tested (Walker et al., 1984). In the current study the presence of ambient noise did not influence the sound-field conditions more adversely than those obtained under insert earphones, with the possible exception of the minimum response levels obtained for 4kHz. This can be seen when the results obtained (see Figure 4.4) are considered.

According to Picton and colleagues (1998), the background noise could possibly imitate a mild sensorineural hearing loss with recruitment. Other authors (Lins et al., 1996; Rickards et al., 1994) have commented that the difficulty in obtaining ASSEP minimum response levels at 0.5 kHz could partly be attributed to "the enhanced masking effect" of ambient noise at lower frequencies. This correlates well with results obtained under insert earphone conditions in the current study, as the greatest mean values were obtained at 0.5 kHz (35 dB HL). Other studies, such as Aoyagi and colleagues (1994) have noted the same difficulty in estimating low frequency hearing sensitivity, where the lower frequencies (0.25 kHz) showed the greatest mean values (34 dB HL). Rickards and colleagues (1994) also reported difficulty (50 dB SPL) in the estimation of low frequency thresholds (0.5 kHz). Valdes, Perez-Abalo, Martin, Savio, Sierra, Rodriguez and Lins (1997) obtained similar results, which relate to the difficulty in estimating low frequency thresholds.

The results obtained under sound-field conditions also show a greater than average ASSEP minimum response level (26 dB HL) at 0.5 kHz. However the greatest mean ASSEP minimum response level under sound-field conditions was obtained at 4 kHz. Although the influence of the "enhanced masking effect" of ambient noise at lower frequencies also holds true for results obtained under sound-field conditions, other additional influences now comes into play. These influences (with specific reference to 4 kHz) will be discussed under effects of the acoustic environment, later in this section.

There is a significant difference between the actual behavioural pure tone thresholds obtained under either insert earphone- or sound-field conditions, when compared with the ASSEP minimum response levels obtained with the same transducers. Although ambient noise levels were measured for this study (results available in Appendix M), it seems that noise levels in the test room, although higher than the prescribed ANSI standards, did not have a significant influence on the results obtained. The noise levels did, however, comply with the standards set out by the South African Buro of Standards (SABS). This is deducted from the fact that, for both insert earphone presentation as well as sound-field speaker presentation, the behavioural pure tone thresholds obtained did not differ significantly from the behavioural modulated tone thresholds. This difference was within 5 dB HL for 0.5, 1, 2 & 4 kHz, which according to Katz (1985) is acceptable seeing as a minimum standard error of +/- 5dB is introduced for behavioural testing. Furthermore there was no significant difference between these sets of data when they were statistically analyzed. It seems therefore that other variants, rather than ambient noise had an influence on the ASSEP minimum response levels obtained under insert earphone conditions, again with the possible exception of 0.5 kHz. The possible influence of the acoustic environment will be discussed later on (under effects of the acoustic environment) in this chapter.

- **The Influence of Amplitude Modulation on Frequency Specificity**

When the results of the current study are considered in terms of frequency specificity, the minimum response levels obtained provided reasonable estimates of the behavioural pure tones for all the frequencies tested. Amplitude modulated stimuli are reasonably frequency specific, and therefore the minimum response levels recorded should not be affected by "frequency splatter" observed in brief duration stimuli such as clicks (Lins et al., 1996). The problem however is not related to frequency specificity as much as to "place-specificity" (Starr & Don, 1988). When low frequency stimuli are presented at moderate to high intensity levels they can possibly cause activation of the more basal regions of the cochlea, which is concerned with high frequency stimulation, and in so doing cause distortion of the response (Lins et al., 1996). However, stimulation at higher intensity levels was not required during the current study, as all the participants had normal-hearing sensitivity. It is highly unlikely that the minimum response levels obtained in the current study were "distorted" as the modulation rate employed already ensures frequency specificity (Lins et al., 1996) and the presentation of stimuli was below moderate to high intensities.

Modulation effects, with specific reference to results obtained under sound-field conditions also have to be considered. According to Picton and colleagues (1998) the depth of modulation is bound to decrease from 100%, because of acoustic reflections within the room arriving at the participants' head with different delays. This might account for the statistical differences noted under different transducers (for all frequencies tested except 2 kHz). Although a high probability exists that the modulation might have decreased to some extent, the effect thereof is bound to be minimal, since the response is stable at modulation depths that exceed 50 percent (Lins et al., 1995). The possibility exists, that other influential variables, rather than modulation effects attributed to the statistical differences observed across transducers, in the current study.

- **The Physiological Influence on Response Estimation**

When considering the results obtained in the current study it is evident that the MRLs at 0.5 kHz reveal a much greater mean difference when compared to the actual behavioural pure tone thresholds, than any other frequency except for 4kHz under sound-field conditions. Other reports (Aoyagi et al., 1994; Lins et al., 1996; Rance et al., 1995) mention similar findings when using either sequential (single) frequency presentation or simultaneous (multiple) frequency presentation. Lins and colleagues

(1996) related the difficulty in estimating 0.5 kHz thresholds to the influence of ambient noise (previously discussed).

Prominent among other explanations is the explanation that higher frequencies, during multiple frequency stimulation, would interact and most likely affect the estimation of the 0.5 kHz response, either through suppression or masking (Perez-Abalo et al., 2001). The fact that other researchers (Aoyagi et al., 1994; Valdes et al., 1997), while using sequential frequency presentation, have experienced similar difficulties makes this explanation unlikely.

A further explanation is related to group delays (Goldstein et al., 1971), which postulates that phases of the ASSEP can be sensibly converted to latencies and that these latencies are related to frequency-related delays (John & Picton, 2000). According to John & Picton (2000) there are five main factors that contribute to the latency of a neuro-physiological response, namely acoustic delays, transport delays, filter built-up times, synaptic delays and conduction delays. The problem is that the latency of a neural response is not simply a sum of these five delays and that the recorded response may not derive from only a single generator. However, many different regions of the auditory system generate responses following the stimulation through a modulated tone. Each of these regions has a specific phase and latency relationship to the stimulus and the recorded response on the scalp is made up from an overlapping of all of these responses (John & Picton, 2000).

Studies performed on animals (Joris & Yin, 1992) have found group delays relating to the carrier frequency used around 0.5 kHz. These results cannot be used to validate present findings in human participants, as there are specie-related differences. Some of the larger delays could, however, probably relate to frequency-related change in conduction delay (John & Picton, 2000). The results obtained in the current study substantiate reports in the literature, as mean minimum response levels were elevated for 0.5kHz, and more so in males than females. These elevated minimum response levels can possibly be attributed to differences in length of the basilar membrane found between males and females (John & Picton, 2000).

Lastly, threshold estimation in the lower frequency region (i.e. 0.5 kHz) might be problematic due to the intrinsic characteristics of the responses. Lins and colleagues

(1996) mentioned that the responses to lower frequencies are attenuated because of "jitter" in the transmission time between cochlear receptors and the neural generators of these responses. This "jitter" would then go on to cause the neurons to desynchronize in their generation of responses, and subsequently this will then lead to a decrease in response amplitude (Lins et al., 1996). The "jitter" mentioned by Lins and colleagues (1996) could be caused by a wider activation of the basilar membrane. It is important to mention however, that their theory is specifically related to the activation of the basilar membrane in infants and might not hold true for adult subjects.

It seems therefore that conduction delays (John & Picton, 2000), related to the specific carrier frequency, as well as the effect of ambient noise (Lins et al., 1996) might cause problems when estimating thresholds in the lower frequency region. Research conducted by Herdman & Stapells (2001) contradicted findings by other researchers (Aoyagi et al., 1994; Rickards et al., 1994), reporting minimum response levels within 10 dB of the behavioural thresholds. They attributed their results to low levels of ambient noise (10-12 dB SPL). Picton and colleagues (1998) suggested that irrespective of the amount of averaging used, minimum response levels are highly unlikely to be recorded within 10 dB of the hearing threshold, due to the latency "jitter" at near threshold intensities. Even though the threshold estimations obtained by Herdman & Stapells seem promising, proving that the ASSEP technique can estimate thresholds within 10 dB of the actual behavioural threshold, some concerns regarding clinical feasibility arise. Stringent threshold criteria, such as prolonged averaging and low ambient noise levels, employed by Herdman & Stapells (2001) translate to prolonged test time, which, within the clinical setup is not always feasible. The question regarding the feasibility of prolonged test time is aggravated within the difficult-to-test population. Further studies, however, are needed to investigate these possibilities.

- **Influence of the Acoustic Environment**

Although ambient noise levels in the test room might have an effect on the behavioural pure tone thresholds obtained under insert earphone conditions, as discussed earlier, the effects of the acoustic environment have a more pronounced effect on results obtained under sound-field conditions. Arlinger & Jerlvall (1987) commented that "*when earphones cannot be used the interaction between the test* *stimuli and the test room acoustics assumes critical importance*" (Arlinger & Jerlvall, 1987:21). When the results obtained during monotic ASSEP testing under sound-field conditions are considered, it seems likely that the acoustic environment had at least some impact on the minimum response levels obtained at 4 kHz.

There is limited literature available regarding the effect of the acoustic environment on the modulated stimuli used during monotic ASSEP testing. This becomes evident when compared to the extensive research (Arlinger & Jerlvall, 1987; Beynon & Munro, 1995; Dillon, 1982; Dillon & Walker, 1980; Dillon & Walker, 1982; Orchik & Rintelman, 1978; Walker et al., 1984) available regarding the influence of the acoustic environment on behavioural pure tone measures obtained in the sound-field. According to Beynon & Munro (1995) there are several different directional components, which show a more pronounced effect at higher frequencies. This might serve as explanation as to why the minimum response level obtained at 4 kHz under sound-field conditions was elevated (36 dB HL/ 51 dB SPL). Although ASSEP testing was conducted in the direct field and control measures were taken to ensure minimal head movement by the research participants, the effects of the acoustic environment might still have influenced the ASSEP minimum response level obtained at 4 kHz. Some of these factors include reflective surfaces, shape of the room, placement of research participants and test arrangements.

During the current study the following measures were taken to ensure minimal interference through test room acoustics. All reflective surfaces were covered with material, with the exception of the walls of the test room. The problem is that the test room wall, although sound treated, could possibly be somewhat reflective. According to Walker, (1979) the influence of any reflective surface becomes more pronounced as its size increases and the closer the proximity to the person being tested. As one of the walls was uncovered and directly next to the research participants, reflectivity might have impacted on the results obtained and especially for the higher test frequencies. This could possibly account for the "right-ear-effect" (observed at some frequencies) $p<0.05$ analyzed for ear effects. Other researchers have also observed this effect (Picton et al., 2002), however it is worth mentioning that they used noise stimulation. The test room complies with prescribed standards for audiometric testing (ANSI, 1996), rendering this explanation somewhat unlikely. The "right-ear-effect" has been described in the literature as the "right ear advantage" and postulates that stimuli presented to the right ear are more quickly and accurately processed (Clark, 2002).

All subjects were placed at a zero degree azimuth in relation to the speaker for the electro-physiological testing, done in the direct field. According to Walker and colleagues (1984) the frequency response obtained in the reverberant field will differ little from the measurements made in the direct field at an azimuth of zero degrees. Research participants were, furthermore placed so that the centre of their heads were in line with, and at the same height, as the centre of the loudspeaker's cone. It seems, therefore, that subject placement did not have a pronounced effect on the ASSEP minimum response levels obtained. The elevated minimum response level obtained at 4 kHz under sound-field conditions could therefore most likely be attributed to directional components affecting higher frequencies more adversely than lower frequencies (Beynon & Munro, 1995).

4.4 A Comparison between the actual Behavioural Thresholds (for both pure tone and modulated tone stimulation) obtained and the GSI AUDERA System's accuracy in predicting these Thresholds by means of an Algorithm, for Insert Earphone and Sound-field Conditions

This sub-aim will detail and discuss the results from four related groups of data pertaining to its focus. The results will be discussed as listed below:

- The accuracy of the GSI AUDERA System's Algorithm in predicting Behavioural Thresholds obtained under Insert Earphone conditions
- The accuracy of the GSI AUDERA System's Algorithm in predicting Behavioural Thresholds obtained under Sound-field conditions
- Discussion on the accuracy of the GSI AUDERA System's Algorithm in predicting Behavioural Thresholds obtained under both Insert Earphone and Sound-field Conditions

4.4.1 The accuracy of the GSI AUDERA System's Algorithm in predicting Behavioural Thresholds obtained under Insert Earphone Conditions

Table 4.9, below provides a summary of the behavioural pure tone thresholds, obtained under insert earphone conditions, as well as the predicted behavioural thresholds (based on the calculation by the GSI AUDERA system's algorithm).

Table 4.9 Mean and Standard Deviation values for Behavioural Pure Tone thresholds, Behavioural monotic ASSEP minimum response levels and the Predicted Thresholds under insert earphone conditions (n = 50)

Under Insert Earphone Conditions		500 Hz	1000 Hz	2000Hz	4000 Hz
Behavioural Pure Tone Thresholds	**Mean (*SD*)**	7 (+/-7)	1 (+/-5)	1 (+/-6)	1 (+/-7)
Behavioural Monotic ASSEP Thresholds	**Mean (*SD*)**	7 (+/-7)	3 (+/-5)	2 (+/-5)	3 (+/-7)
Predicted Behavioural Pure Tone Thresholds	**Mean (*SD*)**	12 (+/-11)	9 (+/-10)	11 (+/-8)	7 (+/-9)

The predicted thresholds, based on the algorithm of the GSI AUDERA system, are more predictive of the actual behavioural monotic ASSEP minimum response levels across 1-2 kHz, when compared to the behavioural pure tone thresholds obtained under insert earphone conditions. The only instance where the predicted threshold resembled the actual mean behavioural pure tone threshold more closely was at 4 kHz, while identical mean differences (5 dB) were obtained at 0.5 kHz for both the behavioural pure tones as well as the behavioural monotic ASSEP minimum response levels. The smallest mean difference between the predicted and actual pure tone thresholds was found at **0.5 kHz**, namely 5 dB. The greatest mean difference was recorded at **2 kHz**, namely 10 dB. The mean difference obtained for **1 kHz** was 8 dB, while the mean difference at **4 kHz** was 6 dB.

When the comparison was drawn between the predicted thresholds and the actual behavioural monotic ASSEP minimum response levels, the following mean differences were noted. The smallest mean difference was recorded for **4 kHz** were the mean difference was 4 dB. The greatest mean difference was found at **2 kHz**, namely 9 dB. The mean difference recorded for **0.5 kHz** was 5 dB, while **1 kHz** recorded a mean difference of 6 dB. Standard deviations for the predicted thresholds were slightly elevated (8-11 dB) in comparison to the actual behavioural thresholds obtained using the pure tone (5-7 dB) and monotic ASSEP technique (3-7 dB).

Although most literature do not make mention of algorithms employed by the equipment used, subsequently making comparison with relevant literature problematic, it seems that the GSI AUDERA system is quite accurate in predicting behavioural pure tone thresholds obtained under insert earphone conditions. Mean differences varied between 5-10 dB above the actual threshold. Slightly smaller variations were observed when predicted thresholds were compared to the behavioural monotic ASSEP minimum response levels, namely 4-9 dB. When the mean differences from the two comparisons were analyzed on a frequency-to-frequency basis there were no greater than 5 dB differences between them.

There were significant differences between the predicted pure tone thresholds (as based on the GSI AUDERA system's algorithm) and the actual pure tone thresholds, obtained under insert earphone conditions, for all the frequencies tested, except at 0.5 kHz on a 5% level of significance. These results are available in Appendix D. It is important to note, however that for 1-4 kHz the differences were within 10 dB from each other, which in patients with no reliable behavioural thresholds are still acceptable.

4.4.2 The accuracy of the GSI AUDERA System's Algorithm in predicting Behavioural Thresholds obtained under Sound-field Conditions

Table 4.10, below provides a summary of the behavioural FM tone thresholds, obtained under sound-field conditions, as well as the predicted behavioural thresholds (based on the calculation by the GSI AUDERA system's algorithm).

Table 4.10 Mean and Standard Deviation values for Behavioural FM Tone thresholds, Mixed Modulated Tone thresholds and the Predicted Thresholds under sound-field conditions (n = 50)

Under Sound-field Conditions		500 Hz	1000 Hz	2000Hz	4000 Hz
Behavioural FM Tone Thresholds	**Mean (*SD*)**	4 (+/-6)	-2 (+/-4)	-1 (+/-5)	3 (+/-5)
Behavioural Mixed Modulated Tone Thresholds	**Mean (*SD*)**	1 (+/-6)	0 (+/-5)	-1 (+/-4)	7 (+/-7)
Predicted Behavioural FM Tone Thresholds	**Mean (*SD*)**	12 (+/-11)	9 (+/-10)	11 (+/-8)	7 (+/-9)

Identical mean differences (12 dB) were obtained at **2 kHz** for both the behavioural FM tones, as well as the behavioural mixed modulated tone thresholds. For the comparison between the behavioural FM tone thresholds and the predicted thresholds the smallest mean difference between the predicted and actual FM tone thresholds was found at **0.5 kHz**, namely 8 dB. The greatest mean difference was recorded at **1 kHz**, namely 11 dB. The mean difference obtained **4 kHz** was 4 dB.

The smallest mean difference (0 dB) between the behavioural mixed modulated tone thresholds and the predicted thresholds were recorded at **4 kHz**, where the predicted threshold was identical to the actual behavioural mixed modulated tone threshold. The greatest mean difference (12 dB) was found at 2 kHz (as mentioned above), while the mean difference for **0.5 kHz** was 8 dB. The mean difference recorded at 1 kHz was 11 dB. Standard deviations for the predicted thresholds were slightly elevated (8-11 dB) in comparison to the actual behavioural thresholds obtained using the FM tone (4 - 6 dB) and monotic ASSEP technique (4 - 7 dB). These standard deviations closely resemble those obtained under insert earphone conditions.

There were significant differences between the predicted FM tone thresholds (as based on the GSI AUDERA system's algorithm) and the actual FM tone thresholds obtained for all the frequencies tested, except at 0.5 kHz on a 5% level of significance (when tested under sound-field conditions). These results are available in tabulated form in Appendix D. It is important to note, however that for 1-4 kHz the differences were within 10 dB from each other, which in patients with no reliable behavioural thresholds are still acceptable.

4.4.3 Discussion on the accuracy of the GSI AUDERA System's Algorithm in predicting Behavioural Thresholds obtained under both Insert Earphone and Sound-field Conditions

In order to facilitate the discussion of results a visual representation of the predicted thresholds will be presented in Figure 4.7, below together with the actual behavioural thresholds. The visual representation includes the predicted- and actual thresholds for both insert earphone and sound-field speaker presentation.

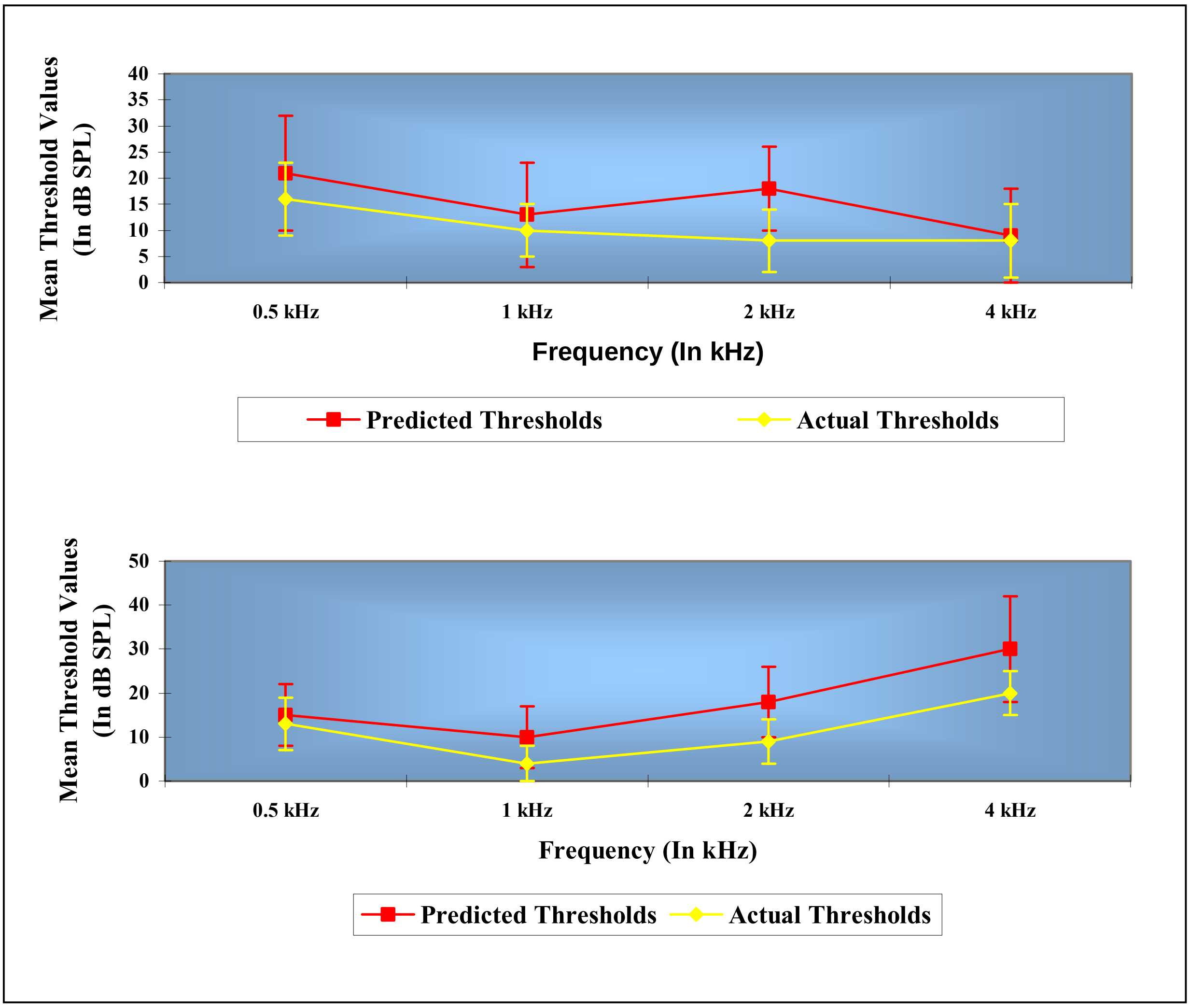


Figure 4.7 Mean Predicted Thresholds versus Actual Thresholds for insert earphone presentation (top) and Sound-field Speaker Presentation (bottom) in dB SPL

When the predicted thresholds (based on the GSI AUDERA System's algorithm) are compared across the transducers it is clear that for all the frequencies tested except 4 kHz they more closely approximate the thresholds obtained under insert earphone conditions. However given the high standard deviations these figures are unlikely o have a significant influence on predictive value of the algorithm employed by the GSI AUDERA system. When the predicted thresholds are compared with the behavioural modulated tone thresholds, they (predicted thresholds) again more closely approximate the thresholds obtained under insert earphone conditions, with the exception of 4 kHz. As the GSI AUDERA system is the first ASSEP test protocol to include an algorithm for the prediction of actual hearing thresholds, the limited amount of available research literature becomes evident.

It is therefore almost impossible to validate these findings in terms of relevant literature. It is, however, clear from the results obtained, that the system was quite accurate in predicting both the behavioural pure and -FM tone thresholds as well as the behavioural mixed modulated tone thresholds regardless of the transducer used. It is important, though, to mention that in the majority of the cases analyzed the predicted thresholds more closely approximated the thresholds obtained under insert earphone conditions, regardless of the stimulus presentation employed. This is likely to be because the algorithm is based on research that focused on threshold estimations obtained under insert earphone conditions. Therefore, the effect of the acoustic environment as well as transducer-related influences was most likely not taken into account when the algorithm was developed. Further investigation into this matter will be required before assumptions regarding the accuracy of the GSI AUDERA System's algorithm can be validated. Put simply, before clinicians can rely on the predictive function (algorithm) of the GSI AUDERA system further research will have to be done to validate these preliminary findings.

4.5 Summary

This chapter reported and discussed the results obtained in the current study according to the three sub-aims specified in chapter three. These sub-aims were specifically selected in an attempt to address the main aim of the study. Each of the sub-aims provided results pertaining to its focus, and integrated these results with the current literature to ascertain the validity thereof. Conclusions will subsequently be drawn in relation to the specific sub-aims in the final chapter of the study.

CHAPTER FIVE: CONCLUSIONS

This chapter aims to draw relevant conclusions and stipulate implications obtained from the current study. It will, furthermore, critically evaluate the findings obtained in the current study and make recommendations for further research.

5.1 Introduction

Since the early 1980's objective procedures such as the Auditory Brainstem Response (ABR) have been used, not only to categorize, but also to assess appropriate amplification fittings (Beauchaine & Gorga, 1988; Hecox, 1983; Kileny, 1982; Mahoney, 1985). Since then the literature is replete with certain disadvantages (discussed in the second chapter of this study) relating to the technique and this has subsequently led to limited application of the ABR in the assessment of amplification within the clinical arena. However with the arrival of Auditory Steady State Evoked Potentials on the diagnostic scene, the old question of whether it will be a suitable alternative in the aided Auditory Evoked Potential test battery has resurfaced.

Preliminary investigations (Cone-Wesson et al., 2001; Picton et al., 1998) have stirred interest in the validation of Auditory Steady State Evoked Potentials, as a valuable instrument during the initial habilitation of hearing-impaired individuals. Picton and colleagues (1998) found that the minimum response levels obtained in their study correlated well with previous research using normal-hearing subjects. The average minimum response levels from their study (Picton et al., 1998) ranged between 26-36 dB SPL. Other authors seem to be in agreement (Lins et al., 1996; Aoyagi et al., 1994). These SPL minimum response levels were significantly higher than the normal HL levels from the research participants tested (Picton et al., 1998). They continue to report the difference between electro-physiological minimum response levels and behavioural thresholds to range between 18-26 dB. When compared to their previous study (Lins et al., 1996), this is a greater difference. They (Picton et al., 1998) contributed the higher differences obtained to the acoustic environment in which the data was collected. Unlike their (Picton et al., 1998) previous study (1994), the latter (1998) was conducted in a sound-attenuated chamber. Therefore, the presence of low-level background noise in the earlier study (1994) could have elevated behavioural thresholds without affecting the minimum response levels (Picton et al., 1998). In other words, the background noise imitated a mild sensorineural hearing loss with recruitment.

Their study (Picton et al., 1998) also reported that there were no differences between stimuli presented simultaneously and those presented sequentially. The implication for the current study would be that the minimum response levels obtained, through sequential stimulation can be related to both the minimum response levels obtained through sequential and simultaneous stimulation obtained in their study.

Lastly, Picton and colleagues (1998) reported that there were no significant differences between the minimum response levels obtained under supra aural earphone and sound-field conditions. Their measures made use of SPL measurements and did not correct for small differences in HL levels between supra aural headphones and sound-field conditions (Picton et al., 1998). This implies that the minimum response levels obtained under earphone conditions would have been slightly lower, as 0 dB HL correlates with 7 dB SPL for earphone testing and 4 dB SPL for sound-field testing (with an azimuth of 0º). According to their (Picton et al., 1998) calculations, these differences would not have affected the results obtained.

In light of the conclusions drawn from their study, the aim of the current study was to contribute to the existing body of knowledge by addressing the research question set out in chapter one, namely:

How accurate is monotic auditory steady state evoked potentials in the prediction of thresholds using sound-field stimulation, when compared to insert earphone stimulation, in a group of normal-hearing adults?

This chapter aims to logically conclude the current research endeavour by providing answers to the respective sub-aims in an attempt to answer the main aim. It will subsequently highlight and discuss the strengths and weaknesses of the current study and through this critical evaluation introduce recommendations for future research.

5.2 Conclusions: Theoretical and Clinical Implications Identified

This section delineates the respective sub-aims set out in an attempt to answer the main aim of the study. Each sub-aim is concluded in terms of the results obtained, the theoretical and clinical implications, and finally their relation to the main aim.

5.2.1 A comparison between pure tone-, frequency modulated (FM) and mixed modulated (AM/FM) tone behavioural thresholds at 0.5, 1, 2 & 4 kHz under insert earphone and sound-field speaker conditions

This sub-aim was structured to obtain results, presented in relation to two comparisons, namely a comparison across **stimulus presentation**, and one across **transducers.** Both of these comparisons were controlled for gender- and ear effects. The comparison of the behavioural thresholds using the two different stimulus presentations, for both insert earphones and sound-field speaker presentation, aimed to establish a basis from where the accuracy of the calibration of the different stimulus presentations and transducers could be argued. These comparisons also aimed to establish a basis from where the accuracy of the minimum response levels obtained using the monotic ASSEP technique under both insert earphone and sound-field conditions could be argued.

- **When the behavioural thresholds obtained were compared across stimulus presentation, the pure tone-, FM tone- and mixed modulated tone thresholds they were comparable with one another, for both insert earphone and sound-field conditions.**

This finding is supported by the statistical analyses (Friedmann Test), as none of the thresholds obtained (at 0.5, 1, 2 & 4 kHz) revealed significant differences for p values < 0.05. The findings of the statistical analysis were supported by the fact that the mean difference between the thresholds (obtained at each specific frequency) under the different stimulus presentations was < 5 dB. Therefore it seems that the calibration across pure tone and modulated stimuli are comparable. Put simply, if the thresholds, obtained from behavioural pure tone-, FM tone- and mixed modulated tone testing, are comparable within a specific transducer, the calibration for the two stimulus presentations are comparable as well. Keeping in mind those factors, other than stimulus presentation, influencing the minimum response levels obtained, and this comparison lays the foundation for comparison of behavioural thresholds with minimum response levels. This correlates with available research (Bacon & Viemeister, 1985; Picton et al., 1998) stating that a modulated tone should be distinguishable from an un-modulated tone at 5dB above the hearing threshold.

The results, across stimulation presentation, were furthermore analyzed to determine whether the gender of the research participants had a significant impact on the thresholds obtained. **The statistical analyses revealed that gender did not impact significantly on the thresholds obtained across stimulus presentation, and within a specific transducer, when the results were analyzed with $p < 0.01$**. When the results were analyzed on a 5% level of significance, most of the thresholds obtained still did not reveal any significant differences. However, when insert earphones were used, there was a statistical difference at 2 kHz ($p < 0.05$) between male and female research participants. Thresholds obtained under sound-field conditions also revealed a significant difference when a 5% level of significance was used to analyze the results. However, this time the differences were observed at 0.5 kHz. Put simply, it seems that gender does not affect the thresholds obtained under different stimulus presentations, when viewed on a 1% level of significance.

Lastly, the results across stimulus presentation were analyzed to determine whether ear effects had a significant impact on the thresholds obtained. When the stimulus presentation was compared under insert earphone conditions there were no significant differences on either a 5% or 1% level of significance. Results from stimulus presentation under sound-field conditions revealed a significant difference at 0.5 kHz for $p < 0.05$ between left and right ears for pure tone stimulation. No statistical differences were noted for thresholds obtained under sound-field conditions between the left and right ears for modulated tone stimulation. **Thus, the statistical analyses revealed that ear effects did not significantly impact on the thresholds obtained across stimulus presentation, and within a specific transducer, when the results were analyzed with $p < 0.01$**.

- **When compared across transducer, the behavioural thresholds obtained under insert earphone- and sound-field conditions were not comparable with one another, for neither pure tone-, FM tone- nor mixed modulated tone stimulation on a statistical level.**

This is based on the fact that statistical analyses revealed significant differences between the thresholds using $p < 0.05$. These differences were obtained between insert earphone- and sound-field conditions, for all the frequencies tested, irrespective of the stimulus presentation used. When a significance level of 1% was used to analyze the results relating to the comparison across transducers, for pure tone stimulation, significant differences were obtained at all the frequencies tested except at 4 kHz. When the same comparison was made for modulated tone stimulation, all the frequencies tested showed significant differences except at 2 kHz.

Within the clinical arena the comparison across transducer, and within a specific stimulus presentation, would be comparable for most of the frequencies tested. This is based on the fact that the thresholds, during mixed modulated tone presentation, were within 5 dB from one another for all the frequencies tested, except at 0.5 kHz. Furthermore, during pure tone and FM tone stimulation the thresholds, for all the frequencies tested, were within 5 dB from each other. Thus, the 5 dB minimum standard error introduced for behavioural testing would still allow for comparison at most of the frequencies tested, while the statistical test showed a greater sensitivity and prohibits comparison across transducers.

Therefore, within the clinical arena comparison across transducers is permissible. The behavioural thresholds obtained under insert earphone- and sound-field conditions were within 5 dB from one another which complies with the 5 dB minimum standard error. Put simply, it seems that although the calibration across transducers is most likely accurate (thresholds for most frequencies were within 5 dB HL of each other) other influences within the test environment as well as the greater sensitivity of the statistical measures highlighted significant differences for the comparison across transducers. Therefore, behavioural thresholds obtained under a specific transducer could serve as the basis for comparison with minimum response levels obtained using either insert earphones or sound-field speakers as the transducer.

The results, across transducers, were furthermore analyzed to determine whether the gender of the research participants had a significant impact on the thresholds obtained. **The statistical analyses revealed that gender did not impact significantly on the thresholds obtained across transducers, and with specific reference to stimulus presentation, when the results were analyzed with $p < 0.01$**. When the results were analyzed on a 5% level of significance, most of the thresholds obtained still did not reveal any significant differences. However, when pure tone and FM tone stimulation was used, there was a statistical difference at 2 kHz ($p < 0.05$) between male and female research participants. Thresholds obtained through mixed modulated tone stimulation did not reveal any significant differences for either a 1% or 5% level of significance. Put simply, it seems that gender does not affect the thresholds obtained under different transducers, when viewed on a 1% level of significance.

Lastly, the results across transducers were analyzed to determine whether ear effects had a significant impact on the thresholds obtained. When the transducers were compared under pure tone and FM tone stimulation no significant differences were noted for any of the frequencies tested on either a 5% or 1% level of significance, with the exception of 0.5 kHz ($p < 0.05$). Results from mixed modulated tone presentation under insert earphone- and sound-field conditions revealed no significant differences at any of the frequencies tested, for $p < 0.05$ or $p < 0.01$ between left and right ears. **Thus, the statistical analyses revealed that ear effects did not significantly impact on the thresholds obtained across stimulus presentation, and within a specific transducer, when the results were analyzed with $p < 0.01$**.

To summarize, thresholds obtained under different stimulus presentations are comparable, while thresholds obtained under different transducers are not. When analyzed on a 1% level of significance neither gender, nor ear effects had a significant impact on the thresholds obtained, irrespective of stimulus presentation and/or transducers.

These findings correlate well with other reports in the literature (Bacon & Viemeister, 1985; Picton et al., 1998), stating that a 100% modulated tone is distinguishable from a pure tone at 5 dB above the hearing threshold. The comparison of modulated tone thresholds under the different transducers, and with specific reference to 0.5 kHz, is the only comparison that delivered unexpected results. The 6 dB difference for modulated tone stimulation between the different transducers exceeds the minimum standard error (Katz, 1985) of 5 dB. Within the clinical arena, where behavioural testing is usually associated with 5 dB increments, this finding will compromise test-retest reliability, regardless of whether the statistical analysis of the results found significant differences or not.

The implication for the clinical arena is that data obtained from behavioural tone testing is comparable across transducers. Therefore, unaided thresholds obtained through behavioural pure tone testing, under insert earphone conditions, are comparable with aided minimum response levels obtained under sound-field conditions (and vice versa).

It is possible that the influence of the acoustic environment (Anderson, 1979; Magnusson et al., 1997; Walker et al., 1984) on thresholds obtained under sound-field conditions could have distorted the comparison with thresholds obtained under insert earphone conditions. Picton and colleagues (1998) reported no significant differences between results obtained under insert earphone and sound-field conditions. It is important to note that their experiment did not make use of the same research participants in the repeated measures, whereas the current study did. Although there is extensive research available regarding sound-field audiometry, the only other published literature investigating transducer influences on ASSEP was by Picton and colleagues (1998). Further research is needed to establish if the thresholds, and subsequently, the minimum response levels obtained under different transducers are comparable.

5.2.2 A comparison between minimum response level detection at 0.5, 1, 2 & 4 kHz using a monotic ASSEP technique under insert earphone and sound field speaker conditions

This sub aim was structured to obtain results, presented in relation to three comparisons, namely a comparison across **stimulus presentation**, one across **transducers** and the last across both **stimulus presentation as well as transducers**. All of the comparisons were controlled for gender- and ear effects. The stimulus presentation comparison aimed to establish the relationship between behavioural thresholds and monotic ASSEP minimum response levels (controlled separately for insert earphone and sound-field speaker presentation). The comparison relating to transducers aimed to establish the relationship between behavioural thresholds and monotic ASSEP minimum response levels (controlled separately for pure tone and modulated tone stimulation). From these two assessments a basis of comparison is established from where the experiment across both stimulus presentation and transducers can be argued. The last assessment provides the vital comparison between the minimum response levels obtained under insert earphone and sound field conditions. Based on the results from sub aim one, these thresholds were converted to dB SPL in order to make the comparison valid.

The **comparison relating to stimulus presentation**, controlled for **insert earphone presentation**, revealed that the minimum response levels obtained more closely approximated the modulated thresholds for all the frequencies tested, except 0.5 kHz. The difference between the mean minimum response level and the mean behavioural thresholds for both pure tone- and mixed modulated tone stimulation at 0.5 kHz was identical (28 dB mean difference). Considering that modulated tones are distinguishable from un-modulated tones at 5 dB above the hearing threshold (Bacon & Viemeister, 1985; Picton et al., 1998), the closer correlation between minimum response levels and modulated thresholds, under insert earphone conditions, seems accurate.

The **comparison relating to stimulus presentations**, controlled for the **sound-field condition**, revealed mixed results with the mixed modulated thresholds correlating more closely at 1 and 4 kHz, while FM tone thresholds correlated better at 0.5 kHz. Both FM tone thresholds and mixed modulated tone thresholds showed a mean difference of 22 dB at 2 kHz. The acoustic environment could possibly have affected results obtained under sound-field stimulation. The comparison across stimulus presentation, and controlled for sound-field speaker presentation between pure tone and modulated tone thresholds did not reveal significant differences ($p < .05$) as discussed in 5.2.1. Furthermore, the same participants were tested in each of the conditions. The only variant during the comparison was the influence of the test room acoustics. Participants were tested in the reverberant field during behavioural FM tone testing and in the direct field during behavioural mixed modulated tone testing. Reflectivity of the rooms' surfaces were different under the different stimulus presentations, as participants were seated on a chair during FM tone testing, while they were lying on a bed on during mixed modulated tone testing.

The **comparison across transducers** revealed that the minimum response levels obtained using the different transducers closely approximated each other at 1 kHz (5 dB SPL mean difference) and 2 kHz (2 dB mean difference). The correlation at 0.5 kHz is somewhat elevated (9 dB mean difference) between the two transducers, while the greatest mean difference between the minimum response levels obtained from the two transducers was found at 4 kHz (22 dB). Statistical analysis of the results obtained revealed significant differences for all the frequencies tested, except 2 kHz on both a 5% and 1% level of significance.

The last experiment relating to the comparison across both stimulus presentation and transducers revealed that both the thresholds obtained under insert earphone- and sound-field conditions more closely approximated the minimum response levels obtained under sound-field conditions, in the majority of cases. The closer correlation is apparent between the behavioural pure tone and FM tone thresholds (obtained under insert earphone and sound-field conditions) and the minimum response levels (obtained under sound-field conditions) across 0.5-2 kHz. Both sets of pure tone data more closely approximated the minimum response level obtained at 4 kHz, under insert earphone presentation.

By implication the minimum response levels obtained under sound-field conditions more closely approximated the actual behavioural thresholds in the majority of cases, and with the exception of 4 kHz. **Therefore behavioural data should be used as a basis for comparison with minimum response level data on a transducer specific basis. In other words unaided thresholds, as well as unaided minimum response levels, obtained under a specific transducer should serve as the basis of comparison with the aided minimum response levels.** Put more simply, if a clinician requires aided thresholds estimations using the monotic ASSEP technique, he/she will have to ensure that the unaided thresholds are obtained under sound-field conditions.

The findings of the current study contradict previous literature available (Picton et al., 1998), which found no significant differences between minimum response levels obtained under insert earphone- and sound-field conditions. Although the results of the current study do not support the findings of Picton and colleagues (1998), it is worth mentioning that in the current study the same research participants were used in repeated measures during the course of the study. This was not the case with the study done by Picton and colleagues (1998). **Although the minimum response levels obtained in the current study, for both insert earphone- and sound-field speaker presentation correlate well with the literature available, further research is needed to validate the comparison of minimum response levels across different transducers**.

5.2.3 A Comparison between the actual Behavioural thresholds (for both pure tone and modulated tone stimulation) obtained and the GSI AUDERA System's accuracy in predicting these thresholds by means of an Algorithm, for Insert Earphone and Sound-field Conditions

This sub aim was structured to obtain results relating to the GSI AUDERA system's accuracy in predicting the actual behavioural thresholds. In order to address the sub aim, two experiments were conducted. The first focused on the system's accuracy in predicting actual behavioural thresholds obtained under insert earphone conditions and the second on predicting the actual thresholds obtained under sound-field conditions.

For the comparison across stimulus presentation and transducers the predicted thresholds obtained under sound-field conditions more closely approximated the actual thresholds obtained under insert earphone conditions for all the frequencies tested except 4 kHz. For the same comparison, with predicted thresholds obtained under insert conditions the closer approximation was again with the actual thresholds obtained under insert earphone conditions. Nevertheless the predicted thresholds showed a strong correlation with the actual thresholds obtained under sound-field conditions. None of the mean differences exceeded 5 dB regardless of which transducer was used. **Therefore the predicted thresholds (based on the algorithm of the GSI AUDERA equipment) are closely related to the actual behavioural thresholds. While the predicted thresholds more closely approximate the actual thresholds obtained under insert earphone conditions, the correlation between predicted thresholds and the actual thresholds obtained under sound-field conditions are also strong.** At present there limited literature available to compare the GSI AUDERA system's predicted thresholds with. This is because the GSI

AUDERA system is one of very few ASSEP test protocols to include an algorithm for the prediction of actual thresholds.

Finally, the results of the sub-aims, when viewed as a whole provides the following answer to the main aim of the study. Behavioural thresholds obtained from different stimulus presentations correlate strongly with one another. When the comparison was drawn across transducers significant differences were obtained, indicating that comparison across transducers is not viable. The thresholds obtained for the different transducers show a strong correlation, with the MRLs obtained under sound-field speaker presentation being slightly better in the majority of cases (0.5-2 kHz). Both the minimum response levels obtained under insert earphone and sound-field conditions provide a reasonable estimation of thresholds when compared to the current body of knowledge. The estimation of actual thresholds through the predictive function (algorithm) of the GSI AUDERA equipment revealed excellent correlations, with the actual thresholds. The mean differences between predicted- and actual thresholds ranged between 0-10dB HL. The findings of the current study relating to the predictive function of the GSI AUDERA equipment will have to be validated by subsequent research, as the GSI AUDERA system was the first ASSEP test protocol to include an algorithm for the prediction of thresholds from minimum response levels obtained.

5.3 Critical Evaluation of the Current Study

A critical evaluation of the empirical research component of any research endeavour is essential in the determination of the value of the results obtained therein. Reliability and validity of the results as well as the influence of identified limitations, inherent to the study, is required to ensure appropriate interpretation thereof (Dane, 1990).

One factor that needs to be considered is the sampling method employed, in the current study, during the selection of research participants. The research design, namely a within group comparative experimental design, minimizes the effect of variability relating to research participants, in that all the participants are tested in all of the conditions of the experiment (Graziano, 2000). Furthermore the sample size can be described as being sufficient for making inferences regarding the results obtained, as a total of 50 ears (25 research participants) were analyzed. However, although the gender distribution was approximately equal (13 female vs. 12 male), the disproportion could have affected the results obtained from the statistical tests during analyses of gender effects. In order to determine the effect, if any, of gender on the thresholds obtained, an equal distribution of male and female participants would probably provide more reliable results.

Furthermore the age distribution of the current study represents an adult population and inferences as well as conclusion from the results are therefore not applicable to, for example a pediatric population. Previous research (Olsho, Koch, Carter, Halpin, & Spetner, 1988; Schneider & Trehub, 1992) reported minimum response levels obtained from infants and adult research participants' that revealed mean differences ranging between 10-30 dB. According to Werner, Folsom and Manel (1993) the higher minimum response levels obtained from infants could possibly attributed to the fact that neural response systems develop independently from sensory systems.

Another possibility is that the minimum response levels to low frequency stimulation could be attenuated because of a "jitter" in the transmission between cochlear transducers and neural receptors, thereby activating a wider range of activation on the basilar membrane of infants. Put simply, the cochlear- as well as neural development of infants could possibly cause an elevation in minimum response levels obtained when compared with those obtained for adults. Thus it is clear that the thresholds obtained in the current study would not suffice as normative data for pediatric testing. Due to the age distribution of the current study, inferences and conclusions drawn from the results obtained will only apply to populations showing similar age distributions. The age range represented in the current study varied, primarily between 15-25, with reasonable distribution between 26-45 years of age.

Another factor, the influence of the test environment has to be considered. Two factors could possibly have influenced the results obtained. Firstly the ambient noise levels in the test room complied with the standards set out by the South African Buro of Standards, but exceeded the acceptable noise levels used by other researchers (e.g. Picton et al., 1998) and prescribed by ANSI standards (1996). According to Perez-Abalo and colleagues (2001) as well as Picton and colleagues (1998) the ambient noise levels within the test room could affect behavioural thresholds without affecting the minimum response levels obtained through ASSEP testing. Although the behavioural thresholds for both pure tone- and modulated tone stimulus presentation generally correlated well with each other across transducers, a discrepancy is noted at 0.5 kHz for the comparison of modulated tone presentation across transducers. It is furthermore possible that the behavioural thresholds were slightly elevated by the ambient noise levels. As this elevation would have occurred for both insert earphone and sound-field conditions it is unlikely that a discrepancy would be noted between thresholds obtained under different transducers. However, seeing as the ambient noise levels do not affect the minimum response levels obtained it is possible that the results obtained revealed distorted estimations of the actual thresholds.

In other words, if the ambient noise levels were within the prescribed international range (ANSI, 1996), it is possible that the behavioural thresholds for both pure tone and modulated tone stimulation would have been slightly lower. This would imply that the mean differences obtained between behavioural data and electro-physiological data would be greater than those reported in the current study.

Also, the influence of the acoustic environment could possibly have distorted the results obtained in the current study. According to Beynon and Munro (1995) the directional components, during sound-field testing, are more pronounced for higher frequencies. This factor could possibly have attributed to the elevation of the threshold estimations obtained under sound-field conditions at 4 kHz. Minimum response levels obtained at 4 kHz revealed a mean value of 51 dB SPL under sound-field conditions compared to the 29 dB SPL obtained under insert earphone conditions. Although the fact that directional components are more pronounced for high frequencies, under sound-field testing, this inherent factor cannot be seen as a limitation of the current research endeavour on its own, although it might have attenuated the elevated threshold estimation (at 4 kHz) in conjunction with other factors.

These include placement of the research participants and maintenance of the placement in relation to the speaker (Walker et al., 1984). The test position was clearly identifiable and research participants were placed on a height-adjustable chair. Participants were asked to sit as still as possible during the test procedure, after the chair had been adjusted so that the head of the participant was in line with the centre of the speakers' cone (at an azimuth of zero degrees). During the test procedures the researcher as well as another qualified audiologist monitored the maintenance of the test position. It is debatable whether small head movements were overseen and what the influence of these movements would have been on the results obtained. The critical question is how viable is the technique (under sound-field conditions) if these movements have such a profound impact on the results obtained. And more so, if the technique is aimed at assessing hearing sensitivity in the difficult-to-test population who is generally less cooperative than other populations.

Further influences of the test environment on the MRLs obtained under sound-field conditions include the influence of reflective surfaces within the test room (Walker, 1979), directivity of the speaker, shape of the room, as well as test arrangements. Of these influences there are two more influences that deserve mention. During the data collection of the current study, and specifically during the recording of ASSEP minimum response levels under sound-field conditions, research participants were placed in close proximity to a large reflective surface, namely the wall of the test room. Although the test room is sound treated, some degree of reflectivity cannot be helped.

According to Walker (1979) reflective surfaces can influence responses obtained under sound-field stimulation, and the extent of the influence increases as the size of the surface increases. The study (Walker, 1979) does not however mention the exact extent to which the responses are influenced. Thus it is clear that the reflectivity of the rooms' surfaces could have impacted on the minimum responses levels obtained, although the degree to which the MRLs were influenced, if at all, is not known.

Lastly, participants were tested in the reverberant field during behavioural testing and in the direct field during electro-physiological testing, due to calibration of the equipment prior to the conduction of the current study. This is a major limitation of the current study as reverberant field-testing is influenced by direct, as well as the reflected characteristics of the stimulus (Walker et al., 1984).

Yet another factor that has to be considered is the recording procedure utilized during minimum response level detection. Although both behavioural data and electro-physiological data were obtained using 5dB intensity increments, the minimum response levels for each research participant were taken as the lowest recorded response. When the signal to noise ratio rendered reliable response detection impossible the stimulus was presented again at the same intensity, however due to the prolonged test time involved in the current study, if a response was still not recorded due to the influence of noise, it was considered as a no-response. It is therefore possible that lower than recorded minimum response levels could have been obtained if repeated measures were made for intensity levels where the signal to noise ratio was not favourable. Thus, further averaging could have shown minimum response levels at intensities closer to the actual behavioural thresholds. Within the clinical arena this would mean that if ASSEP is applied under sound-field conditions to obtain aided thresholds a closer approximation would relate into a better performance evaluation of the specific aid.

The critical evaluation of the current study, as well as the implications thereof has revealed several research implications that are discussed in the following section of this chapter.

5.4 Recommendations for Future Research

"Whoever, in the pursuit of science, seeks after immediate practical utility, may generally rest assured that he will seek in vain…" (von Helmholz, 1863). Results from the current study showed that minimum response levels provided accurate threshold estimations, recorded through sound-field stimulation. A previous paper by Picton and colleagues (1998) also reported promising results. However, like Picton and colleagues (1998) the researcher admits that there is still much to be done, and "admits to cautious optimism" (Picton et al., 1998:329).

- **The first recommendation is to compare the accuracy of the monotic ASSEP technique in the estimation of aided and un-aided hearing thresholds in hearing-impaired individuals.** This type of study will validate the estimation of aided thresholds. While the current study aimed to determine the influence of transducers on ASSEP minimum response level detection, further investigation into the estimation of aided thresholds will serve to validate the findings obtained by Picton and colleagues (1998). Although their (Picton et al., 1998) findings indicated that smaller mean differences (13-17 dB) were obtained for aided testing conditions when compared to those for normal subjects (26-36dB), these findings have to be corroborated by further research in order to be validated.

More information regarding the effect of stimulus presentation on aided threshold estimation is required. Results from the study done by Picton and colleagues (1998), furthermore indicated that the threshold estimations obtained from single stimulus presented alone was much more accurate than when the stimulus was presented as part of a combined stimulus. A possible explanation would be that when multiple stimuli are presented simultaneously the low frequency stimuli might interfere with the response to high-frequency stimulation. Although this would only occur at high intensity levels for normal-hearing individuals, it occurs close to threshold in individuals with hearing loss (Picton et al., 1998).

Picton and colleagues (1998) postulated that minimum response levels at high frequencies were elevated when presented as part of a combined stimulus. This might reflect on the "effective" hearing sensitivity of the individual being tested. In other words, although a stimulus in the absence of competing stimuli might be audible, the frequency information might not be available in the stimuli of everyday environmental sounds. Therefore, research aimed at determining the ability of the monotic ASSEP technique to estimate aided thresholds would provide additional information to the limited body of knowledge currently available.

- **The second recommendation would be to compare the test-retest-reliability of ASSEP minimum response levels obtained under sound-field conditions for normal-hearing as well as hearing-impaired individuals**. This type of study would validate the ASSEP technique as a valid and reliable tool in the estimation of thresholds under sound-field conditions.

In order to determine whether any technique provides valid and reliable results, it has to be able to produce similar results for the same individual in test-retest measures. If thresholds estimations obtained from the same individual differs significantly from one test to the next, the technique does not provide valid or reliable results. Within the clinical arena over-estimation of the amount of gain provided by the hearing aid, might lead to an individual receiving insufficient amplification.

Also, if the technique reveals a significant range of variance during test-retest measures for normal-hearing individuals, differentiation between normal-hearing and a mild hearing loss could be unreliable. Previous research has established that thresholds obtained through pure tone stimulation under sound-field conditions correlated well for test-retest reliability. The need now arises to determine whether factors other than the acoustic environment could possibly influence the minimum response levels obtained from the ASSEP technique.

- **The third recommendation would be to determine whether a correlation between ASSEP minimum response level amplitudes and loudness exists**. If such a correlation exists it could provide information regarding optimal hearing aid settings. Previously auditory brainstem responses were used in an attempt to assess the optimal hearing aid settings. The rationale was to adjust the hearing aid settings until wave V of the auditory brainstem response (obtained with click stimulation) fell within normal limits (Beauchaine et al., 1988; Kileny, 1982; Mahoney, 1985). The application of this technique was limited, as click evoked auditory brainstem responses correlate mainly to high frequency gain (Serpanos, 1997). The technique also revealed a low correlation between wave V latency and loudness, which was aggravated for sloping hearing losses (Serpanos, 1997).

  Current literature available (John et al., 1998) suggests that the ASSEP technique would provide information mainly about the low range intensities, as interactions occur between stimuli at high intensities. Research using a monotic sequential ASSEP technique, under sound-field stimulation, is required to confirm this hypothesis. It might therefore be possible to provide objective assessment of comfort levels, by presenting a stimulus close to threshold level and adjusting the hearing aid to provide optimal amplitudes without substantial harmonics (indicating distortion).

  Another advantage of the ASSEP technique is that minimum response levels obtained is sufficiently frequency specific, so that masking is not required, as is the case with the auditory brainstem response. This does not however, exclude the possibility that the minimum response levels obtained will not be place-specific, for low frequency stimulation and even more so than for high frequency stimulation (Picton et al., 1998).

Lastly, ASSEP can be presented at sufficiently high intensity levels to detect hearing losses that would not have been detected by auditory brainstem response testing, due to the severity of the loss (Rance et al., 1998). Therefore not only does the technique provide a method for accurate diagnosis, but it also puts in place a means of assessing the initial habilitation of individuals with identified losses (Picton et al., 1998).

- **The fourth recommendation would be to assess supra threshold hearing in the selection and fitting of amplification devices in order to ensure optimally discernable sound input.** Another possible contribution of the ASSEP technique, under sound-field conditions would be to assess supra threshold hearing. Gain measurements of hearing aids can be assessed with in the ear measures. These measures only provides information regarding sound pressure levels at the eardrum, while ASSEP minimum response levels recorded for aided conditions would incorporate the perception of the aided sound after being processed in the brain (Picton et al., 2002a).

  In order to determine if the amplification provided is sufficient for comfortable speech discrimination, older children and adults are evaluated with word recognition tests. Supra threshold assessments through the ASSEP technique, under sound-field conditions, might provide valuable information in the pediatric- and difficult-to-test populations who would not be able to comply with word recognition testing. Preliminary results (Picton, 2002b) allowed for optimism, however these results will have to be validate through further research.

- **The fifth recommendation would be to establish an optimal range relating to test time and the amount of averages required to obtain reliable and accurate threshold estimations**. Picton, Dimitrijevic, John and Van Roon (2001) reported that test times in excess of 20 minutes are required to comprehensively evaluate representative thresholds. This type of study could delineate what the test time and amount of averaging required would be and whether this range would be clinically applicable. Thereby defining stimulus-, acquisition- and recording parameters that are, both optimal for accurate threshold estimation, as well as time-efficient, and subsequently clinically applicable.

5.5 Final Comments

This study has investigated the influence of transducers on the monotic Auditory Steady State Evoked Potential. The use of these potentials to measure the audiogram of individuals identified as hearing-impaired, has been justified by previous research (Picton et al., 2002a). However, even concerning the diagnostic application of ASSEPs there is a need for more research regarding the accuracy of the various techniques, to improve stimulation techniques as well as recording parameters (Picton et al., 2002a). Auditory Steady State Evoked Potentials are currently entering the realm of hearing screening, but yet again there is a need for ongoing investigation into its validity, as well as its reliability.

Research regarding the management of the hearing-impaired individual through Auditory Steady State Evoked Potentials is in its "infancy". Future research on these and other techniques are required to validate the use of evoked potentials in the identification, evaluation and management of infants, and others within the difficult-to-test population. As Picton and colleagues stated: "If we do not do so, we shall never know that our present techniques are indeed the best. We must not lock ourselves in 20-year old technologies…" without the means to collect data to improve our management of hearing loss (Picton et al., 2002a:33).

5.6 Summary

This chapter drew conclusions to each of the sub-aims formulated in chapter three. The conclusions were discussed to address the main aim of the study. Following the conclusions a critical evaluation of the current study followed. Recommendations for future research were presented based on the results of the current study as well as literatureavailable.

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APPENDIX A

University of Pretoria

Research Proposal and Ethics Committee
Faculty of Humanities

2 August 2002

Dear Doctor Schmulian

Project:	***The influence of insert earphones and sound-field stimulation on monotic auditory steady state evoked potentials***
Researcher:	**JJ Marais**
Supervisor:	**Dr D Schmulian**
Department:	**Communication Pathology**
Reference number:	**97157830**

Thank you for the application you submitted to the Research Proposal and Ethics Committee, Faculty of Humanities.

I have pleasure in informing you that the Research Proposal and Ethics Committee formally approved the above study on 1 August 2002.

The committee requests you to convey this approval to Mr Marais.

We wish you success with the project.

Sincerely

Brenda Louw

Prof Brenda Louw
Chair: Research Proposal and Ethics Committee
Faculty of Humanities
UNIVERSITY OF PRETORIA

APPENDIX B

June 2002

Dear Sir / Madam

Thank you, so much for showing interest in this research project being conducted at the Hearing Clinic, Department of Communication Pathology at the University of Pretoria. The Audiology Department is very exited about the arrival of the GSI AUDERA Auditory Steady State Evoked Potential equipment, a state-of-the-art objective hearing evaluation procedure. We are currently undertaking clinical trails of the equipment and we need your assistance. We need to establish norms for normal-hearing ears using both insert earphones and sound-field speaker presentation with this technique, and we kindly ask for your participation in this study.

<u>Participation in this study will involve the following:</u>
You will undergo a standard hearing evaluation (pure tone behavioural audiometry), where you are required to respond to sound stimulation. You will need to repeat this test using insert earphones and sound-field speaker presentation. This procedure takes approximately 15 min. The same (behavioural) procedure will then be followed using the auditory steady state evoked potential equipment. This procedure also takes about 15 min.

An Auditory Steady State Evoked Potential (ASSEP) test, using insert earphones, will follow. No response is required during this procedure. You will simply be asked to lie down on a bed, with three electrodes attached to your head. This test takes approximately 90 min.

The last procedure, again, involves the ASSEP test, this time using a sound-field speaker. Again, no response is required during this procedure. You will lie down on a bed, with three electrodes attached to your head. This time the sound stimulation will come from the speaker and not from the insert earphones as in the second procedure. Again this test will take approximately 90 min.

All the procedures (tests) are non-invasive and only the behavioural procedures require responses from you. The test battery will be divided into two sessions of no longer than two hours each. All acquired information will be treated as confidential and no names will be used. A copy of your results will be made available to you, should you request it. Thank you for your assistance.

Should you require any further information, you are welcome to contact us.

Yours sincerely

____________________	________________________	__________________________
Prof. René Hugo Head of Department	Mr De Wet Swanepoel Research Supervisor	Mr Cobus Marais Researcher

APPENDIX B CONTINUED

University of Pretoria

Department Communication Pathology: Audiology

Name: ______________________ Occupation: _________________.

Age: ______________________ Contact numbers: ______________.

Date of birth: ____________________(mm/dd/yy/)

____

Please complete the following reply slip:

I ___________________________________ hereby agree to participate in this project. I am aware that I can withdraw from this project, at any time, should I want to.

______________________ ________________________

Signature Date

APPENDIX B CONTINUED

June 2002

Dear Parents

Thank you, so much for showing interest in this research project being conducted at the Hearing Clinic, Department of Communication Pathology at the University of Pretoria. The Audiology Department is very exited about the arrival of the GSI AUDERA Auditory Steady State Evoked Potential equipment, a state-of-the-art objective hearing evaluation procedure. We are currently undertaking clinical trails of the equipment and we need your child's assistance. We need to establish norms for normal-hearing ears using both insert earphones and sound-field speaker presentation with this technique, and we kindly ask for your child's participation in this study.

<u>Participation in this study will involve the following:</u>
Your child will undergo a standard hearing evaluation (pure tone behavioural audiometry), where he/she will be required to respond to sound stimulation. He/she will need to repeat this test using insert earphones and sound-field speaker presentation. This procedure takes approximately 15 min. The same (behavioural) procedure will then be followed using the auditory steady state evoked potential equipment. This procedure also takes about 15 min.

An Auditory Steady State Evoked Potential (ASSEP) test, using insert earphones, will follow. No response is required during this procedure. Your child will simply be asked to lie down on a bed, with three electrodes attached to his/her head. This test takes approximately 90 min.

The last procedure, again, involves the ASSEP test, this time using a sound-field speaker. Again, no response is required during this procedure.

Your child will lie down on a bed, with three electrodes attached to his/her head. This time the sound stimulation will come from the speaker and not from the insert earphones as in the second procedure. Again this test will take approximately 90 min.

All the procedures (tests) are non-invasive and only the behavioural procedures require responses from your child. The test battery will be divided into two sessions of no longer than two hours each. All acquired information will be treated as confidential and no names will be used. A copy of your child's results will be made available to you, should you request it.
Thank you for your assistance.

Should you require any further information, you are welcome to contact us.

Yours sincerely

Prof. René Hugo	Mr De Wet Swanepoel	Mr Cobus Marais
Head of Department	Research Supervisor	Researcher

APPENDIX B CONTINUED

University of Pretoria

Department Communication Pathology: Audiology

Name: ____________________ Occupation: ________________.

Age: ____________________ Contact numbers: ______________.

Date of birth: ____________________(mm/dd/yy/)

____

Please complete the following reply slip:

I ________________________________ parent/guardian of ________________ ________________________________hereby give permission that he/she may participate in this project. I am aware that my child can withdraw from this project, at any time, should he/she or I want to.

____________________ ____________________

Signature Date

APPENDIX C

Type A Tympanogram: Normative Data

Tympanometric parameters	Physical parameters	References
Ear canal volume	1.0-1.4 cc	Silman & Silverman, 1991
Compliance	0.50-1.75 ml	Silman & Silverman, 1991
Pressure (daPa)	-50 - +50 daPa	Silman & Silverman, 1991

Categorization of Degree of Hearing Loss

Categorization of Degree of Hearing Loss		
0-25 dB	Normal	Goodman, 1965
26-40 dB	Mild	Goodman, 1965
41-55 dB	Moderate	Goodman, 1965
56-70 dB	Moderately-Severe	Goodman, 1965
71-90 dB	Severe	Goodman, 1965
> 91 dB	Profound	Goodman, 1965

APPENDIX D

(X-No significant difference √-Significant difference)

Non Parametric Statistics				
	Comparison	**Frequencies Tested**	**Sign Test: Z-Stat**	**P<0.05**
Insert Earphone Presentation	Behavioural Pure Tone vs. Behavioural Mixed Modulated Tone Thresholds	**0.5 kHz**	0.12	**X**
		1 kHz	1.05	**X**
		2 kHz	0.4	**X**
		4 kHz	1.55	**X**
Sound-field Presentation	Behavioural FM Tone vs. Behavioural Mixed Modulated Tone Thresholds	**0.5 kHz**	1.59	**X**
		1 kHz	0.89	**X**
		2 kHz	0.04	**X**
		4 kHz	2.21	**X**
Insert Earphone Presentation	Behavioural Pure Tone Thresholds vs. ASSEP Minimum Response Levels	**0.5 kHz**	7.94	√
		1 kHz	8.56	√
		2 kHz	9.06	√
		4 kHz	9.02	√
Sound-field Presentation	Behavioural FM Tone Thresholds vs. ASSEP Minimum Response Levels	**0.5 kHz**	7.28	√
		1 kHz	8.83	√
		2 kHz	9.02	√
		4 kHz	9.68	√
Insert Earphone Presentation	Behavioural Mixed Modulated Tone vs. ASSEP Minimum Response levels	**0.5 kHz**	8.06	√
		1 kHz	7.51	√
		2 kHz	9.10	√
		4 kHz	7.47	√
Sound-field Presentation	Behavioural Mixed Modulated Tone vs. ASSEP Minimum Response levels	**0.5 kHz**	8.87	√
		1 kHz	7.94	√
		2 kHz	8.99	√
		4 kHz	7.47	√
Insert Earphone Presentation	Behavioural Pure Tone Thresholds vs. Predicted Thresholds (ASSEP Algorithm)	**0.5 kHz**	1.47	**X**
		1 kHz	3.10	√
		2 kHz	4.61	√
		4 kHz	2.90	√
Sound-field Presentation	Behavioural FM Tone Thresholds vs. Predicted Thresholds (ASSEP Algorithm)	**0.5 kHz**	0.66	**X**
		1 kHz	3.60	√
		2 kHz	4.57	√
		4 kHz	9.683.60	√

APPENDIX D CONTINUED
(X-No significant difference √-Significant difference)

Non Parametric Statistics

	Comparison	Frequencies Tested	Sign Test: Z-Stat	P<0.05
Insert Earphone Presentation	Behavioural Mixed Modulated Tone vs. Predicted Thresholds (ASSEP Algorithm)	**0.5 kHz**	1.59	**X**
		1 kHz	2.05	**X**
		2 kHz	4.65	√
		4 kHz	1.36	**X**
Sound-field Presentation		**0.5 kHz**	2.25	**X**
		1 kHz	2.71	√
		2 kHz	4.53	√
		4 kHz	1.39	**X**
Insert Earphone Presentation	ASSEP Minimum Response Levels vs. Predicted Thresholds (ASSEP Algorithm)	**0.5 kHz**	6.47	√
		1 kHz	5.46	√
		2 kHz	4.45	√
		4 kHz	6.12	√
Sound-field Presentation		**0.5 kHz**	6.62	√
		1 kHz	5.23	√
		2 kHz	4.45	√
		4 kHz	6.08	√

APPENDIX E

(X-No significant difference √-Significant difference)

Analysis of Gender Effects: Mann-Whitney

	Frequency Tested	Mean Value for Male Participants	Mean Value for Female Participants	P-Value	P<0.05	P<0.01
Behavioural Pure Tone Thresholds obtained under Insert Earphones	0.5 kHz	8.9583	5.1923	0.2092	X	X
	1 kHz	2.0833	0.7692	0.1770	X	X
	2 kHz	2.9167	-0.3846	0.0340	√	X
	4 kHz	3.1250	-1.1538	0.0915	X	X
Behavioural Mixed Modulated Tone Thresholds under Insert Earphones	0.5 kHz	7.0833	6.9231	0.9921	X	X
	1 kHz	2.9167	3.0769	0.9513	X	X
	2 kHz	2.2917	0.7692	0.2089	X	X
	4 kHz	5.2083	1.7308	0.1642	X	X

Analysis of Ear Effects: Mann-Whitney

	Frequency Tested	Mean Value for Left Ears	Mean Value for Right Ears	P-Value	P<0.05	P<0.01
Behavioural Pure Tone Thresholds obtained under Insert Earphones	0.5 kHz	6.2	7.8	0.5369	X	X
	1 kHz	1.6	1.2	0.7714	X	X
	2 kHz	2.2	0.2	0.3548	X	X
	4 kHz	2.4	-0.6	0.2375	X	X
Behavioural Mixed Modulated Thresholds obtained under Insert Earphones	0.5 kHz	7.6	6.4	0.6767	X	X
	1 kHz	3.2	2.8	0.8788	X	X
	2 kHz	2.4	0.6	0.1913	X	X
	4 kHz	4.2	2.6	0.6700	X	X

APPENDIX F
(X-No significant difference √-Significant difference)

Analysis of Gender Effects: Mann-Whitney

	Frequency Tested	Mean Value for Male Participants	Mean Value for Female Participants	P-Value	P<0.05	P<0.01
Behavioural FM Tone Thresholds obtained under Sound-field Conditions	0.5 kHz	3.5417	3.8461	0.5968	X	X
	1 kHz	-0.8353	-0.1154	0.2620	X	X
	2 kHz	-1.8750	-0.5769	0.2450	X	X
	4 kHz	3.1250	2.3077	0.9587	X	X
Behavioural Mixed Modulated Tone Thresholds obtained under Sound-field Conditions	0.5 kHz	-0.2083	2.5000	0.1117	X	X
	1 kHz	-0.8333	0.3846	0.6804	X	X
	2 kHz	-1.6667	-0.1923	0.1827	X	X
	4 kHz	7.2917	6.5385	0.9840	X	X

Analysis of Ear Effects: Mann-Whitney

	Frequency Tested	Mean Value for Left Ears	Mean Value for Right Ears	P-Value	P<0.05	P<0.01
Behavioural FM Tone Thresholds obtained under Sound-field Conditions	0.5 kHz	2	5.4	0.0463	√	X
	1 kHz	-2	-1	0.3984	X	X
	2 kHz	-1.2	-1.2	0.9250	X	X
	4 kHz	3	2.4	0.9176	X	X
Behavioural Mixed Modulated Tone Thresholds obtained under Sound-field Conditions	0.5 kHz	1.8	0.6	0.3212	X	X
	1 kHz	-0.6	0.2	0.6360	X	X
	2 kHz	-0.4	-1.4	0.5123	X	X
	4 kHz	7.4	6.4	0.9920	X	X

APPENDIX G

(X-No significant difference √-Significant difference)

Wilcoxon: Paired T-Test

Comparison	Sign Test	P<0.05	P<0.01
Pure Tone (inserts): FM Tone (sound-field) at 0.5kHz	0.001	√	√
Pure Tone (inserts): FM Tone (sound-field) at 1kHz	0.0002	√	√
Pure Tone (inserts): FM Tone (sound-field) at 2kHz	0.003	√	√
Pure Tone (inserts): FM Tone (sound-field) at 4kHz	0.03	√	**X**

Wilcoxon: Paired T-Test

Comparison	Sign Test	P<0.05	P<0.01
Mixed Modulated Tone (inserts): Mixed Modulated Tone (sound-field) at 0.5kHz	0.00001	√	√
Mixed Modulated Tone (inserts): Mixed Modulated Tone (sound-field) at 1kHz	0.0002	√	√
Mixed Modulated Tone (inserts): Mixed Modulated Tone (sound-field) at 2kHz	0.01	√	**X**
Mixed Modulated Tone (inserts): Mixed Modulated Tone (sound-field) at 4kHz	0.0014	√	√

Wilcoxon: Paired T-Test

Comparison	Sign Test	P<0.05	P<0.01
ASSEP MRLs (inserts): ASSEP MLRs (sound-field) at 0.5kHz	0.00001	√	√
ASSEP MRLs (inserts): ASSEP MRLs (sound-field) at 1kHz	0.0002	√	√
ASSEP MRLs (inserts): ASSEP MRLs (sound-field) at 2kHz	0.0744	**X**	√
ASSEP MRLs (inserts): ASSEP MRLs (sound-field) at 4kHz	0.0005	√	√

APPENDIX H

(X-No significant difference √-Significant difference)

Analysis of Gender Effects: Mann-Whitney

	Frequency Tested	Mean Value for Male Participants	Mean Value for Female Participants	P-Value	P<0.05	P<0.01
Behavioural Pure Tone Thresholds obtained under Insert Earphone Conditions	**0.5 kHz**	8.9583	5.1923	0.2092	**X**	**X**
	1 kHz	2.0833	0.7692	0.1770	**X**	**X**
	2 kHz	2.9167	-0.3846	0.0340	√	**X**
	4 kHz	3.1250	-1.1538	0.0915	**X**	**X**
Behavioural Mixed Modulated Thresholds obtained under Insert Earphone Conditions	**0.5 kHz**	7.0833	6.9231	0.9921	**X**	**X**
	1 kHz	2.9167	3.0769	0.9513	**X**	**X**
	2 kHz	2.2917	0.7692	0.2089	**X**	**X**
	4 kHz	5.2083	1.7308	0.1642	**X**	**X**
ASSEP MRLs obtained under Insert Earphone conditions	**0.5 kHz**	37.0833	33.4614	0.1539	**X**	**X**
	1 kHz	26.8749	23.0768	0.2406	**X**	**X**
	2 kHz	28.1249	23.4615	0.0155	√	**X**
	4 kHz	28.5416	25.9614	0.3472	**X**	**X**

APPENDIX I

(X- No significant difference √-Significant difference)

Analysis of Ear Effects: Mann-Whitney

	Frequency Tested	Mean Value for Left Ears	Mean Value for Right Ears	P-Value	P<0.05	P<0.01
Behavioural Pure Tone Thresholds obtained under Insert Earphone Conditions	**0.5 kHz**	6.2	7.8	0.5369	**X**	**X**
	1 kHz	1.6	1.2	0.7714	**X**	**X**
	2 kHz	2.2	0.2	0.3548	**X**	**X**
	4 kHz	2.4	-0.6	0.2375	**X**	**X**
Behavioural Mixed Modulated Tone Thresholds obtained under Insert Earphone Conditions	**0.5 kHz**	7.6	6.4	0.6767	**X**	**X**
	1 kHz	3.2	2.8	0.8788	**X**	**X**
	2 kHz	2.4	0.6	0.1913	**X**	**X**
	4 kHz	4.2	2.6	0.6700	**X**	**X**
ASSEP MRLs obtained under Sound-field conditions	**0.5 kHz**	34.1999	36.1999	0.5294	**X**	**X**
	1 kHz	24.1999	25.5999	0.5543	**X**	**X**
	2 kHz	25.9999	25.3999	0.7287	**X**	**X**
	4 kHz	26.7999	27.5999	0.6883	**X**	**X**

APPENDIX J

(X- No significant difference √-Significant difference)

Analysis of Gender Effects: Mann-Whitney

	Frequency Tested	Mean Value for Male Participants	Mean Value for Female Participants	P-Value	P<0.05	P<0.01
Behavioural FM Tone Thresholds obtained under Sound-field Conditions	**0.5 kHz**	3.5417	3.8461	0.5968	**X**	**X**
	1 kHz	-0.8353	-0.1154	0.2620	**X**	**X**
	2 kHz	-1.8750	-0.5769	0.2450	**X**	**X**
	4 kHz	3.1250	2.3077	0.9587	**X**	**X**
Behavioural Mixed Modulated Thresholds obtained under Sound-field Conditions	**0.5 kHz**	-0.2083	2.5000	0.1117	**X**	**X**
	1 kHz	-0.8333	0.3846	0.6804	**X**	**X**
	2 kHz	-1.6667	-0.1923	0.1827	**X**	**X**
	4 kHz	7.2917	6.5385	0.9840	**X**	**X**
ASSEP MRLs obtained under Sound-field conditions	**0.5 kHz**	29.5832	22.8845	0.0325	√	**X**
	1 kHz	16.4583	19.6153	0.3077	**X**	**X**
	2 kHz	19.5833	22.3076	0.2460	**X**	**X**
	4 kHz	36.4582	34.6153	0.6167	**X**	**X**

APPENDIX K

(X-No significant difference √-Significant difference)

Analysis of Ear Effects: Mann-Whitney

	Frequency Tested	Mean Value for Left Ears	Mean Value for Right Ears	P-Value	P<0.05	P<0.01
Behavioural FM Tone Thresholds obtained under Sound-field Conditions	**0.5 kHz**	6.2	7.8	0.5369	**X**	**X**
	1 kHz	1.6	1.2	0.7714	**X**	**X**
	2 kHz	2.2	0.2	0.3548	**X**	**X**
	4 kHz	2.4	-0.6	0.2375	**X**	**X**
Behavioural Mixed Modulated Tone Thresholds obtained under Sound-field Conditions	**0.5 kHz**	7.6	6.4	0.6767	**X**	**X**
	1 kHz	3.2	2.8	0.8788	**X**	**X**
	2 kHz	2.4	0.6	0.1913	**X**	**X**
	4 kHz	4.2	2.6	0.6700	**X**	**X**
ASSEP MRLs obtained under Sound-field conditions	**0.5 kHz**	26.3999	25.7999	0.7023	**X**	**X**
	1 kHz	17.5999	18.5999	0.7687	**X**	**X**
	2 kHz	21.5999	20.3999	0.8906	**X**	**X**
	4 kHz	33.9999	36.9999	0.2240	**X**	**X**

APPENDIX L

Correction Factors Earphone Testing			
Frequency Tested	**TDH 49 -Supra Aural Headphones- (Martin, 1994)**	**ER-3A – Insert Earphones- (Martin, 1994)**	**Sound Field Presentation (SABS 0182-1998)**
0.5 kHz	13.5	8.5	9.0
1 kHz	7.5	3.5	5.5
2 kHz	11.0	6.5	11.5
4 kHz	10.5	1.5	15.0

APPENDIX M

PERMISSIBLE AMBIENT NOISE LEVELS				
Frequencies Tested	**Test Room (Actual Noise Levels)**	**SABS 0182-1998 (Permissible Sound Pressure Levels for Insert Earphone Testing**	**SABS 0182– 998 (Permissible Sound Pressure Levels for sound-field testing)**	**ANSI Standards (Prescribed Acceptable Noise Levels)**
0.5 kHz	11.8 dB SPL	20.5 SPL	7.5 SPL	14.5 dB SPL
1 kHz	<10 dB SPL	24.0 SPL	6.5 SPL	12.5 dB SPL
2 kHz	10.8 dB SPL	31.0 SPL	6.0 SPL	8.5 dB SPL
4 kHz	12.7 dB SPL	37.0 SPL	2.0 SPL	9.0 dB SPL