# Estimating Pure Tone Behavioural Thresholds with the Dichotic Multiple Frequency Auditory Steady State Response Compared to an Auditory Brainstem Response Protocol in Normal Hearing Adults

by

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*To my Lord, Jesus Christ – be all the glory both now and forevermore*

# Abstract

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|---|---|
| **Title:** | Estimating Pure Tone Behavioural Thresholds with the Dichotic Multiple Frequency Auditory Steady State Response compared to an Auditory Brainstem Response Protocol in Normal Hearing Adults |
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Audiologists are reliant on objective audiometric procedures to predict auditory sensitivity in difficult-to-test populations. A technique to estimate frequency-specific hearing thresholds in a time-efficient way for difficult-to-test populations, who are unable to provide behavioural responses, has long been the hope of audiologists. The auditory brainstem response (ABR) has dominated the field of objective electrophysiological audiometry for the past three decades. Although it provides a useful method of estimating auditory sensitivity, it presents with its own set of limitations. Recently the auditory steady state response (ASSR) has demonstrated promise of addressing the limitations of the ABR as it is an evoked response uniquely suited to frequency-specific measurement. An optimised version of the ASSR, the dichotic multiple frequency (MF) ASSR, has been proposed as a time-efficient way of evaluating different frequencies simultaneously in both ears. The aim of this study was to evaluate the clinical usefulness of the dichotic MF ASSR technique for estimating pure tone behavioural thresholds at 0.5, 1, 2, and 4 kHz, compared to a 0.5 kHz tone burst and broadband click ABR protocol in a sample of normal hearing adults (56 ears).

A comparative experimental research design was selected in order to compare thresholds obtained with the different procedures. The results indicated that both the dichotic MF ASSR and a 0.5 kHz tone burst and broadband click ABR protocol provided a reasonable estimation of PT behavioural thresholds in a time-efficient manner for a group of normal hearing subjects. The click ABR did, however, present with 1, 2, and 4 kHz PT threshold estimations that were almost 50 % closer than that of the dichotic MF ASSR according to the mean and normal deviation. This increased accuracy and reliability of the click ABR is however compromised by its lack of frequency-specificity. In the low frequency region of 0.5 kHz, the tone burst ABR and dichotic MF ASSR evidenced estimations of the pure tone threshold that were, on average, very similar. The tone burst ABR, however, presented with a mean threshold slightly (3 dB) closer to the pure tone threshold than the dichotic MF ASSR. The 0.5 kHz dichotic MF ASSR presented with a smaller range of normal deviation in the estimation of pure tone thresholds which suggested a more reliable measure than the 0.5 kHz tone burst ABR. The dichotic MF ASSR evaluation provided eight thresholds (4/ear) in 23 minutes on average compared to 25 minutes on average required by the ABR protocol to evaluate 4 thresholds (2/ear).

This research concluded that the dichotic MF ASSR is useful for estimating frequency-specific pure tone thresholds reasonably well in a time-efficient manner but that this technique should be used in a test-battery alongside the ABR. Both the dichotic MF ASSR and the ABR comprise unique qualities that can be combined in a cross-check principle approach in order to provide complementary information that will verify results obtained with each procedure.

**Key terms:** Difficult-to-test populations, objective audiometry, estimation of pure tone thresholds, auditory brainstem response, auditory steady state response, dichotic multiple frequency auditory steady state response, frequency-specific, time-efficient, test battery, cross-check principle.

# Opsomming

**Titel:** Voorspelling van Suiwertoondrempels met behulp van die Digoties Veelvuldige Frekwensie Ouditiewe Standhoudende Respons in Vergelyking met 'n Ouditiewe Breinstam Respons Protokol in Normaalhorende Volwassenes

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Oudioloë is afhanklik van objektiewe oudiometriese prosedures om ouditiewe sensitiwiteit in moeilik-toetsbare populasies te voorspel. 'n Tegniek wat frekwensie-spesifieke gehoordrempels voorspel op 'n tydseffektiewe manier is al vir baie jare die hoop van oudioloë. Die ouditiewe breinstam respons (OBR) het die veld van elektrofisiologiese oudiometrie oorheers die afgelope drie dekades. Hoewel dit 'n handige manier is om ouditiewe sensitiwiteit te beraam, presenteer die tegniek met sy eie stel beperkings. Onlangs het die ouditiewe standhoudende respons (OSR) belofte getoon om die beperkings van die OBR aan te spreek aangesien dit 'n ouditiewe ontlokte response uniek geskik vir frekwensie-spesifieke metings is. 'n Optimale weergawe van die OSR, die digoties veelvuldige frekwensie (VF) OSR, is voorgestel as 'n tydseffektiewe manier om verskillende frekwensies gelyktydig in beide ore te evalueer. Die doel van hierdie studie was om die kliniese bruikbaarheid van die digotiese VF OSR tegniek vir die beraming van suiwertoon gedragsdrempels by 0.5, 1, 2, en 4 kHz te bepaal en te vergelyk met 'n 0.5 kHz toonbreuk en 'n wyeband klik OBR protokol in 'n groep normaalhorende volwassenes (56 ore).

‘n Vergelykende eksperimentele navorsingsontwerp is geselekteer om drempels, met die verskillende tegnieke verkry, te vergelyk. Die resultate het getoon dat beide the digoties VF OSR en die 0.5 kHz toonbreuk en wyeband klik OBR protokol, ‘n redelike beraming van suiwertoon gedragsdrempels op ‘n tydseffektiewe wyse vir ‘n groep normaalhorende persone verskaf. Die klik OBR het egter met 1, 2, en 4 kHz suiwertoon beramings vertoon wat amper 50 % nader is aan die van die VF OSR volgens die gemiddelde en standaard afwyking. Hierdie verhoogde akkuraatheid en betroubaarheid van die klik OBR word egter benadeel deur die feit dat dit nie frekwensie-spesifiek is nie. In die lae frekwensie gebied van 0.5 kHz het die toonbreuk OBR en die digoties VF OSR suiwertoondrempel beramings getoon wat, oor die algemeen, baie dieselfde was. Die toonbreuk OBR het egter ‘n gemiddelde drempel wat effens nader (3 dB) aan die suiwertoondrempel was vertoon toe dit vergelyk is met die digoties VF OSR. Die 0.5 kHz digoties VF OSR het ‘n kleiner afwyking van die normale vertoon in die beraming van suiwertoondrempels wat dui op ‘n meer betroubare meting as die 0.5 kHz toonbreuk. Die digoties VF OSR evaluasie het agt drempels (4/oor) in ‘n gemiddeld van 23 minute verskaf in vergelyking met 4 drempels (2/oor) in ‘n gemiddeld van 25 minute vir die OBR protokol.

Hierdie navorsing het bevind dat die digoties VF OSR redelik nuttig is vir die beraming van frekwensie-spesifieke suiwertoondrempels op ‘n tydseffektiewe wyse maar dat die tegniek egter deel moet vorm van ‘n toetsbattery wat tesame met die OBR gebruik moet word. Beide die digoties VF OSR en die OBR beskik oor unieke eienskappe wat gekombineer kan word in ‘n kruis-kontrole beginsel benadering om komplementerende inligting te verskaf wat die resultate van elke prosedure sal verifieer.

**Sleutelwoorde:** Moeilik-toetsbare populasie, objektiewe oudiometrie, beraming van suiwertoon drempels, ouditiewe breinstam respons, ouditiewe standhoudende respons, digoties veelvuldige frekwensie ouditiewe standhoudende respons, frekwensie-spesifiek, tydseffektief, toetsbattery, kruis-kontrole beginsel.

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## Abbreviations

The text of this study utilizes various discipline-specific abbreviations. The following list of these abbreviations with their meanings is provided.

| Abbreviation | Term |
|---|---|
| AER | Auditory Evoked Response |
| ABR | Auditory Brainstem Response |
| ASSR | Auditory Steady State Response |
| BT | Behavioural Threshold |
| dB | decibel |
| EEG | Electroencephalogram |
| ERA | Evoked Response Audiometry |
| FFT | Fast Fourier Transform |
| HL | Hearing Level |
| Hz | Hertz |
| LLR | Late Latency Response |
| MF | Multiple Frequency |
| MLR | Middle Latency Response |
| nHL | normal Hearing Level |
| PT | Pure Tone |
| PTA | Pure Tone Audiometry |
| PTT | Pure Tone Threshold |
| SF | Single Frequency |
| SLR | Short Latency Response |
| SPL | Sound-Pressure Level |
| SSEP | Steady State Evoked Potentials |
| SSR | Steady-State Response |
| TB | Tone Burst |

# Chapter 1

# Background and Rationale of Study

**Aim:** To introduce the problem this study confronts, to provide the rationale thereof, to describe the terminology used and, to present an overview of the content and organization of the study

## 1.1 Introduction

Audiology is the professional field responsible for hearing (O'Neill & Oyer, 1970); it is the science of hearing. This science is defined as the art of hearing assessment and the (re)habilitation of individuals with hearing impairment (Roeser, Valente, & Hosford-Dunn, 2000). According to Katz (1994) the ultimate aim of any assessment or diagnostic procedure is rehabilitation. Therefore rehabilitation is dependent upon the diagnostic procedure, which provides the information required to initiate and direct the rehabilitative process.

"The hearing evaluation serves as a first step in the rehabilitation of hearing handicap" (Stach 1998:164). An individual with a hearing disorder must therefore rely on an assessment of auditory function as the foundation of the rehabilitation process. For the last few decades, the area of hearing measurement, or the assessment of auditory sensitivity, has been referred to as the field of audiometry (O'Neill & Oyer, 1970). The term audiometry refers to methods and procedures employed in the measurement of hearing and provides a convenient label that embraces the terms of *hearing* and *measurement* (Low, 1981; O'Neill & Oyer, 1970). Hall and Mueller (1997) specifies the scope for diagnostic audiometry as procedures serving to describe the type, degree, and whenever possible, the site of lesion of auditory dysfunction. Audiometry, therefore, involves the collection of sufficient information regarding a persons auditory function as a critical first step in the evaluation of communicative disorders on which rehabilitative procedures are based (Goldstein & Aldrich, 1998).

Rehabilitation of individuals with a hearing-loss requires appropriate amplification of the auditory signal. According to Hall (2001) it is a major responsibility for every clinician to accurately identify frequency-specific hearing thresholds for persons with hearing-loss in order to ensure appropriate rehabilitation, especially in the first critical six months of age (Yoshinaga-Itano, 1995). Yoshinaga-Itano (2001) specified four criteria, apart from monitoring the status of the middle ear, to be addressed before amplification of a hearing-loss can be done. The **degree**, **configuration** and **type of hearing-loss** must be determined as well as the **difference between the two ears**. Without this information no amplification, and therefore very limited habilitation, can be done (Yoshinaga-Itano, 2001).

Diagnostic audiometry, although maintaining the same essential goal, has evolved considerably over the years (Hall & Mueller, 1997). It is a dynamic science characterized by transformations of new discoveries into clinical procedures (Gorga, 1999), often producing new techniques that render traditional procedures obsolete. Discoveries within the field and from other fields have lead to recent phenomenal advances, specifically in the area of electrophysiological audiometric procedures (De Waal, 2000). The value of any of these diagnostic procedures, according to Roeser, Valente and Hosford-Dunn (2000), depends on its ability to perform as intended, meaning that the procedure must be able to accurately assess and describe a disorder. In the field of diagnostic audiometry a variety of procedures are currently available, resulting in questions such as: which tests are most effective and for which population (Roeser, Valente and Hoshford-Dunn, 2000)?

## 1.2 Background

Historically, behavioural pure tone audiometry has constituted the cornerstone of audiology becoming the standard behavioural procedure for describing auditory sensitivity (Bess, 1995). The most important of all audiometric procedures is the measurement of auditory thresholds for pure tones (Haughton, 1980). According to Roeser, Valente and Hoshford-Dunn (2000) pure tone audiometry is the very foundation of every audiological evaluation. For most patients and most purposes pure tone audiometry is not only the least expensive but also, more importantly, the **most definitive** of all audiometric procedures (Goldstein and Aldrich, 1999) evaluating the entire auditory system at **specific frequencies** (Cope, 1995) in a **time-efficient** manner (De Waal, 2000).

The behavioural pure tone audiogram is a measure of auditory threshold[1] as a function of frequency. Auditory thresholds presented in this way have become the standard for defining hearing-loss in terms of degree and configuration (Gorga, 1999). The audiogram configuration provides fundamental baseline information for the selection of a suitable amplification system marking the initiation of the rehabilitation process (Picton, 1991). It is understandable then that pure tone audiometry has remained the audiometric procedure of choice. It embodies the gold standard for frequency-specificity and threshold establishment against which all other audiometric measures are compared.

There are, however, instances where patients are unable to provide voluntary behavioural responses necessary for the measurement of hearing thresholds and for whom accurate behavioural evaluation of hearing sensitivity is not

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[1] According to Haughton (1986) threshold represents the lowest intensity at which a given stimulus can elicit a specified response. Different auditory thresholds represent different aspects of auditory function and are determined for various reasons in the clinical assessment of hearing. The term threshold in this text will refer to detection thresholds (Haughton, 1986). For pure tone audiometry a threshold is where an auditory signal is perceived 50% of the time. Threshold for electrophysiological audiometric procedures will refer to the minimum response level, the intensity where the last significant response was recorded (Herdman & Stapells, 2001).

possible (Gorga, 1999; Hood, 1998). These are difficult-to-test patients, of which the paediatric population has always constituted a primary group, having become even more prominent with the recent emphasis on early intervention (JCIH, 1994). The Joint Committee on Infant Hearing (1994) recommended that hearing-impaired infants should be detected within the first few months of life and treatment should be initiated by the age of 6 months. According to Balfour, Pillion and Gaskin (1998) these so-called difficult-to-test populations do not consist of the too young to test only but also the too critically ill to test, subconscious patients, patients mentally incapable of providing cooperation, as well as subjects who refuse to cooperate. In some cases, even when behavioural audiometry can be performed with compliant patients, test results may not be reliable enough to draw valid conclusions about their threshold levels (Hall, 2001; Goldstein & Aldrich, 1998).

All these populations need audiometric measurements that do not rely on behavioural responses from the patient (Gorga, 1999). This has necessitated the development of electrophysiological audiometric procedures to provide an objective assessment of auditory sensitivity at different frequencies in the difficult-to-test population (Hall, 1992).

The last three decades have seen the development of many electrophysiological measurements, which have been adapted for audiometric purposes in an attempt to provide an objective prediction of pure tone thresholds (Gorga, 1999; Rance, Dowell, Rickards, Beer & Clark, 1998). These objective tests are not a measurement of hearing as such, but evaluate the integrity of the auditory pathway at various levels, never in its entirety (Cope, 1995). These procedures have included acoustic-immitance measures, otoacoustic emissions, and auditory evoked responses. Although acoustic-immitance and otoacoustic emission measures have proven to be useful screening devices providing valuable information about the integrity of the peripheral auditory mechanism, they do not provide a direct measure of threshold sensitivity yet (Goldstein & Aldrich, 1998; Roeser, Valente and Hoshford-Dunn, 2000; Hall, 2000).

Evoked response audiometry (ERA) remains the most useful and effective electrophysiological evaluation of the auditory system (Goldstein and Aldrich, 1999; Rance et al., 1998). Auditory evoked responses[2] (AERs) are combined electrical potentials representing the neural activity in response to auditory stimuli from the eighth cranial nerve to the cortex (Chiappa, 1990). AERs have provided an invaluable audiological avenue into the neural activity of the hearing process, and as more knowledge is being made available in this area it is clear that AERs will become an even more prominent diagnostic tool in the future of Audiology (Roeser, Valente, and Hoshford-Dunn, 2000). According to Hood (1998), the AER is central to objective audiometry, providing a powerful method for assessing the neural integrity of the auditory pathways.

Various AER techniques have been used to predict auditory sensitivity. Most of these techniques, however, have not received widespread clinical appeal because the responses are often dependent on state of consciousness and maturation of the nervous system. The auditory brainstem response (ABR), however, has gained clinical appeal dominating the field of objective electrophysiological audiometry for the past three decades (Arnold, 2000; Hood, 1998). This is attributed to the fact that the ABR is unaffected by sleep or sedation and can be detected in all age populations near the behavioural threshold (Ferraro & Durant, 1994; Chiappa, 1990; Hall, 1992).

The ABR is usually elicited by brief acoustic stimuli, the more abrupt the stimulus onset, the more neural fibres will respond in synchrony and therefore the more clearly defined the ABR will be (Gorga, 1999). The ideal and most

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[2] This text will refer to auditory evoked responses (AERs) as electrical responses recorded from the scalp representing activation of the auditory pathways from the eighth cranial nerve up to the cortex. Oto-acoustic emissions do not fit this definition and although they are

commonly used stimulus for eliciting the ABR is a broadband click. This is due to the rapid onset of the click and its broad frequency spectral content that results in the activation of a wide area of the basilar membrane (Hood, 1998). Since, however, a broad range of frequencies is stimulated, information about hearing sensitivity at specific frequencies cannot be obtained (Oates & Stapells, 1998). On average, the correlation between click ABR and the frequency region of the cochlea is best between 2 - 4kHz (Gorga, 1999; Hood, 1998; Hall, 1992), although this may not be true for individual cases (Oates & Stapells, 1998). Therefore the click ABR provides a general assessment of high frequency hearing but does not assess thresholds at different frequencies (Lins, Picton, Picton, Champagne and Durieux-Smith, 1995). This poor frequency-specificity of the ABR using click stimuli is an important limitation in light of rehabilitative measures based on such results. According to Yoshinaga-Itano (2001) no accountable amplification can be fitted on click ABR results alone.

Several types of stimuli and recording methods in combination with ABR measurements have been developed and proposed to provide information for narrower more precise frequency regions (Hood, 1998; Gorga, 1999). These alternative stimuli and methods include tone bursts and filtered clicks produced with various types of noise and masking techniques (Hood, 1998). Each type of stimulus has proven advantageous in the estimation of more frequency-specific thresholds but has not been without limitations. The selection of the stimulus to be used appears to be dependent upon the desired frequency-specificity, the type of response being recorded, the available amount of time, and availability of equipment (Hood, 1998). Most of these techniques are time consuming, technologically complex, and requires a trained professional to interpret results (Lins, et al., 1995). This could possibly explain why these methods have not been introduced into clinical practice on a large scale (Gorga, 1999).

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responses evoked by an auditory signal, the response is not electrical but rather acoustical (Hall, 2000).

Although the ABR provides a very useful method of estimating auditory sensitivity it presents with its own set of limitations. Both clicks and tone bursts contain energy over a range of frequencies, and evoked responses to these stimuli may be evoked by any of these frequencies present in the spectrum of the stimuli (Hood, 1998; Oates & Stapells, 1998). Thus the click ABR provides a general assessment of auditory sensitivity but does not assess hearing at different frequencies. Tone burst stimuli and other masking techniques can provide more frequency-specific information but are time consuming (Lins et al., 1995) and require complex instrumentation (Arnold, 2000). Furthermore the interpretation of ABR results is subjective. Although the ABRs do not require subjective responses from the subject being tested, determining whether a response is present or not requires subjective interpretation by a trained professional (Lins et al., 1995). Another shortcoming is that the maximum presentation level of both click and tone burst ABR stimuli is limited. The possibility of residual hearing at profound levels, therefore, cannot be investigated thoroughly (Rance et al., 1998).

In light of the importance for accurate assessment of hearing ability for rehabilitative purposes (Yoshinaga-Itano, 2001), and the limited clinical test time available (Arnold, 2000; Bachmann & Hall, 1998) to perform such a procedure, the ABR's limitations must be taken into consideration. There is a need for an objective audiometric technique that addresses the limitations of the ABR being able to provide an accurate estimate of hearing thresholds across the frequency range in a time-efficient manner

Recently, additional types of auditory evoked responses have been studied using amplitude-modulated tones to stimulate responses (Lins, Picton, Boucher, Durieux-Smith, Champagne, Moran, Perez-Abalo, Martin and Savio, 1996; Hood, 1998). These responses are more commonly referred to as auditory steady state responses (ASSRs) or steady state evoked potentials (SSEPs). Unlike ABRs obtained with brief transient stimuli, ASSRs are evoked using sustained continuous tones (Hood, 1998). These tones are modulated over time in the amplitude domain resulting in small changes or modulations in the stimuli that can be recorded and phase-locked to the modulation frequency of the stimulus (Perez-Abalo, Savio, Torres, Martin, Rodriguez, & Galan, 2001; Hood, 1998). These modulated tones are very frequency-specific because spectral energy is contained only at the frequency of the carrier tone and the frequency of modulation (Hood, 1998). A modulation rate of between 75 - 110Hz is not significantly affected by sleep or sedation and, therefore, very suitable for audiometric purposes (Lins et al., 1995; Lins et al., 1996; Rickards, Tan, Cohen, Wilson, Drew & Clark, 1994).

## 1.3 Rationale

ASSRs have definite advantages over transient evoked responses such as the ABR in the prediction of frequency-specific thresholds. According to Lins et al. (1995), the measurement of the ASSR is in the first instance a simple procedure. The response can be measured at the frequency of stimulation by a computer, inferring that no subjective judgement by an interpreter is necessary. Clear, well-established statistical procedures are used to determine whether a response is present or not. Steady state responses prove more frequency-specific and can probably provide a better evaluation of hearing aids than transient ABR stimuli. Despite these convincing advantages, however, the procedure can be time consuming if each frequency for both ears is explored separately (Perez-Abalo et al., 2001).

More recently, an optimised variant of the ASSR was proposed using multiple simultaneous amplitude-modulated tones (Lins & Picton, 1995). This implies that distinct modulation rates, that are more than one octave apart, are used for carrier tones at different frequencies. The modulated tones are added into a complex acoustic stimulus capable of simultaneous activation of different frequency regions within the cochlea. This technique is further optimised if two differently modulated multiple frequency (MF) stimuli are presented simultaneously to the left and right ears. In such a case multiple frequencies are explored simultaneously in both ears (Perez-Abalo et al., 2001). This multiple-stimulus technique can therefore significantly decrease the time needed to evaluate thresholds at multiple audiometric frequencies dichotically (Lins et al., 1996). According to Lins et al. (1995) using the MF ASSR to estimate pure tone behavioural thresholds could be several times more efficient than using an ABR protocol and can be used to present results in the form of a conventional audiogram.

The multiple frequency auditory steady state evoked response (MF ASSR) technique has shown promising results in relatively small samples of normal adults, well babies, and hearing impaired adolescents in the estimation of hearing thresholds (Lins & Picton, 1995; Lins et al., 1996; Perez-Abalo, et al., 2001). The clinical validation of this technique, however, is still somewhat limited especially as far as the use of dichotic multiple-stimulation is concerned. Thus the question remains whether the dichotic MF ASSR technique can reliably estimate behavioural thresholds in a time-efficient manner (Herdman & Stapells, 2001). According to John (2001) the technique may not yet be ready for clinical practice. More trials and endeavours to optimise the stimulus and recording parameters are required to validate this procedure.

## 1.4 Problem Statement

In light of the limited **clinical** validation of the MF ASSR technique and the widespread clinical use of the ABR, the question that arises is:

**How useful is the dichotic multiple frequency auditory steady state response (MF ASSR) technique for estimating pure tone (PT) behavioural thresholds (BT) compared to an auditory brainstem response (ABR) protocol in a clinical setting for a sample of normal hearing adults?**

In order to answer this question a research endeavour consisting of both a theoretical and empirical approach was implemented. The basic structure of the study is outlined in paragraph 1.5.

## 1.5 Division of Chapters

☐ **Chapter one:** ***Orientation and Statement of the Problem***

This chapter will provide an overview of the importance of diagnostic audiometry as the initial step toward rehabilitation, the need for electrophysiological procedures to estimate pure tone behavioural thresholds in difficult-to-test populations and the most widely used procedure, auditory evoked responses (AERs), specifically the auditory brainstem response. The ABR is contrasted with a new AER technique, the multiple frequency auditory steady state response (MF ASSR), to estimate PT BTs. This delineates the purpose of the study, to determine the clinical usefulness of the MF ASSR in the estimation of PT BTs compared to an ABR protocol

☐ **Chapter two:** ***Evoked Response Audiometry in Clinical Practice: The Auditory Brainstem Response and the Emergence of the Auditory Steady State Response***

This chapter will discuss evoked response audiometry, defining the terms and discussing existing clinical procedures available. The ABR will be discussed as the most widely used ERA procedure in clinical practice and in terms of different protocols available to provide more frequency-specific information with this procedure. A critical evaluation of the ABR will serve as an introductory background to the discussion of the steady state response as a new procedure that is becoming available. Thorough theoretical and clinical advantages of how the ASSR might address the limitations of the ABR will be provided along with the latest optimised techniques and normative studies performed.

☐ **Chapter three:** ***Research Methodology***

This chapter will describe the operational framework implemented to conduct the empirical research. This framework dictates the scientific process implemented to determine the clinical validity of the dichotic MF ASSR technique compared to an ABR protocol

☐ **Chapter four:** ***Results and Discussion***

This chapter will present the results obtained with the statistical analysis. Results will be presented according to the sub-aims stipulated in chapter three. After each result is described, an interpretation and discussion of its value and meaning in relation to the literature will be performed.

☐ **Chapter five:** ***Conclusions and Implications***

This chapter will summarize the results obtained and provide an outline of the significant results and the way they contribute to current literature. Future research recommendations will be provided and a conclusion regarding the current study will be formulated to conclude the study with.

## 1.6 Summary

This chapter aimed to provide relevant background information in order to elucidate the topic of the study and to create a broad perspective on the importance of the rationale for this research study. The assessment of auditory thresholds as a first step toward rehabilitation was discussed with special reference to the gold standard of pure tone behavioural audiometry. Attention was drawn to the need for objective audiometric measures approximating the gold standard of pure tone behavioural audiometry for the difficult-to-test population. The ABR was discussed, being the most widely used objective audiometric measure, in terms of its advantages and limitations. An introduction to the new ASSR procedure followed by a brief theoretical explanation and discussion of its advantages over the ABR was provided. Finally an optimised version of the ASSR, the dichotic MF ASSR, was indicated and its advantages emphasised in the light of limited clinical validation. Therefore, the need to determine the usefulness of this technique in estimating pure tone thresholds compared to an ABR protocol was made apparent.

# Chapter 2

# Evoked Response Audiometry in Clinical Practice: The Auditory Brainstem Response and the Emergence of the Auditory Steady State Response

**Aim:** This chapter serves as a theoretical underpinning for the empirical research and provides a critical evaluation and interpretation of the relevant literature

## 2.1 Introduction

Auditory evoked responses (AERs) have developed into a vital audiological tool invaluable in auditory diagnosis (Thornton, 2001). When behavioural tests become impossible, these findings become critical for diagnosis, audiologic treatment, and management strategies (Bachmann & Hall, 1998). It has proved to be a powerful objective assessment of the neural integrity of the auditory pathways often employed for the audiometric purpose of predicting the behavioural pure tone audiogram (Goldstein & Aldrich, 1998). The AER has provided an invaluable audiological avenue into the neural activity of the hearing process and as more knowledge is being made available in this area it is clear that AERs will become an even more prominent diagnostic tool in the future of Audiology (Roeser, Valente, & Hosford-Dunn, 2000).

The use of AERs for the screening of infant hearing and estimation of hearing sensitivity has had a major impact on the ability of clinicians to identify and describe hearing impairment in children and other difficult-to-test populations

(Stach, 1998). Gorga (1999) insists that habilitation for these populations depend primarily on information about the **magnitude** and **configuration** of hearing-loss. Initiation of an inappropriate habilitation program because of a lack of knowledge regarding an individual's hearing-loss could have potential harmful effects (Gorga, 1999). Thus, it is essential that evoked response audiometry (ERA) is able to provide accurate estimations of the magnitude and configuration of a hearing-loss.

The auditory brainstem response, since its first identification in 1971 by Jewet & Williston (1971), has become the most widely used clinical AER for estimating auditory threshold (Hood, 1998; Hall III & Mueller, 1997). A number of ways have been developed and proposed in which the ABR can be used to estimate the magnitude and configuration of a hearing-loss. Many reports exist demonstrating the usefulness of these techniques but they are not in widespread clinical use (Gorga, 1999; Arnold, 2000). Although the ABR has enjoyed clinical prominence for objective audiometry it has not been without some important limitations.

Recently a new ERA technique, the Auditory Steady State Response (ASSR), has emerged on the clinical arena demonstrating promise in addressing some of the ABR limitations. Initial experiments and validations of the technique have indicated its usefulness in accurate estimation of frequency-specific behavioural thresholds providing important information regarding the magnitude and configuration of an individual's hearing-loss. Continued investigation of the ASSR by various laboratories has produced an optimised version of the response, proposed by Lins & Picton (1995), called the Multiple Frequency Auditory Steady State Response (MF ASSR). This technique, whilst having the same characteristics for accurate frequency-specific estimation of behavioural thresholds as the single ASSR, promises a very time-efficient evaluation of multiple auditory thresholds. Thus, it demonstrates the potential to provide accurate information on the magnitude and configuration of a hearing-loss in a time-efficient manner.

**The purpose of this chapter is to evaluate the current clinical use of AERs to estimate behavioural thresholds, and to contrast the most widely used ERA technique, the ABR, with the ASSR - specifically the optimised version - dichotic MF ASSR. The history, nature, type of stimuli, test protocols, accuracy, and limitations of the ABR technique will be discussed. This will be followed by a thorough discussion of the ASSR technique. A discussion of the history and theoretical principles of the ASSR will be provided; reviewing studies performed using the ASSR to estimate pure tone behavioural thresholds and contrasting results to the ABR. Subsequently, the MF ASSR will be reviewed in terms of theoretical principles, advantages, and normative studies reported thus far.**

## 2.2 Auditory Evoked Responses

The following section will provide some background on AERs, providing a brief history and information on the definition, the measurement, and the classification of AERs. This will serve as an introduction to the discussion of the ABR and ASSR techniques.

### 2.2.1 Description of Auditory Evoked Responses

The development of AERs has closely followed the advances in electronic technology. The earliest AER recorded in a human was accomplished by a Russian scientist, Vladimirovich Pravdich-Neminsky, in 1913 (McPherson & Ballachanda, 2000). His recordings consisted of dim tracings on a cathode tube oscilloscope. In 1939, evoked responses to acoustic stimuli were being recorded in the waking brain by P.A. Davis and in the sleeping brain by H. Davis (Reneau & Hnatiow, 1975). Subsequent investigators found these responses somewhat difficult to detect because they are frequently smaller than the EEG activity.

In 1948, Doerfler stated that electroencephalographic recordings are too unwieldy to be utilized in clinical audiology (Reneau & Hnatiow, 1975). Since that statement, however, phenomenal technological developments have facilitated and improved the investigation of AERs, rendering the statement made in 1948, grossly inaccurate. Today the AER is a vital screening and diagnostic tool in clinical audiology (Hood, 1998; Stach, 1998).

Evoked responses represent electrical potentials as a manifestation of the brain's reception of an external stimulus. Auditory evoked responses (AERs), therefore, are electrical potentials of the nervous system in response to externally presented auditory stimuli (Chiappa, 1990). Responses infer a summation of electrical potentials generated in the auditory nerve. This electrical activity represents the synchronous neural firing (Rance, 1998) of AERs generated at various anatomical regions along the neural pathways from the auditory nerve through the brainstem and into the cortex. The ascending auditory pathway is complex, and because incoming stimuli may be processed in parallel, contributions from different neural structures may contribute to the AER at the same latency (Hall, 1992).

Although inferences can be made about hearing from the evoked response data it is not a test of hearing, but rather a test of synchronous neural function; the ability of the central nervous system to respond to external stimulation in a synchronous manner (Hood, 1998). The AERs are small, low amplitude signals buried in larger signals such as electroencephalographic (EEG) activity and other general muscle activity (De Waal, 2000). Thus, measuring these responses involves the extraction of tiny electrical amplitudes of the auditory system from surrounding electrical activity (Chiappa, 1990). The fact that the AER is a far-field response with a low amplitude compared to surrounding electrical activity, makes it very difficult to distinguish between a single AER and other electrical signals.

Separating the low amplitude AERs from higher amplitude background noise is accomplished by using specialized equipment. A large number of responses are averaged together, time locking the onset of the stimulus with the onset of the computer analysis window (Hood, 1998). Time locking allows the evoked response of interest to be summed, while the background noise, because of its random nature, averages toward zero and therefore becomes attenuated (Ferraro & Durant, 1994; Chiappa, 1990).

A common mode or artefact rejection routine is also included in the recording procedure to prevent waveform contamination from large spurious voltage changes. This entails that when a signal is detected during an average run that is larger than a specified value within the sensitivity range, the entire sweep is excluded from the average (Ferraro & Durant, 1994; Hood, 1998). Thus, the recording procedure rejects signal sweeps with too much artefacts, aiming to amplify the auditory response and reduce the background electrical interference by only averaging signal sweeps within a specified artefact range (Herdman & Stapells, 2001).

### 2.2.2 Classification of Auditory Evoked Responses

Numerous approaches have been used to classify AERs along various dimensions such as speed (fast vs. slow), anatomy (electrocochleography vs. auditory brainstem response), a general property of response generation (exogenous or endogenous), or some more specific generator property (stimulus-related vs. event related) (Hall, 1992). The most commonly used classification of AERs is according to the time domain, probably because this is simpler than comparisons along other dimensions (Aldrich & Goldstein, 1998).

The time domain within which the response occurs after stimulus onset, known as the 'latency epoch' (Ferraro & Durant, 1994), is divided into three epochs (Ferraro & Durant, 1994): Short latency responses (SLRs), occuring in the first 10-15 milliseconds, middle latency responses (MLRs) occuring between 10-50 milliseconds, and late latency responses (LLRs) occuring beyond 50-80 milliseconds post-stimulus onset (Kraus, Kileny & McGee, 1994).

In addition to the time domain, the stimulus-response relationship is often used to further clarify and describe AERs. The stimulus-response relationship, according to the type of response evoked by different stimuli, divides AERs into two categories. These categories are known as transient (onset) responses and sustained responses (Ferraro & Durant, 1994). Transient responses represent a single response that result from a single stimulus. The neural units generating these responses are onset-sensitive, thus responding to the onset of a stimulus. In contrast, sustained responses are responses that reflect either repeated or continual stimulation (Hood, 1998).

In order to describe AERs more fully it is necessary to further discuss them in terms of the time domain.

### 2.2.2.1 Middle Latency Response (MLR) and Late Latency Response (LLR) Auditory Evoked Responses

Although almost all AERs can be applied to the prediction of hearing sensitivity, not all procedures is in widespread clinical use. Middle latency and late latency AERs, intensively studied in the 1950s and 1960s, proved useful but require subjects to be awake, cooperative, and alert during testing (Hood, 1995). This sensitivity to subject state of consciousness has limited its popularity as objective diagnostic audiometric procedures (Ferraro & Durant, 1994; Goldstein & Aldrich, 1998; Mcpherson & Ballachanda, 2000). Both middle and late latency AERs are not considered as mainstream electrophysiological tests in routine audiology practice. They do, however, demonstrate promise to be a valuable tool in diagnosing various auditory processing problems (McPherson & Ballachanda, 2000).

#### 2.2.2.2 Short Latency Response (SLR) Auditory Evoked Responses

Unlike the MLR and LLR, the SLR is unaffected by sleep and sedation (Ferraro & Durant, 1994; Hall, 1992). This has led to the popularity and widespread clinical utility of SLRs. There is general consensus that the SLR originates from the cochlea and auditory nerve through neural structures in the lower brainstem up to the midbrain region (Aldrich & Goldstein, 1998). The sub-cortical localization of the SLR generators explains why the response is resistant to sleep and sedation (Hall, 1992).

Two types of SLR procedures are currently used in clinical practice. The first is, electrocochleography, which is used to evaluate cochlear function and integrity and not clinically as a measure of hearing sensitivity (Hall, 2001). The electrocochleogram is mainly comprised of the compound action potential that occurs at the distal portion of the auditory nerve. The relatively invasive nature of this technique, and the fact that it measures only the most peripheral function of the auditory system, has limited its clinical use (Stach, 1998).

The second clinically used SLR is the Auditory Brainstem Response (ABR). Since its discovery, this response has become the most widely used electrophysiological technique for the estimation of hearing sensitivity (Hall, 1992). Its resistance to state of consciousness and sedation has ensured that the ABR has become the measure of choice for objective audiometry (Hall & Mueller, 1997).

## 2.3 The Auditory Brainstem Response (ABR)

There is no doubt that the ABR is the most clinically used AER technique evaluating auditory hearing sensitivity (Arnold, 2000; Rance, Dowell, Rickards, Beer, & Clark, 1998; Ferraro & Durant, 1994). According to Gorga

(1999) the ABR is crucial in the provision of information about auditory sensitivity for difficult-to-test populations in order to initiate habilitation.

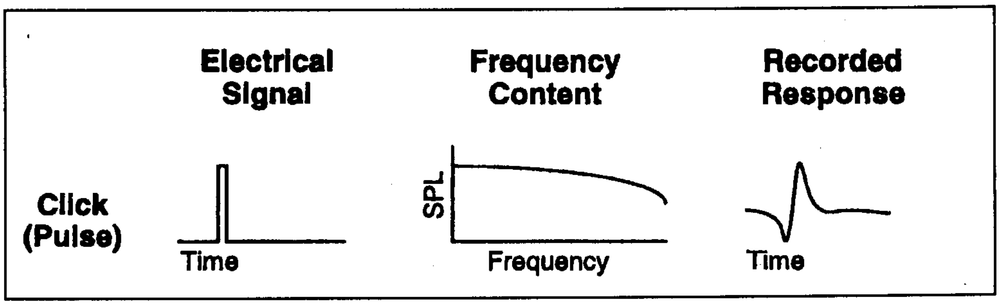
### 2.3.1 Description of the Auditory Brainstem Response

The ABR was first reported in 1967 by Sohmer and Feinmesser and subsequently described by Jewet, Romano & Williston in 1970 (Hood, 1998). This initiated a revolution in the field of evoked response audiometry dominating clinical attention amongst AERs for the last 3 decades. The auditory brainstem response is most commonly abbreviated as ABR, but is also referred to as the BAER (brainstem auditory evoked response), BAER (brainstem auditory evoked response), or the BER (brainstem evoked response) (Hood, 1998; Goldstein & Aldrich, 1998).

The ABR represents the electrical activity generated by the eighth cranial nerve and neural centres and tracts within the brainstem that is responsive to auditory stimulation (Chiappa, 1990; Hall, 1992, Hood, 1998). In general the ABR is recorded with electrodes on the scalp, measuring electrical responses to stimulation of the ear with brief auditory signals such as pulses (clicks) or tone bursts. The series of waveforms acquired over approximately the first 2-12 milliseconds after stimulation is averaged by time-locking the occurrence of the stimulus to the computer digitisation of the neural response (Hood, 1998; Ferraro & Durant, 1994).

The ABR is a transient response elicited by brief acoustic stimuli. A stimulus with an abrupt onset stimulates a large number of neural fibres to respond in synchrony across a range of frequencies. Thus the more abrupt the stimulus the more clearly defined the ABR will be (Oates & Stapells, 1998; Gorga, 1999; Hood, 1998). The acoustic principle underlying this phenomenon pertains to the relationship between the duration of a stimulus and its frequency content. There is a trade-off between frequency-specificity and neural synchrony. The more abrupt the acoustic onset of a stimulus, the more frequencies that stimulus contains (Gorga, 1999). Stimulating a broad region of the cochlear partition all at once will activate a large number of neurons simultaneously, resulting in a synchronous neural discharge. The more synchronous the neural discharge, the better the resulting ABR, but the poorer the frequency-specificity. The longer the duration of a stimulus, the more frequency-specific the stimulus will be (Hood, 1998; Goldstein & Aldrich, 1998).

An example of a very frequency-specific stimulus is a pure tone, which has a long rise time and duration. Unfortunately, because of their long onset, single pure tones are not efficient to elicit enough neural synchrony for an ABR (Goldstein & Aldrich, 1998). In contrast, a click, which is abrupt in onset and brief in duration, is better able to elicit a synchronous neural response but, this type of stimuli lacks frequency-specificity as can be seen in figure 2.1.



(Source: Adapted from Hood 1998:97)

Figure 2.1 Properties of the click stimulus

The transient nature and broad spectrum of frequency content causes the click stimulus to be of little value in the estimation of frequency-specific thresholds. Furthermore, because the ABR is a far-field recording method, a large number of neurons must be activated at precisely the same time to observe a response (Arnold, 2000; Hood, 1998).

### 2.3.2 Stimuli to Elicit Auditory Brainstem Responses

Various stimuli have been used in the acquisition of an ABR. The most widely used, however, is the broadband click.

#### 2.3.2.1 Broadband Click Stimuli

The ideal stimulus and most commonly used stimulus for eliciting the ABR is a broadband click (Oates & Stapells, 1998; Gorga, 1999, Hood, 1998). This is due to the rapid onset of the click and its broad frequency spectral content that results in the activation of a wide area of the basilar membrane. While a broad range of frequencies is stimulated, information about hearing sensitivity at specific frequencies cannot be obtained (Oates & Stapells, 1998). On average, the correlation of the click ABR is best between the 2 - 4 kHz region (Gorga, 1999; Hood, 1998; Hall 1992; Oates & Stapells, 1998). Although this is true on average across a large group of subjects, it must be said that in certain individual cases of hearing-loss it may not be a reliable estimate of the 2 – 4 kHz region (Oates & Stapells, 1998). According to Oates and Stapells (1998) this is most likely in sloping hearing-losses due to the fact that significant contributions to the response may derive from the more sensitive lower-frequency regions of the cochlea. The general consensus about the frequency range of the response evoked by click stimuli, however, resides between 2 – 4 kHz. This characteristic frequency of stimulation is attributed to the mechanical properties of the cochlea (Rance et al 1998; Gorga, 1998) as well as to the primary frequency emphasis of the earphones (Hood, 1998).

Based on these two factors, the broadband click can be described as somewhat frequency-specific, providing a general assessment of hearing in the high frequency region. It does not, however, assess thresholds at specific frequencies (Lins, Picton, Picton, Champagne and Durieux-Smith, 1995). According to Arnold (2000) the click ABR can predict auditory sensitivity in the high frequency region to within 5 to 20dB of the behavioural threshold.

### 2.3.2.2 Frequency-Specific Stimuli for Eliciting Auditory Brainstem Responses

Several types of stimuli and recording methods in combination with ABR measurements have been developed and proposed to provide information for narrower more precise frequency regions (Hood, 1998; Gorga, 1999; Oates & Stapells, 1998). These alternative stimuli and methods include tone bursts and filtered clicks produced with various types of masking techniques (Hood, 1998). Each type of stimulus has proven advantageous in the estimation of frequency-specific thresholds, but their use has not been without limitations (Gorga, 1998). The most commonly used frequency-specific stimulus for recording an ABR is the tone burst (Hood, 1998).

Tone burst stimuli are now widely available on commercial ABR instrumentation (Arnold, 2000). These stimuli have narrower frequency spectra than clicks, but are substantially broader than the pure tone stimuli used for conventional audiometry, because of the brief rise/fall time. This type of stimulus is the result of an attempt to find the 'best compromise' that would maximize both frequency-specificity, and neural synchrony (Hood, 1998; Hall, 1992).

Tone bursts contain sidebands of energy at frequencies above and below the predominant energy peak. Because the sidebands are less intense than the peak of energy, the frequency spread is more of a problem at high levels of stimulation (Gorga, 1999; Hood, 1998; Arnold, 2000). This frequency spread has been shown to be more problematic for low frequency tone bursts, than mid- to high-frequency tone bursts (Arnold, 2000). At high stimulus intensities, however, stimulation can still spread to adjacent frequency areas with better hearing, because of basilar membrane mechanics (Oates & Stapells, 1998).

A possible alternative way to ensure higher frequency-specificity with the tone burst is to combine different masking methods with the stimuli (Gorga, 1999, Oates & Stapells, 1998). The notched noise is currently the most comprehensively described, and clinically used masking technique (Gorga, 1998; Arnold, 2000). Notched noise is similar to wide band noise, containing energy across frequencies, except within a certain narrow range of frequencies (the notch). The frequency, at which the notch occurs, corresponds to the frequency of the tone burst being used. Thus, the side bands of energy present in the tone burst are masked out, restricting the area of stimulation to the nominal frequency of the tone burst. This ensures that the tone burst ABR is generated only by the neurons sensitive to the test frequency (Oates & Stapells, 1998; Gorga, 1999, Hood, 1998). A disadvantage of the notched noise technique, however, is the spread of masking into the notch, especially for the low-frequency stimuli.

Even though the audiometric advantages of notched noise tone bursts have been documented comprehensively, it is not currently implemented in widespread clinical use (Gorga, 1998; Arnold 2000). The reasons for this is not obvious, but is probably related to such issues as the specific populations served, technical demands related to waveform manipulation, (Gorga, 1999) and the lack of readily available software to generate sophisticated stimuli. According to Arnold (2000) the notched noise masking procedure requires more sophisticated instrumentation than is currently available on most commercial ABR instrumentation.

The validity with which tone bursts can predict behavioural thresholds has been studied extensively (Gorga, 1999; Stapells, Durieux-Smith, & Picton 1994; Oates & Stapells, 1998). Thresholds established by brief tone burst stimuli presented in quiet or in notched noise masking can provide reasonably accurate estimates of the pure tone behavioural audiogram from 0.5 kHz – 4 kHz for all age populations (Oates & Stapells, 1998). Threshold differences are usually in the region of 20 dB for lower frequencies, and 10 dB for higher frequencies (Stapells, Gravel, & Martin, 1995; Stapells, Picton, Durieux-Smith, Edwards, & Moran, 1990). Notched noise is used to enhance the frequency-specificity of the tone burst stimuli. According to Oates & Stapells (1998), in studies that employed notched noise masking, results were similar to notched noise in quiet, with more than 90% of the ABR threshold estimations within 20 dB of pure tone behavioural thresholds with the majority within 10 dB. The low frequency tone burst thresholds, however, are often elevated and according to Stapells et al. (1995; 1990), the average tone burst ABR threshold for 500 Hz was about 10 dB higher than for the mid- to high frequencies.

### 2.3.3 Clinical Auditory Brainstem Response Protocols

Clinically used ABR test protocols aim to gather as much frequency-specific threshold information in the shortest possible time (Arnold, 2000). The duration of an ABR test session for infants and young children is determined by the length of time they will remain sleeping. Even for adult subjects, long testing procedures are very tiring and undesirable. Because the available testing time is often quite limited, it is very important to collect ABR data in an efficient, and judicious manner (Hall, 2001; Arnold, 2000) at different frequency regions. Click ABR information is not sufficient to understand auditory function across the frequency range or to appropriately fit amplification (Ferraro & Durant, 1994; Hood, 1998, Yoshinaga-Itano, 2001). Without low frequency tone burst data, the overall hearing configuration could be misjudged. Acquisition of responses to low frequency stimuli, in combination with the high frequency information provided by the click, is therefore necessary to define the configuration of hearing sensitivity (Arnold, 2000; Hood, 1998).

A commonly suggested ABR test protocol entails using the click ABR for high frequency information and the 0.5 kHz tone burst ABR for the low frequency region (Arnold, 2000; Hood, 1998; Goldstein & Aldrich, 1998; Hall, 2001). If there is still time available, a high frequency tone burst at 2 or 3 kHz could also be performed, or if more frequency-specific information is needed another appointment should be scheduled (Arnold, 2000; Goldstein & Aldrich, 1998).

### 2.3.4 Critical Evaluation of the Auditory Brainstem Response

Although the ABR provides a very useful method of estimating auditory sensitivity, it is not without its limitations (Rance et al., 1998; Perez-Abalo, 2001). Both clicks and tone bursts contain energy over a range of frequencies, and evoked responses to these stimuli may be evoked by any of these frequencies present in the spectrum of the stimuli (Hood, 1998, Oates & Stapells, 1998). The spread of energy to frequencies other than the nominal frequency is known as spectral splatter. The degree of spectral splatter is influenced by several parameters of the stimuli including rise time, duration, intensity, and temporal shaping, as well as by the type of transducer employed (Oates & Stapells, 1998).

The click ABR therefore, provides a general assessment of hearing but does not estimate hearing at different frequencies (Gorga, 1999; Oates & Stapells, 1998, Hall, 1992). On the other hand, tone burst stimuli and other techniques can provide more frequency-specific information, but are time consuming (Lins, et al. 1995) and require complex instrumentation (Gorga, 1999). In general it seems that the selection of the stimulus to be used appears to be dependent upon the desired frequency-specificity, the type of response being recorded, the available amount of time, and availability of equipment (Hood, 1998).

Furthermore, the interpretation of ABR results is subjective. Although the ABRs do not require subjective responses from the subject being tested, determining whether a response is present or not requires the subjective interpretation of a trained professional (Lins et al, 1995). Interpreting ABR waves, and especially tone burst ABRs require a large degree of experience and expertise. Researchers are often very familiar with this type of interpretation and this ensures threshold measurements at the lowest possible intensity. Clinicians on the other hand, who are relatively inexperienced, might possibly underestimate thresholds because of a lack of experience, and the time-pressure in clinical practice.

Another limitation is that the maximum presentation level of both click and tone burst ABR stimuli is restricted. The possibility of residual hearing at profound levels, therefore, cannot be investigated thoroughly by the sole use of the ABR (Rance et al, 1998).

## 2.4 The Auditory Steady State Response (ASSR)

Recently, additional types of auditory evoked responses have been studied using amplitude-modulated tones to stimulate responses (Lins, et al. 1996; Hood, 1998). These responses are more commonly referred to as steady state responses (ASSRs) or steady state evoked responses (SSEPs) representing the synchronous discharge of auditory neurons in the brainstem (Perez-Abolo et al., 2001). Unlike ABRs obtained with brief transient stimuli, ASSRs are evoked using sustained continuous tones (Hood, 1998) that produce evoked responses occurring during the time-varying stimulus rather than occurring after an abrupt onset of a stimulus.

ASSRs are elicited by amplitude-modulated tones. Researchers, however, have recently combined stimuli modulated in both the amplitude and frequency domain in an effort to increase the amplitude of the response (John, Dimitrijevic, van Roon & Picton, 2001). Initial results have indicated that mixed amplitude and frequency modulation of stimuli could generate responses that are larger than simple amplitude-modulated tones, and warrant further investigation for clinical practice (John, Dimitrijevic, van Roon & Picton, 2001). This text will only discuss responses evoked by amplitude-modulated tones, as frequency modulation of stimuli is currently less well understood and described (John, Dimitrijevic, van Roon & Picton 2001).

### 2.4.1 Brief History of the Auditory Steady State Response

For the past 2 decades the ASSR has been under close scrutiny as an evoked response, uniquely suited to frequency-specific measurement (Jerger, 1998). Over the years the ASSR has been elicited by a wide variety of stimuli in both awake and sleeping adults (Galambos et al, 1981; Rickards & Clark, 1984; Picton et al, 1987; Cohen, Rickards, & Clark, 1991).

Earlier studies used modulation frequencies between 35 and 55 Hz to estimate hearing thresholds (Galambos et al., 1981; Kuwada et al., 1986; Picton, Skinner, Champagne, Kellet, & Maiste, 1987; Cohen et al, 1991). At these lower modulation rates ASSR hearing threshold estimations proved to be very difficult and unreliable, because the response was affected by state of consciousness (Herdman & Stapells, 2001). Fortunately, increased interest in the ASSR followed after the discovery that at certain repetition (modulation) rates the response seemed quite strong (Rickards & Clark, 1984), particularly at 40Hz (Galambos et al, 1981). The 40Hz response, however, although being able to elicit good estimations of behavioural thresholds in normal and hearing impaired adults at low and high frequencies, is considerably affected by sleep and sedation (Rickards et al, 1994). Thus these lower frequency modulation rates did not translate into clinically viable techniques.

Alternative rates of stimulation have since been introduced and investigated to find optimal modulation frequencies for audiometric purposes. This optimal type of modulation rate should elicit responses that are resistant to state of consciousness and maturation, and can reliably be recorded in children of all ages, including neonates (Rance et al., 1998). Several laboratories have recently proposed such optimal modulation frequencies for audiometric purposes (Lins & Picton, 1995; Levi, Folsom, & Dobie, 1993, Cohen et al, 1991). This has lead to renewed interest in, and the development of, the ASSR as a clinically usable objective ERA technique for estimating frequency-specific hearing thresholds (Rance et al, 1998).

### 2.4.2 Nature of the Auditory Steady State Response

The ASSR is a periodic, central nervous system electrical response to a periodically changing auditory stimulus. The period of the stimulus variation is the same as that of the response and therefore, is easily characterized by the amplitude and phase of the fundamental, and second harmonic frequency components of the response (Rance et al., 1998).

The principle underlying the ASSR is based on the following cochlear mechanics as outlined by Lins et al. (1996): Sound waves cause polarization and depolarisation of the inner hair cells. Only the depolarisation of inner hair cells cause auditory nerve fibres to transmit action potentials. The output of the cochlea therefore contains a rectified version of the acoustic stimuli serving as a kind of biologic Fast Fourier Transformer (Dimitrijevic, John & Picton, 2001). This rectification causes the output of the cochlea to have a spectral component at the frequency at which the carrier was modulated. This component, not present in the spectrum of the stimuli, can be used to assess the response of the cochlea to the frequency of the carrier tone.

The ASSR is generated when the carrier frequency is presented at a rate (the modulation frequency) that is sufficient to cause an overlapping of transient responses, therefore being a sustained response (Lins et al., 1995). A carrier frequency stimulus vibrates a specific region of the basilar membrane, stimulating a group of hair cells and auditory nerve fibres at this location, at the rate of modulation (Lins et al., 1996). This means that the carrier frequency stimulates the cochlea with pockets of energy at the rate of the modulation frequency.

The transduction process of the hair cell and auditory nerve fibre involves compressive rectification of the signal waveform. The compound electrical activity recorded from the cochlear nerve therefore contains a spectral component at the rate of modulation (Lins et al., 1996). Because the stimuli occur very rapidly, the brain's response to each stimulus is evoked before the response to the prior stimulus has terminated. Rather than being allowed to return to a baseline state, a steady state response is elicited, which can be recorded at the spectral component at the frequency of modulation (MASTER homepage).

### 2.4.3 Stimuli Eliciting the Auditory Steady State Response

The ASSR stimuli consist of a carrier frequency (test frequency) modulated over time in the amplitude domain at a frequency of modulation (Perez-Abalo et al., 2001). The stimulus is produced by modulating the amplitude of a carrier sine wave with another sine wave, the frequency of modulation (Hood, 1998; Lins & Picton, 1995). Figure 2.2 demonstrates the modulation of a pure tone.

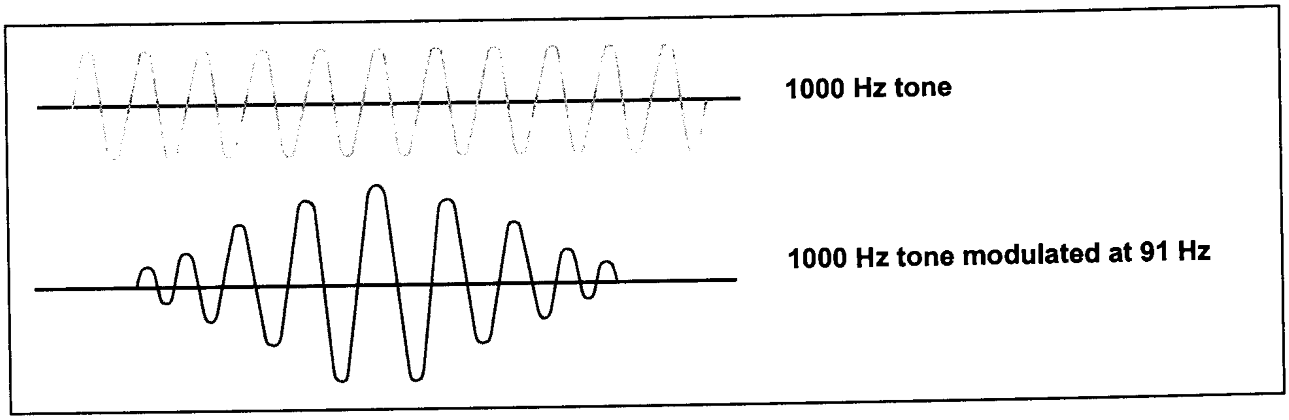


**Figure 2.2. A single tone and a modulated tone**

The carrier sine wave is the frequency being tested and can be presented at any low or high frequency tone as in pure tone testing. These modulated tones are therefore very frequency-specific because spectral energy is contained only at the frequency of the carrier tone, and the frequency of modulation (Hood, 1998). Examples of different frequency steady state stimuli are represented in figure 2.3.

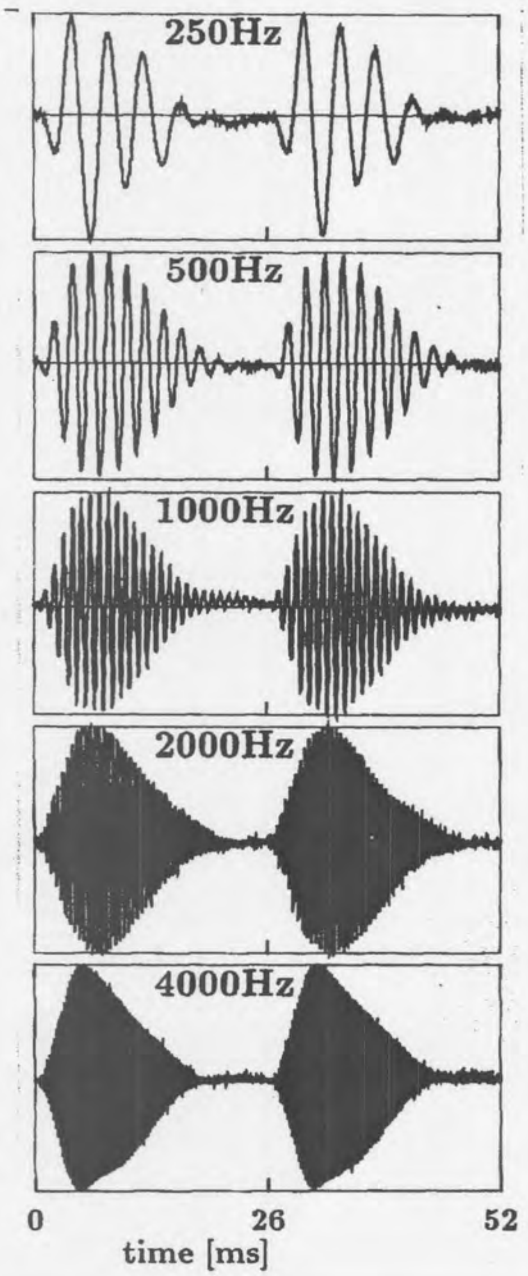


**Figure 2.3** **represents the steady state stimuli. These stimuli consist of a carrier frequency (test frequency), indicated above each picture, and a frequency of modulation. The steady state stimuli combine two different sine waves; the carrier, and modulation frequency. The carrier frequency is segmented into pockets of energy by the slower modulation frequency.**

(Source: Adapted from Pantev et al. 1996:65)

**Figure 2.3 Auditory steady state stimuli**

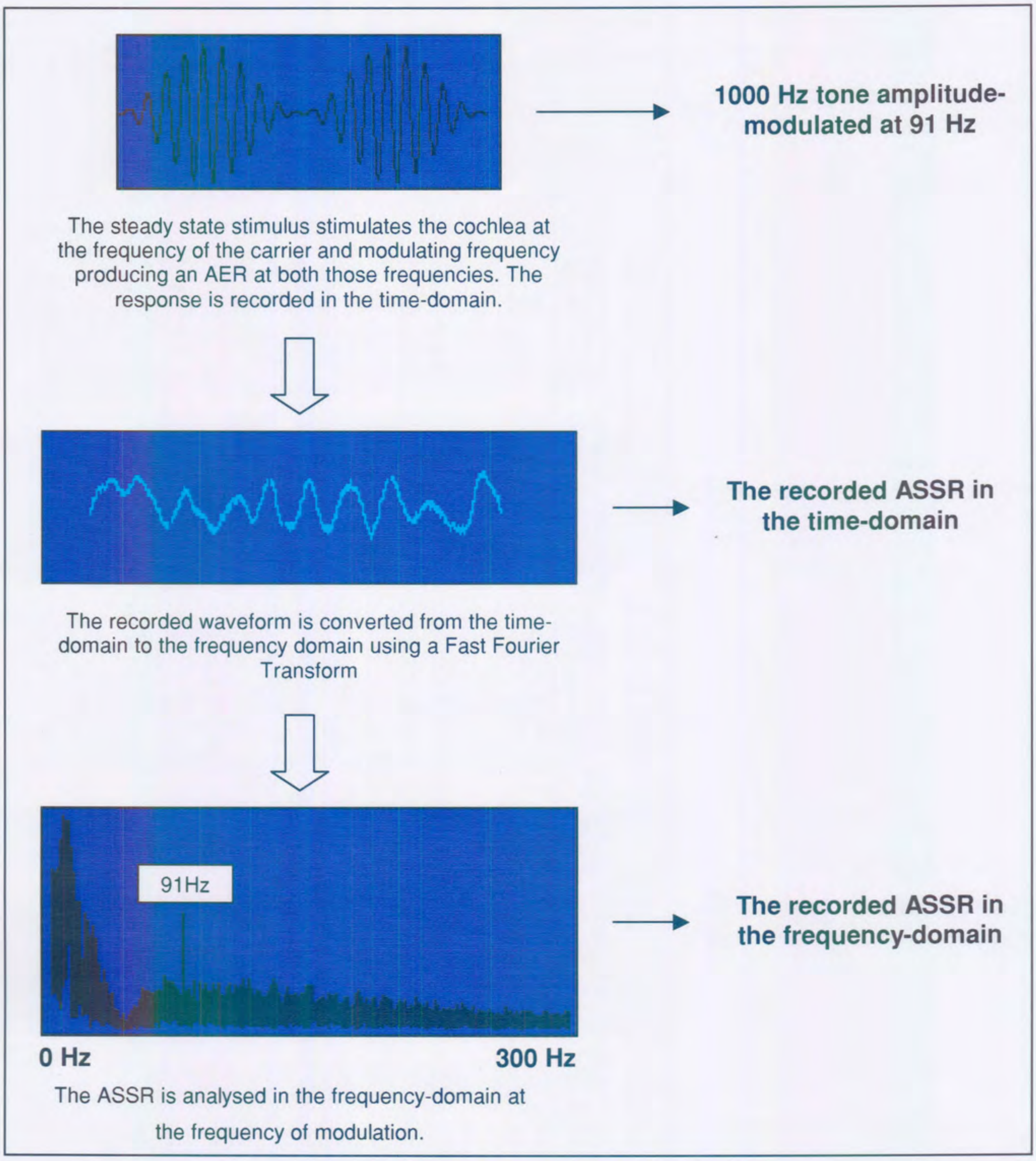
The modulation frequency is the rate of stimulation. Carrier tones can be modulated at various frequencies, eliciting different auditory evoked responses. Rates of a few stimuli per second (5 - 20 Hz) elicit steady state versions of the late latency auditory evoked responses (Maiste & Picton, 1989), but these responses are small and vary with the state of the subject.

The 40-Hz response is the steady state version of the middle latency evoked response (Lins et al., 1995). Unfortunately, the 40-Hz response is not reliable in young infants, probably because the auditory cortex and its connections are not yet fully developed and the response is attenuated during sleep (Lins et al., 1995). The best modulation rate for audiometric purposes appears to be between 75-110Hz. This could be because these responses may present the steady state versions of the transient ABR and are therefore not significantly affected by sleep or sedation (Lins et al., 1995; Lins et al., 1996; Rickards et al., 1994). The fact that the ASSR is a sustained response means that the latency of the response cannot be represented on the time axis and must therefore be inferred (Herdman, Lins, Van Roon, Stapells, Scherg, & Picton 2001).

### 2.4.4 Recording the Auditory Steady State Response

The carrier frequency determines the tonal area on the basilar membrane that will be stimulated. The hair cells at the tonal area of the carrier frequency, fire at the rate of the amplitude modulation (MASTER homepage). Thus, the steady state stimulus 'drives' the brain at the same frequency as the rate of modulation (Lins et al. 1995). This rate at which the brain is 'driven', results in a spectral component at the rate of stimulation. This produces a response that can be recorded and phase locked to the modulation frequency of the stimulus (Perez-Abalo, 2001; Hood, 1998).

The scalp-recorded, far-field, response is generated by open-field sources in the ascending auditory pathways. Therefore, the recorded activity is a combination of the ASSR at the modulation rate and the electrical noise produced by the brain and scalp muscles (Lins et al., 1995). The effect of each carrier frequency on the cochlear transducer can be evaluated by measuring the spectral component of the response at the modulation-frequency of that tone (Perez-Abalo et al., 2001). The energy in the resultant response is at the frequency of modulation and its harmonics, allowing analysis of the response in the frequency domain (Herdman & Stapells, 2001). Figure 2.4 illustrates this procedure.



**1000 Hz tone amplitude-modulated at 91 Hz**

The steady state stimulus stimulates the cochlea at the frequency of the carrier and modulating frequency producing an AER at both those frequencies. The response is recorded in the time-domain.

**The recorded ASSR in the time-domain**

The recorded waveform is converted from the time-domain to the frequency domain using a Fast Fourier Transform

**The recorded ASSR in the frequency-domain**

The ASSR is analysed in the frequency-domain at the frequency of modulation.

**Figure 2.4 Recording the ASSR**

According to Lins et al., (1995) the response amplitude is unaffected by the frequency of the carrier. Responses can be detected using automatic and objective response detection protocols (Lins et al., 1996) that compare the response to the background EEG activity. By recording responses at descending intensities, a steady state threshold can be obtained at the lowest intensity eliciting a response (Lins et al., 1995).

### 2.4.5 Analysis of the Auditory Steady State Response

Automatic response detection protocols rely on statistical methods to decide whether a response is present or not. The time-domain waveforms are converted to the frequency-domain by a Fast Fourier Transform (FFT). In the frequency domain, the response to the carrier frequency can be assessed by the amplitude and phase of the FFT component corresponding to the frequency of modulation of the carrier. Responses are combined, whilst maintaining phase as well as amplitude information, to attain an averaged response (Lins et al., 1996; Perez-Abalo et al., 2001)

Two statistical methods are used to decide whether responses are present or not, namely the F- & T2- technique. The F-technique basically evaluates whether a response at the frequency of stimulation (modulation) is different from the noise at adjacent frequencies (Lins et al., 1996; Perez-Abalo, 2001). The T2-technique has been used in various ways to determine whether an evoked response is present or not. For ASSR analysis the T2 statistic is used to evaluate statistically whether the two-dimensional response is replicable across a number of averaged responses (Valdes et al., 1997).

Lins et al. (1996) found the F-test to be slightly more effective but suggested that these tests would be equivalent when based on the same degrees of freedom. A study by Valdes et al. (1997) also compared these statistical indicators for the detection of ASSRs. The results of their study indicated that there was no significant difference in determining ASSRs between the F- and T2- statistical techniques.

### 2.4.6 Objective Threshold Audiometry with the Auditory Steady State Response

Experiments have demonstrated that the ASSR can reliably be recorded at intensities near behavioural auditory thresholds in normal adults, well babies and hearing impaired subjects (Cohen et al, 1991; Aoyagi et al, 1994; Rickards et al, 1994; Lins & Picton, 1995; Lins et al, 1996; Rance et al, 1998; Hood, 1998; Perez-Abalo et al., 2001). Thresholds in well babies can be detected in the first four days of life and are similar to thresholds obtained using unmasked tone bursts in sleeping adults (Rickards et al., 1994).

Studies to determine the clinical usefulness of the ASSR technique for hearing impaired subjects has been published (Aoyagi et al., 1996; Aoyagi, Suzuki, Yokota, Furuse, Watanabe & Ito, 1997). An interesting finding is that research demonstrates that the difference between the behavioural threshold and the ASSR threshold is smaller in hearing impaired subjects than in normal subjects (Lins et al., 1996; Picton, Durieux-Smith, Champagne, Whittingham, Moran, Giguére, & Beauregard, 1998; Rickards et al., 1994; Perez-Abalo, 2001). These authors suggest that the small threshold differences in hearing impaired subjects could probably be attributed to an abnormal increment in the response amplitude at above threshold intensities, due to the presence of recruitment.

#### 2.4.6.1 Normative Auditory Steady State Response Studies

Several authors have reported that ASSRs for normal hearing subjects predict behavioural thresholds reasonably well (Lins et al., 1995; Aoyagi et al., 1994; Valdes et al., 1997; Lins & Picton, 1995; Lins et al., 1996; Perez-Abalo, 2001). The average threshold differences between behavioural thresholds and ASSR thresholds varied from 16dB at 1 kHz (Lins & Picton, 1995) up to 34 dB at 0.25 kHz, 29dB at 1 kHz, and 30dB at 4 kHz (Aoyagi et al., 1994). These studies used single amplitude-modulated tones between 70 – 110 Hz. The results suggest that ASSR thresholds, for normal hearing subjects, demonstrate some variability being recorded at between 16 - 30 dB of behavioural thresholds. According to Lins et al., (1995) these differences may be accounted to possible inter-subject variability, different recording time periods, and different statistical response detection techniques used in the studies.

Various authors have commented that there appeared to be relative difficulty estimating the 0.5 kHz ASSR (Perez-Abalo, 2001; Rance et al., 1995; Lins et al., 1996; Aoyagi et al., 1994). Lins et al., (1996) pointed out that this could partly be due to the enhanced masking effect of ambient noise in lower frequencies, or it could reflect the characteristics of the responses themselves. The low frequency response might have a greater intrinsic jitter, due to neural asynchrony, which would cause the relative difficulty in threshold detection (Lins et al., 1996). Clarification of this matter, however, warrants further studies (Perez-Abalo, 2001).

### 2.4.7 Advantages of the Auditory Steady State Response Compared to the Auditory Brainstem Response

Various experiments have demonstrated that the ASSR can be reliably recorded at intensities near behavioural thresholds (Lins et al., 1995; Valdes et al., 1997). The ASSR evoked responses present definite advantages over transient evoked responses such as the ABR in the prediction of frequency-specific thresholds.

According to Lins et al. (1995) steady state responses are, first of all, frequency-specific. This is because the steady state stimuli are continuous tones that do not suffer the spectral distortion problems associated with brief tone bursts or clicks (Rance et al., 1998). Secondly, since the response is periodic, it can best be represented in the frequency domain, simplifying measurements. The response can be determined at the frequency of modulation by a computer using well-established statistical procedures, inferring that no subjective judgment by an interpreter is necessary (Perez-Abalo et al., 2001; Lins et al., 1995; Lins et al., 1996). Thirdly, steady state stimuli can probably provide a better evaluation of hearing aids than transient stimuli. Hearing aids and cochlear implants will more readily process steady state stimuli with much less signal distortion because it does not have the abrupt changes over time characteristic of transient stimuli (Lins et al., 1996; Collet, et al., 2001). According to Rance et al., (1998) a fifth advantage of the ASSR to transient AERs lies in the continuous nature of the steady state stimuli offering a presentation level advantage over transient stimuli. This enables a better investigation of ears with minimal amounts of hearing than the ABR.

These advantages are very convincing and demonstrate numerous promising applications of the ASSR technique in clinical practice. It must be considered, however, that if each frequency for both ears is explored separately the procedure can still prove to be very time consuming (Perez-Abalo, 2001). Evaluating each frequency consecutively will require the same amount of time as an evaluation across frequencies with tone burst ABRs.

## 2.5 Latest Auditory Evoked Response Development: The Multiple Frequency Auditory Steady State Response (MF ASSR)

An optimised variant of the ASSR was proposed more recently using multiple simultaneous amplitude-modulated tones (Lins & Picton, 1995). This implies that distinct modulation rates, that are more than one octave apart, are used for carrier tones at different frequencies. The modulated tones are added into a complex acoustic stimulus capable of simultaneous activation of different frequency regions within the cochlea. This technique is further optimised if two differently modulated multiple frequency stimuli are presented simultaneously to the left and right ears (Perez-Abalo et al., 2001). Figure 2.5 illustrates and explains this technique.

**STIMULI**

| Carrier (Hz) | Modulation (Hz) | |
|---|---|---|
| | Left | Right |
| *500* | *77* | *79* |
| *1000* | *85* | *87* |
| *2000* | *93* | *95* |
| *4000* | *101* | *103* |

The carrier frequencies are 500, 1000, 2000, and 4000 Hz and the modulation frequencies for the left ear (77, 85, 93, 101) must be different than those for the right (79, 87, 95, 103). The four separate stimuli for each ear are combined in the time domain and are presented to the subject as a complex tonal signal for the left ear and a different complex tonal signal to the right ear. These are presented simultaneously to the left and right ear respectively.

⇩

**COCHLEA**

The tonotopically organized cochlea of each ear is stimulated by the 4 tones at the respective tonal area of the basilar membrane.

⇩

**BRAIN**

The hair cells in each tonal area fire with the maximum of the amplitude modulation for each frequency, and therefore the evoked steady state responses are produced at the frequency of modulation of each carrier frequency. The signals are compared to background EEG activity in the frequency domain using statistical measures. If the signal to noise ratio is large enough a response is considered significant.

(Source: Adapted from MASTER homepage)

**Figure 2.5 Dichotic MF ASSR technique**

John et al., (1998) reported that ASSR amplitudes to the simultaneous presentation of four steady state tones to one ear were not significantly different from amplitudes when each steady state tone was presented alone, provided the carrier frequencies were at least one octave apart. More recently Herdman & Stapells (2001) reported that presenting multiple steady state tones simultaneously to both ears produced thresholds that were the same as single or multiple steady state tones presented to just one ear. These results indicate that there are no significant interactions between multiple stimuli presented simultaneously that have a significant effect on the amplitude of the ASSR. Herdman, Picton & Stapells (2001) have also recently demonstrated that the place specificity in the cochlea for both single and multiple ASSRs for normal hearing subjects are good.

Thus, multiple frequencies can be explored simultaneously in both ears (Perez-Abalo, 2001), significantly decreasing the time needed to evaluate thresholds at multiple audiometric frequencies binaurally (Lins et al, 1996). According to Lins et al. (1995) using the MF ASSR for estimating hearing thresholds could be several times more efficient than using an ABR protocol and results could be represented as a conventional audiogram indicating the minimum response level of the ASSR at each frequency.

### 2.5.1 Normative Multiple Frequency Auditory Steady State Response Studies

The MF ASSR technique has shown promising results in relatively small samples of normal adults, well babies, and hearing impaired adolescents in the estimation of behavioural thresholds (Lins & Picton, 1995; Lins et al, 1996; Perez-Abalo, 2001). The usefulness of the MF ASSR to estimate hearing thresholds has been evaluated less extensively than the single frequency (SF) ASSR, and only in very small samples of normal hearing subjects using different combinations of stimuli in each case (Lins & Picton, 1995; Lins et al., 1996). The interest of this study, being a normative study, is in data from normal hearing subjects, to obtain important information regarding the range of normality. According to Herdman & Stapells (2001) there are few available threshold data for the dichotic amplitude-modulated MF ASSR technique. Threshold data are only available for the two stimuli per ear condition and until very recently (Perez-Abalo, 2001; Herdman & Stapells, 2001), none were available for the four stimuli per ear condition.

#### 2.5.1.1 Multiple Frequency Auditory Steady State Response Estimations of Behavioural Pure Tone Thresholds

Lins & Picton (1995) used the dichotic MF ASSR technique in normal hearing subjects for two frequencies in both ears. The results indicated average ASSR thresholds of 31 dB HL for 0,5 kHz and 25 dB HL for 2 kHz. The average difference between ASSR and behavioural thresholds was 18dB for the 0.5 kHz stimulus and 12dB for the 2 kHz stimulus.

A subsequent study by Lins et al., (1996) monaurally evaluated four frequencies simultaneously in 15 normal hearing subjects. Results indicated an average difference between the ASSR and behavioural thresholds of 12dB. The behavioural and ASSR thresholds and the differences between the two for each frequency are shown in table 2.1.

**Table 2.1 MF ASSR and behavioural thresholds (dB HL) in normal adults reported by Lins et al. 1996 (Carrier frequencies in kHz; means ± SD; 30 ears)**

| Frequency (kHz) | Behavioural | ASSR | Difference |
|---|---|---|---|
| 0.5 | 25 ± 7 | 39 ± 10 | 14 ± 11 |
| 1 | 17 ± 5 | 29 ± 12 | 12 ± 11 |
| 2 | 18 ± 7 | 29 ± 11 | 11 ± 8 |
| 4 | 18 ± 10 | 31 ± 15 | 13 ± 11 |

(Source: Lins et al. 1996:88)

The behavioural and ASSR thresholds reported in this study were relatively high. These elevated thresholds may be due to the presence of high ambient noise levels in the test booth and the fact that the recording room was not sufficiently sound attenuated (Lins, 1996; Herdman & Stapells, 2001).

More recently, Picton et al. (1998) using MF ASSR, reported higher differences between responses and behavioural thresholds ranging between 10 – 30 dB. In this case all testing was done in a sound attenuated chamber and the authors suggested that the lower levels of ambient noise would reduce the behavioural thresholds increasing the difference between the ASSR and behavioural thresholds.

During the year 2001, when the current study was being completed, the first reported threshold results on the use of the dichotic amplitude-modulated MF (using four frequencies per ear) ASSR was reported (Perez-Abalo, 2001; Herdman & Stapells, 2001) for normal hearing subjects. These studies are discussed in the following paragraphs.

#### 2.5.1.2 Dichotic Multiple Frequency (four frequencies per ear) Auditory Steady State Response Results Reported for Normal Hearing Subjects

Perez-Abalo et al., (2001) tested 40 normal hearing subjects with the dichotic MF ASSR technique at 0.5, 1, 2, and 4 kHz. The average threshold differences between the behavioural and ASSR thresholds were better than those reported by Picton et al. (1998), averaging between 11 – 15 dB. According to Perez-Abalo et al., (2001) this could be attributed to the fact that all testing in this case was done in a sound treated room and not in a properly sound attenuated chamber as in Picton et al., (1998). The overall acoustical noise level measure was 65 dB SPL with the spectral composition measured at 0.5, 1, 2, and 4 kHz to be 30, 30, 27, and 21 dB SPL respectively. These levels of ambient noise exceed the maximum permissible ambient noise levels specified by ANSI (ANSI S3.1-1999). As pointed out earlier, the lower levels of ambient noise in a properly sound attenuated chamber would reduce the behavioural thresholds increasing the difference between the ASSR and behavioural thresholds. Higher levels of ambient noise as in the study by Perez-Abalo et al., (2001) could have caused the reduced difference between behavioural and ASSR thresholds. ASSR thresholds obtained in acoustic environments with high levels of ambient noise are evoked using higher levels of stimulation. Lins et al. (1996) reported that louder sounds elicit a larger response thus higher levels of stimulation contribute to stronger evoked responses that could more closely approximate behavioural thresholds in environments with high levels of ambient noise.

The results of the study however, fall within the range of reported values for both single and multiple frequency stimulation techniques, although closer to the lowest reported values. According to these authors the dichotic MF ASSR technique was able to detect significant frequency-specific responses for 80.9 % of ears within 20 dB from the corresponding behavioural threshold. The thresholds and standard deviations for this sample (80.9%) of ears are represented in table 2.2.

**Table 2.2 Difference between behavioural thresholds and ASSR thresholds for 80.9 % of the sample as reported by Perez-Abalo et al. 2001(Mean ± SD)**

| Frequency (kHz) | PT threshold (dB SPL) | MF ASSR threshold (dB SPL) | Difference (PT – ASSR thresholds) |
|---|---|---|---|
| 0.5 | 30 ± 8 | 41 ± 11 | 12 ± 11 |
| 1 | 21 ± 8 | 34 ± 9 | 13 ± 10 |
| 2 | 23 ± 7 | 33 ± 10 | 10 ± 11 |
| 4 | 23 ± 8 | 36 ± 11 | 12 ± 10 |

(Source: Compiled from Perez-Abalo et al. 2001)

The thresholds in table 2.2 are composed only of those obtained in 80.9 % of the ears. This 80.9 % presented with ASSR thresholds within 20 dB of behavioural thresholds. Some higher difference scores of between 20 and 39dB were however reported in a number of normal hearing ears at certain frequencies.

Herdman & Stapells (2001) reported thresholds for the dichotic MF (using four frequencies per ear) ASSR technique for 10 normal hearing subjects. ASSR recordings and behavioural audiometry were performed with subjects in a double-walled sound-attenuated booth with low levels of acoustic background noise (10 – 12 dB SPL across 0.5, 1, 2, & 4 kHz). Table 2.3 presents the behavioural and ASSR thresholds as well as the average difference.

**Table 2.3 Behavioural and ASSR Thresholds for normal hearing adults in Herdman & Stapells 2001 (Means ± SD)**

| Frequency (kHz) | PT threshold (dB SPL) | MF ASSR threshold (dB SPL) | Difference (PT – ASSR thresholds) |
|---|---|---|---|
| 0.5 | 11 ± 3 | 25 ± 9 | 14 ± 10 |
| 1 | 9 ± 4 | 17 ± 8 | 8 ± 7 |
| 2 | 8 ± 4 | 15 ± 7 | 8 ± 9 |
| 4 | 7 ± 5 | 22 ± 9 | 15 ± 9 |

(Source: Compiled from Herdman & Stapells 2001)

The threshold difference scores for this study ranged between 8 – 15 dB being similar to those reported by Lins & Picton (1995). The study of Perez-Abalo et al. (2001), also presented similar results with average threshold difference scores between 11 – 15 dB. The MF ASSR technique estimated behavioural thresholds within 20 dB for 87% of thresholds obtained. This correlates well with the 80.9% reported by Perez-Abalo et al. (2001), even though this study recorded thresholds in a sound-attenuated chamber whilst Perez-Abalo et al. (2001), recorded thresholds in a sound treated room. This similarity in thresholds obtained in different acoustic environments warrants further investigation. The fact that lower levels of ambient noise might reduce behavioural thresholds increasing the difference between the ASSR and behavioural thresholds, as well as the possibility that ASSR thresholds obtained in higher levels of ambient noise at higher levels of stimulation might approximate behavioural thresholds more closely, needs to be investigated.

#### 2.5.1.3 Recording Time of the Dichotic Multiple Frequency Auditory Steady State Response

A critical aspect to take into consideration is the recording time required by the dichotic MF ASSR technique to provide a frequency-specific objective audiogram. Perez-Abalo et al. (2001), reported to have the first quantifiable evidence to substantiate the claim that the dichotic MF ASSR technique can radically minimize testing time. The reported recording time for recording four audiometric frequencies in two ears at six intensity steps were less than 35 minutes averaging 21 minutes per subject. According to Perez-Abalo et al. (2001), this means that to obtain similar frequency-specific information with alternative methods based on the transient ABR, or even the SF ASSR, would require more than threefold the time (71 minutes at best).

Herdman & Stapells (2001) also reported recording times for MF ASSR evaluations. The authors reported the time taken for estimating four single frequencies in both ears to be 164 minutes. In contrast to this they reported a time of 83 minutes to evaluate four frequencies in each ear simultaneously using the dichotic MF ASSR technique. This indicates that the dichotic MF ASSR technique is up to four times more efficient than determining thresholds separately for each frequency.

Although both Perez-Abalo et al. (2001) and Herdman & Stapells (2001) suggest a more efficient recording time for the dichotic MF ASSR procedure, the average recording time between the two studies differ by 62 minutes. This is a substantial difference that warrants investigation. The most notable difference between the two studies is the acoustical environment.

The acoustical background noise in the study by Herdman and Stapells (2001) was significantly lower by between 10 – 20 dB SPL. The lower levels of ambient noise cause lower behavioural thresholds that might increase the difference between ASSR and behavioural thresholds (Picton et al., 1998). Approximating behavioural thresholds at low intensity levels might take longer because the steady state stimuli at lower intensities have reduced amplitudes (Lins & Picton, 1995) and therefore might require longer periods of averaging to attain significance. In contrast, the higher levels of ambient noise in the study by Perez-Abalo et al. (2001) increased behavioural thresholds, and therefore ASSR thresholds were elicited at higher intensities. These increased levels of stimulation might evoke larger amplitude ASSRs able to approximate behavioural thresholds more closely in a shorter period of time. This aspect however, demands further in-depth investigation.

### 2.5.2 Clinical Validation of the Dichotic Multiple Frequency Auditory Steady State Response

The initial studies using the dichotic MF ASSR demonstrates great promise as an objective frequency-specific, time-efficient audiometric procedure for all age groups. The clinical validation of this technique is still somewhat limited and especially in view of limited studies concerning dichotic MF stimulation. Studies often do not replicate clinical settings and are therefore limited in their applicability. Clinical validation of the technique must include normative studies correlating the MF ASSR to corresponding behavioural thresholds, and establishing an average range of MF ASSR recording times.

In agreement with Herdman & Stapells (2001) the question remains whether the dichotic MF (four stimuli per ear) ASSR technique can reliably estimate behavioural thresholds in a time-efficient manner. According to John (2001), the technique may not yet be ready for clinical practice before more studies investigating optimal parameters have been performed to validate the usefulness thereof.

## 2.6 Conclusion

The need for a technique to estimate frequency-specific hearing thresholds in a clinically time-efficient way for difficult-to-test populations who are unable to provide behavioural responses, has long been the hope of audiologists (Hall, 1992). In the past 3 decades the use and implementation of AERs in the field of objective audiometry has made large strides in addressing this important need.

The most widely used AER technique currently used in clinical practice is the ABR (Arnold, 2000; Hood, 1998). This technique can provide a general evaluation of the high frequency region (2 – 4 kHz) using a click stimulus, or more frequency-specific thresholds using tone bursts at various frequencies. Although it is a valuable tool used to describe hearing-loss in difficult-to-test populations, it presents with important limitations. These limitations and advantages are represented in table 2.4.

**Table 2.4. Advantages and limitations of the ABR**

| ABR | |
|---|---|
| **Advantages** | **Limitations** |
| • First AER in widespread clinical use<br>• Resistant to state of consciousness<br>• Recordable, close to behavioural thresholds<br>• Tone burst stimuli can be used to provide more frequency-specific info | • Stimuli contain energy over a range of frequencies and may evoke a response at any of these<br>• Click ABR provides only general assessment of high frequency region<br>• Tone burst stimuli can be time-consuming<br>• Interpretation of ABR results are subjective<br>• Residual hearing at profound levels cannot be investigated thoroughly |

Recently a new objective audiometric procedure has emerged, the Auditory Steady State Response (ASSR) that has demonstrated promise of addressing the limitations of the ABR. According to Jerger (1998) the ASSR 'fills the gap between the desirable properties of the transient-induced ABR and the often excessive state dependence of the later, frequency-specific evoked responses'. This technique indicates important advantages in estimating frequency-specific thresholds reasonably close to behavioural thresholds in normal hearing, and hearing impaired ears (Lins et al., 1995; Aoyagi et al., 1994). The ASSR technique, however still faces a shared limitation with the ABR; it is time-consuming. Table 2.5 indicates the limitations and advantages of this technique.

**Table 2.5 Advantages and limitations of the ASSR**

| ASSR | |
|---|---|
| **Advantages** | **Limitations** |
| • Frequency-specificity approximating pure tones<br>• Resistant to state of consciousness<br>• Recordable, reasonably close to behavioural thresholds<br>• Simplified objective automatic detection of response with statistical procedures<br>• Provides for better evaluation of hearing aids<br>• Allows for investigation of residual hearing at profound levels of hearing-loss | • Obtaining a single frequency at a time can be as time consuming as the ABR<br>• Requires clinical validation – to identify limitations |

In 1995 Lins & Picton (1995) proposed an optimised version of the ASSR using multiple stimuli simultaneously in both ears. This technique shows promise to evaluate frequency-specific thresholds in a time-efficient manner capable of estimating profound levels of hearing impairment (Lins et al. 1996; Picton et al. 1998). The possible advantages and limitations of this technique are presented in table 2.6.

**Table 2.6 Advantages and limitations of the dichotic MF ASSR**

| MF ASSR | |
|---|---|
| **Advantages** | **Limitations** |
| • Frequency-specificity approximating pure tones | • Requires clinical validation – to identify limitations |
| • Resistant to state of consciousness | |
| • Recordable, reasonably close to behavioural thresholds | |
| • Simplified objective automatic detection of responses with statistical procedures | |
| • Provides for better evaluation of hearing aids | |
| • Allows for investigation of residual hearing at profound levels of hearing-loss | |
| • Able to obtain multiple auditory thresholds simultaneously, making it time-efficient | |

This technique indicates that it has the potential of addressing the most important limitations of the ABR and the single ASSR. The clinical validation of the technique has, however, only been performed on small samples of subjects. Although initial results underline the advantages of this technique, the question remains whether the dichotic MF ASSR can accurately estimate PT thresholds in a time-efficient way (Herdman & Stapells, 2001).

## 2.7 Summary

This chapter aimed to orientate the reader on the topic and to provide a critical evaluation and interpretation of relevant literature. In order to achieve this aim the invaluable role of AERs in objective audiometry for the difficult-to-test population was emphasised, accompanied by a brief description of AERs. The most widely clinically used AER technique for estimating auditory thresholds, the ABR, was described, critically evaluated, and discussed according to clinically used test protocols. Subsequently the ASSR was discussed as an AER promising to address the current limitations of the ABR. A brief history and description of the ASSR technique was provided. An evaluation of the advantages promised by the ASSR over the ABR was discussed as a prelude to the introduction of the optimised variant of the ASSR, the dichotic MF ASSR. A description of this technique, its advantages, and the limited clinical validity thereof, was discussed. Finally the general ideas of the chapter were summarized in the conclusion.

# Chapter 3

# Research Methodology

**Aim:** To provide the methodological approach implemented in conducting the empirical research component of this study

## 3.1 Introduction

Leedy (1997) compares the broad definition of *research methodology* to the extraction of valuable metals from ore. The ore is like data containing desirable aspects of the truth. To extract from the data their meaning, is the research methodology. It 'is merely an operational framework within which the data are placed so that their meaning may be seen more clearly' (Leedy, 1997:104).

The research question underlying the current research project has been stated extensively in Chapter 1 and 2. The need for an objective clinical procedure to provide estimations of hearing thresholds across a range of frequencies in a time-efficient manner has led to the development of an AER technique called the dichotic MF ASSR. This technique has demonstrated promising initial results that suggest a time-efficient procedure for accurate estimation of hearing thresholds across different frequencies. Clinical validation of this technique, however, is very limited.

**The purpose of this chapter is to describe the research method, or operational framework, dictating the scientific process of this study to determine the clinical validity of the dichotic MF ASSR technique.**

## 3.2 Aims of Research

The aims of the research project are as follows.

### 3.2.1 Main Aim

The aim of this study was to evaluate the clinical usefulness of the dichotic multiple frequency auditory steady state response (MF ASSR) technique for estimating pure tone (PT) behavioural thresholds (BT), compared to an auditory brainstem response (ABR) protocol in a sample of normal hearing adults.

This study centred on normal hearing adult subjects in order to provide normative data for the dichotic MF ASSR technique. This is necessary because standardization of a technique is dependent on normative data as the initial validation. This provides a range of normality (Leedy, 1997) as backdrop to the study of pathological auditory function.

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

### 3.2.2 Sub Aims

- To determine the estimation of pure tone behavioural thresholds at 0.5, 1, 2, and 4 kHz with the dichotic MF ASSR compared to a broadband click and 0.5 kHz tone burst ABR protocol
- To determine the time-efficiency of the dichotic MF ASSR technique compared to the ABR protocol in the estimation of PT BTs

## 3.3 Research Design

A comparative experimental research design (Leedy, 1997; Neuman, 1997; Johnston & Pennypacker, 1993) was selected for this study. According to Johnston & Pennypacker (1993), the conclusions and implications that can be derived from any experimental design depends primarily on only three basic components. The dependent or measured variable, the experimental setting and the independent or manipulated variable. This study investigated the usefulness of the MF ASSR technique in the estimation of PT BT compared to an ABR protocol. The manipulated variable for this study was the three test procedures used to estimate hearing thresholds. The measured variable was the threshold estimations and the time needed to complete each procedure. The pure tone behavioural hearing threshold estimations served as the gold standard or reference of hearing threshold, against which the dichotic MF ASSR and ABR protocol was compared.

A single experimental setting, as far as sound attenuation and same-day evaluations, was used to ensure representative data comparable between independent variables (Johnston & Pennypacker, 1993; Neuman, 1997). The experimental setting is a controlled environment that must provide a stable context for seeing the effects of the independent variable (Leedy, 1997). Control variables were applied to the experimental setting. These are factors controlled by the researcher to cancel out or neutralize any effect they may otherwise have on the observed phenomenon (Bless & Higson-Smith, 1995)

The variables of this study are as follows.

**Manipulated or independent variables:**

- Pure tone behavioural threshold audiometry
- Dichotic multiple frequency auditory steady state response audiometry (MF ASSR)
- An auditory brainstem response (ABR) audiometry protocol

**Measured or dependent variables:**

- PT BT measurements at 0.5, 1, 2, & 4 kHz
- Dichotic MF ASSR threshold measurements at 0.5, 1, 2, & 4 kHz
- ABR threshold measurements at 0.5 kHz for tone burst stimuli and between 1 - 4 kHz (Gorga, 1999; Hood, 1998; Hall, 1992) for click stimuli
- Recording time for the dichotic MF ASSR procedure
- Recording time for the ABR protocol

**Controlled variables:**

- Age – adult subjects were selected between 17 – 38 years of age
- Gender – an even gender distribution was selected
- Normal hearing – Subjects were required to have pure tone behavioural thresholds less than 25 dB HL across all frequencies

The following figure outlines the experimental design.

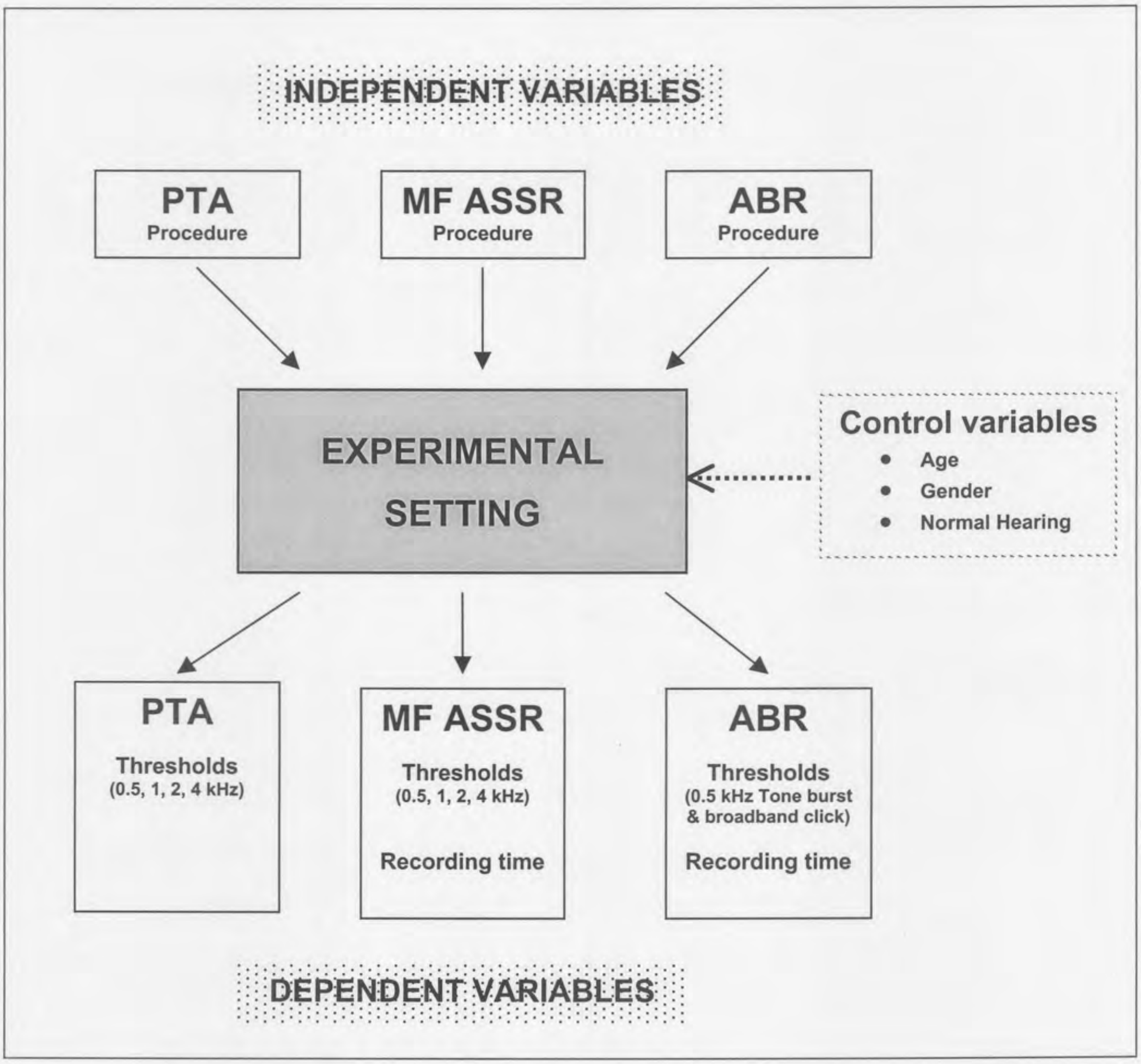


**Figure 3.1 Experimental design**

Johnston & Pennypacker (1993:233) states that the 'overriding strategic goal of arranging experimental comparisons is to create distinct sets of data whose comparison will clarify the role of the independent variable'. The procedures (independent variables) were compared in terms of the correlation of corresponding MF ASSR and ABR pure tone threshold estimations (dependent variable) as well as the recording time required for each procedure (dependent variable).

The interpretation of data consisted of comparing the estimation of PT BT with the MF ASSR and the ABR protocol. The recording time required to complete the dichotic MF ASSR and the ABR protocol, was analysed, by determining the average test time and standard deviation, to compare the average range of recording times required by the different techniques.

## 3.4 Subjects

For this study, 28 subjects (56 ears) aged between 17-38 years were selected. The subjects were required to have normal hearing ability and were recruited from the student body and personnel at the University of Pretoria. Subjects included 16 males and 12 females.

### 3.4.1 Criteria for the Selection of Subjects

Subjects were selected according to the following criteria:

#### 3.4.1.1 Hearing Ability

Subjects were required to have hearing thresholds equal to or less than 25dB HL across the test frequencies of 0.5, 1, 2, and 4 kHz. Although 0dB HL is considered as the 'perfect' normal hearing sensitivity range, thresholds between 0-25 dB HL are considered within normal limits for adults (Roeser, Buckley, & Stickney, 2000).

#### 3.4.1.2 Normal Middle Ear Functioning

Subjects were required to have normal middle ear functioning. A 25 dB HL cut-off for normal hearing does not exclude middle ear pathology or slight conductive hearing-loss (Stach, 1998). It is therefore very important to evaluate the condition of the middle ear for this study. Any conduction problems caused by middle ear pathology influence the accuracy of the pure tone thresholds, the amplitude of the steady state responses, and the wave latency and morphology of ABR recordings (Yantis, 1994; Hall & Mueller, 1997). Normal middle ear functioning will be determined by an otoscopic examination and tympanometry.

#### 3.4.1.3 Subject Age and Gender

According to Hood (1998), studies have shown no significant age effects on the auditory brainstem response for subjects between the ages 10 – 60 years. Subjects, therefore, were selected to fall within this range. The subjects ranged between 17 – 38 years of age. Subjects were selected in an attempt to acquire an even gender distribution to ensure a representative sample. Although small differences occur for auditory brainstem responses in males and females the clinical importance of this fact is generally minimal due to the substantial normal variability (Hall, 1992).

### 3.4.2 Subject Selection Procedures

Non-probability quota sampling (Neuman, 1997) was used in selecting research subjects. According to Neuman (1997) this means selecting anyone in predetermined groups. Subjects were selected according to the selection criteria and their availability in terms of time constraints. The procedure followed in the selection of subjects included informed consent by a subject (Appendix A), the use of biographical information, otoscopy, tympanometry, and pure tone audiometry.

#### 3.4.2.1 Biographical Detail

Subjects were selected based on their age, gender and subjective perception of hearing acuity. Their availability to participate in the study was also taken into account.

#### 3.4.2.2 Otoscopic Examination

An otoscopic examination was performed on each subject in both ears to inspect whether there was any visible obstruction that could affect the conduction of sound to the tympanic membrane (Ballachanda, 1995; Stach, 1998). The condition of the tympanic membrane was also inspected, where possible, for inflammation, perforation, or any other obvious abnormalities. If a light reflex is visible it is most often indicative of a healthy tympanic membrane (Ballachanda, 1995; Hall & Chandler, 1994).

#### 3.4.2.3 Tympanometry

Middle ear functioning was measured using tympanometry in order to ensure subjects had no middle ear involvement that could influence results (Hall & Chandler, 1994). Therefore, the tympanometric results for each subject included in the study had to fall within the normal ranges as stipulated by Stach (1998) presented in table 3.1.

**Table 3.1 Tympanometry norms specified for the current study**

| | |
|---|---|
| **Ear canal volume** | 0.5 - 1.5 cc |
| **Compliance** | 0.3 - 1.6 cc |

#### 3.4.2.4 Pure Tone Audiogram

The data obtained from the pure tone audiograms were used to select normal hearing subjects by determining whether their hearing was within normal limits, 0-25 dB HL across 0.5, 1, 2, and 4 kHz (Roeser, Buckley, & Stickney, 2000).

Apart from constituting part of the selection criteria for subjects, the pure tone audiograms also provided measured variables for this study that will serve as the gold standard to which MF ASSR and ABR results can be compared. This procedure will be discussed in paragraph 2.5.1

## 3.5 Description of Subjects

The sample consisted of 28 normal hearing subjects, 12 females and 16 males. The subjects varied between 17 – 38 years of age. Figure 3.2 represents the age and gender distribution of the normal hearing subjects across five age intervals of five years each.

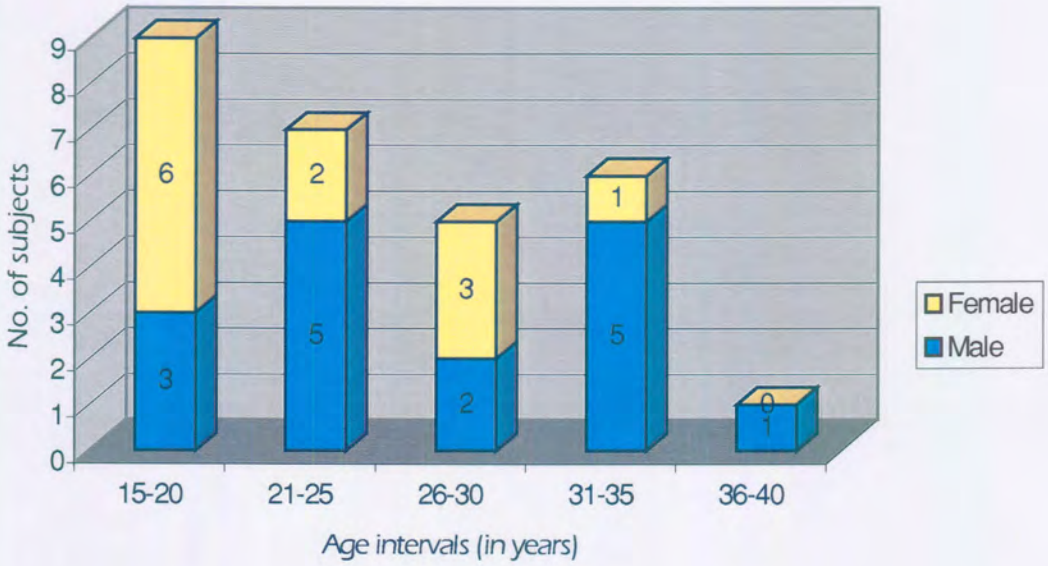


**Figure 3.2 Age and gender distribution of subjects**

## 3.6 Apparatus

The apparatus used in the different research sections were as follows:

### 3.6.1 Subject Selection Apparatus

- The otoscopic examination of the external meatus and tympanic membrane was performed with a **Heine mini 2000 otoscope**.
- Tympanometric evaluation of the middle ear was performed with a **GSI 33** middle ear analyser, calibrated January 2001 (Testing was performed February 2001).
- Pure tone threshold audiometry was performed using a **GSI 60 Clinical Audiometer**, calibrated January 2001. Acoustic stimuli were presented through **TDH 39 supra-aural headphones** in a **double-walled soundproof booth**

### 3.6.2 Data Collection Apparatus

- Pure tone thresholds were obtained for the selection of subjects using a **GSI 60 Clinical Audiometer**, calibrated January 2001. Acoustic stimuli were presented through **TDH 39 supra-aural headphones** in a **double-walled soundproof booth.**
- MF ASSRs and ABRs were obtained with the **AUDIX** system (Neuronic S.A., Havana, Cuba). The equipment (Clinical Edition, 2000) consisted of a specialized hardware component connected to a Pentium microcomputer. The system is operated by a software package specifically designed for the acquisition and analysis of auditory evoked responses (AER) including the MF ASSR, and the ABR to click and

tone burst stimuli. Calibration of the AUDIX system acoustic stimuli was performed in January 2001. The AER measurements were obtained in a **single wall soundproof booth** using **TDH-39 supra-aural earphones** to present acoustic signals whilst subjects were lying on a bed.

### 3.6.3 Data Analysis Apparatus

- The analysis of data was performed on Excel for Windows 1998

## 3.7 Data Collection Procedures

Three sets of data were collected from each subject, behavioural pure tone thresholds, as well as MF ASSR and ABR thresholds. The data for all procedures were collected on the same day for each subject. Behavioural pure tone thresholds were obtained first, as part of the selection criteria, followed by the recording MF ASSR and ABR data. Data collection was performed at the Department of Communication Pathology, University of Pretoria.

### 3.7.1 Preliminary Study

A preliminary study was conducted to determine clinically accountable stimulus parameters.

#### 3.7.2.1 Determination of Stimulus Parameters

Four frequencies were selected to serve as comparative reference points between the three test procedures. Test stimuli included pure tones for behavioural thresholds, carrier frequencies for ASSR, and tone burst stimuli for ABRs at 0.5, 1, 2, and 4 kHz. These frequencies were selected to ensure that high and low frequency information central to the speech spectrum was obtained at comparable points.

Tone burst stimuli were initially selected for recording ABRs at comparable frequencies to the MF ASSR and PT BT. During the preliminary study, however, it was evident that obtaining ABR thresholds with tone burst stimuli at four frequencies in each ear was extremely time consuming (± 60 min). In addition to the time consuming nature of recording tone burst ABRs across the frequency range in both ears, the literature suggested that most clinically used ABR protocols did not follow this procedure (Hood, 1998; Arnold, 2000). On account of these facts it was decided to include a 0.5 kHz tone burst stimulus for low frequency information and a broadband click stimulus for high frequency information (Hood, 1998), as the ABR protocol. The literature indicates that click stimuli is still the clinical procedure of choice for high frequency information due to better, more robust wave morphology (Gorga 1999, Arnold, 2000). Thus, to ascertain the clinical value of the MF ASSR compared to the clinical value of an ABR protocol, it follows logically to use a clinically representative ABR protocol. The test stimuli selected for this study on account of the preliminary study for each of the audiometric procedures, are presented in table 3.2.

**Table 3.2 PTA, MF ASSR, and ABR Test Stimuli**

| PROCEDURE | STIMULI (kHz) | | | |
|---|---|---|---|---|
| PTA | *0.5* | *1* | *2* | *4* |
| MF ASSR | *0.5* | *1* | *2* | *4* |
| ABR Protocol | *0.5 Tone burst* | *Broadband Click* | | |

Steady state stimulus intensity for the preliminary study commenced at 70dB HL. This initial intensity, however, proved to be uncomfortably loud for normal hearing subjects increasing the EEG noise in the recording. This was most probably due to muscle artefact (Rickards, 2001). Taking this fact into consideration, testing procedure commenced at 50dB HL.

A detailed description of the data collection procedure for each of the three audiometric techniques follows.

### 3.7.3 Data Collection using Pure Tone Audiometry

Pure tone air conduction thresholds were obtained for 0.5, 1, 2 and 4 kHz in each ear during the subject selection and the data collection procedure.

A pure tone air conduction audiogram was obtained for each subject once it was confirmed by otoscopy and tympanometry that they had normal middle ear functioning. The frequencies evaluated during PTA included 0.5, 1, 2, and 4 kHz. These frequencies were selected to provide corresponding points in comparing the data from the MF ASSR and ABR protocol.

A subjects' hearing was considered within normal limits when thresholds at 0.5, 1, 2 and 4 kHz were equal to, or less than, 25dB HL (Roeser, Buckley, & Stickney, 2000). Thresholds were determined using a descending intensity step of 10 dB and an ascending intensity step of 5dB until 50% accurate responses were obtained at a specific dB level.

### 3.7.4 Data Collection using the Multiple Frequency Auditory Steady State Response

The second set of data that was collected was each subject's dichotic MF ASSR thresholds, as well as the time taken for the procedure.

### 3.7.4.1 Specification of Stimulus Parameters for the Auditory Steady State Response

The stimulus parameters used in determining MF ASSR thresholds follows.

- ***Selection of carrier and modulation frequencies***

  Multiple amplitude-modulated tones with selected carrier frequencies of 0.5, 1, 2 and 4 kHz modulated between 80 – 110 Hz, at least one octave apart, were used. Multiple carrier frequencies were selected to provide high and low frequency information central to the speech spectrum comparative to data points collected with pure tone audiometry and an ABR protocol. The carrier frequencies were 95% amplitude-modulated between 80 – 110 Hz. These faster modulation rates were used because of their resilience to state of consciousness (Lins et al, 1995) and the fact that responses to these rates show much less interaction than modulation rates of 35 – 55 Hz (John et al., 1998). Studies have also indicated significant interactions between carrier frequencies when they are modulated at one half-octave or less, probably due to interactions in the activation patterns of the basilar membrane (John et al., 1998).

- ***Selection of dichotic multiple stimulation***

  Four frequencies were evaluated for each ear simultaneously using the dichotic multiple stimulation technique. This complex type of stimuli was used because studies indicate no significant difference between results obtained with, as well as cochlear place specificity of, single and multiple stimulation for the ASSR (Herdman, Picton & Stapells 2001; Lins & Picton, 1996). Furthermore, Herdman & Stapells (2001) indicated monotic and dichotic stimulation to provide similar results, at least for normal hearing subjects. Dichotic multiple stimulation for evoking the ASSR shows promise of more time-efficient testing with no significant variation from monotic single stimulation (Perez-Abalo et al., 2001; Lins & Picton 1996; John et al., 1998).

- ***The selection of the stimulus intensity and threshold criteria***

  All stimulation commenced at a supra-threshold level. The initial intensity, as determined in the preliminary study, was at 50 dB HL. A descending threshold seeking procedure using 10 dB steps was used until no response was present. Threshold was taken as the intensity level where the last response was detected, in other words the *minimum response level.*

### 3.7.4.2 Multiple Frequency Auditory Steady State Response Recording Procedure

- MF ASSR recordings were performed directly after the subject selection procedure
- Electrode discs of Ag/AgCl were fixed with electrolytic paste to the scalp at Cz (positive), Oz (negative) and Fpz (ground). Preliminary results by Mens, Gelders, Van Eeghem, Reijden, Snik & Wouters (2000), suggest that a high sensitivity can be obtained with the positive electrode at Cz
- Impedance values were kept below 3 000 Ohms
- Supra-aural TDH-39 earphones were used to present the stimuli to the ears
- Subjects were asked to lie on a bed in a soundproof booth and were encouraged to sleep or relax
- Stimulation was presented dichotically at a supra threshold intensity of 50dB HL, as determined by the preliminary study
- The bioelectric activity was amplified with a gain of 100 000 and analogue filtered between 30 and 300 Hz
- The notch filter was switched on at 50 Hz to avoid any line interference
- No less than 10, and no more than 40 epochs of 8 192 samples (digitised with a sampling period of 1.37ms) each, were averaged in a response

- A Fast Fourier Transform (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 for significant amplitude difference
- Artefact rejection was carried out with shorter epoch sections of 512 points
- A rejection level of 50 micro Volts was specified to reject any responses with amplitudes greater than the specified value
- Threshold was established in descending intensity steps of 10dB until no response was present. A no-response, however, could only be determined after 40 epochs had been collected and averaged. The minimum response level (or the lowest obtained response) for each frequency in each ear was taken as the threshold
- The software recorded the test data, and the time the procedure started and ended, allowing for exact measurement of the time taken for each subject

### 3.7.5 Data Collection using the Auditory Brainstem Response Protocol

The specifications for the stimulus parameters and the recording procedure for the click and tone burst ABR are described in the following section.

#### 3.7.5.1 Specification of Stimulus Parameters for the Click Evoked Auditory Brainstem Response

The stimulus parameters used in determining ABR thresholds with click stimuli, are summarized in table 3.3

**Table 3.3 Click ABR stimulus parameters**

| | |
|---|---|
| **Synchronism** | Internal (no external sound generators were used) |
| **Stimulus** | Click |
| **Periodic stimulus rate** | 21.0 Hz (to avoid repetition rates that are multiples of 50Hz that could introduce power-line artefact into the response (Hood, 1998)) |
| **Study side** | Left or Right |
| **Polarity** | Positive (According to Hood (1998) any polarity can be used) |
| **Duration of click** | 0.10 msec |
| **Intensity Scale** | dB nHL |
| **Output** | Monotic |
| **Intensity** | Starting intensity of 60 dB nHL |

### 3.7.5.2 Click Evoked Auditory Brainstem Response Recording Procedure

- ABR recordings were performed directly after the MF ASSR procedure
- Electrode discs of Ag/AgCl were fixed with electrolytic paste to the scalp at Cz, mastoid ipsilateral (Mip), and mastoid contralateral (Mc). Mip & Mc were switched between reference and ground depending on the test side because it was a single channel recording
- Impedance values were kept below 3 000 Ohms
- Supra-aural TDH-39 earphones were placed on the ears of the subjects
- Subjects were asked to lie on a bed in a single wall soundproof booth and were encouraged to sleep or relax

- Stimulation was presented monotically at a supra threshold intensity of 60 dB nHL starting with the left ear.
- The bioelectric activity was amplified with a gain of 100 000 and analogue filtered between 10 and 3 000 Hz
- A maximum of 2 000 recordings were averaged for each intensity although less averages were often adequate because of the low levels of ambient noise in the soundproof booth
- A recording window of 0 – 15 ms was implemented for recordings (Hood, 1998; Bachmann & Hall, 1998)
- A noise level rejection level of 10 was used
- Threshold was established in descending intensity steps of 10dB until no response was present. The minimum response level for each frequency in each ear was taken as the threshold
- The left ear was evaluated first, followed by the right ear
- The software recorded the test data, and the time the procedure started and ended, allowing for exact measurement of the time taken for each subject

### 3.7.5.3 Specification of Stimulus Parameters for the 0.5 kHz Tone Burst Auditory Brainstem Response

The stimulus parameters used in determining ABR thresholds with 0.5 kHz tone burst stimuli are summarized in table 3.4

**Table 3.4 0.5 kHz tone burst stimulus parameters**

| | |
|---|---|
| **Synchronism** | Internal (no external sound generators were used) |
| **Stimulus** | Tone burst |
| **Periodic stimulus rate** | 21.0 Hz (to avoid repetition rates that are multiples of 50Hz that could introduce power-line artefact into the response. (Hood, 1998)) |
| **Study side** | Left or Right |
| **Frequency** | 0.5 kHz |
| **Duration** | 6 msec |
| **Rise/ Fall** | 2.00 msec |
| **Plateau** | 2 ms |
| **Envelope** | Blackman (Hood, 1998; Bachmann & Hall) |
| **Polarity** | Negative (According to Hood 1998, any polarity except alternating polarities) |
| **Intensity Scale** | dB nHL |
| **Output** | Monotic |
| **Intensity** | Starting intensity of 60 dB SL |

#### 3.7.5.4 0.5 kHz Tone Burst Auditory Brainstem Response Stimulus Recording Procedure

- ABR recordings were performed directly after the MF ASSR procedure
- Electrode discs of Ag/AgCl were fixed with electrolytic paste to the scalp at Cz (positive), mastoid ipsilateral (Mip), and mastoid contralateral (Mc). Mip & Mc was switched between reference and ground depending on the test side, because it was a single channel recording

- Impedance values were kept below 3 000 Ohms
- Supra-aural TDH-39 earphones were placed on the ears of the subjects
- Subjects were asked to lie on a bed in a single wall soundproof booth and were encouraged to sleep or relax
- Stimulation was presented monotically at a supra threshold intensity of 60dB SL (Sensation Level), starting with the left ear.
- The bioelectric activity was amplified with a gain of 100 000 and analogue filtered between 10 and 3 000 Hz
- The notch filter was switched on at 50 Hz to cut-out the line-interference
- A maximum of 1 024 recordings were averaged for each intensity although less averages were often adequate because of the low levels of ambient noise in the sound proof booth
- A recording window of 0 – 20 ms was implemented for recordings (Hood, 1998; Bachmann & Hall, 1998)
- A noise level rejection level of 10 was used
- Threshold was established in descending intensity steps of 10 dB until no response was present. The minimum response level for each frequency in each ear was taken as the threshold
- The left ear was evaluated first, followed by the right ear
- The software recorded the test data, and the time the procedure started and ended, allowing for exact measurement of the time taken for each subject

## 3.8 Data Preparation Procedures

The raw quantitative data was prepared and organized into a data set suitable for analysis (Neuman, 1997). The following preparatory procedures were performed.

### 3.8.1 Hearing Sensitivity Threshold Estimation

The PT BT served as the gold standard reference for hearing sensitivity against which the dichotic MF ASSR and ABR protocol were compared. In order to compare the data threshold levels of the different procedures, a consistent arbitrary measure of hearing for all procedures was required. For the purpose of this study, decibel (dB) hearing level (HL) was used as the measure of threshold. The lowest sound intensity that stimulates normal hearing at the different frequencies represents zero hearing level (HL) (Stach, 1998).

The ABR stimuli were, however, calibrated in dB nHL, for a group of normal hearing listeners. According to Gorga et al. (1993) it is important to ensure that ABR thresholds measured in dB nHL are comparable to behavioural thresholds measured in dB HL. The deviation between the 0.5 kHz tone burst at 0 dB nHL was not significantly different to the 0 dB HL standard for a 0.5 kHz pure tone behavioural thresholds as specified by ANSI (S3.6-1996). Therefore, the 0.5 kHz tone burst ABR in dB nHL and pure tone behavioural thresholds in dB HL for this study, are comparable without any significant deviation. The 0 dB nHL for the click stimulus was compared to the pure tone behavioural threshold standard of 0 dB HL specified by ANSI (S3.6-1996) at 1, 2, and 4 kHz. No significant deviation between the 0 dB nHL for click stimuli and the 0 dB HL at 1, 2, and 4 kHz for pure tone stimuli was evident. Because there was no significant difference between the dB nHL intensity scale for the ABR stimuli and the dB HL intensity scale of PT and MF ASSR stimuli, thresholds will be compared in dB HL.

The interpretation of the ABR waveforms to establish a threshold was performed after data for all subjects were recorded. A panel of three clinicians, familiar with the interpretation of ABR waves with click and tone burst stimuli, determined the thresholds for each ABR procedure for every subject. Three clinicians were used to provide an increased level of reliability.

Consensus between two clinicians represented a positive criterion. Having obtained a value representing ABR thresholds, these values were presented in dB HL because there was no significant difference between the dB nHL and dB HL of PT BT and the ABR stimuli used. Thus the final ABR threshold levels were entered into the Microsoft Excel (1998) Worksheet along with the PT and dichotic MF ASSR thresholds.

### 3.8.2 Recording Time

The recording time required by the dichotic MF ASSR and ABR protocol are measured variables of this study that are significant to the experimental comparison and were therefore, measured.

The software recorded the time taken to record dichotic MF ASSR thresholds in both ears at the various frequencies for each subject. The recorded time represents the actual time required to record dichotic MF ASSR thresholds, not including preparation time. The time required for each subject was represented in minutes and entered into a Microsoft Excel (1998) Worksheet.

The time required to complete the ABR protocol involved two measurements for each subject. The first recording time measured was for the click ABR in both ears. The second measured recording time was for the 0.5 kHz tone burst ABR in both ears. The software recorded the time required for each procedure. To obtain the recording time required to record the entire ABR protocol, it was necessary to add the recording time of the click ABR and the 0.5 kHz tone burst ABR. The recorded time represents the actual time required to record the ABR protocol, not including preparation time. The time required for each subject was represented in minutes and entered into a Microsoft Excel (1998) Worksheet.

## 3.9 Data Analysis Procedures

The prepared data organized on Microsoft Excel (1998) Worksheets were analysed with statistical measures. According to Neuman (1997), data analysis means to search for patterns in data. This involves examining, sorting, categorizing, evaluating, comparing, synthesizing, contemplating and reviewing the data (Neuman, 1997). The following procedures were successively pursued to process and analyse the data:

- The mean and standard deviation for every threshold obtained with PTA, the dichotic MF ASSR, and the ABR protocol was calculated;
- The mean difference and standard deviation between comparable thresholds of the 3 techniques were calculated;
- The average recording time required to acquire thresholds with the dichotic MF ASSR and the ABR protocol was calculated as a mean and standard deviation value.

## 3.10 Summary

This chapter provided a thorough description of the procedures implemented in the research methodology to acquire the data according to the sub-aims, in order to address the main aim of the study. The need for clinical validation of the dichotic MF ASSR technique used for the estimation of PT BTs, compared to an existing objective audiometric ABR protocol for normal hearing subjects, was the driving force behind this project. The experimental design was described, followed by the selection criteria and description of subjects used in this study. The apparatus used for the selection of subjects, the collection of data and analysis thereof was discussed subsequently, followed by the data collection procedures pursued by the three audiometric techniques. The chapter was concluded by an overview of the data preparation and analysis procedures implemented.

# Chapter 4

# Results and Discussion

**Aim:** To present the results of the empirical research and to elucidate the meaning and significance thereof

## 4.1 Introduction

The methodological approach specified in Chapter 3 has provided the operational framework for extracting the necessary data for addressing the main aim of this study. The statistical analysis of the data allows for arrangement and grouping of relevant information. This provides a body of knowledge from which inferences can be drawn, and relationships between variables indicated, in order to make accurate predictions and provide comparable results (Smit, 1983). According to Neuman (1997), comparison is the key to all research. The meaning and significance of results depend upon appropriate interpretation, relevant conclusions, and generalizations based on the analysed data (Smit, 1983).

Analysed results for the current study are therefore grouped, reported, interpreted, and subsequently discussed in relation to relevant and comparable literature. The main aim of this study, evaluating the usefulness of the dichotic MF ASSR technique compared to an ABR protocol, was addressed through the realisation of two closely related sub-aims. This process is represented in Figure 4.1.

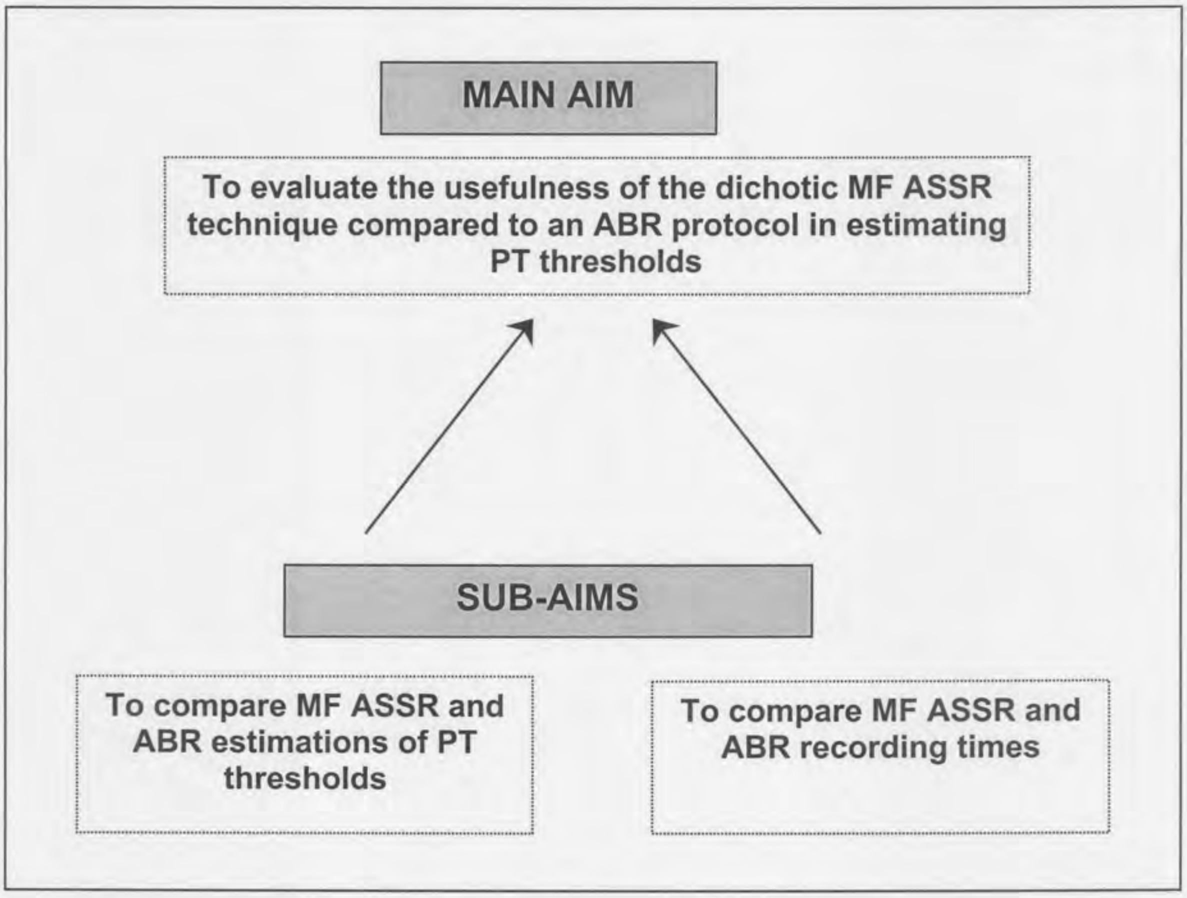


**Figure 4.1 Research basis: Main aim and sub-aims of study**

The first sub-aim endeavoured to determine and compare auditory thresholds obtained with PT audiometry, an ABR protocol, and the dichotic MF ASSR technique. PT thresholds serve as the gold standard for representing hearing sensitivity thresholds, against which the ABR and MF ASSR thresholds were compared. According to Gorga (1999), these objective audiometric procedures must provide information regarding the **degree** and **configuration** of a hearing-loss. The second sub-aim purposed to determine the recording time required for obtaining PT threshold estimations with the ABR protocol and the dichotic MF ASSR. According to Bachmann & Hall (1998), objective audiometry, specifically for the paediatric population, must provide sufficient information regarding an individual's hearing status in as short a time as possible. Thus the second sub-aim will compare how **time-efficient** each of these procedures were in estimating the PT thresholds. This represents the data obtained by the first sub-aim.

The first sub-aim will be approached by reporting the thresholds obtained with each procedure, followed by a discussion thereof, and the integration of relevant literature. This information will precede the comparison and discussion of the difference between PT and ABR, as well as PT and dichotic MF ASSR thresholds, to determine how closely these two techniques can estimate PT thresholds. The results of the second sub-aim will follow the results and discussion of the first sub-aim. The results will then be discussed and compared to reports in the literature. Finally, the results of both sub-aims will be summarized and discussed in the conclusion of this chapter.

**The purpose of this chapter, therefore, is to present the results of this study according to the two sub-aims, in order to address the main aim of the study. The results are presented and discussed by integrating the current body of knowledge, and extracting the significance of results obtained. The results for each sub-aim will be presented, followed by an interpretation and discussion of results alongside current literature. In the final section of this chapter, general conclusions from the study are drawn and the main research question is answered.**

The results and discussion of each sub-aim follow.

## 4.2 Multiple Frequency Auditory Steady State Response Estimations of Pure Tone Behavioural Thresholds at 0.5, 1, 2, and 4kHz Compared to a 0.5 kHz Tone Burst and Broadband Click Auditory Brainstem Response Protocol

This sub-aim will report and discuss two related groups of data pertaining to its focus. The first results to be reported and discussed are the thresholds obtained with PT audiometry, the ABR protocol and the dichotic MF ASSR. Comparing the thresholds obtained with the ABR protocol and the MF ASSR protocol will conclude this group of results. Following this, the threshold differences between the dichotic MF ASSR and PT thresholds, as well as between the ABR protocol and PT thresholds, will be presented and discussed. Comparing the dichotic MF ASSR and ABR estimations of PT thresholds will conclude this sub-aim.

### 4.2.1 Pure Tone, Multiple Frequency Auditory Steady State Response, and Auditory Brainstem Response, Thresholds

The mean audiogram obtained from the three procedures is presented in figure 4.2, and the actual threshold intensities and standard deviations are provided in table 4.1.

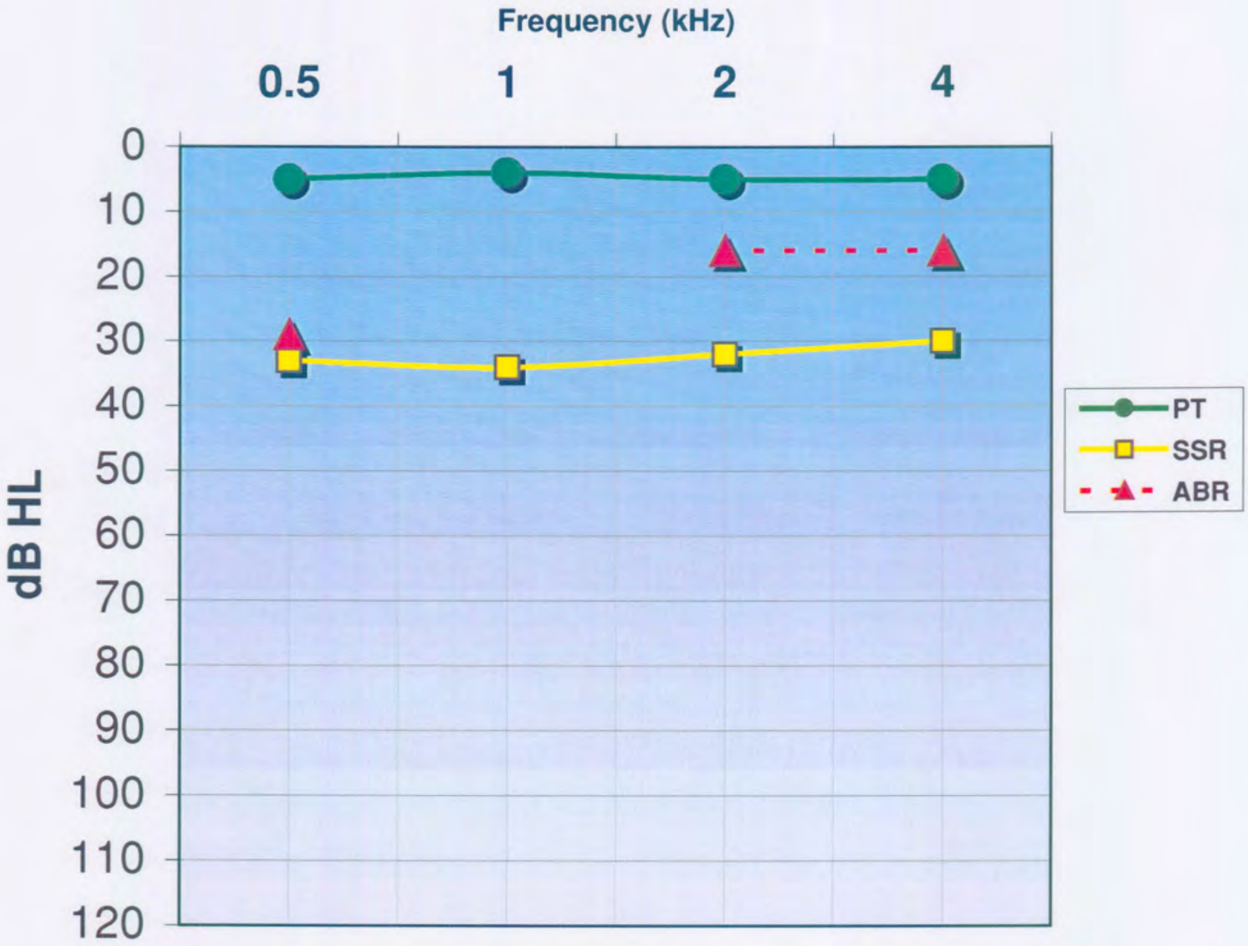


**Figure 4.2 Mean audiogram representing PT, dichotic MF ASSR, and ABR thresholds (n=56)**

**Table 4.1 Mean and standard deviation values for PT BT, MF ASSR, and ABR thresholds (Mean ± SD)**

| Frequency (kHz) | PT BT (dB HL) | MF ASSR (dB HL) | ABR protocol (dB nHL) |
|---|---|---|---|
| **0.5** | 5 ± 5 | 33 ± 11 | 29 ± 16 |
| **1** | 4 ± 6 | 34 ± 11 | 16 ± 7 |
| **2** | 5 ± 5 | 32 ± 11 | |
| **4** | 5 ± 6 | 30 ± 11 | |

The thresholds for each of these three procedures will be discussed separately in the following sections.

#### 4.2.1.1 Pure Tone Behavioural Thresholds

The PT BTs closely approximated 0 dB HL. The 0 dB HL represents the 'perfect' normal hearing sensitivity standard (Roeser, Buckley, & Stickney, 2001). Mean thresholds across the test frequencies were between 5 - 6 dB HL. Although a normal hearing level cut-off of 25 dB HL across all frequencies was used to select subjects, most subjects presented threshold levels close to, or at the 0 dB HL. A large percentage of PT thresholds (75%) were equal to, or less than 5 dB HL. This percentage grows to 88% if all PT BT equal to, or less than 10 dB HL, is included. Thus, the overwhelming majority of ears had PT BT less than 10, and even 5 dB HL. The standard deviation of the mean PT BT across the different frequencies was consistent, only varying between 5 – 6 dB. According to Haughton (1980), PT BT measurements generally demonstrate a small standard deviation of 6 dB across frequencies indicative of a reliable hearing assessment instrument.

#### 4.2.1.2 Dichotic Multiple Frequency Auditory Steady State Response Thresholds

The mean dichotic MF ASSR thresholds were distributed between 30 – 34 dB HL (40 – 44 dB SPL). The majority, 61.6%, of MF ASSR thresholds were equal to or less than 30 dB HL whilst only 25.9% were less than, or equal to 20 dB HL. Of the MF ASSR thresholds at 20 dB HL, 80.8% represented PT BT between 0 – 5 dB HL, and of the MF ASSR thresholds at 30 dB HL, 76.2% represented PT BT between 0 – 5 dB HL. The percentage of MF ASSR thresholds across frequencies at various intensities is represented in table 4.2.

**Table 4.2 Percentage dichotic MF ASSR thresholds present at different intensities**

| Frequency (kHz) | Intensities | | | | |
|---|---|---|---|---|---|
| | 10 dB HL | 20 dB HL | 30 dB HL | 40 dB HL | 50+ dB HL |
| **0.5** | 5.4 % | 19.6 % | 30.4 % | 33.9 % | 10.7 % |
| **1** | 3.6 % | 17.9 % | 32.1 % | 25 % | 21.4 % |
| **2** | 1.8 % | 28.6 % | 35.7 % | 17.9 % | 16.1 % |
| **4** | 8.9 % | 17.9 % | 44.6 % | 17.9 % | 10.7 % |

The mean MF ASSR thresholds demonstrated a consistent standard deviation of ± 11 dB. This denotes the range of normal deviation from the mean for MF ASSR thresholds to be between 19 – 45 dB HL. The range of normal deviation for each MF ASSR frequency is represented in figure 4.3.

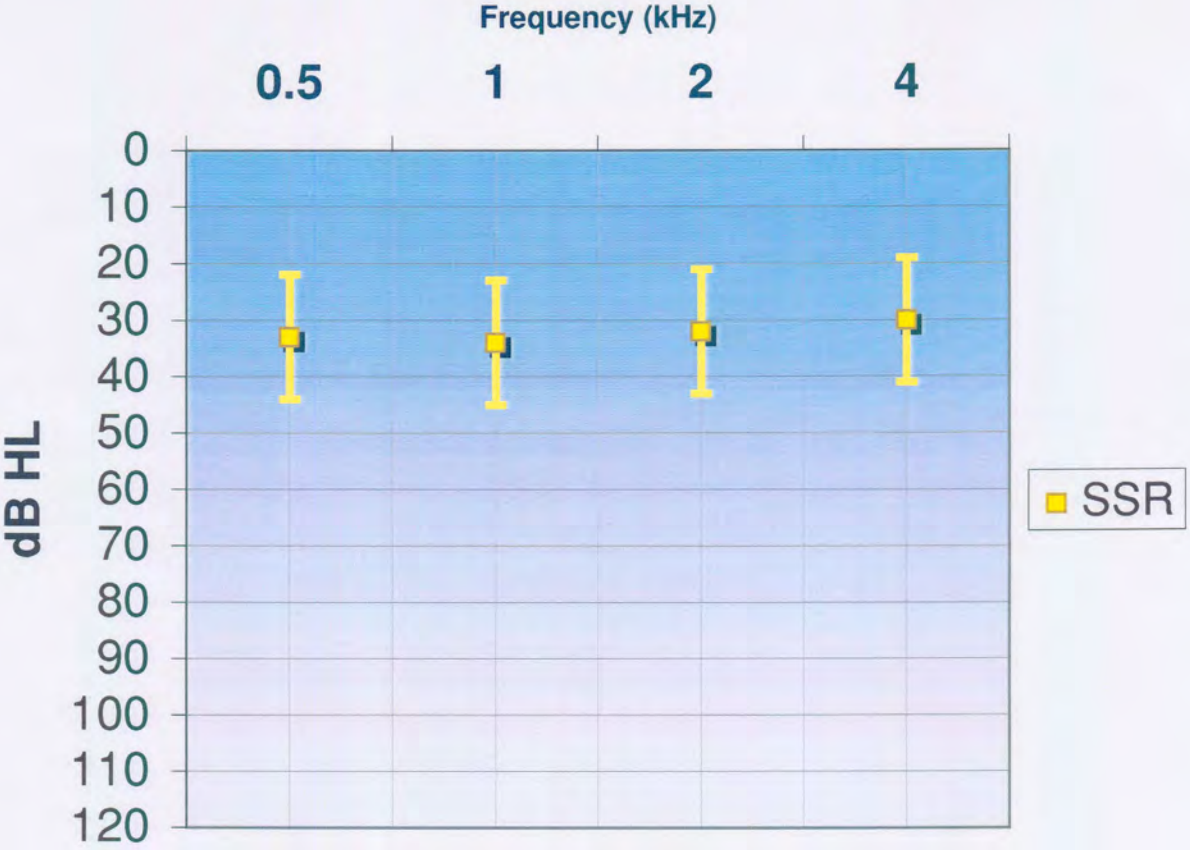


**Figure 4.3 Mean dichotic MF ASSR thresholds and the standard deviation of each**[1]

The ASSR thresholds obtained in the current study are generally higher than, or equal to the ASSR thresholds previously reported in the literature (Aoyagi et al., 1994; Lins et al., 1995; Picton et al., 1998; Perez-Abalo et al., 2001; Herdman & Stapells, 2001). Mean ASSR thresholds for the current study ranged between 30 – 34 dB HL for the carrier frequencies between 0.5 – 4 kHz. Aoyagi et al. (1994), reported ASSR thresholds for normal hearing adults of 29 dB HL for single stimuli with a carrier frequency of 1kHz amplitude-modulated at 80 Hz. Using the multiple stimulus technique to obtained thresholds for four stimuli (two in each ear) in normal hearing subjects, Lins & Picton (1995), reported mean thresholds of 31 dB HL for 0.5 kHz and 25 dB HL for 2 kHz. In a subsequent study by Picton et al. (1998), ASSRs were measured for normal hearing subjects using the multiple stimulus technique

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[1] Mean thresholds are plotted for 0.5, 1, 2, and 4 kHz with the standard deviation of each. The SD is represented as a range up and down from the threshold, and the threshold is indicated with the range ± the SD

with four stimuli presented simultaneously to one ear. The mean ASSR thresholds obtained at 0.5, 1, 2, and 4 kHz were approximately 20, 29, 19, and 17 dB HL (converted from dB SPL) respectively.

ASSR thresholds for the current study were obtained using the dichotic amplitude-modulated MF (four frequencies in each ear) technique and will therefore, primarily, be compared to thresholds reported using the same technique. Until now, ASSR thresholds using the dichotic amplitude-modulated MF (four frequencies in each ear) technique has only been reported by Herdman & Stapells (2001), and Perez-Abalo et al. (2001). Mean thresholds and standard deviations reported by these studies are contrasted with those obtained in the current study, in table 4.3. The threshold data for the current study is converted to dB SPL according to the ANSI (1996) standards in order to compare results.

**Table 4.3. Dichotic MF (four frequencies in each ear) ASSR thresholds and standard deviations reported in dB SPL (Mean ± SD)**

| Frequency (kHz) | Herdman & Stapells (2001) | Perez-Abalo et al., (2001) | Current study (2001) |
|---|---|---|---|
| **0.5** | 25 ± 9 | 41 ± 11 | 44 ± 11 |
| **1** | 17 ± 8 | 34 ± 9 | 41 ± 11 |
| **2** | 15 ± 7 | 33 ± 10 | 41 ± 11 |
| **4** | 22 ± 9 | 36 ± 11 | 40 ± 11 |

Herdman and Stapells (2001), reported mean MF ASSR thresholds for 10 normal hearing subjects between 15 - 25 dB SPL across 0.5 – 4 kHz frequencies. These thresholds are 10 dB lower (better) than those reported by Lins & Picton (1995), for simultaneous presentation of two amplitude-modulated tones to both ears. The authors suggest that this improvement of threshold sensitivity can probably be attributed to the lower ambient acoustic noise levels in the test environment of the study by Herdman & Stapells (2001). Perez-Abalo et al. (2001), reported MF ASSR thresholds for 40 normal hearing subjects across 0.5 – 4 kHz between 32 – 42 dB SPL. These thresholds are higher than those reported by Herdman & Stapells (2001), and are most probably due to higher levels of acoustic ambient noise in the test environment. The current study also presented with higher mean thresholds ranging between 40 – 44 dB SPL across the frequencies of 0.5 – 4 kHz.

The range of normal deviation from the mean averages for thresholds in each study is fairly consistent. The standard deviations vary between ± 7 dB to ± 9 dB (Herdman & Stapells, 2001), ± 9 dB to ± 11 dB (Perez-Abalo et al., 2001), and ± 11 dB for the current study. The slightly smaller range of normal deviation reported by Herdman & Stapells (2001), is most probably due to the same reason that thresholds for that study was lower than other studies, namely, the lower levels of acoustic ambient noise.

When comparing different studies, a significant observation from the mean dichotic MF ASSR thresholds evident in Table 4.3, however, is that thresholds at 0.5 kHz are the highest thresholds for all three studies. Similar findings were reported by other researchers using single or multiple frequency stimuli (Aoyagi et al., 1994; Lins et al. 1996; Rance et al. 1995). Lins et al. (1996), proposed three possible explanations for this phenomenon. Firstly, it could partly be due to the enhanced masking effect of the 0.5 kHz steady state stimuli by ambient noise at lower frequencies. Ambient noise is often concentrated at the lower frequencies (Frank, 2000), and therefore this provides a possible explanation. The second possible explanation proposed is, that higher frequencies within the MF stimuli could suppress or mask the 0.5 kHz stimuli. This explanation, however, has not been widely accepted because studies using single frequency stimuli have reported similar difficulties (Aoyagi et al. 1994; Valdes et al. 1997). The third explanation claims that the problems in the estimation of the 0.5 kHz ASSR could reflect the characteristics of the responses themselves. The low-frequency response has a greater intrinsic jitter due to neural asynchrony, which could cause the relative difficulty of threshold detection. Further studies, however, must investigate these possibilities.

Different levels of ambient acoustic noise in the test environments of the different studies, and differing mean behavioural thresholds for subjects in each study, prompts attention to be focussed on the difference between PT behavioural and ASSR thresholds rather than on the mean ASSR thresholds only. This is discussed in paragraph 4.2.2.1.

#### 4.2.1.3 Auditory Brainstem Response Protocol Thresholds

ABR stimuli were calibrated in dB nHL for a group of normal hearing listeners. According to Gorga et al. (1993), it is important to ensure that ABR thresholds measured in dB nHL are comparable to behavioural thresholds measured in dB HL. The deviation between the 0.5 kHz tone burst at 0 dB nHL was not significantly different to the 0 dB HL standard for 0.5 kHz pure tone behavioural thresholds, as specified by ANSI (S3.6-1996). Therefore, the 0.5 kHz tone burst ABR in dB nHL, and pure tone behavioural thresholds in dB HL for the current study, are comparable without any significant deviation. The 0 dB nHL for the click stimulus was compared to the pure tone behavioural threshold standard of 0 dB HL specified by ANSI (S3.6-1996) at 1, 2, and 4 kHz. There was no significant deviation between the 0 dB nHL for click stimuli, and the 0 dB HL at 1, 2, and 4 kHz for pure tone stimuli. Because there is no significant difference between the dB nHL intensity scale for the ABR stimuli and the dB HL intensity scale of PT and MF ASSR stimuli, thresholds will be compared in dB HL.

The mean 0.5 kHz tone burst and broadband click ABR thresholds differed considerably from each other. The mean 0.5 kHz tone burst ABR threshold was 29 dB nHL. Almost a half, 48.2%, of the thresholds were equal to, or less than 20 dB HL, and 60.7% were equal to, or less than 30 dB nHL. Of the 0.5 kHz tone burst ABR thresholds at 20 dB HL, 66.7% represented PT BT between 0 – 5 dB HL, and of the thresholds at 30 dB HL, 73.4% represented PT BT between 0 – 5 dB HL.

The mean broadband click ABR threshold was 16 dB HL. Of these thresholds 91.1% were equal to, or less than 20 dB HL, and 48.2% were equal to 10 dB HL. The click ABR thresholds at 10 dB HL represented 73.5% of PT BT between 0 – 5 dB HL, and the thresholds at 20 dB HL represented 70.8% of PT BT between 0 – 5 dB HL. Only 8.9% of click ABR thresholds were measured above a 20 dB HL intensity.

The standard deviation for the mean thresholds of the two ABR procedures differed as much as the thresholds themselves. The 0.5 kHz tone burst ABR proved a standard deviation of ± 16 dB. This leads to a wide range of normal deviation between 13 – 45 dB HL. The click ABR evidenced a standard deviation of only ± 7, leading to a smaller range of normal deviation between 9 – 23 dB HL. The mean thresholds and the range of standard deviation for each procedure are illustrated in figure 4.4.

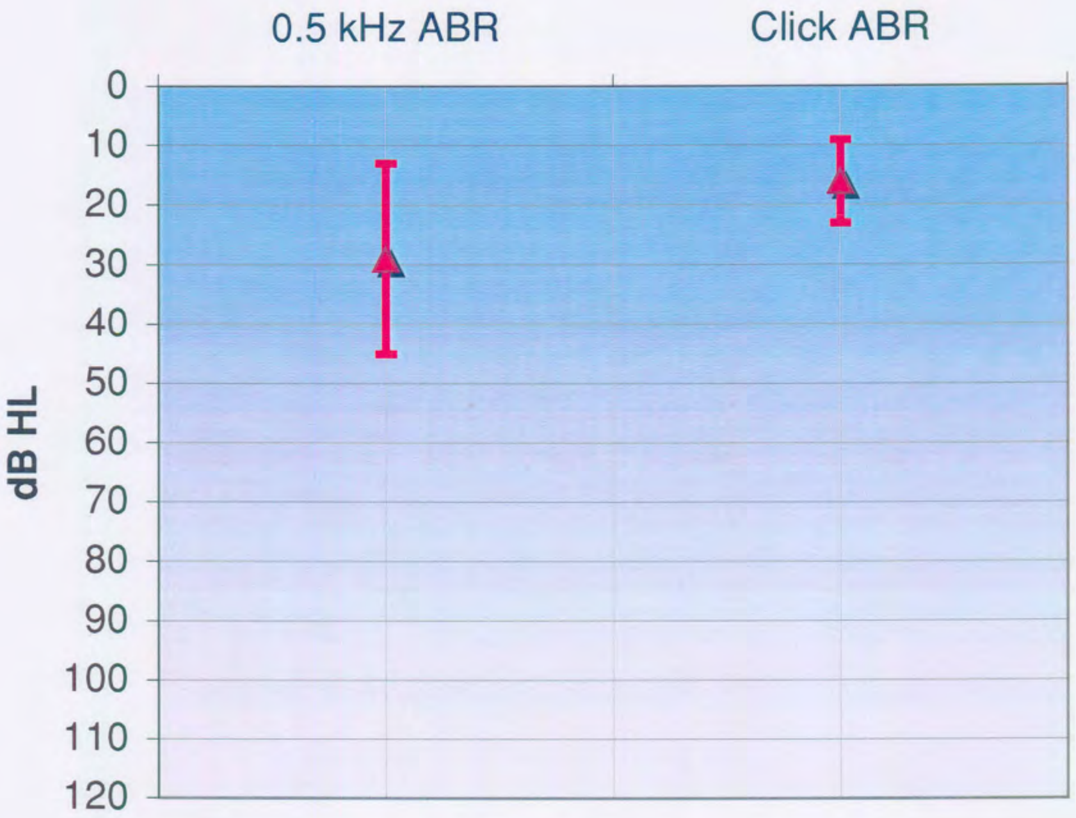

**Figure 4.4 Mean thresholds and standard deviations of the ABR protocol**

The ABR thresholds in the current study fall well within the range of thresholds for normal hearing subjects reported in the literature. The mean 0.5 kHz tone burst thresholds for the current study was 29 dB HL, falling well within the range of 25 – 35 dB above the PT threshold for normal hearing subjects as specified by Hood (1995). The mean click ABR threshold obtained for the current study was 16 dB HL, which is well within the range of 15 – 25 dB nHL reported by Hood (1995), as the average threshold range for normal hearing subjects.

As pointed out before, the accuracy of estimating PT thresholds with objective audiometric techniques depends upon the difference between the response threshold and the behavioural threshold, and will therefore be discussed in more detail in paragraph 4.2.2.1.

### 4.2.1.4 Mean Dichotic Multiple Frequency Auditory Steady State Response Thresholds Compared to Mean Auditory Brainstem Response Thresholds

The mean thresholds of the ABR protocol and the MF ASSR technique are represented in table 4.4

**Table 4.4 Mean dichotic MF ASSR and ABR thresholds (Mean ± SD)**

| Frequency | MF ASSR thresholds (dB HL) | ABR thresholds (dB HL)<br>0.5 kHz tone burst & Click |
|---|---|---|
| 0.5 | 33 ± 11 | 29 ± 16 |
| 1 | 34 ± 11 | 16 ± 7 |
| 2 | 32 ± 11 | |
| 4 | 30 ± 11 | |

The mean 0.5 kHz tone burst ABR threshold was 4 dB lower than the mean 0.5 kHz MF ASSR threshold. This small difference favours the 0.5 kHz tone burst, but becomes less significant when considering the large range of normal deviation, ± 16, with which the 0.5 kHz tone burst presented. The mean click ABR threshold was lower than mean MF ASSR thresholds at 1, 2, and 4 kHz. The mean threshold differences between the click ABR thresholds and PT behavioural thresholds at 1, 2, and 4 kHz dB are 18 (± 12), 16 (± 12), and 15 (± 10) dB, respectively. The click ABR thresholds therefore, correlated most closely with the 4 kHz, followed by the 2 kHz MF ASSR threshold. It is widely accepted that the broadband click stimulus produces a response in the high frequency region between 2 – 4 kHz (Gorga, 1999; Hood, 1998). The fact that the click ABR more closely correlates with MF ASSR thresholds in this region probably indicates that the MF ASSR technique is, on average, reliably estimating frequency-specific thresholds.

The large differences between the thresholds estimated with the two techniques indicate that the click ABR more closely estimated normal hearing. The fact, however, remains that the click ABR does not estimate a PT threshold because it uses a broad band click stimulus, stimulating a large area of the basilar membrane, which produces a response that is not frequency-specific (Oates & Stapells, 1998). As mentioned earlier, the response most probably represents an auditory threshold in the high frequency region between 2 – 4 kHz (Gorga, 1999).

Limited data exists comparing thresholds predicted by ABR protocols to those obtained using the ASSR (Aoyagi et al., 1999; Johnson & Brown, 2001). Johnson & Brown (2001) recently presented preliminary results comparing the correlation of ABR and ASSR thresholds to PT thresholds. The results compare how closely ABR and ASSR thresholds estimate PT thresholds and will be discussed in paragraph 4.2.2.3.

### 4.2.2 Difference Between Objective (ABR & MF ASSR) and Behavioural (PT) Audiometric Thresholds

The PT BT is the gold standard for hearing sensitivity. According to Picton (1991), the main aim of objective audiometry is to estimate PT behavioural thresholds. Thus, the difference between the thresholds obtained with objective procedures and PTA provides an indication of how close a procedure estimates the most familiar measure of hearing sensitivity (Gorga et al. 1993). The difference between MF ASSR and PT thresholds, and between ABR and PT thresholds are therefore a measure of how accurate a technique can estimate hearing sensitivity. The differences are therefore reported and discussed as follows.

### 4.2.2.1 Difference Between Dichotic Multiple Frequency Auditory Steady State Response and Pure Tone Thresholds

The mean difference and normal range of deviation between MF ASSR and PT thresholds are illustrated in figure 4.5.

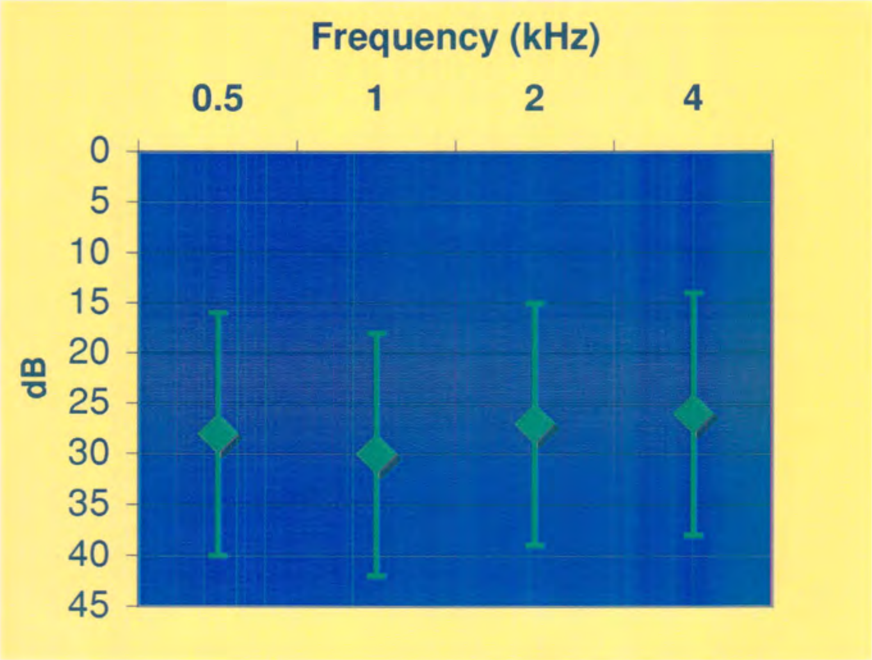

**Figure 4.5 Mean difference and standard deviation between dichotic MF ASSR and PT thresholds (Mean ± SD)**

The mean difference between MF ASSR and PT thresholds vary between 26 – 30 dB across the frequencies of 0.5, 1, 2, and 4 kHz. These difference scores indicate that the MF ASSR thresholds in the current study are, on average, within 26 - 30 dB of PT behavioural thresholds. The standard deviation is consistent across frequencies at ± 12 dB. This provides a reasonably large spread of normal deviation for the average difference values between PT, and MF ASSR thresholds across frequencies ranging between 14 – 42 dB. The difference between the PT behavioural, and MF ASSR thresholds for each frequency is summarized in table 4.5.

**Table 4.5 PT behavioural and MF ASSR thresholds (dB HL) and the difference between these (Mean ± SD)**

| Frequency (kHz) | PT BT | MF ASSR | Difference |
|---|---|---|---|
| **0.5** | 5 ± 5 | 33 ± 11 | 28 ± 12 |
| **1** | 4 ± 6 | 34 ± 11 | 30 ± 12 |
| **2** | 5 ± 5 | 32 ± 11 | 27 ± 12 |
| **4** | 5 ± 6 | 30 ± 11 | 26 ± 12 |

The mean difference between the thresholds can be represented by a normal distribution of these differences. The percentage of threshold differences equal to, or less than 20 dB, 25 dB, 30 dB, and 35 dB, was 36%, 46%, 70%, and 79%, respectively. A breakdown of the percentages for each frequency is set out in table 4.6.

**Table 4.6. Threshold difference (PT – ASSR) percentage at 0.5, 1, 2, and 4 kHz**

| Threshold difference | 0.5 kHz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|
| Less than, or equal to **20 dB** | 34 % | 34 % | 41 % | 36 % |
| Less than, or equal to **25 dB** | 45 % | 41 % | 55 % | 45 % |
| Less than, or equal to **30 dB** | 68 % | 59 % | 75 % | 77 % |
| Less than, or equal to **35 dB** | 82 % | 66 % | 80 % | 86 % |

It is evident from table 4.6 that the high frequencies, 2 and 4 kHz, estimated PT thresholds slightly more accurately than 0.5 and 1 kHz when considering that 75 % and 77 % of MF ASSR thresholds for 2 and 4 kHz were within 30 dB or less of the PT thresholds. This difference, however, is not significant because of the scope of variability evident across frequencies.

A wide range of mean PT and ASSR threshold difference values have been reported in the literature for normal hearing subjects, using the single or multiple frequency technique. These values have ranged from between 8 – 18 dB (Lins & Picton, 1995; Lins et al., 1996), to 28 – 34 dB (Aoyagi et al., 1994). Lins et al. (1995), accounted these differences between reported results to possible inter-subject variability, different recording time periods, and different statistical response detection techniques. The threshold differences in the current study fall within the range of values for normal hearing subjects previously reported in ASSR literature, although in the upper limit of reported values. (Aoyagi et al. 1994; Picton et al. 1998). Aoyagi et al. (1994), reported threshold differences using the single frequency technique varying from 34 dB at 0.25 kHz, 28 dB at 1 kHz, and 30 dB at 4 kHz. These differences range between 28 – 34 dB, being close to the range of differences in the current study of between 26 – 30 dB.

Whilst these differences are at the upper end of reported values, Lins & Picton (1995), and Lins et al. (1996), reported threshold difference values ranging between 8 – 18 dB. More recently however, Picton et al. (1998), found larger threshold differences for normal hearing subjects between 18 – 26 dB across the frequencies 0.5 – 4 kHz. Picton et al. (1998), commented on the relatively small differences between the behavioural and ASSR thresholds obtained in previous studies, such as Lins & Picton (1995), and Lins et al. (1996), stating that it was probably due to the fact that subjects were studied without significant sound attenuation. They underscored the fact that in these previous studies the presence of low-level background masking could have elevated the behavioural thresholds without significantly affecting the ASSR thresholds.

The ASSR thresholds in the current study were determined using the dichotic MF ASSR (using four stimuli per ear) technique on normal hearing subjects and will therefore, primarily, be compared to the current literature reporting results using the same technique. Lins & Picton (1995), and Lins et al. (1996), reported ASSR threshold differences, ranging between 11 – 18 dB, when using the MF dichotic (two stimuli per ear) and monotic (four stimuli per ear) ASSR techniques. It was these studies and initial reports that prompted studies of the dichotic MF ASSR technique using four stimuli per ear. Thus, the current study will primarily be contrasted and compared to the reports by Herdman & Stapells (2001), as well as Perez-Abalo et al. (2001). Both these groups reported results using the dichotic MF (four frequencies per ear) ASSR technique on normal hearing subjects.

The behavioural and MF ASSR threshold differences reported for the current study, are compared to those reported by Herdman & Stapells (2001), and Perez-Abalo et al. (2001) in table 4.7.

**Table 4.7. Mean PT behavioural and dichotic MF (four frequencies in each ear) ASSR threshold differences and standard deviations reported (dB)**

| Frequency (kHz) | Herdman & Stapells (2001) | Perez-Abalo et al., (2001) | Current study (2001) |
|---|---|---|---|
| **0.5** | 14 ± 10 | 12 ± 11 | 28 ± 12 |
| **1** | 8 ± 7 | 13 ± 10 | 30 ± 12 |
| **2** | 8 ± 9 | 10 ± 11 | 27 ± 12 |
| **4** | 15 ± 9 | 12 ± 10 | 26 ± 12 |

The threshold differences reported by Herdman & Stapells (2001), are very similar to those reported by Perez-Abalo et al. (2001). There is, however, a significant difference between the values reported in those studies and the threshold differences reported in the current study. The difference between the values reported by Herdman & Stapells (2001), and the current study, varies on average between 11 – 22 dB, whilst those of Perez-Abalo et al. (2001) varies on average between 14 –17 dB.

80% of thresholds obtained by Herdman & Stapells (2001), and Perez-Abalo et al. (2001), estimated behavioural thresholds within 20 dB or less, whilst only 36% of MF ASSR thresholds in the current study estimated behavioural thresholds within 20 dB or less. 79% of MF ASSR thresholds for the current study estimated behavioural thresholds within 35 dB or less.

These differences are significant and require further investigation to evaluate possible influences and explanations. It was therefore decided to evaluate each of the reported studies in order to contrast and compare them to the current study in terms of methodological context so as to ascertain the possible influences on results. The prominent differences in methodology discussed are summarized in table 4.8.

**Table 4.8 Methodological differences between the current study, Herdman & Stapells 2001 and Perez-Abalo et al. 2001**

| Dichotic MF ASSR studies (4 frequencies/ear) | Threshold seeking procedure | Stimulus for behavioural audiometry | Acoustical test environment | Averaging procedure |
|---|---|---|---|---|
| **Herdman & Stapells (2001)** | 10 dB steps down and 5 dB steps up | Amplitude-modulated tones | Double-walled, sound-attenuated booth | 12 – 48 sweeps of 16.38 s |
| **Perez-Abalo et al. (2001)** | 10 dB steps down | Pure tones | Sound treated room | 16 – 24 sweeps of 11.14 s |
| **Current study** | 10 dB steps down | Pure tones | *Behavioural thresholds:* single wall, sound-attenuated booth. *ASSR thresholds:* double-walled, sound-attenuated booth | 10 – 40 sweeps of 11.14 s |

The first obvious difference in methodology is evident in the threshold seeking procedure utilized by Perez-Abalo et al. (2001), the current study, and Herdman & Stapells (2001). Perez-Abalo et al. (2001), and the current study used a threshold seeking procedure only sensitive to intensity steps of 10 dB, in contrast to a threshold seeking procedure sensitive up to 5 dB intensity steps used by Herdman & Stapells (2001). This discrepancy in threshold determining procedures could account for less than, or equal to 5dB of the behavioural estimation differences obtained in the current study, and those reported by Herdman & Stapells (2001). A 10 dB step threshold seeking procedure, although less sensitive, was selected for the current study to represent widely accepted clinical practice in estimating behavioural thresholds with AER measurements (Hood, 1995).

Another variable that must be taken into account is the stimulus used to determine the behavioural thresholds of each study. PT stimuli were used to determine behavioural thresholds for Perez-Abalo et al. (2001), and the current study. Herdman & Stapells (2001), however, used amplitude-modulated tones to determine behavioural thresholds at the various frequencies. According to Lins et al. (1996), behavioural thresholds with AM tones are usually 5 dB higher than would be expected with pure tones. Thus, the behavioural thresholds reported by Herdman & Stapells (2001), might be approximately 5 dB higher than those obtained with PTs in the study by Perez-Abalo et al. (2001), and the current study. This would cause a decreased difference between ASSR and behavioural thresholds and can therefore, to a certain extent, account for the difference between behavioural threshold estimations reported by Herdman & Stapells (2001), and the current study.

A very important influence affecting results of each study, is the levels of acoustic ambient noise (Picton et al. 1998; Herdman & Stapells, 2001). Different test environments present with different levels of acoustic ambient noise, which in turn affects results in varying degrees. Mühler, Pethe, and von Specht, (2001), recently reported large inter- and intra-subject variability in regard to background noise in ASSR recordings at low levels of stimulation. They emphasised the importance of taking this variability into consideration when estimating hearing thresholds with the ASSR technique.

The behavioural and ASSR thresholds reported by Herdman & Stapells (2001), were recorded in a double-walled, sound-attenuated booth with low levels of acoustic ambient noise between 10 – 12 dB SPL across the octave bands centred at 0.5, 1, 2, and 4 kHz. These low levels of acoustic ambient noise are specified as the most probable reason for the relatively small difference between ASSR and behavioural thresholds.

Perez-Abalo et al. (2001), did not obtain behavioural and ASSR thresholds in a sound-attenuated booth, but in a sound treated room. The acoustic ambient noise levels in this study were higher than permissible (ANSI, 1999), varying between 21 – 40 dB SPL across the octave bands centred on 0.25, 0.5, 1, 2, and 4 kHz. According to Picton et al. (1998), higher levels of acoustic ambient noise can elevate behavioural thresholds without affecting the ASSR thresholds. Thus these higher levels of acoustic ambient noise could reduce the difference between behavioural, and ASSR thresholds. This could contribute to the difference between behavioural threshold estimations with the ASSR reported by Perez-Abalo et al. (2001), and the current study.

In the current study, PT behavioural thresholds were measured in a double-walled, sound-attenuated booth whilst the ASSR recordings were performed in a single-walled, sound-attenuated booth. According to Frank (2000), a double-walled, sound-attenuated booth provides between 20 – 30 dB more attenuation of external ambient noise than a single wall room. The PT thresholds were therefore obtained in an acoustic environment with less ambient noise than the test environment in which the ASSR thresholds were obtained. The PT thresholds are most probably lower than they would have been if determined in the same test environment as the ASSR recordings. This may account for some degree of increased difference between the PT and ASSR thresholds in the current study when compared to the results reported by Herdman & Stapells (2001), and Perez-Abalo et al. (2001).

An aspect that deserves attention is the difference in averaging procedures used by the various studies. Table 4.8 indicated the averaging procedures used in the current study compared to those used by Herdman & Stapells (2001), as well as Perez-Abalo et al. (2001). The time taken to complete one EEG sweep for the current study and that of Perez-Abalo et al. (2001), was 11.14 s. Herdman & Stapells (2001), took slightly longer at 16.38 s per single sweep. The number of sweeps required to identify a significant response varied between a minimum and maximum number of sweeps, with higher numbers of sweeps usually required for low intensity signals. A no-response could only be determined after the maximum number of sweeps were averaged.

Herdman & Stapells (2001), had the highest maximum value of sweeps along with the longest duration for a single sweep. This infers that more data was averaged in determining whether a response was present or not, when compared to the other studies. According to Picton et al. (1998), longer periods of averaging might show responses closer to behavioural thresholds as is the case in prolonged averaging of the ABR. Thus the results reported by Herdman & Stapells (2001), might present with reduced differences between behavioural and ASSR thresholds when compared to the current study, because of longer duration sweeps and the higher quantity of averaged sweeps. These differences are reflected in the average time taken to complete an ASSR recording as reported by these three studies. The average recording time reported by Herdman and Stapells (2001), is almost three times longer than those reported by Perez-Abalo et al. (2001), and the current study. This aspect of average recording times will be discussed more extensively in paragraph 4.3.

#### 4.2.2.2 Difference Between Auditory Brainstem Response and Pure Tone Thresholds

The mean difference between ABR and PT thresholds was determined by comparing the 0.5 kHz tone burst ABR threshold with the 0.5 kHz PT threshold, and the broadband click ABR threshold with PT thresholds at 1, 2, and 4 kHz. Figure 4.6 illustrates the mean differences and the normal range of deviation at the various frequencies.

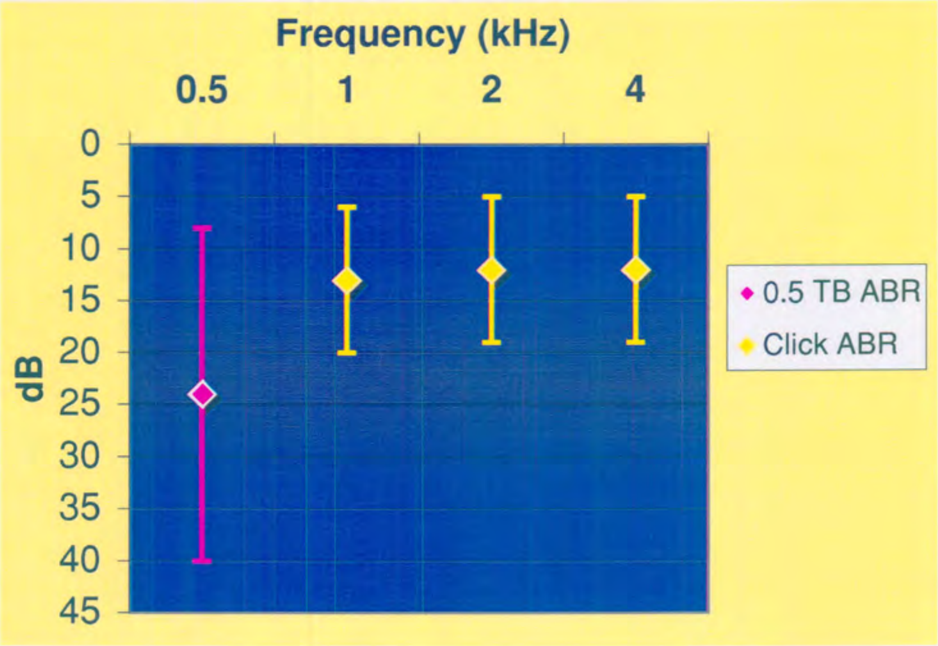

**Figure 4.6 Mean difference and standard deviation between ABR and PT thresholds (Mean ± SD)**

The mean difference between the 0.5 kHz tone burst is 24 dB with a large standard deviation of ± 16.5 dB. This implies a large range of normal deviation for the difference between 0.5 kHz tone burst ABR, and PT thresholds of 8 – 40 dB.

The mean difference between the click ABR threshold and PT thresholds at 1, 2, and 4 kHz, was between 12 – 13 dB with a consistent standard deviation across the PT frequencies of ± 7 dB. Thus the range of normal deviation for the difference between the click ABR, and higher frequency (1, 2, and 4 kHz) PT thresholds, are between 5 – 20 dB.

These mean threshold differences can be represented by a normal distribution of differences. The percentages of threshold differences between the 0.5 kHz tone burst and 0.5 kHz PT being equal to or less than 20, 25, 30, and 35 dB, was 52%, 59%, 66%, and 75%, respectively. The percentage threshold differences between the click ABR threshold and the 1, 2, and 4 kHz PT thresholds were not significantly different from each other. On average, the click ABR estimated 61%, 73%, and 95% of PT behavioural thresholds within 10, 15, and 20 dB or less, respectively.

The difference between behavioural and ABR thresholds reported in the current study are within the broad range of normality, as specified in the literature. The 0.5 kHz tone burst ABR presented with an average threshold difference of 24 dB. This is well within the range of 20 – 30 dB specified by Hall (1992), and in the upper limit of 10 – 25 dB specified by Hood (1998). The large standard deviation (± 16.5) of the mean 0.5 kHz tone burst ABR estimation of the 0.5 kHz PT threshold, indicates a large range of variability. Aoyagi et al. (1996), mentions the fact that the reliability of the low frequency, and specifically the 0.5 kHz tone burst ABR, is not high enough for accurate predictions of pure tone thresholds. This variability is an important rationale, along with the increased frequency spread evidenced by low frequency tone bursts (Arnold, 2000), for the use of middle latency or late latency responses to ascertain low frequency threshold information (Hood, 1998) instead of tone bursts.

The click ABR behavioural threshold estimation, compared to behavioural PT thresholds at 1, 2, and 4 kHz (12 – 13 dB) was well within reported ranges for normal hearing subjects. Hood (1998) reported an average range of agreement between click ABR thresholds and behavioural thresholds of 6 – 20 dB whilst Bachmann & Hall (1998), reported similar ranges for normal hearing subjects of between 5 – 15 dB. The relatively small standard deviation (±7) of the threshold difference between the click ABR and PT thresholds at 1, 2, and 4 kHz is indicative of a reliable measure of auditory sensitivity.

Even though the threshold difference between the ABR and behavioural thresholds for the current study fall within the ranges of normality, it is often near the upper limit (Hood, 1998; Bachmann & Hall, 1998). Several methodological differences could account for this, but two prominent considerations must, however, be mentioned. Firstly, prolonged averaging would certainly decrease the ABR thresholds by a few dB (Hall, 1992; Picton et al. 1998). A fixed number of averages, representative of clinical practice, were selected for the current study to ensure results that are directly applicable to the clinical situation.

The second possible methodological difference was mentioned earlier. The current study measured PT behavioural thresholds in a double-walled, sound-attenuated booth whilst ABR and ASSR thresholds were measured in a single wall, sound-attenuated booth. According to Frank (2000) a double-walled, sound-attenuated booth can attenuate between 20 – 30 dB more acoustic ambient noise than a single wall, sound-attenuated booth. If behavioural and ABR thresholds were measured in the same sound-attenuated booth in similar acoustical environments, the threshold differences might have proved less.

#### 4.2.2.3 Comparison of Pure Tone Threshold Estimations with the Multiple Frequency Auditory Steady State Response and Auditory Brainstem Response Protocol

The mean difference of the ABR and MF ASSR thresholds compared to behavioural thresholds are summarized in table 4.9 with the standard deviation of each.

**Table 4.9 Dichotic MF ASSR and ABR mean threshold differences between PT thresholds (Mean ± SD)**

| Frequency (kHz) | Diff between MF ASSR and PT thresholds | Diff between ABR and PT thresholds |
|---|---|---|
| **0.5** | 28 ± 12 | 25 ± 16.5 (0.5 kHz TB) |
| **1** | 30 ± 12 | 13 ± 7 (Click) |
| **2** | 27 ± 12 | 12 ± 7 (Click) |
| **4** | 26 ± 12 | 12 ± 7 (Click) |

Limited data exists comparing the PT threshold estimations with the tone burst ABR and the ASSR (Aoyagi et al. 1999). Recently Johnson & Brown (2001) reported preliminary results, which suggest that, of the two techniques, the ASSR tended to show a stronger correlation with the PT threshold at 0.5 kHz. In the current study, however, the 0.5 kHz tone burst ABR technique presented with a mean PT estimated threshold difference of 3 dB less than the mean PT estimated threshold difference of the 0.5 kHz MF ASSR. This small difference, favouring the tone burst ABR, must however be seen within the range of normal deviation for the PT threshold estimations of each procedure. The 0.5 kHz tone burst ABR PT threshold estimation presented with a large standard deviation of ± 16.5 dB compared to a standard deviation of ± 12 for the 0.5 kHz MF ASSR PT threshold estimation. This large range of normal deviation for the 0.5 kHz tone burst ABR suggests that it provided thresholds with some variability and with less consistency than the 0.5 kHz MF ASSR.

When comparing the results from the current study to those reported by Johnson & Brown (2001), it is important to consider that the results by these authors were obtained from 10 subjects of whom only three had normal hearing. Previous studies have conclusively shown that ASSR estimations of

PT thresholds are more closely correlated in subjects with hearing impairment than in normal hearing subjects (Rickards et al. 1994; Lins et al. 1996; Picton et al. 1998). Because only 3 of the 10 subjects had normal hearing in the study by Johnson & Brown (2001), the ASSR estimation of the 0.5 kHz PT would have been better than for a sample of normal hearing subjects only. Therefore when this study is compared to the current study, improved correlation between the average ASSR and PT thresholds are observed in the results by Johnson & Brown (2001), because of the seven hearing-impaired subjects included in their sample.

On average, the 0.5 kHz tone burst ABR estimated 0.5 kHz PT thresholds 3 dB closer than the MF ASSR, although the larger range of normal deviation by the 0.5 kHz tone burst ABR suggests less consistency in threshold determination than that of the MF ASSR. This degree of variability in estimating PT thresholds with the 0.5 kHz tone burst ABR compared to the 0.5 kHz MF ASSR might, in part, be due to the response detection procedure. The MF ASSR is detected by automatic protocols, leaving less room for subjective variability (Lins et al. 1996). The ABR thresholds, however, are determined by subjective interpretation that could allow a larger degree of variability in response threshold detection than the objective detection of thresholds used for the ASSR.

Although the click ABR does not evaluate a specific frequency but rather the high frequency region between 1 – 4 kHz, and more specifically between 2 – 4 kHz (Bachmann & Hall, 1998; Gorga, 1999), it has been compared to PT thresholds at 1, 2, and 4 kHz in the current study to provide comparable points. The difference between the mean click ABR and MF ASSR PT threshold estimations at 1, 2, and 4 was 17, 15, and 14 dB respectively. The MF ASSR and the click ABR estimations of PT thresholds most closely correlated at 4 kHz and at 2 kHz consistent with the best click ABR estimates of PT thresholds in the same frequency region (Gorga, 1999; Hood, 1998). These results indicate that, on average, the click ABR estimated PT thresholds between 14 – 17 dB better than the MF ASSR at 1, 2, and 4 kHz in the current study.

The range of normal deviation for the click ABR estimation of PT thresholds was consistent at ± 7 dB across the 1, 2, and 4 kHz frequencies, whilst the MF ASSR estimation of PT thresholds revealed a consistent standard deviation across all measured frequencies of ± 12 dB. This indicates a larger range of variation for the MF ASSR estimates of PT thresholds than that of the click ABR.

The click ABR demonstrated a narrower range of normal deviation and closer approximation of 1, 2, and 4 kHz PT thresholds compared to the MF ASSR in the current study. This most probably relates to the nature of the stimulus used for each procedure. The acoustic principle pertains to the relationship between the duration of a stimulus and its frequency content. There is a trade-off between frequency-specificity and neural synchrony (Gorga, 1999). The click ABR is evoked by a broadband click stimulus with an abrupt onset containing energy across many frequencies (Oates & Stapells, 1998). This stimulates a broad region of the cochlear partition all at once activating a large number of neurons simultaneously, resulting in a significant synchronous neural discharge. A continuous or sustained stimulus such as an amplitude-modulated tone, however, only activates a specific region of the cochlear partition resulting in a smaller, though continuous, neural discharge. The more synchronous the neural discharge, the better the resulting response, but the poorer the frequency-specificity (Hood, 1998).

The click ABR represents a larger neural response than the ASSR and is therefore able to produce better, more reliable responses at low levels of stimulation. This most probably accounts for the better correlation between the click ABR estimations of PT thresholds at 1, 2, and 4 kHz, compared to those by the MF ASSR. It must be kept in mind however, that the click ABR is not able to estimate frequency-specific thresholds, but rather estimates auditory sensitivity in a frequency region, especially the high frequencies (Gorga, 1999). The fact that it is able to estimate PT thresholds, at 1, 2, and 4 kHz, better than the MF ASSR is compromised by the fact that it is not able to estimate frequency-specific thresholds. According to Picton (1991), being able to record frequency-specific information is an essential aim of objective audiometry.

Both the dichotic MF ASSR and the ABR protocol estimated PT thresholds reasonably well, with the exception of the click ABR, which closely estimated high frequency PT thresholds. It is clear from these results that the MF ASSR and the ABR present with unique advantages as well as disadvantages in estimating auditory thresholds. The MF ASSR presents with frequency-specificity similar to PT behavioural thresholds, whilst the click ABR provides a more accurate and reliable yet general estimation of high frequency PT thresholds.

## 4.3 Comparing Recording Times for the Dichotic Multiple Frequency Auditory Steady State Response and Auditory Brainstem Response Protocol

The mean time taken to determine thresholds in both ears with the dichotic MF ASSR technique and the ABR protocol is represented in figure 4.7.

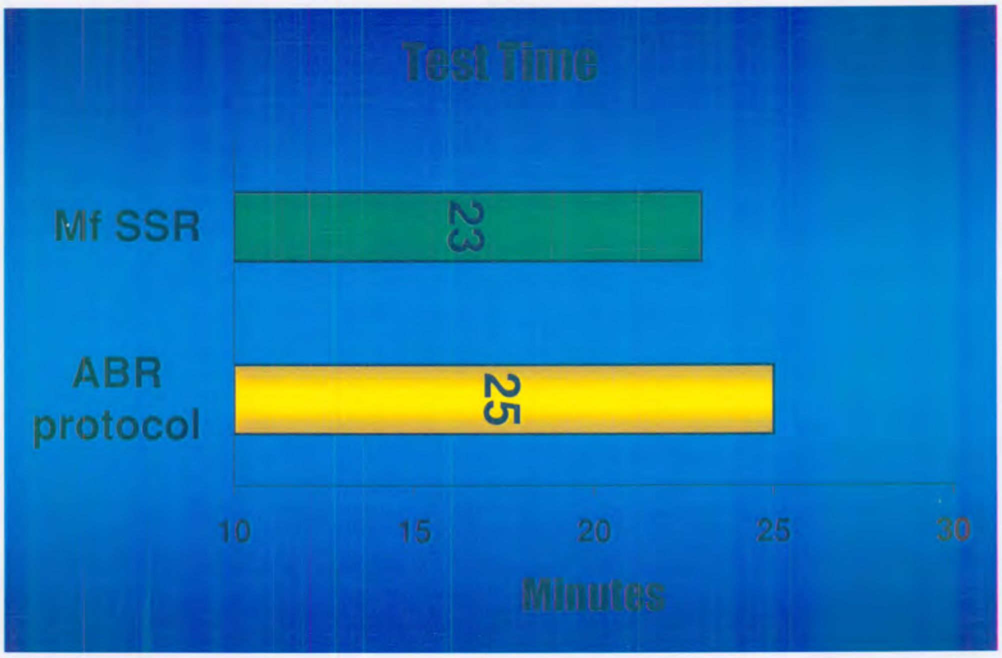

**Figure 4.7 Recording time for the dichotic MF ASSR technique and the ABR protocol**

The dichotic MF ASSR technique recorded thresholds using eight simultaneous signals (4 in each ear) in a mean time of 23 minutes with ± 8 minutes standard deviation. The normal range of deviation for recording thresholds using the dichotic MF ASSR technique was therefore 15 – 31 minutes.

The ABR protocol recorded thresholds using four single signals (2 in each ear) in a mean time of 25 minutes with ± 8 minutes standard deviation. The normal range of deviation for recording thresholds with the ABR protocol was therefore between 17 – 33 minutes.

The average recording time of the MF ASSR and ABR protocol thresholds was not significantly different although the average MF ASSR recording time was 2 minutes shorter. What is significant to note, however, is that the MF ASSR evaluated auditory sensitivity at 4 frequencies in each ear in less time than the ABR protocol required evaluating 2 frequency regions in each ear.

According to Bachmann & Hall (1998), the recording time is of fundamental importance, especially for paediatric populations, because it invariably affects the amount of information that can be gathered regarding an individual's auditory status. Being able to obtain more information regarding auditory sensitivity in a shorter period of time is a very important advantage.

Herdman & Stapells (2001), as well as Perez-Abalo et al. (2001), reported average recording times for the dichotic MF (4 frequencies/ear) ASSR technique. These average recording times and standard deviations are presented with those reported by the current study in table 4.10.

**Table 4.10 The mean dichotic MF ASSR recording times and standard deviation of the current study compared to Herdman & Stapells 2001 and Perez-Abalo et al. 2001**

| Studies | Mean recording time and SD (minutes) |
|---|---|
| **Current study** | 23 ± 8 |
| **Herdman & Stapells (2001)** | 83 ± 19 |
| **Perez-Abalo et al. (2001)** | 21 (SD not available) |

Results from the current study and those by Perez-Abalo et al. (2001), indicate similar recording times whilst the recording time reported by Herdman & Stapells (2001), differs significantly. There is a difference of approximately 60 minutes between the recording time of Herdman & Stapells (2001), and the other two studies. Possible reasons for these differences in recording time have already been mentioned in paragraph 4.2.2.1. The averaging procedure used by Herdman & Stapells (2001), utilized longer sweeps and a larger maximum amount of sweeps than either of the other studies, and was the only study to determine thresholds in a more time-consuming manner with 10 dB down and 5 dB up intensity steps.

A related reason for the extended recording times is the low levels of stimulation at which ASSR thresholds were recorded by Herdman & Stapells (2001). MF ASSR thresholds were recorded at intensities significantly lower than the other two studies, with a mean response threshold intensity of 13.5, 10, 6, and 12,5 dB HL (converted from dB SPL) at 0.5, 1, 2, and 4 kHz, respectively. According to Picton et al. (1998), at near threshold intensities there is probably too much latency jitter in the ASSR to allow averaging to detect a response. They suggest that there would not be recognizable ASSR responses below 10 dB HL. The mean ASSR thresholds reported by Herdman & Stapells (2001), however, were recorded at or near this level. The averaging process involved in determining MF ASSR thresholds at such low intensities requires the maximum amount of averaging to determine a significant ASSR. This means a maximum amount of time necessary because of the inherent difficulty in determining a significant ASSR at these low intensities.

Estimating PT thresholds at very low levels of stimulation with the ASSR requires an increased amount of averages, which means an increase in recording time. According to Picton (2001), the recording time required to determine accurate thresholds with the dichotic MF ASSR technique should probably reach beyond the ± 20-minute time frame.

## 4.4 Conclusion

The results of the current study suggest that both the dichotic MF ASSR and a 0.5 kHz tone burst and broadband click ABR protocol provided a reasonable estimation of PT behavioural thresholds in a time-efficient manner for a group of normal hearing subjects. The click ABR did however present with 1, 2, and 4 kHz PT threshold estimations that were almost 50 % closer than that of the dichotic MF ASSR according to the mean and normal deviation. This increased accuracy and reliability of the click ABR is however compromised by its lack of frequency-specificity. These results indicate a trade-off between frequency-specificity, characteristic of the MF ASSR, and the accurate estimation of auditory sensitivity, characteristic of the broadband click ABR.

In the low frequency region of 0.5 kHz, the tone burst ABR and ASSR evidenced estimations of the PT threshold that were, on average, very similar. The tone burst ABR did however present with a mean threshold slightly (3 dB) closer to the PT threshold than the MF ASSR. This small difference, favouring the tone burst ABR, is however negated by the large range of normal deviation demonstrated by the 0.5 kHz tone burst ABR. The 0.5 kHz dichotic MF ASSR presented with a smaller range of normal deviation in the estimation of PT thresholds, suggesting a more reliable measure than the 0.5 kHz tone burst ABR.

The recording time required for determining thresholds using the dichotic MF ASSR and ABR protocol, favoured the dichotic MF ASSR by 2 minutes, but was on average, very similar. An important aspect to note, however, is that the dichotic MF ASSR evaluation provided eight thresholds (4/ear) whilst the ABR protocol evaluated 4 thresholds (2/ear). Thus the dichotic MF ASSR provided twice the amount of threshold information regarding auditory sensitivity in less time (on average), than the 0.5 kHz tone burst and broadband click ABR protocol.

## 4.5 Summary

This chapter reported and discussed the results obtained in this study according to the two specified sub-aims. These sub-aims were selected in an attempt to answer the main aim of this study. Each sub-aim provided results that were discussed and integrated with current literature to ascertain the validity thereof. Conclusions were drawn from the results in each sub-aim and summarized at the end of the chapter. These conclusions provided by the two sub-aims were discussed in order to answer the main aim of the study, and to provide empirical, as well as clinical implications borne out of the results reported in this study.

# Chapter 5

# Conclusions and Implications

**Aim:** To draw general conclusions and implications from the research, critically evaluate findings, and make recommendations for future research

## 5.1 Introduction

'All agree that the role of diagnostic audiology is changing rapidly and will continue to change with the almost daily modifications that are occurring in healthcare' (Jerger, et al., 2000:615). This implies that amidst all the changes, audiologists must also adapt continuously in order to incorporate new procedures and techniques into their clinical practice. Test procedures available to audiologists are increasing with the growth in technological advancement, which incurs a growing need to ascertain, comparatively, the clinical usefulness of these techniques for different populations. This sentiment has been the underlying driving force behind the research endeavour of this study.

The field of objective audiometry has very recently gained a new technique promising to provide an invaluable addition to the clinically used AER 'family'. The ASSR and more specifically the optimised dichotic MF ASSR, proposed by Lins & Picton (1995), demonstrates unique characteristics to address many of the limitations presented by the most widely used AER, the ABR. The question that arises is whether one AER technique is able to provide all the necessary information for objective audiometry in a clinically viable way. According to Picton (1991), the aim of objective audiometry is to obtain an audiogram, if not at all frequencies, then at least between 0.5 and 4 kHz.

Picton (1991) specifies five criteria for the 'perfect' AER in estimating behavioural auditory thresholds. Firstly, the response must provide a reasonably accurate assessment of hearing threshold. Secondly, the response should be easily recorded during different states, and changes of arousal. Thirdly, the response must be easily recognizable at all ages. Fourthly, the response should be present at all frequencies of the conventional audiogram. Fifthly, the stimulus used must evoke responses that measure thresholds specific to different frequencies. The issue in this case is not the response, but the stimulus used to elicit the response. A sixth criterion for the 'perfect' AER, not mentioned by Picton (1991), but by other authors (Bachmann & Hall, 1998; Arnold, 2000), is the time required to obtain this information. Objective audiometry must be performed as quickly as possible especially in the paediatric population.

These criteria supply a framework from which to view emerging AER techniques providing comparisons with existing techniques, such as the ABR, in order to determine the advantages and limitations of each. This study was designed to draw conclusions for two (1 & 6) of the six specified criteria pertaining to the MF ASSR and an ABR protocol. The other criteria for the perfect AER have already been reported on in some depth in current literature for these two AER techniques.

**The purpose of this chapter is to draw relevant conclusions from the results reported and discussed in chapter 4, relating it to the summarized criteria for a 'perfect' AER and providing the theoretical and clinical implications of the study. A critical evaluation of the study is subsequently provided to identify the inherent and methodological limitations of this study, followed by recommendations for future research. Finally a conclusion and summary of the chapter is supplied.**

## 5.2 Conclusions: Theoretical and Clinical Implications

According to Uys & Hugo (1997), research is inherently linked to teaching and service delivery, implying that conclusions from this research study should infer theoretical and clinical implications. This comparative experimental design has provided conclusions regarding the usefulness of the dichotic MF ASSR as compared to an ABR protocol in estimating PT behavioural thresholds for normal hearing individuals, that construe specific theoretical and clinical implications. The conclusions drawn from this study are viewed according to a set of criteria for a 'perfect' objective audiometric AER technique. The conclusions from this study address two of the six criteria for a 'perfect' objective audiometry AER technique. These are summarized in table 5.1, together with previously reported results addressing the other four criteria in order to provide a comprehensive context from which to make theoretical and clinical implications.

**Table 5.1 Dichotic MF ASSR compared to the ABR protocol according to the 'perfect' objective audiometry AER technique**

🟥 - *Results of current study*

| 'Perfect' AER Criteria | ABR protocol (0.5 kHz TB & click) | Dichotic MF ASSR (0.5, 1, 2, & 4 kHz) |
|---|---|---|
| **1. Estimation of hearing threshold** | Estimated PT thresholds reasonably accurately. The click ABR when compared to PT thresholds at 1, 2, & 4 kHz estimated PT thresholds on average within 12 – 13 dB. The 0.5 kHz tone burst ABR estimated 0.5 kHz PT thresholds within 26 dB on average. (With a large standard deviation of ± 16.5 dB however) | Estimated PT thresholds reasonably accurately within 26 – 30 dB on average. The click ABR, however, was considerably more sensitive whilst the 0.5 kHz TB ABR estimated PT thresholds in a similar range. The 0.5 kHz TB ABR present with a range of normal deviation considerably larger than that of the ASSR. |
| **2. State of arousal not significant** | Not significant (Hall, 1992; Hood, 1998) | Not significant (Lins et al 1995; Lins et al, 1996; Rickards et al., 1994) |
| **3. Recognizable at all ages** | Recognizable across all ages (Hall, 1992; Hood, 1998) | Recognizable across all ages (Lins et al., 1996; Picton et al., 1998; Rickards et al., 1994) |
| **4. Responses present at all frequencies of the audiogram** | Click ABR response in high frequency region (not at a specific frequency). 0.5 kHz TB present at 0.5 kHz region (Gorga, 1999; Oates & Stapells, 1998) | Responses are present at important audiometric frequencies, 0.5, 1, 2, & 4 kHz (Lins et al., 1996) |
| **5. Frequency-specific stimuli** | Click stimuli are not frequency-specific (contains a broad spectrum of frequencies). 0.5 kHz TB stimuli are more frequency-specific with energy primarily at 0.5 kHz region but with energy spread especially at high intensities and at low frequencies (Gorga, 1999; Hood, 1998) | Amplitude-modulated tones used to evoke ASSRs are very frequency specific, similar to pure tones (Picton et al, 1995; Levi et al, 1993, Cohen et al, 1991) |
| **6. Recording time** | Recording time (25 ± 8 min) to evaluate 2 frequency regions in 2 ears | Recording time (23 ± 8 min) to evaluate 4 frequency regions in 2 ears |

The results reported by this study evidence a spread of advantages and disadvantages between the ABR protocol and the dichotic MF ASSR technique. The dichotic MF ASSR indicated the ability to estimate PT thresholds (4 frequencies in each ear), on average, reasonably accurately in a time-efficient manner. The estimation of PT thresholds was however expected to be better when compared to reported literature. This was most probably due to several influences including a difference in threshold seeking procedure used for the behavioural and physiological responses, different acoustical environments for behavioural and objective measurements, and response averaging periods that were too short. According to Picton (2001), ASSR averaging time periods for determining thresholds should most probably extend beyond ± 20 minutes to ensure accurate estimations of hearing thresholds.

The click ABR provided an estimation of hearing significantly closer to the PT thresholds in the high frequency region (1, 2, & 4 kHz) than the MF ASSR. Although the click ABR is compromised by a lack of frequency-specificity (Oates & Stapells, 1998) it provides a valuable estimation of general hearing ability in the high frequency region for most cases. The 0.5 kHz tone burst ABR presented with an average PT threshold estimation similar to within 3 dB of the MF ASSR, but was compromised by exhibiting a large range of normal deviation which indicated a fair degree of variability. The average recording time required to complete the ABR protocol was 2 minutes longer than for the dichotic MF ASSR, and it evaluated four thresholds whilst the dichotic MF ASSR evaluated eight thresholds.

The final goal of objective audiometry is to provide hearing thresholds in a frequency-specific manner in order to construct an audiogram without any conscious response from a subject (Aoyagi et al., 1996). Since objective audiometry is mostly aimed at the paediatric population (Aoyagi et al., 1996), it also requires that the maximum amount of auditory threshold information be acquired in the shortest possible time (Bachmann & Hall, 1998). These requisites for objective audiometry are therefore the primary concern when evaluating different techniques.

It is clear that both the dichotic MF ASSR and the ABR protocol provided valuable information regarding hearing sensitivity, with each procedure presenting its own advantages and disadvantages. Regan (1989:39) emphasised this fact by stating that 'at a practical level, transient and steady state recording are to some extent complementary: each has its own advantages and its disadvantages'. This prompts a change of perspective affirming that these audiometric procedures should not be used in an 'either or' manner, but rather in the best possible combination.

Perhaps there should be a return to the principle extrapolated by Jerger & Hayes in 1976 (Jerger & Hayes, 1976), namely the cross-check principle. This principle is an extension of the test battery approach, stating that the results of a single test must be cross-checked by an independent test measure (Hannley, 1986). The most important rationale for employing a cross-check principle approach to auditory assessment is the fact that the information provided by an assessment provides the foundation for intervention and rehabilitation (Hannley, 1986). Inappropriate or incomplete diagnostic conclusions will lead to inappropriate management plans and the results can be devastating (Gorga, 1999).

The MF ASSR and the ABR present with unique qualities that can be combined to provide complementary results, which will serve to verify results obtained with each procedure. Instead of comparing these two procedures to decide which is best to use, comparisons should aim to identify the differentiating qualities in both procedures, in order to best combine the outstanding qualities of each procedure in a test battery. A crucial consideration to be taken in account in the selection of such a test battery is the amount of time available for the entire patient contact (Hannley, 1986). For the paediatric population, which the ABR and ASSR are primarily used for, time is limited and results must be obtained in a time-efficient way. This concludes that the test battery must be composed of procedures that yield the most reliable results, in the shortest possible time.

Thus the question, 'which objective procedure most accurately estimates behavioural thresholds in the most time-efficient way?' is most probably too simplistic. The question should be changed to, 'how can these objective audiometric procedures best be incorporated into test batteries capable of accurately, and reliably estimating behavioural thresholds in a time-efficient manner?'

Although the dichotic MF ASSR technique requires further validation and experimentation with different recording and stimulus parameters (John, 2001), a few suggestions regarding its usefulness in combination with ABR procedures can be deduced from this research endeavour.

The click ABR has proven itself over the last 3 decades as a reliable predictor of auditory sensitivity in the high frequency region. It has remained the most commonly used objective audiometric procedure, despite its lack of frequency-specificity, because of the high reproducibility and stability of the response, which allows close estimations of pure tone thresholds (Aoyagi et al., 1996). Results from this study indicated that the click ABR was the procedure that most closely approximated pure tone thresholds. The results for the dichotic MF ASSR, even though not as accurate as the click ABR, demonstrated the ability to determine frequency-specific pure tone threshold estimations in the same range as the 0.5 kHz tone burst ABR. The dichotic MF ASSR thresholds were however determined with less variability than the 0.5 kHz tone burst, in a significantly reduced recording period. The dichotic MF ASSR was also able to obtain thresholds simultaneously in both ears reducing the recording time significantly.

These results suggest a test-battery, cross-check principle approach to objective audiometry, including a complete evaluation of auditory sensitivity with the dichotic MF ASSR cross-checked and compared to a click ABR evaluation in each ear. These two techniques are independent measures of auditory sensitivity that are able to provide different, though complementing information. This establishes a more comprehensive set of data regarding hearing threshold from which rehabilitative decisions can be made with more assurance.

Accurate and reliable information regarding auditory sensitivity for a hearing-impaired individual is essential to rehabilitation (Gorga, 1999). Using different techniques to complement each other and to cross-check results is the foundation of responsible and effective auditory assessment (Hannley, 1986).

## 5.3 Critical Evaluation of the Current Study

A critical evaluation of an empirical research endeavour is essential to determine the value of the results obtained. According to Dane (1990), the identification of limitations and the reliability and validity of data is necessary to ensure that the significance of results is rightly interpreted. Several aspects deserving critical evaluation will be discussed in the following paragraphs.

The first aspect to be considered is the sampling methods of the current study. The sampling size required for a study depends on the type of study and is required to provide a representative population from which inferences can be drawn regarding a specific phenomenon in a specific population (Neuman, 1997). The sample size of the current study can be described as significant for making inferences and conclusions when it is taken into consideration that each subject had two normal ears implying two independent observations per subject. Although the sample was representative of both sexes it was not significantly representative of a wide range of ages. This limits the generalizations and inferences that can be drawn from the results of this study to those ages that were significantly represented by the sample. The ages that were primarily represented were between 15 – 25 years, with reasonable representation between 26 – 35 years of age.

The second aspect that needs to be taken into consideration is the test environment. All thresholds were obtained in a sound-attenuated booth on the same day for each subject to ensure minimal intra-subject variability. The pure tone behavioural thresholds were, however, obtained in a double-walled, sound-attenuated booth whilst the objective electrophysiological thresholds were obtained in a single wall booth. According to Frank (2000), a double-walled, sound-attenuated booth can reduce acoustic ambient noise between with 20 – 30 dB compared to a single wall, sound-attenuated booth. The acoustical ambient background noise levels were not measured for this study and therefore did not allow for comparison between the acoustic noise levels in the double, and single wall, sound-attenuated booth. The possible difference was not accounted for and must therefore be taken into consideration when interpreting the results. Higher levels of ambient acoustic noise in the single wall booth might cause elevated thresholds whilst lower levels of ambient noise in the double-walled booth might decrease thresholds. Thus the threshold differences could be inflated on account of the variability in the test environments.

A third factor requiring critical attention is the recording procedure utilized in obtaining data for the current study. The pure tone behavioural thresholds were determined in intensity steps that measured sensitivity at threshold level in 5 dB steps. Thresholds for the MF ASSR and ABR protocol were, however, only measured in 10 dB intensity steps in order to represent widely recommended clinical practice (Hood, 1995; Bachmann & Hall, 1998). This difference in intensity step for threshold sensitivity between the behavioural pure tone and objective audiometric procedures, reveal an inherent limitation to the comparison of results. This difference in threshold seeking procedures requires a correction between comparative thresholds of equal to or less than 5 dB. This fact must be taken into consideration when results are interpreted.

Another element of the recording procedure that must be considered is mentioned in brief. The current study used a maximum amount of stimulus presentations as the criteria for determining an ABR. If a clear response was visible before the maximum amount of presentations was reached, the next intensity was evaluated. This type of criteria does not consider the variability of internal noise artefacts evidenced by different subjects. It will be useful to include the sound-noise ratio as criteria for the amount of averages required to obtain a response, instead of only utilizing a maximum number of stimulus presentations. This could allow for more consistent criteria that would facilitate improved comparative response reliability between subjects.

The fourth aspect identified in the critical evaluation of the current study is the lack of test-retest reliability measures. According to Johnson and Pennypacker (1993), this is a method of assessing the reliability of a test by correlating results from two administrations of the same procedure. Test-retest reliability measurements of the ABR are extensively reported on (Hall, 1992), but because of the recent development of the dichotic MF ASSR this is not the case for this procedure. Test-retest measures of the dichotic MF ASSR technique would have provided a valuable contribution to the results obtained in this study. The stability of ASSR measurements have recently been reported to demonstrate large inter- and intra-subject variability in regard to background noise in ASSR recordings at low levels of stimulation (Mühler et al. 2001). It would therefore be of significance to obtain test-retest data to determine the stability reliability (Neuman, 1997) of the ASSR procedure in a controlled test environment.

A fifth possible limitation of the current study is the fact that supra-aural earphones were used to measure thresholds instead of insert earphones. Insert earphones are often preferred to supra-aural earphones because it avoids the risk of a collapsing ear canal, reduces the need for masking, and provides enhanced stability of sound delivered to the ear (Stach, 1998). Fortunately, however, thresholds for all procedures were obtained with the same supra-aural earphones establishing a controlled transducer type.

The critical evaluation of the current study and consideration of the significance of the results obtained has revealed several future research implications that are discussed in the following paragraph.

## 5.4 Recommendations for Future Research

A hypothesis answered raises a multitude of questions. The current study was no exception. Several significant aspects requiring further investigation were revealed by the results obtained, and conclusions drawn from the current study. These are discussed in order to provide guidelines and suggestions toward future research endeavours.

- The first recommendation is to replicate the ASSR measurements of the current study using a single frequency ASSR technique evaluating each frequency sequentially instead of simultaneously. This type of study can provide empirical evidence for the advantages and disadvantages involved in the use of each ASSR procedure.

- The second and related recommendation is to compare dichotic MF ASSR thresholds with tone burst ABR thresholds, obtained at all the ASSR frequencies. This information will provide comparative data relating to the accuracy, reliability and time-efficiency demonstrated by each procedure.

- A third recommendation involves the manipulation of the test environment. Results from the current study and previously reported (Lins et al., 1996; Picton et al., 1998; Perez-Abalo et al., 2001) results indicate that the acoustic ambient background noise exerts a significant influence on the

ASSR results. The influence of acoustical background noise should therefore be investigated. Comparative ASSR threshold data obtained in different acoustical environments will provide important information regarding the influence of acoustical background noise on the ASSR. Recently Mühler et al. (2001), indicated that the stability of ASSR measurements demonstrate large inter- and intra-subject variability in regard to background noise in ASSR recordings at low levels of stimulation. Research in this area would therefore provide a significant contribution toward an endeavour to validate the ASSR technique for clinical practice in various settings.

- A fourth future research investigation involves the establishment of an optimal range of time or amount of averaging required to obtain reliable and accurate ASSR thresholds. According to Picton (2001), recording times for evaluating representative thresholds in both ears with the ASSR should exceed the ± 20 minute period. It is therefore essential that the average amount of time required to comprehensively evaluate both ears in a consistent acoustical environment be investigated. However, it must be remembered that the required number of averages together with the sound-noise ratio must be taken into consideration when this type of endeavour is pursued.

- A fifth recommendation for future investigation is the establishment of stability reliability of the ASSR, specifically the dichotic MF ASSR technique. According to Neuman (1997), the degree of stability reliability of a technique can be examined by using the test-retest method, with which you retest or re-administer the procedure to the same group of subjects. The validation of the dichotic MF ASSR technique as a clinically reliable and accurate measure of auditory sensitivity requires the investigation of its test-retest reliability in samples of normal and hearing-impaired individuals.

- A sixth recommendation for future directions in ASSR research revolves around recent developments demonstrating promise of improved response detection. John, Dimitrijevic, & Picton (2001), reported that the use of weighted averaging instead of normal averaging in determining responses proved more effective especially at lower intensities often requiring less data. This averaging technique calls for further investigation. Another technique recently proposed by John, Dimitrijevic, van Roon, & Picton (2001), demonstrating potential for better response detection is the use of mixed modulation. This technique involves the modulation of a carrier frequency in the amplitude and frequency domain. Thus, instead of only using amplitude-modulated tones, the tones are now modulated in amplitude and frequency. Initial results indicated that responses evoked by these stimuli are more rapidly detected than those evoked by amplitude-modulated tones only (John, Dimitrijevic, van Roon, & Picton, 2001). The possibility of combining the weighted averaging and mixed modulation techniques in the detection of responses must be investigated and compared to the detection of responses using normal averaging and amplitude-modulated tones.

## 5.5 Conclusion

Audiologists are reliant on objective audiometric procedures to predict auditory sensitivity in difficult-to-test populations. Technological, and research advancements have aided the development of this field ensuring the continuation of endeavours to generate a technique that approximates the accuracy, reliability, frequency-specificity, and time efficiency of behavioural pure tone audiometry. In 1991 Picton stated that 'Once one has come to the idea that there is more to evoked potential audiometry than the ABR, it may not be hard to accept that there is more to audiometry than clicks and tones' (Picton, 1991:9). These words are ringing true with the recent advent of the ASSR evoked with amplitude-modulated tones, promising to establish a new precedent for objective audiometry.

The investigation of this new technique compared to the existing ABR technique has demonstrated its ability to estimate behavioural pure tone thresholds reasonably well in a time-efficient manner. The results, however, also suggest that until the 'perfect' AER technique for objective audiometry has been established, it is important to critically consider currently available procedures alongside new procedures. This becomes essential in order to implement available techniques in accordance with the advantages and disadvantages prominent to each. The implication therefore is the re-visitation of the test-battery approach, specifically the cross-check principle. A test-battery approach to assessment should incorporate different techniques, aiming to optimise the process of obtaining information regarding auditory sensitivity, in order to provide the maximum amount of information in the most time-efficient manner.

The results of the current study evidenced that both the ABR and dichotic MF ASSR presented with unique characteristics that can and should be incorporated into an objective audiometry test battery to complement, and cross-check results. A test battery suggested in view of the results obtained in the current study entails a comprehensive evaluation of auditory sensitivity with the dichotic MF ASSR, followed by an evaluation with the broadband click ABR. This combination incorporates the advantages of both techniques and provides information regarding different auditory processes.

In the final analysis, assessment efforts aim to provide reliable and accurate information regarding patients. These efforts are of crucial importance to ensure that appropriate intervention strategies are implemented based on accurate assessment information. Intervention based on inaccurate assessment information is ineffective and can often have devastating effects (Gorga, 1999; Hannley, 1986). The author therefore agrees with Jerger & Hayes (1976), stating that 'Whatever technique may be used in testing…hearing, it is important to confirm the results with an independent cross-check…The key concept governing our assessment strategy is the cross-check principle. The basic operation of this principle is that no result be accepted until it is confirmed by an independent measure…We believe that the application of the cross-check principle to our clinical population has…an appreciable effect on the accuracy with which we can identify and quantify hearing-loss' (Jerger & Hayes, 1976:64-65).

Audiologists have the obligation to use everything at their disposal to provide the best possible services to our patients because in the end, ***'The most compelling argument for applying the cross-check principle to auditory assessment is that the results of the assessment will have a direct impact on the patient's life' (Hannley, 1986:3).***

> ***'Auditory evoked responses have been used in diagnostic audiology for more than 3 decades, and as more knowledge is being made available in this area, it is clear that auditory electrophysiological measures will become an even more prominent diagnostic tool in audiology in the future'***
>
> **(Roeser, Valente, & Hoshford-Dunn, 2000:10)**

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# Appendix A

## Informed consent letter

## Chapter 2

# Evoked Response Audiometry in Clinical Practice: The Auditory Brainstem Response and the Emergence of the Auditory Steady State Response

Aim: This chapter serves as a theoretical underpinning for the empirical research and provides a critical evaluation and interpretation of the relevant literature.

## 2.1 Introduction

Auditory evoked responses (AERs) have developed into a vital audiological tool invaluable in auditory diagnosis (Thornton, 2001). When behavioural tests become impossible, these findings become critical for diagnosis, audiologic treatment, and management strategies (Bachmann & Hall, 1998). It has proved to be a powerful objective assessment of the neural integrity of the auditory pathways often employed for the audiometric purpose of predicting the behavioural pure tone audiogram (Goldstein & Aldrich, 1998). The AER has provided an invaluable audiological avenue into the neural activity of the hearing process and as more knowledge is being made available in this area it is clear that AERs will become an even more prominent diagnostic tool in the future of Audiology (Roeser, Valente, & Hosford-Dunn, 2000).

The use of AERs for the screening of infant hearing and estimation of hearing sensitivity has had a major impact on the ability of clinicians to identify and describe hearing impairment in children and other difficult-to-test populations

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Department of Communication Pathology
Speech, Voice and Hearing Clinic

Date:

**To Whom It May Concern:**

Thank you for participating in this research project being conducted at the University of Pretoria, Department Communication Pathology. The project involves determining the reliability and validity of a new objective audiometric instrument (Auditory Steady State Responses) used in estimating hearing thresholds. This instrument will be compared to two existing audiometric procedures used in estimating hearing thresholds, namely a subjective test (Pure tone audiometry) and an objective test (Auditory Brainstem Responses). All three procedures are non-invasive and only one procedure requires a response from the subject. The entire test battery should take approximately one and a half hours to complete. All acquired information will be treated as confidential and no names will be used. Each research subject will be given a copy of his or her hearing status, if requested.

For any further information the project mentor, Prof René Hugo, be contacted at the Communication Pathology Department, University of Pretoria, Tel: (012) 420 2357.

Thank you for your assistance.

______________________________
Mr. De Wet Swanepoel

……

**University of Pretoria**
**Department Communication Pathology**

Surname:__________________ Name:____________________________

Age:_____________________ First language:_____________________

I hereby consent to participate as a research subject in the research project at the University of Pretoria, Department Communication Pathology:

__________________________ Date:_____________________________
Signature