Threshold estimation in normal and impaired ears using Auditory Steady State Responses

by

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For my family and close friends,
especially my mom and dad.
Their contributions to my life
were deeply grasped and appreciated
and their love and support were
without limitations.

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Abstract

Title	Threshold estimation in normal and impaired ears using Auditory Steady State Response
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The Auditory Steady State Response (ASSR) procedure has been established as a frequency specific, objective audiologic measure, which can provide reliable thresholds to within 10 dB of the behavioral thresholds. In order for ASSR to find its place in the existing framework of audiometric procedures, the full potential of the procedure needs to be explored. The aim of this study was to determine the accuracy of monotic ASSR in estimating hearing thresholds in a group of 15 normal hearing subjects and 15 hearing-impaired subjects. A comparative research design was implemented. Indicating that results obtained in the study was compared to relevant literature where dichotic multiple ASSR was implemented. This was done in order to ascertain ASSR's capabilities with regard to stimulus presentation methods. Monotic single ASSR predicted behavioural thresholds in the normal hearing subjects within an average of 24 dB across the frequency range (0.5, 1, 2 & 4 kHz). In the hearing-impaired group, ASSR thresholds more closely resembled behavioural thresholds, with an average difference of 18 dB, which is consistent with recent literature. The literature suggests that better prediction of behavioural thresholds will occur with greater degrees of hearing loss, due to recruitment. The focus in this group also centered on the accurate prediction of the configuration of the hearing loss. It was found that ASSR could reasonably accurately predict the configuration of the hearing loss. In the last instance, monotic single and dichotic multiple ASSR were compared with regard to threshold estimation and prediction of configuration of the hearing loss in the hearing-impaired group. Little difference was reported between the two techniques with regard to the estimation of thresholds in both the normal hearing and hearing impaired groups.

In conclusion it was established that monotic ASSR could predict behavioural thresholds of varying degrees and configurations of hearing loss in normal and hearing-impaired subjects with a reasonable amount of accuracy. At this stage, however, more research is required to establish the clinical validity of the procedure, before it is routinely included within an objective test battery.

Key terms: frequency-specific hearing thresholds, “difficult-to-test”, objective physiological procedures, extensive diagnostic information, monotic single ASSR, dichotic multiple ASSR, prediction of behavioural thresholds, test battery, cross-check principle.

Opsomming

Titel	Drempelbepaling in normaal en gestremde ore met behulp van Ouditiewe Standhoudende Respons
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Die bepaling van frekwensie-spesifieke drempels sonder enige respons van die individu is ’n belangrike prioriteit in die veld van oudiologie. Veral in kinders en babas wat geklassifiseer word as deel van die moeilik-toetsbare-populasie, as gevolg van die onvermoë van gedragsoudiometrie om betroubare gehoordrempels te bepaal. Betroubare resultate is nodig vir die doeltreffende bestuur van die geïdentifiseerde gehoorverlies. Gevolglik is inligting ten opsigte van die tipe, graad en konfigurasie van die gehoorverlies nodig. Die tipe prosedures wat die oudiometriese raamwerk ter evaluering van die moeilik-toetsbare-populasie uitmaak word gedomineer deur objektiewe fisiologiese prosedures en in dit is in hierdie raamwerk wat die Ouditiewe Standhoudende Response (OSR) sy plek moet vind. Die prosedure is frekwensie-spesifiek, kan betroubare drempels binne 10 dB van die gedragsdrempels bepaal en geen respons is van die individu nodig nie. Die doel van hierdie studie was om die akkurate drempelbepaling van monogotiese enkele OSR in ’n groep van 15 normaal horende en 15 gehoorgestremde proefpersone te bepaal. ’n Vergelykende navorsingsontwerp is geïmplimenteer en van die resultate wat verkry is, is vergelyk met bestaande literatuur wat digotiese veelvuldige OSR gebruik het vir drempelbepaling. Die vergelyking is gedoen om OSR se geskiktheid in die huidige raamwerk te bepaal.

Monogotiese enkel OSR het die suiwertoon gedragsdrempels in die normaal horende proefpersone, met ’n gemiddelde verskil van 24 dB versprei oor die relevante frekwensies (0.5, 1, 2 7 4 kHz) redelik akkuraat voorspel. Bevindinge in die literatuur ondersteun die resultate van die huidige studie ten opsigte van die gehoorgestremde groep, waar OSR drempels ’n nouer verwantskap met die gedragsdrempels toon met ’n gemiddelde verskil van 18 dB. Die nouer verwantskap van OSR drempels en gedragsdrempels word toegeskryf aan luidheidsopbou van gehoorgestremde proefpersone by hoë intensiteite. In hierdie groep is die graad en konfigurasie van die gehoorverlies ook redelik akkuraat voorspel deur OSR. Laastens is monogotiese enkel OSR en digotiese veelvuldige OSR vergelyk ten opsigte van drempelbepaling en voorspelling van die graad en konfigurasie van die gehoorverlies. Min verskil is opgemerk tussen die twee tegnieke in beide groepe proefpersone.

Die gevolgtrekking wat gemaak kan word, is dat OSR gedragsdrempels en verskeie grade en konfigurasies van gehoorverlies in normaal horende en gehoorgestremde proefpersone kan voorspel met ‘n redelike hoeveelheid akkuraatheid. Alhoewel die prosedure akkurate voorspellings lewer, behoort dit nog steeds deel uit te maak van ’n ouditiewe toetsbattery, totdat volledige kliniese bevestiging van die tegniek vasgelê word.

Sleutelterme: frekwensie-spesifieke gehoordrempels, moeilik-toetsbare-populasie, objektiewe fisiologiese prosedures, diagnostiese inligting, monogotiese enkele OSR, digotiese veelvuldige OSR, voorspelling van gedragsdrempels, toetsbattery, kruis-toets beginsel.

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List of Abbreviations

The text of this study utilizes various discipline specific abbreviations. These abbreviations and their meanings are depicted in the flowing list.

AEP	Auditory Evoked Potentials
ABR	Auditory Brainstem Response
AM	Amplitude-Modulated
ANOVA	Analysis of Variance
ASSR	Auditory Steady State Response
dB	Decibel
ERA	Evoked Response Audiometry
EEG	Electro Encephalo Gram
FFT	Fast Fourier Transform
FM	Frequency Modulated
HL	Hearing Level
Hz	Hertz
kHz	Kilo Hertz
MASTER	Multiple Auditory STEady state Responses
MLR	Middle Latency Response
MRL	Minimum Response Level
ms	milliseconds
OAE	Oto Acoustic Emissions
PTA	Pure Tone Audiometry
PTBT	Pure Tone Behavioural Thresholds
SABS	South African Bureau of Standards
SD	Standard Deviation
SPL	Sound-Pressure Level

1

Introduction

Threshold estimation in normal and impaired ears using ASSR

This chapter aims to sketch the scenarios in which current and new audiological techniques interact, the origin of relevant problems and the rationale of this study.

1.1 Introduction

A hearing impairment that goes undetected in infants and young children compromises optimal development and personal achievement. The early detection of hearing impairment in this population has therefore been a longstanding clinical priority in audiology (Diefendorf, 2002). This population forms part of the "difficult-to-test" population because of the difficulties in performing standard audiometric procedures. The neonatal population, patients with additional disabilities (whether it be adults or children), as well as patients with a functional hearing loss have been classified as being "difficult-to-test" due to of factors such as lack of attention, motivation and understanding of instructions (Fulton & Lloyd, 1969; Picton, 1991).

Obtaining accurate and reliable diagnostic information is critical, as it forms the basis of early intervention. This process is complicated in the "difficult-to-test" population since many factors preclude the use of traditional audiometric test procedures (Fulton & Lloyd, 1969; Katz, 1994). An audiometric procedure should be reliable under a variety of conditions and be diagnostically sensitive to the patients' auditory functioning (Diefendorf, 2002). In this population, physiological measures of the auditory system are required to obtain reliable audiometric information (Diefendorf, 2002).

Effective management of the hearing-impaired child or infant requires frequency-specific audiometric thresholds (Yoshinaga-Itano, 2001). Appropriate amplification can only be provided if accurate, ear specific information on the type, degree and configuration of a hearing loss is available (Yoshinaga-Itano, 2001). Pure tone behavioural audiometry is considered the golden standard when it comes to frequency-specific threshold audiometry, however behavioural measures are often unreliable or impossible to obtain with regard to the "difficult-to-test" population (Stach, 1998). In contrast, physiological measures[1] do not demonstrate this variability and reliable responses can be obtained objectively without any behavioural response from the individual.

Presently, when assessing the functioning of the auditory system of the "difficult-to-test" population, clinicians rely mainly on immittance measures, Oto Acoustic Emissions (OAE) and Auditory Brainstem Response (ABR) testing (Diefendorf, 2002). Although these measures accurately evaluate the integrity of the auditory pathway (from the external ear to the lower brainstem), only the ABR procedure can estimate physiological auditory thresholds (Diefendorf, 2002).

In relation the **Auditory Steady State Response** (ASSR) procedure (Galambos, Makeig & Talmachoff, 1981; Lins & Picton, 1995) is a new addition to the clinically available test procedures in the objective physiological framework (John & Picton, 2000; Lins & Picton, 1995; Perez-Abalo, Savio, Torres, Martin, Rodriquez & Galan, 2001; Picton, Durieux-Smith, Champagne, Whittingham, Moran, Giquére & Beauregard, 1998; Rance, Dowell, Rickards, Beer & Clark, 1998; Schmulian, 2002; Swanepoel, 2001).

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[1] Physiological measures: more commonly known as electrophysiological measures, referring to measures where the change in the electrophysiological mechanisms of an individual can be monitored, that might be induced by the introduction of acoustic stimuli (Martin, 1997).

1.2 Rationale of study

The ASSR procedure is an objective measure that estimates hearing thresholds in a frequency-specific manner (John, Lins, Boucher & Picton, 1998; Lins & Picton, 1995; Perez-Abalo et al. 2001; Picton et al. 1998; Rance et al. 1998). In relation to the existing framework of objective measures that facilitate hearing assessment in the "difficult-to-test" population, two procedures are highlighted and briefly discussed: the ABR and OAE procedures (Diefendorf, 2002; Lins, Picton, Boucher, Durieux-Smith, Champagne, Moran, Perez-Abalo, Martin & Savio, 1996).

Both these procedures are deemed reliable, objective and are capable of detecting hearing loss (Diefendorf, 2002). Also, both have established their place in neonatal screening and the ABR is presently the procedure of choice with regard to the "difficult-to-test" population (Diefendorf, 2002; Lins, Picton & Picton, 1995). With regard to these procedures, certain limitations exist when the degree and configuration of the hearing loss needs to be delineated, especially to facilitate further management of the hearing loss.

Oto Acoustic Emissions provide information on the functioning of the outer hair cells of the cochlea, however it is not a test of hearing and does not evaluate the functioning of the auditory neural pathways (Hall, 2000). Although the stimulus presented is transient in nature like that of the ABR, the ABR procedure has proven to provide near threshold audiometric information. When implementing click-evoked ABR, the degree of frequency-specificity of the response is best described as correlating with behavioural thresholds in the region of 2 to 4 kHz (Durieux-Smith, Picton, Bernard, MacMurray & Goodman, 1991; Gorga, 1999; Rance, Rickards, Cohen, De Vidi & Clark, 1995; Stapells, 1989). Tone-burst ABR combined with notched-noise masking has been shown to provide much greater frequency-specificity (Gorga, 1999). Unfortunately, the apparatus is expensive and not readily available. Also the interpretation of the responses is complex and many clinicians are not familiar with the procedure (Gorga, 1999; Oates & Stapells, 1998; Swanepoel, 2001). The ASSR addresses some of these limitations. It is frequency-specific, can provide near threshold information, is objective, and uses automated response detection algorithms that simplify clinician interpretation (Lins et al. 1996).

Whereas ABR are transient in nature, ASSR represents the synchronous discharge of auditory neurons in the peripheral and central pathways of the auditory system to continuous modulated tones (Lins et al. 1996). The tones are amplitude modulated over time at higher rates than other Auditory Evoked Potentials (AEP) measurements, with subsequent higher repetition of responses (Perez-Abalo et al. 2001). These responses are recorded at the frequency of modulation, representing the specific carrier or nominated frequency (Perez-Abalo et al. 2001).

Historically ASSR evolved from experiments done in the early 1980s by Galambos and colleagues. Stimuli were presented at a rate of 40 Hz and involved single presentation to individual ears (Galambos et al. 1981). In later years, experiments were done at higher stimulus rates after it was determined that the subject's state of arousal had a significant effect on the amplitudes of the responses at 40 Hz rate of modulation (Jerger, Chmiel, Frost & Coker, 1986; Stapells, Galambos, Costello & Makeig, 1988). These higher modulation rates were between 70 and 110 Hz and tested reliably during sleep in young children, as well as adults (Rickards, Tan, Cohen, Wilson, Drew & Clark, 1994). The monotic[1] presentation of single stimuli is able to test at high intensity levels and for this reason ASSR has greater potential in cochlear implant candidacy testing (Rickards et al, 1994).

Most of the early research in ASSR was in establishing normative data and examining test variables (Galambos et al. 1981; Kankkuren & Rosenhall, 1985; Linden, Campbell, Hamel & Picton, 1985; Lynn, Lesner, Sandridge & Daddario, 1984; Stapells, Linden, Suffield, Hamel & Picton, 1984; Rodriquez, Picton, Linden, Hamel & Laframboise, 1986). In later years the emphasis shifted more towards the estimation of thresholds in hearing-impaired children, with particular emphasis on the severe to profound hearing-impaired group (Aoyagi, Kiren, Furuse, Fuse, Suzuki, Yokota & Koike, 1994; Griffiths & Chambers, 1991; Kuwada, Batra & Maher, 1986; Milford & Birchall, 1989; Picton et al. 1998; Rance et al. 1995; Rodriquez et al. 1986).

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[1] Monotic: stimuli presented to only one ear (Hall & Mueller, 1997).

Stimulus variables were further investigated and included the use of dichotic[3] and multiple stimulus presentation (Lins et al. 1996). Multiple stimulus presentation involves the presentation of modulated carrier frequencies in combinations of two, four or eight. These combinations are then presented to both ears simultaneously, hence the term dichotic presentation of stimuli. The principle of presenting multiple continuous tones simultaneously, although new to the field of audiology, has been used successfully in the field of visual steady state evoked potentials. The visual steady state evoked potentials formed the basis for the same multiple dichotic presentation of modulated tones in the auditory modality. Early experiments were done by Regan and Cartwright (1970) and revised by Regan in 1989 (Regan, 1989). These findings suggested that several simultaneous stimuli could be recorded and analysed independently if each stimulus is modulated at a different rate. Although there are numerous ways of presenting ASSR stimuli, two distinctive measures have moved into the clinical arena: the presentation of single stimuli to one ear at a time (monotic single ASSR) and the presentation of multiple stimuli to both ears simultaneously (dichotic multiple ASSR). These procedures have been made available to clinicians in the form of GSI Audera and the MASTER system as part of the Biologic software (Swanepoel, 2001; Schmulian, 2002).

Before these systems achieved clinical applicability, various comparisons were made between ASSR and other AEP procedures. Certain influential variables such as stimulus rates and subject state were explored and more importantly the ability of threshold estimation using ASSR (Kuwada et al. 1986; Jerger et al. 1986; Rodriquez et al. 1986; Cohen, Rickards & Clark, 1991; Swanepoel, 2001). For ASSR to be a clinically applicable procedure in diagnosing hearing impairment, accurate information on the degree and configuration of the hearing loss needs to be obtained (Yoshinaga-Itano, 2001).

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[3] Dichotic: different stimuli presented to each of two ears (Hall & Mueller, 1997)

1.3 Problem Statement

Since monotic single ASSR found its origin in cochlear implant candidacy and can accurately predict thresholds at high intensity levels, most of the research using this technique has been in children with severe to profound hearing losses (Rance et al. 1995; Rance et al. 1998; Rickards et al. 1994). Limited research has been done to explore the ability of monotic single ASSR to estimate hearing thresholds across the range of hearing sensitivity (from normal hearing to profound hearing loss). Subsequently the focus of this study will be the ability of monotic single ASSR to accurately predict hearing thresholds across the range of hearing sensitivity. In order to investigate this ability the following research question has been formulated.

How accurate is monotic single ASSR in estimating pure tone behavioural thresholds for a group of normal hearing and hearing-impaired subjects?

This research endeavour consists of both a theoretical and empirical approach that evaluates the clinical applicability of ASSR to estimate hearing thresholds. This ability of monotic single ASSR was also compared with dichotic multiple ASSR. This was achieved by comparing the current study's results to those of Schmulian (2002) and Swanepoel (2001), where the same hearing-impaired subjects were used and the same selection criteria for the normal hearing subjects.

1.4 Definition of terminology used during the study

In research related to ASSR, researchers make use of the same terminology to describe different events, procedures and techniques. To give the reader a clear understanding of what is meant by the basic terminology used in this study, some potentially ambiguous terms will be defined. The terminology will be discussed in a logical flow of the electrophysiological process when implementing the ASSR procedure (reference is made to Figure 1.1).

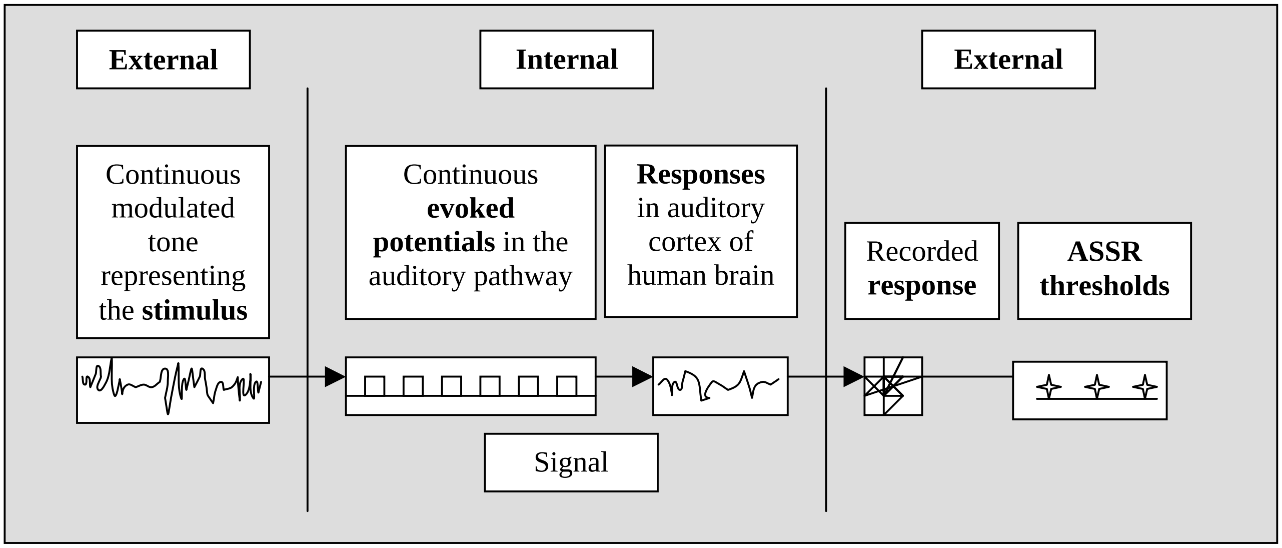

Figure 1.1 Illustration of terminology used in current study

The modulated tone generated by the ASSR hardware is referred to as the **stimulus**[4]. The term stimulus is defined as something, which excites or produces temporary increase of vital action (*The Concise Oxford Dictionary*, 1990). The arousal of the auditory organ or parts of the auditory pathway is responsible for the action potentials that are evoked (Lins et al. 1996).

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[4] Stimulus: something that evokes reactions in an organ or tissue or stimulating effect (*The Concise Oxford Dictionary*, 1990)

The **evoked**[5] **potentials**[6] are event related, meaning that the initial potential induces the following potential to be evoked, thus providing the continuous production of evoked potentials along the auditory pathway (Lowery, Robinson, Eswaran, Verba, Haid & Cheung, 1998). This continuous stream of evoked potentials is referred to as the signal**.** When the signal has been conveyed to the auditory cortex, a **response**[7] to the signal or change in electrical potential is acknowledged (On line medical dictionary: www.http://cancerweb.ncl.ac.uk/cgi/omd, Lowery et al. 1998).

Changes in stimulus intensity have a direct and proportioned effect on the electrical activity. At low stimulus intensities the electrical activity may dampen down to the extent that no response can be recorded. This is because in comparison to other electrical activity of the human body, the evoked electrical activity becomes significantly small. The comparison is referred to as the **signal-to-noise ratio**, where the noise refers to other activity in the human body but can also refer to external acoustic ambient noise (Picton et al. 1998).

The minimum intensity level to which **responses** to the stimuli presented are recorded from the human scalp and analyzed by the ASSR software are plotted on an audiogram and then referred to as **ASSR thresholds**.

1.5 Division of Chapters

☙ Chapter one: Orientation and Problem Statement

This chapter provides an overview of the difficulty in obtaining accurate hearing thresholds in the "difficult-to-test" population. The currently implemented objective procedures are discussed briefly and some of their limitations highlighted. To introduce ASSR as an audiometric procedure, it is placed in the existing audiometric framework by defining the procedure. The chapter explains the problem and subsequently the purpose

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[5] Evoked: an induced response (*The Concise Oxford Dictionary*, 1990).

[6] Potential: electrical activity coming into action (*The Concise Oxford Dictionary*, 1990).

[7] Response: a change caused by a stimulus (*The Concise Oxford Dictionary*, 1990)

of this study: to investigate the accuracy of threshold estimation using the ASSR procedure, in subjects with normal hearing abilities and hearing impairment.

- **Chapter two: Introduction to the clinical Auditory Steady State Response realm: from stimulus presentation to the recording of responses.**

This chapter discusses ASSR as an audiometric procedure, defining related terms and explaining the underlying physiological and audiological concepts. A historical overview is given to describe the development of the procedure. The electronic and mathematical techniques that have been implemented and which aided the process of recording are briefly discussed, as well as the characteristics of ASSR. The influential variables are highlighted and brought into perspective. A further critical evaluation of the different means of stimulus presentation is provided, as well as the advantages and limitations. The comparison between ASSR and other similar objective procedures (introduced in the introductory chapter) are discussed. The clinical application of ASSR as the result of current clinical research is discussed and integrated.

- **Chapter three: Research Methodology**

This chapter describes the method that was used to implement this study. The research design of the current study is stipulated. As well as the selection of subjects, procedures implemented, apparatus used and data collecting procedures are described.

- **Chapter four: Results and Discussions**

This chapter presents the results of the current study. The data is discussed in accordance with the sub-aims presented in chapter three and the relevant data is presented graphically. Each result is followed by an interpretation of the data and discussion with regard to the literature.

- **Chapter five: Conclusions**

In this chapter conclusions are drawn from the results obtained. Significant results are highlighted and their contribution to the literature is discussed. A conclusion regarding the aim of the study is provided. A critical evaluation of the study highlights its limitations and subsequent recommendations for further research is provided.

1.6 Summary

This chapter provided an overview of the problem that arises when dealing with the "difficult-to-test" population in the estimation of hearing thresholds. The existing framework of objective procedures in relation to ASSR was highlighted. The ASSR procedure was discussed briefly as well as the different means of presenting stimuli integrated in the historical overview of ASSR. The rationale of the study was formulated and the problem the research will address was stated. Potentially ambiguous terminology was discussed briefly and the division of the chapters of this study was depicted and served as further footing towards the study.

2

Introduction to the clinical Auditory Steady State Response realm: from stimulus presentation to the recording of responses

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

The basic assumption that early detection followed by early intervention maximises the benefits the child will receive has resulted in an increased number of newborn hearing screening programs (Diefendorf, 2002). The implementation of more hearing screening programs will substantially increase the number of infants and young children who require accurate audiometric evaluation (Stürzebecher, Cebulla & Pschirrer, 2001). These infants and children have been classified as being "difficult to test" due to the limitations of standard audiometric procedures. This could be the reason for the expansion of audiometric procedures into the realm of objective physiological procedures (Goldstein & Aldrich, 1999). Since behavioural audiometry has shown limitations in estimating accurate hearing thresholds of the "difficult-to-test" populations, these objective procedures are necessary to form the basis for further management. This implies that procedures, implementing stimuli that will guarantee the responses are unique to specific ranges of the cochlea (frequency specific) and require only limited cooperation from the subject (objective responses) are needed (Griffith & Chambers, 1991).

Researchers facing this challenge developed the ASSR procedure, as it fulfils the need for an objective measure of frequency-specific hearing threshold in the “difficult-to-test” population (Kuwada et al. 1986; Linden et al., 1985; Sininger & Cone-Wesson, 2002; Stapells et al., 1984).

The rest of this chapter will be dedicated to the discussion of ASSR’s functioning in the existing framework of objective procedures and its characteristics. Reference will be made to the historic origin, modulation of stimuli, generation of potentials, site of generations and the recording of responses. The variables that influence the recording of ASSR will also be discussed. The different methods of stimulus presentation (monotic single ASSR and dichotic multiple ASSR) will be elaborated upon. Following the discussion of the different methods of stimulus presentation, a brief comparison between ASSR and ABR will be provided. The last part of this chapter will focus on current clinical research, which will be integrated with the clinical applications of ASSR. The outline of this literature chapter can be explained on the basis of Figure 2.1 (page 13).

2.2 Existing framework of objective procedures

For ASSR to fit into an existing framework it has to compare with and improve upon other procedures that address the same problems. The audiometric framework ASSR has to improve upon, is primarily the use of OAE and ABR (Lins et al. 1996). These two procedures provide complimentary objective audiometric information but they present with certain limitations that inhibit the clinical evaluation of hearing thresholds at several specified frequencies (Diefendorf, 2002; Picton, Dimitrijevic & John, 2002).

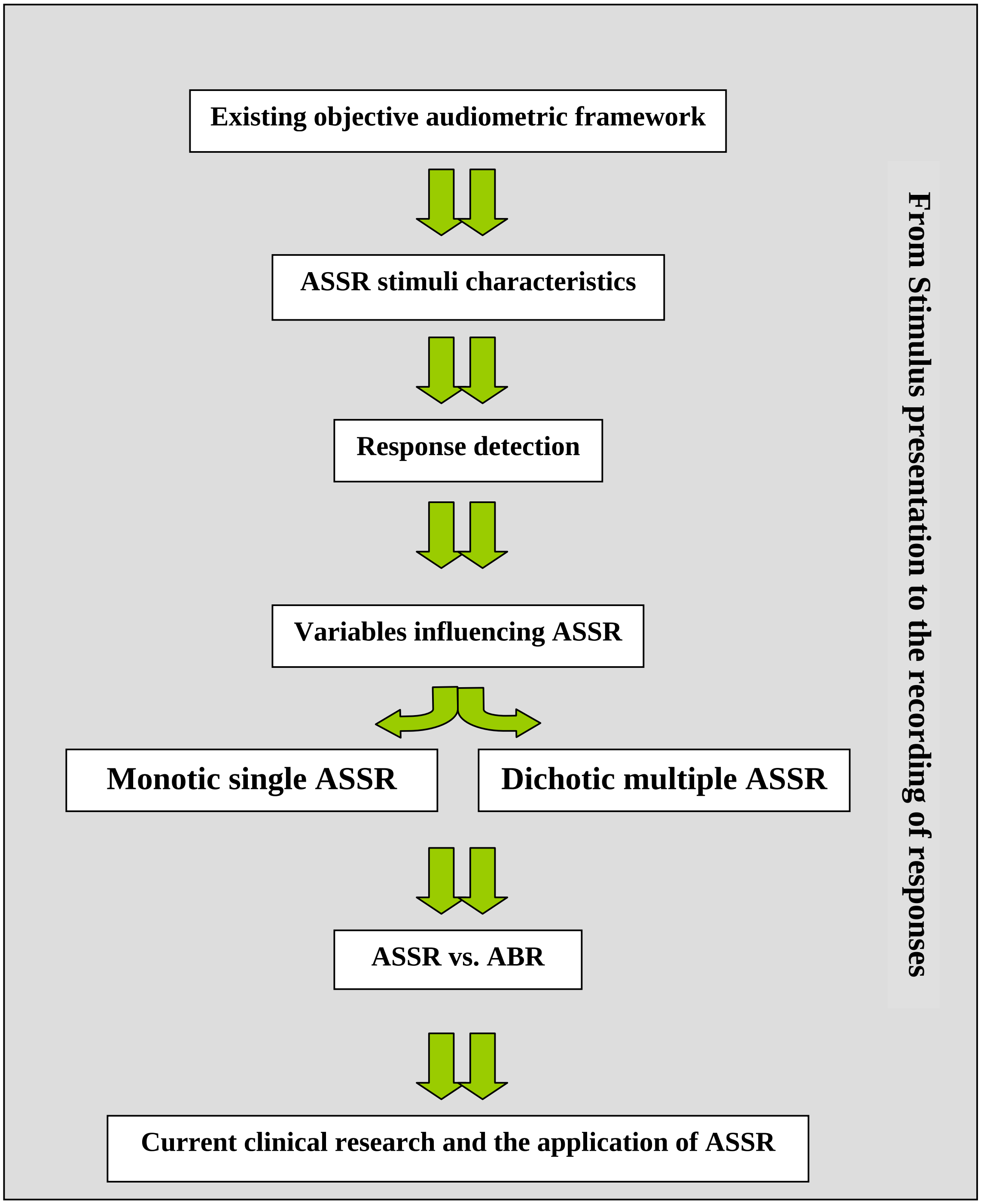

Figure 2.1. Outline of Chapter 2: From stimulus presentation to the recording of responses

Certain types of OAE provide frequency-specific audiological information and can detect cochlear dysfunction before it is evident by pure tone audiometry. However, when determining the hearing thresholds of an individual, OAE can only serve as a preliminary step towards further assessment. This is because of the lack of correlation between OAE and conventional audiometry (Hall, 2000). OAE like ASSR are sinusoidal responses to stimuli but they do not provide the same diagnostic information (Dobie & Wilson, 1996). OAE does not evaluate the functioning of neural auditory pathways and is subsequently not a threshold seeking procedure (Hall, 2000).

On the other hand ASSR, as well as ABR, provide information regarding hearing sensitivity (Gorga, 1999) and presently ABR is the gold standard with regard to the “difficult-to-test” population (Rance et al. 1998). The transient responses of the ABR procedure are elicited with short duration stimuli, providing clearly defined responses (Gorga, 1999). These short duration stimuli are mainly presented in two different ways: click stimuli and tone-burst stimuli.

Firstly, click ABR stimuli have shown limitations with regard to frequency-specificity as the more abrupt the stimuli, the less frequency specific it becomes. Henceforth the responses recorded have been shown to correlate largely with pure tone audiometric thresholds in the region of 2 to 4 kHz (Gorga, 1999; Stapells, 1989; Durieux-Smith et al. 1991; Rance et al. 1995). In comparison, the ASSR procedure implements stimuli that are continuous and subsequently do not suffer these kinds of frequency specificity problems.

Secondly, tone-burst ABR stimuli have been commonly used to facilitate the recording of near threshold frequency-specific information in quiet environments (Gorga, 1999; Lins et al. 1996). Some degree of frequency splatter does occur because it also consists of short duration stimuli. However, tone-burst ABR in conjunction with notched noise to mask frequency splatter ensures better frequency-specificity (Gorga, 1999). High correlation between the results obtained with the notched-noise technique and the pure tone audiogram at 0.5, 2 and 4 kHz was established (Gorga, 1999). Unfortunately, the tone-bursts combined with notched-noise masking technique have been described as time consuming, technologically complex and also requiring significant expertise in interpreting the results. The technique is also not equipped with objective procedures for response detection. In comparison, ASSR takes approximately the same time to record responses as ABR (when implementing dichotic multiple ASSR, the duration of testing is significantly less than that of ABR) and makes use of automated response detection (Oates & Stapells, 1998; Perez-Abalo, 2001; Stürzebecher et al. 2001; Swanepoel, 2001). Thus ASSR is adding and improving on the existing objective audiometric framework.

2.3 ASSR: from stimulus presentation to the recording of responses

The unique characteristics of the ASSR procedure will be elaborated upon, from the presentation of modulated stimuli, the evoking of potentials in the auditory system and the recording of responses from the human scalp.

2.3.1 Characteristics of ASSR Stimuli

Most evoked potential procedures have transient responses[1] to the presentation of auditory stimuli (Linden et al. 1985; Pantev, Roberts, Rob & Wienbruch, 1996; Rance et al. 1998; Stapells et al. 1984) however, when these transient responses merge into each other to the extent that they cannot be clearly identified as separate transient events, the response is classified as a steady-state response. This occurs when the rate of stimulus presentation is significantly higher than with other AEP procedures (Cohen et al. 1991). Aoyagi and colleagues (1996) described this kind of response to stimuli as the “following response” because the evoked potentials follow onto each other without any intervals. Presently steady-state responses to stimuli are classified by different terms, but for the purposes of this study the technique will be referred to as Auditory Steady-State Response (ASSR).

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[1] Transient Responses: Responses recorded using stimulus rates that allow the response to one stimulus to be completed before the next stimulus is presented (John et al. 1998)

In an attempt to describe the effect the ASSR stimuli has on the human auditory system, reference is made to the generation of potentials, as well as the site of generation. Firstly the **generation of potentials**: the sounds presented to the human ear cause polarization and depolarization of the inner hair cells of the cochlea by means of mechano-electrical transduction. Only depolarization of the inner hair cells cause the auditory nerve fibres to transmit action potentials. For this reason the output of the cochlea contains a rectified version of the acoustic stimuli. This rectification causes the output of the cochlea to have a spectral component at the frequency at which the carrier frequency was modulated. This component can be used to assess the response of the cochlea to the stimuli with variation in intensity at the frequency of the carrier (John et al. 1998; Lins et al., 1996).

To describe the **site of generation,** Pantev and colleagues (1996) depicted the tonotopic organization of the sources of steady-state responses and found stimulus rates may selectively activate specific clusters of neurons in the auditory pathways. These neurons receive input from different regions of the cochlea and distribute the information to the cortex in a tonotopic arrangement. John and Picton (2000) stated that these responses are generated by neurons in the brainstem and possibly cortex that respond to both transient stimuli and amplitude-modulated (AM) tones. Later research confirmed the previous statement by saying that the responses may be derived from either thalamo-cortical connections and/or the primary auditory cortex (Boettcher, Poth, Mills & Dubno, 2001).

The stimulus that is presented consists of an acoustic tone, the **modulation of this tone** is a unique characteristic of the ASSR procedure. ASSR stimuli are modulated in amplitude and/or frequency. This occurs when a continuous tone is modulated at frequencies between 3 and 200 Hz, so that a response can be recorded at the frequency of modulation (John & Picton, 2000; Lins et al. 1996; Stapells et al. 1984). The potentials evoked, follow the modulation frequency of the sinusoidal amplitude modulated tone (Levi, Folsom & Dobie, 1995). Reference is made to Figure 2.2 adapted from Lins et al. 1996, explaining the modulation of the tone. The left side of Figure 2.2 shows a carrier tone multiplied with amplitude A by a modulating waveform generating an amplitude-modulated tone. The carrier frequency is the test frequency. The right side of Figure 2.2

shows how four different **amplitude-modulated tones,** each with a different carrier frequency and **modulation frequency,** can be combined to make up a combined stimulus.

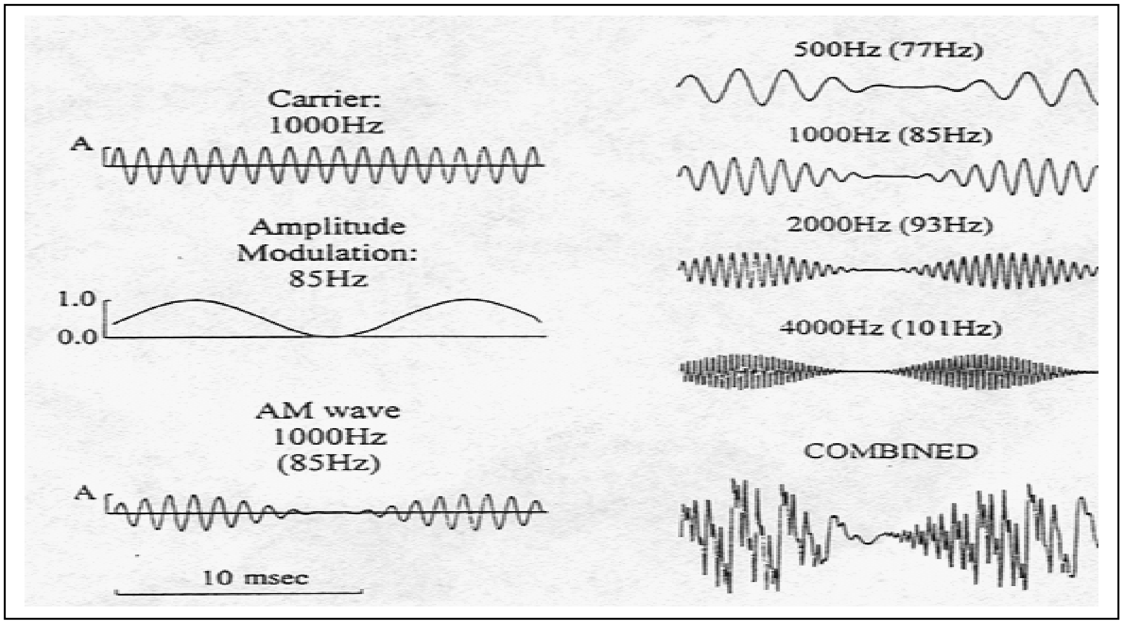

Figure 2.2 Modulation of carrier frequency. Adapted from Lins et al. 1996

The carrier frequency is thus amplitude-modulated (AM) by a modulation frequency, which refers to the **rate at which the carrier frequency is modulated**. Early studies of ASSR (Galambos et al. 1981) used tones modulated at 40 Hz but later studies found that these rates were significantly affected by the state of consciousness (Jerger et al. 1986; Lins & Picton, 1995; Stapells et al. 1988). In later years, the carrier tones were amplitude-modulated by frequencies between 75 and 110 Hz, more commonly referred to as the 80 Hz rate of modulation (Lins et al. 1996). This is evident in Figure 2.2 where higher rates of modulation are illustrated. The most important factor for the variation in rate of modulation can be attributed to the subjects' state of awareness (whether they are asleep or sedated) (Rance et al. 1995). The negative effect of sleep on the recording of responses was the catalyst in the exploration of less susceptible modulation rates. As summarized in Table 2.1. these higher modulation rates are less susceptible to sleep or sedation, making the implementation of these rates more applicable to the "difficult-to-test" population.

Table 2.1 Progression of research from the 40 Hz – 80 Hz rate of modulation.

Findings and progression of relevant research	Researchers
Using a stimulus rate of 40 Hz, reliable responses at approximately 30 ms in latency were elicited, facilitating the estimation of frequency-specific thresholds in subjects.	• Galambos et al. 1981 • Brown & Shallop, 1982 • Shallop & Osterhammel, 1983
Limitations of this stimulus rate included the following: • Significant effect on amplitude of response when subject is sleeping or sedated. • Difficulty to record responses in infants. • Responses are dramatically attenuated during general anesthesia. • Underestimation of behavioural thresholds at 500 Hz for subjects with significant hearing impairment.	• Dauman, Szyfter, Charlet de Sauvage & Cazals, 1984 • Lynn et al. 1984 • Kankkunen & Rosenhall, 1985 • Linden et al. 1985 • Osterhammel, Shallop & Terkildsen, 1985 • Sammeth & Barry, 1985 • Jerger et al. 1986 • Madler & Poppel, 1987 • Stapells et al. 1988 • Plourde & Picton, 1990 • Suzuki, Kobayashi & Umegaki, 1994
Modulation rates between 70 and 110 Hz were implemented and responses recorded with latencies at approximately 10 ms. Thresholds were obtained consistently during sleep at low sound pressure levels. Although responses are smaller than the 40 Hz responses during wakefulness, they are much less affected by sleep.	• Cohen et al. 1991 • Aoyagi, Fuse, Suzuki, Kim & Koike, 1993 • Lins & Picton, 1995 • Aoyagi, Yamazaki, Yokota, Fuse, Suzuki, Itoh & Watanabe, 1996
Reliable responses were elicited to amplitude-modulated tones in sleeping adults and young children at approximately 80 Hz modulation rate.	• Cohen et al. 1991 • Levi, Folsom & Dobie, 1993
Modulation rates between 70 Hz and 110 Hz found to be optimal for obtaining clear ASSR responses in sleeping adults and infants. Although the responses are significantly smaller it is a fast, reliable and accurate procedure.	• Rickards et al. 1994 • John et al. 1998
Amplitude modulated tones between 70 Hz and 110 Hz at varying intensities, indicated that thresholds can be obtained within 10-20 dB of behavioural thresholds in the frequency ranges of 0.5 – 4 kHz.	• Rance et al. 1995 • Lins et al. 1996 • Herdman & Stapells, 2001

Another stimulus characteristic of the ASSR procedure lies in the presentation of the stimuli. Single or multiple tones can be presented to either both ears simultaneously or sequentially. It will be discussed under heading 2.4, where the different methods of ASSR stimulus presentation are discussed.

2.3.2 Recording of ASSR Responses

As with other AEP procedures, ASSR stimuli evoke potentials that are recorded as responses from electrodes on the scalp. The responses to the stimuli are the basis for further management as these serve as estimations of behavioural hearing thresholds. In order to obtain these important responses a significant amount of mathematical equation is required to obtain accurate estimation of thresholds.

A steady state evoked potential is identified by its amplitude and phase (John & Picton, 2000). This implies that for the response to be recorded at the intended frequency, it has to be transformed from the time-domain to the frequency domain. This is done by a **Fast Fourier Transform (FFT)** where the input wave and output response are both sinusoidal (Stapells et al. 1984). The FFT converts the original amplitude-time waveform into a series of cosine waves with specific frequency, amplitude and phases (Milford & Birchall, 1989). The FFT depicts the amplitude and phase of activity at the frequency of stimulation. Therefore the responses to each carrier frequency can be assessed by the amplitude and phase of the FFT component corresponding to the frequency of modulation of the carrier (Lins & Picton, 1995; Lins et al., 1996; Rodriquez et al., 1986).

To determine whether a response was present or not due to low signal-to-noise ratios, various tests can be implemented. According to Dobie and Wilson (1996) there are three tests to detect responses in sinusoidal stimuli, one of which is known as the f-test. This method evaluates whether a response at the frequency of stimulation (modulation frequency) is different from the noise at adjacent frequencies, making the recording of the response more reliable (Dobie & Wilson, 1996; Lins et al. 1996).

The second test is the T^2 test, which also works on the principle of comparing the signal to noise in determining the confidence level of the response (Dobie & Wilson, 1996; Lins et al. 1996). Lastly, if it is assumed that the phase data is always available, some measurements according to John and Picton (2000) calculate “phase coherence”. A response is considered reliable if its phase remains constant over time rather than varying randomly. A further improvement in response detection comes from weighting the detection protocols to recognize responses with phase closer to that which is expected (Picton, Dimitrijevic, John & van Roon, 2001). Another technique that is commonly used is signal averaging. This is not a response detection technique but used to increase the signal-to-noise ratio in order to make the detection and measurement of evoked potentials easier (John, Dimitrijevic & Picton, 2001).

2.3.3 Influential Variables

An intricate relationship between the different variables that influence the recording of steady state responses, make classification of the variables difficult. Certain variables pertain to subject variables and others to audiometric variables such as the age of subjects or the stimulus intensity. These variables share a significant amount of similarity regarding their influences on ASSR, which makes classification difficult.

- **Modulation of stimuli**

  As numerous studies in the field of ASSR have proven over the years, modulation of a tone at a high rate provides valuable information regarding the hearing sensitivity of subjects in a frequency specific manner (Galambos et al. 1981; Cohen et al. 1991; Lins & Picton, 1995; Lins et al. 1996). It was found that by combining AM and FM (frequency modulation) when modulating the carrier tone, larger responses could be elicited without significantly changing the frequency specificity of the stimulus (Picton et al. 1998; Picton et al. 2002).

When using the ASSR procedure the tones are modulated in amplitude by adding a frequency in the range of either around 40 Hz or 80 Hz (rate of modulation) to the carrier frequency (which is the frequency to be assessed). By combining frequency and amplitude modulation in a prescribed ratio, for example FM at 25% and AM at 100%, larger responses can be recorded (Stürzebecher et al. 2001; Perez-Abalo et al. 2001). The amplitude modulated tones are mainly mediated by neurons with characteristic frequencies higher than the carrier frequency of the modulated tone and frequency modulated tones are mediated by neurons with characteristic frequencies lower than the carrier frequency (Dimitrijevic, John, van Roon & Picton, 2001). Thus making the recording of responses more reliable when combining both amplitude and frequency modulation in order to evoke larger potentials. This method, where both amplitude and frequency modulation is implemented is known as mixed modulation and can be varied in ratio.

- **Rate of modulation**

The rate at which ASSR stimuli are presented separates the procedure from other AEP procedures. The sufficiently high rate of presentation is what causes the overlapping of responses, which evokes the steady state potentials (Lins et al. 1996). The progression and development of the rates that were implemented was discussed in Table 2.1. As it was highlighted in Table 2.1, the state of arousal or wakefulness the subject is experiencing is the main influential factor for the rate of modulation. This can be attributed to the anatomic structures allocated to the elicitation of the potentials. In a waking subject the dominant response while implementing 40 Hz rate of modulation, probably derives from the auditory cortex, with the brainstem only contributing minimally (John & Picton, 2000). When a subject is asleep the recorded response reflects the potential evoked mainly in the brainstem, subsequently the response amplitude is much smaller and often difficult to measure (Azzena, Conti, Santarelli, Ottaviani, Paludetti & Maurizi, 1995; John & Picton, 2000; Lins & Picton, 1995). Modulation frequencies ranging between 70 – 110 Hz is resistant against sleep or sedation (Cohen et al. 1991; Levi et al. 1993). Due to the likelihood that higher modulation rates evoke responses at the brainstem level, the latency of the response is shorter and it is known that short latency responses are not effected by sleep or state of arousal, as with the ABR procedure (Levi et al. 1993). In conclusion the use of either modulation rate (40 Hz or 80 Hz) is dependant on the subject's state of wakefulness. Further studies by John and Picton (2000) investigated the use of even higher modulation rates (150 – 170 Hz), potentials were also evoked and it may prove to be a reliable measure in the future.

Both monotic single and dichotic multiple can be modulated with any one of the three rates of modulation regions. The only consideration lies with the dichotic multiple presentation of stimuli, seeing that the modulated tones needs to be an octave apart to keep the responses from attenuating. In a study done by John and colleagues (1998) the results showed that when using 30-50 Hz rates of modulation with the presentation of multiple stimuli the amplitude of the responses is affected. As the number of stimuli simultaneously presented increases the amplitude of the responses decreased. Concluding from that specific study done, when using the dichotic multiple ASSR condition, the higher rates of modulation are more promising than the lower rates (30-50 Hz region). The monotic single ASSR condition shows no such interactions and therefore it can be assumed that any rate of modulation is suitable in this condition (John & Picton, 2000).

Monotic vs. Dichotic presentation

The presentation of stimuli to either one ear at a time or both ears simultaneously describes the different conditions implemented during the ASSR procedure. Reference is made to the monotic and dichotic presentation of stimuli, as discussed in the introductory chapter of this study. With the monotic presentation of stimuli, a combination of modulated tones can be presented to one ear simultaneously, known as monotic multiple, or single tones sequentially, known as monotic single ASSR. The dichotic presentation of stimuli however refers to a combination of modulated tones or one single tone that is presented to both ears simultaneously (Lins et al. 1995; Lins et al. 1996; Picton et al. 1998). Studies have found that at low intensity levels neither monotic nor dichotic presentation of stimuli have a significant effect on the amplitude of the responses (John & Picton, 2000; Lins et al. 1995).

☙ Effects of intensity

The intensity of the stimuli has a significant effect on the recording of individual responses with regard to presentation of multiple stimuli. As with other AEP potential the latency of the responses decrease as intensity increases (John & Picton, 2000). This effect recorded in the time-domain also has an influence in the frequency-domain. As intensity increases, the spread of basal activation along the basilar membrane increase and results in the overlapping of responses. Definite individual responses to each carrier frequency may not be reliably identified (Picton et al. 2002). This can be overcome by separating the carrier frequencies by at least one octave (Herdman & Stapells, 2001; Lins & Picton, 1995; Perez-Abalo et al. 2001; Schmulian, 2002) and thresholds can be obtained at high intensity levels using the dichotic multiple ASSR condition.

Another consideration while presenting multiple tones at high intensity levels is the configuration of the hearing loss. A hearing loss may be sloping and at some frequencies present with normal hearing or only a mild hearing loss and then slope to a severe hearing loss. When simultaneously presenting multiple tones at high intensity levels across the frequency spectrum it may cause discomfort in some subjects (Schmulian, 2002).

Lastly, when presenting stimuli in a sequential manner to either one ear at a time or both, the intensity of the stimulus only has an effect on the amplitude of the response. The amplitude of the ASSR increases with increasing stimulus intensity. This phenomenon is applicable to both the 40 Hz and 80 Hz rate of modulation (Lins et al. 1995; Rodriguez et al. 1986).

- **Multiple stimuli**

  The presentation of multiple stimuli is a time-efficient manner of presenting tones (John et al, 1998; Swanepoel, 2001). However as it has been stated before, at high intensity levels, the accurate estimation of hearing thresholds may be influenced due to the difficulty of recording individual responses. John and Picton (2000) recorded an increase in latency when presenting multiple stimuli simultaneously. They further explained that the increase in latency could be attributed to the traveling wave velocity or frequency-related change in conduction time. The presentation of multiple stimuli is only considered to be diagnostically questionable at intensity levels above 60 dB HL. This variability at high intensities could have a significant effect on the validity of multiple simultaneous presentation of stimuli. However the reduction in amplitude or difficulty in recording individual responses may be overcome by separating the stimuli by an octave (John et al. 1998).

- **Age and Gender**

  Gender has to a certain extent some influence on the ability to record ASSR, this is related to certain anatomical structural differences between male and female subjects. John and Picton (2000) reported that the length of the basilar membrane of males is slightly longer than that of female subjects. This could possibly result in a traveling wave delay along the membrane, so that the time for the response to be recorded could take longer and the time domain transformed into the frequency domain could cause a frequency related delay. Subsequently a slight difference may be recorded in the responses of male and female subjects. Another possible effect of the influence gender may have on the recording of responses is head size. The diameter difference of male and female craniums has been reported by Goldstein and Aldrich (1999) to possibly have an influence on the recording of AEP. The possible influence of head size and length of the basilar membrane has not been significantly explored and subsequently no definite conclusions can be drawn.

The variable of age however has been slightly ambiguous. It was concluded that responses could be evoked in newborns within the first few days of life (Aoyagi, Kiren, Kim, Suzuki, Fuse & Koike, 1992), but in a recent study by Boettcher and colleagues (2001) age-related differences in older subjects has been brought to the attention of researchers. In aged subjects with normal hearing abilities abnormal intensity discrimination have been observed (Florentine, Reed, Rabinowitz, Braida, Durlach & Buus, 1993), possibly attributed to deteriorating neural pathways, however this remains inconclusive. A later study by Boettcher, Madhotra, Poth and Mills (2002) showed that ASSR, in comparison with other AEP techniques (for example ABR), does show that age can play a role with regard to the amplitude of responses. In other AEP techniques the amplitude of responses decrease with age, but to the contrary the amplitude of ASSR responses increases with age (Boettcher et al. 2002). They attributed this to the fact that the source of generation of the different AEP procedures varies. Within the field of ASSR no conclusive evidence was reported that age has any significant influence on the responses of either monotic single or dichotic multiple ASSR (Boettcher et al. 2002), except in infants the responses to multiple presentation of stimuli may be influenced by the underdeveloped neural pathways (Lins et al, 1996). Conclusively no evidence was found to state that age had any significant effect on the recording of ASSRs (John & Picton, 2000; Stapells et al. 1984).

- **State of consciousness**

Earlier in this chapter (reference to Table 2.1) the rate of modulation was discussed, indicating that slower rates of modulation (40 Hz) are significantly affected by sleep but with higher rates of modulation (80 Hz) neither sleep, sedation nor anesthesia has an influence on the recording of ASSR (John, Dimitrijevic & Picton, 2002). It is interesting to note that in the study by Cohen and colleagues (1991), it was found that the different stages of sleep do to some extent influence the ASSR, but not to the extent that it is a consideration in the recording of responses.

- **Hearing sensitivity**

Research done by Rance and colleagues (1998) showed that with an increase in stimulus intensity, an increase in the ASSR amplitudes could be recorded in hearing-impaired subjects. This was attributed to recruitment, which in ears with significant sensory-neural loss can lead to an increase in ASSR amplitude near threshold. These results were also obtained in a previous study by the same researchers in ears with severe to profound hearing losses (Rance et al. 1995). This implies that in hearing-impaired ears ASSR thresholds can be accurately obtained at low sensation levels with high intensities. It is important to note that the findings by Rance and colleagues (1998) were relevant to the monotic single ASSR procedure. The same trend was observed in studies using the dichotic multiple ASSR procedure, where an increase in intensity correlated with a decrease in the difference between the physiological (ASSR) and behavioural thresholds (Perez-Abalo et al. 2001; Picton et al. 1998; Schmulian, 2002).

An interesting concept that contributes to the explanation of this phenomenon is described in a study by Strecker Hesse and Gerken (2002) on the effects of hearing impairment while using the auditory Middle Latency Response (MLR). They based their theory on the increased neural responsiveness that exists in the presence of a hearing loss. This theory explored by Jastreboff (1990) with regard to the perception of tinnitus in the presence of a hearing loss, explains that there may be an increased evoked response in the vicinity of the neural edge, meaning that a hearing loss produces a region of increased gain within the central auditory system. These findings suggest reliable hearing level prediction for ears with significant hearing loss (Rance et al. 1998).

With regard to normal hearing subjects, numerous studies have found that thresholds could be estimated within 10-20 dB of behavioural thresholds (Herdman & Stapells, 2001; Lins et al. 1996; Perez-Abalo et al. 2001; Picton et al. 2002).

2.4 Monotic single and Dichotic multiple ASSR

Two methods of ASSR presentation have been highlighted in the previous section and will now be elaborated upon as separate entities.

2.4.1 Monotic single ASSR

Monotic single ASSR is a variation of the different means of presenting ASSR stimuli, using amplitude modulated (AM) tones of which the carrier frequencies are modulated with frequencies between 3 and 200 Hz. The modulated tones are presented to each ear separately in an attempt to obtain frequency specific information (Herdman & Stapells, 2001; Lins et al. 1996; Picton et al. 1998). This is similar to pure tone and ABR threshold procedures, where a single tone is presented to obtain frequency information to each ear separately. The main characteristic of monotic single ASSR is monaural presentation of single modulated stimuli in a sequential manner. The amplitude-modulated tones usually are also frequency modulated (FM) in an attempt to increase the amplitude of the response to improve recording of the specific response, subsequently referred to as mixed modulation.

C

Historically the monotic single ASSR condition was the first means of presenting steady state stimuli, which evolved out of the research done by Galambos and colleagues (1981). At that stage it was known as the "40-Hz response" (Galambos et al. 1981). This procedure served as the basis for research to follow. It was then mainly developed for threshold estimation in young children but the major clinical application has been the assessment of Cochlear Implant candidacy (Aoyagi et al. 1992; Rickards et al. 1994).

This can be attributed to the fact that with monotic single ASSR responses can be reliably evoked at high intensities (Rickards et al. 1994). This characteristic of monotic single ASSR is what sets it apart from other AEP procedures and, until recently, from other ASSR conditions. With recently available ASSR systems, intensities of approximately 120 dB HL can be obtained (GSI Audera, 2001). Severe to profound hearing losses can thus be identified. It is also possible to present four different frequencies simultaneously to one ear at a time, referred to as monotic multiple ASSR (Herdman & Stapells, 2001)

For the purposes of this study only the monotic single and dichotic multiple ASSR conditions will be highlighted as they represent the extremes of stimulus presentation. A few significant advantages of monotic single ASSR over other AEP procedures and dichotic multiple ASSR will be highlighted (Perez-Abalo et al. 2001; Stürzebecher et al. 2001).

- Being periodic, the responses to ASSR can easily be represented in the frequency domain and subsequently on an audiogram, making the measurements of the hearing sensitivity easier.
- The acoustic stimuli are more frequency-specific than any other AEP technique, even more frequency specific than the multiple presentation of ASSR stimuli, since the spread of activation on the basilar membrane at high intensities cause attenuation (John & Picton, 2000).
- The response evoked by an amplitude-modulated tone is represented as a single peak in the spectrum at the frequency of modulation, because of the rectification properties of the cochlea (Lins et al. 1996). This makes it more easily and accurately detectable with the use of statistical techniques. It is therefore objective in the measurement and interpretation of responses.
- The monotic single ASSR condition can reach high intensities without any loss of amplitude to the responses, meaning that subjects with significant hearing losses can be assessed and thresholds obtained (Picton et al. 1998). This makes the procedure objective and reliable in the estimation of hearing thresholds with the aim of providing amplification in managing the hearing loss (Picton et al. 1998; Rance et al. 1998).

The most significant clinical limitation of monotic single ASSR is the time needed to obtain a full set of results. As the stimuli are presented to each ear individually, the clinician still needs to ascend or descend in intensity to estimate the threshold for each individual frequency (Perez-Abalo et al. 2001).

Example: 4 frequencies (0.5, 1, 2 & 4 kHz)
X 2 ears
X 6 intensity steps (approximately)
= 48 recordings per subject

Additionally, the response to the stimuli can only be recorded once a number of responses have been compared to, for example the adjacent noise, for it to be reliable. Even multiple monotic ASSR is more time consuming than dichotic multiple ASSR, for the simple reason that the ears are tested individually and not simultaneously (Stürzebecher et al. 2001). Due to this limitation some of the focus of research has shifted towards a more time-efficient manner of stimulus presentation (Lins et al. 1996). However, it is important to note that one should not sacrifice accuracy to be time efficient.

2.4.2 Dichotic multiple ASSR

Dichotic multiple ASSR can be described as a technique making use of multiple amplitude modulated tones, frequency modulated into a complex acoustic signal, presented simultaneously to both ears. Lins and Picton (1995) described it as modeling different stimuli at different rates so that the response to the individual stimulus can specifically be assessed in the frequency domain by the spectral component of the corresponding modulation frequency. Provided that distinct modulation rates are used for the different carrier tones so that they are more than one octave apart, these amplitude-modulated tones can be added together by frequency modulating all four tones into a complex acoustic stimulus. It was also determined that if the carrier frequencies were at least one octave apart, the amplitudes to the simultaneous presentation were not significantly different from the individual presentation of stimuli (John et a. 1998). This complex acoustic stimuli is capable of simultaneously activating different regions of the cochlea and in so doing estimate four frequency specific thresholds in each ear at the same time (John et al. 1998; Lins & Picton, 1995; Perez-Abalo et al. 2001). Furthermore the method of multiple presentations to both ears simultaneously defines the term dichotic multiple ASSR. The multiple ASSR condition also known as the MASTER technique (Multiple Auditory Steady-state Response) allows rapid assessment of thresholds at multiple audiometric frequencies at both ears simultaneously (Picton et al. 1998). Some of the latest studies show that multiple ASSR can be easily recorded and objectively measured in the frequency domain (John et al. 2001). Dichotic multiple ASSR may be a very useful and time-efficient tool for measuring hearing thresholds binaurally (Picton et al. 2002).

Historically dichotic multiple ASSR was based on the findings of Regan and Cartwright (1970) and revised by Regan (1989) showed that Visual Steady State Responses to several simultaneous stimuli could be recorded and analyzed independently if each stimulus is modulated at a different rate.

Significant advantages of dichotic multiple ASSR have been reported by John and colleagues (1998). They found that by only separating the different stimuli an octave apart there was no significant decrease in amplitude of the responses when using the multiple stimuli in comparison to single stimuli. With no decrease in response amplitude the reliability of the responses is essentially the same. It can therefore be concluded that single presentations and multiple presentations have the same advantages over other AEP procedures. The main advantage of the multiple stimuli technique however, is its time efficiency. To record eight responses in both ears may take the same amount of time to evoke one response using the single stimuli technique (Perez-Abalo et al. 2001; Picton et al. 1998).

A limitation of dichotic multiple ASSR would be the wide activated range on the basilar membrane of the cochlea (Stürzebecher et al. 2001). This occurs when amplitude modulated tones are frequency modulated which is the case with both techniques but more so with the multiple stimuli technique. The implication is that with both frequency and amplitude modulation this complex acoustic stimulus activates a large region on the basilar membrane of the cochlea. The usual amplitude modulated tone has a spectral width of approximately 180 Hz. With frequency modulation, a wider frequency range can be stimulated, explaining the fact that there has to be at least one octave difference between each frequency for the responses to be separately identified.

At high intensities the range becomes even wider and with this kind of overflow a decrease in amplitude of the response will occur (Stürzebecher et al. 2001). At high intensities the activation patterns for the different stimuli will overlap, resulting in significant interactions in the generation of the electrical responses. Therefore although the basilar membrane is responding to the stimuli, the exact location on the membrane cannot be ascertained (Picton et al. 2002). The intensity level at which this limitation becomes evident was identified to be above 60 dB SPL (John et al. 1998; Picton et al. 1998). Because of this fact, thresholds at high intensities were thought not to be reliably estimated and this was considered a limitation of dichotic multiple ASSR. However, in more recent studies, no significant effect was recorded when estimating thresholds of high intensity, while implementing multiple stimuli (Perez-Abalo et al. 2001; Schmulian, 2002). The capabilities of the dichotic multiple ASSR condition at high intensities therefore remains inconclusive.

2.4.3 ASSR vs. ABR

At this point, it is possible to compare the clinical application of ASSR and ABR. According to Sininger and Cone-Wesson (2002) both the ABR and ASSR could be used to estimate pure tone sensitivity for infants, children, and adults with hearing impairment, yet the value of the two techniques for this application still has to be established. However recent studies, with this aim in mind, have established both techniques as being reliable and accurate in their ability to estimate hearing thresholds (Schmulian, 2002; Swanepoel, 2001). The following comparisons will highlight the differences between ABR and ASSR.

- The ABR procedure is unaffected by sleep or sedation, thus being useful in the "difficult-to-test" population (Rickards et al. 1994). With the ASSR procedure, on the other hand, only the potentials evoked at higher modulation rates are unaffected by sleep or sedation (Picton et al. 1998; Rickards et al. 1994).

- The measurement of ASSR is uncomplicated, in the fact that no interpretation is required to identify responses. This can be attributed to the fact that a computer can record the phase and amplitude of the evoked potential at the frequency of stimulation (Lins et al. 1996). The ABR procedure, on the contrary requires interpretation of the recorded responses before any conclusions can be made (Glascock, Jackson & Josey, 1987; Schmulian, 2002).

- With the ASSR procedure, the presence of responses is clearly definable. One of the techniques used to record responses, compares responses with noise levels of adjacent frequencies and assesses their reliability by means of reproducibility (John & Picton, 2000; Lins et al. 1996). The presence of responses with the ABR is left to subjective interpretation (Lins et al. 1996; Schmulian, 2002).

- The reproducibility and stability of the ABR responses from test to retest is high, whereas the reproducibility of ASSR still has to be determined (Picton et al. 1998). As the recording of ASSR are subjected to a number of influential variables.

- Transient stimuli used to evoke an ABR tend to cause a spread of energy in adjacent frequencies other than the intended testing frequency. This spectral splatter has received much attention and it has been found that notched-noise masking reduces the effect of the spread but it still influences the frequency specificity (Rance et al. 1995; Gorga, 1999). In comparison to this, steady-state responses can be evoked by frequency specific stimuli (Picton et al. 1998). The frequency content of an amplitude-modulated stimulus is concentrated at the carrier frequency presented and at two side bands separated from this frequency by the modulation signal (John &

Picton, 2000; Picton et al. 1998; Lins et al. 1996), indicating that the procedure is frequency specific.

- When using the dichotic multiple ASSR condition, the responses to several simultaneously presented amplitude modulated tones can be obtained (John et al. 1998). The recorded response shows the response to each carrier frequency at its signature modulation frequency. This technique can significantly decrease the time needed to estimate frequency specific thresholds (Lins et al. 1996). In comparison, the time frame of a complete test battery using the ABR procedure does not compare favourably to that of the dichotic multiple ASSR procedure (Swanepoel, 2001).

- Because steady state responses are stable over time and the stimuli are continuous, it is unlikely to be distorted in either a soundfield speaker or hearing aid amplifier. Therefore they can be used to assess aided thresholds (Picton et al. 1998). In comparison ABR stimuli is transient in nature and rapidly changes over time, subsequently it does not experience the same advantage as ASSR in assessing aided thresholds (Hall & Ruth, 1985).

- ABR has been seen as a good indicator for hearing impairment but it is insensitive to threshold variations within the severe to profound hearing loss range, due to stimulus presentation level restrictions (Schmulian, 2002). In comparison the ASSR procedure can reach intensity levels of 120 dB HL and can therefore identify and obtain frequency-specific threshold levels for subjects with a severe to profound hearing loss (Schmulian, 2002).

2.5 Clinical Application

The clinical application of any audiometric procedure establishes its place in the existing field of audiometry. In this section the current clinical research that has been done with regard to the clinical applicability of ASSR will be integrated.

The objective of the Auditory Steady-State Responses procedure as discussed in this chapter, is to obtain frequency-specific thresholds from "difficult-to-test" subjects without any responses required. This fulfils the ultimate goal of any objective audiometric procedure: to obtain substantial information regarding a persons hearing abilities without any behavioural response from the subject in order to manage the impairment if there is any (Aoyagi et al. 1996). To obtain substantial information can be easily done using basic techniques. However, to obtain information from subjects who are either very young (newborns or infants) or subjects who can not reliably respond to sound because of mental or physical incapability or even subjects who would prefer not to respond accurately because of a simulated hearing loss, these "difficult-to-test" subjects would qualify for an objective audiometric procedure (Picton et al. 2001). To quantify an objective audiometric procedure, a number of applications must be discussed: identification of the hearing loss, obtaining substantial information on the hearing capabilities and managing the described hearing impairment.

2.5.1 Identification of Hearing Impairment

As established previously in this chapter and according to various researchers, age has no significant influence on the ASSR measurements (John & Picton, 2000; Schmulian, 2002), making it highly applicable for a variety of subjects from newborn babies to people in the late stages of their lives. The applicability of ASSR also depends on the state of consciousness of the subjects, since young subjects might become restless when awake. Implementing the test while they are asleep and at higher rates (between 70 and 110 Hz) will therefore prove more applicable. Research was undertaken to establish the clinical effectiveness of using ASSR in neonates (Rickards et al. 1994). Three hundred and thirty seven healthy newborn babies, between the ages of 1 – 7 days were tested and findings indicated that testing infants in the first few days of life showed that the responses were well developed and could easily be obtained in a frequency specific manner. Unfortunately no information on the applicability of ASSR in hearing impaired neonates was reported.

In the identification of hearing losses or more simply known as screening, the basic aim is to obtain reliable measurements in a time efficient manner without having to sedate or wait for the subject to sleep before any test can be implemented. The dichotic multiple ASSR procedure can fulfil this aim to provide frequency-specific thresholds, in close estimation of the actual behavioural thresholds, in a time efficient manner. Stimuli, modulated at rates from 70 – 110 Hz ensure that the recording of responses is not effected by sleep or sedation (John et al. 1998; Lins et al. 1996). Furthermore the ASSR procedure is simple in its application and when implementing the dichotic multiple ASSR technique, it is time-efficient as well. The procedure uses automated response detection and is double objective, seeing that no behavioural response from the subject or interpretation by the clinician is necessary (Rickards et al. 1994). Four to eight carrier tones can be presented to each ear simultaneously. In the same time it takes to obtain one threshold in other procedures, eight frequency-specific thresholds can be obtained (Lins et al. 1996; Picton 2002).

In order to establish the applicability of dichotic multiple ASSR a number of studies explored this application, of which a few will be highlighted. Lins and Picton (1995) conducted a study where the focus was on the recording of multiple concurrent steady-state responses, varying the carrier tone and/or modulation frequency. They found that in 40 normal hearing subjects the simultaneous presentation of tones had no significant loss in amplitude with regard to any other means of stimulus presentation. However no measurements were done at that stage in hearing-impaired subjects, where the limitation of this condition proved to be. The same researchers went on and implemented the same kind of study in hearing-impaired and normal hearing subjects using the dichotic multiple ASSR condition (Lins et al. 1996). They substantiated the finding that variability does occur in hearing-impaired subjects at high intensity levels when simultaneously presenting stimuli. In 1998, John, Lins, Boucher and Picton went on to establish stimulus and recording parameters for the MASTER technique. Thirty normal hearing subjects were used and reliable threshold estimation was established. High intensity variability was again substantiated but this finding has not been corroborated until recently. Researchers more recently obtained reliable thresholds at high intensity levels in hearing-impaired subjects using dichotic multiple ASSR (Perez-Abalo et al. 2001; Schmulian, 2002), thus establishing the clinical applicability of this procedure.

2.5.2 Extensive information on Hearing Capabilities

Clinical relevance of the ASSR procedure lies in the ability to reliably predict frequency-specific behavioural thresholds (Rance et al 1995). Thresholds can be recorded between 10 and 20 dB above behavioural thresholds in subjects with normal hearing, as well as hearing impairment, reflecting an accurate configuration of the audiogram (Lins & Picton, 1996). By using statistical techniques the potentials evoked can be accurately recorded in the presence of myogenic- or ambient noise (Picton et al. 2001). The fact that the ASSR thresholds are presented in the form of an audiogram due to the conversion from the time-domain to the frequency-domain, simplifies the interpretation of the results. The configuration as well as degree of the hearing loss can easily be determined to provide appropriate amplification and a standard for early intervention (Lins et al. 1996; Rance et al. 1998).

Furthermore, some researchers early on explored retro cochlear pathology and the functioning of the central auditory pathways while using the ASSR technique. Milford and Birchall (1989) explained that ASSR could give insight, not only to hearing levels but also the functioning of the higher levels of the auditory pathway. This can be attributed to the fact that there are neurons that respond only to changing frequency or amplitude. Responses to amplitude-modulated tones may thus be important in the investigation of the more central parts of the auditory pathway. Current clinical research that explored the estimation of hearing thresholds using ASSR was the following.

Rance and colleagues (1995) examined the relationship between auditory steady state responses and behavioural thresholds in 60 sleeping subjects. They found that the relationship between the ASSR and pure tone thresholds increased with increasing intensity and hearing loss severity. These findings possibly led to the further investigation of ASSR's ability to estimate the degree of hearing loss. Perez-Abalo and colleagues (2001) reported on frequency-specific thresholds in hearing-impaired and normal hearing subjects using dichotic multiple ASSR. Forty three hearing-impaired children and 40 normal hearing adults were used in the study and reliable thresholds were obtained in both groups. The ratio between the ASSR and pure tone thresholds was between 11 and 15 dB in normal hearing subjects and between 5 and 13 dB in hearing-impaired subjects. Like the study by Rance and colleagues, no definite information was provided on the influence of the configuration of the hearing loss on ASSR. Unfortunately the test environment was not adequately controlled for ambient noise levels and subsequently limiting the reliability of the study. The testing environment proved to be an important consideration when implementing ASSR to estimate hearing thresholds.

Herdman and Stapells (2001) compared the estimation of hearing thresholds in 10 normal hearing subjects, while implementing different means of presenting ASSR stimuli. No significant differences between the different means of stimulus presentation were recorded and thresholds within 10 dB of the behavioural thresholds were obtained. This study proved to be of significant value but did not address the recording of ASSR in hearing impaired subjects under different stimulus presentations.

More recently a study by Schmulian (2002) explored the capability of dichotic multiple ASSR at establishing accurate hearing thresholds in comparison to thresholds obtained with the ABR procedure. In order to fully compare the two procedures, the delineation of the hearing impairment served as the focus of the study. With regard to ASSR, it was determined that the degree and configuration of the hearing loss, even at high intensities, could reliably be obtained. Indicating that extensive information on the subject's hearing loss could be obtained using dichotic multiple ASSR.

2.5.3 Managing the Hearing Impairment

Inappropriate habilitation because of a lack of auditory information could possibly have harmful effects (Cohen et al. 1991). Accurate auditory thresholds are essential to select appropriate amplification without relying on behavioural responses. As the ASSR techniques can estimate frequency-specific supra-thresholds at high intensity levels (120 dB HL) it is a useful tool in estimating thresholds and audiogram configurations in subjects with hearing losses (Dimitrijevic et al. 2001). This is even more so with regard to appropriate amplification for subjects with significant hearing loss, as well as estimation of cochlear implant candidacy (Picton et al. 1998; Rance et al. 1998).

In regard to appropriate management of a hearing loss, a considerable contribution was made by Picton et al (1998) when the use of the MASTER technique was employed in the assessment of aided thresholds in the soundfield. Ten normal hearing subjects, 35 children with moderate hearing-impairment and 3 children that had to be fitted with hearing aids were included in the study. The MASTER technique objectively provided thresholds and aided thresholds to subjects who could not respond to behavioural audiometry, through various transducers. This study made a valuable contribution to the realm of ASSR. Not only were reliable thresholds obtained, but reliable aided thresholds were also obtained.

2.6 Conclusion

In conclusion Auditory Steady State Response has proven to be a reliable and objective procedure in the estimation of hearing thresholds in normal hearing and hearing-impaired subjects. The literature revealed that since the initial trials by Galambos and colleagues in 1981, the procedure has evolved into a complex electrophysiological procedure that is finding its place in the existing field of audiometry. However with each answer to a research question another few questions arise. As stated in the clinical application of the ASSR procedure, a number of studies have contributed to establishing ASSR, but as it is with any research endeavor, much still needs to be done (Picton et al. 1998). Most of the studies only focused on threshold estimation. Factors such as, accurately predicting the configuration of the hearing loss as well as the role of ASSR in the management of the person with a hearing loss, have not received sufficient attention until recently. The only study that addressed the limitations in the research to a certain extent was that of Schmulian (2002), but it was only using dichotic multiple ASSR and little amplification applications were explored. Thus highlighting a lack in the current research, as to whether ASSR as a whole can effectively delineate an individual’s hearing capabilities (reference is made to the degree and configuration of the hearing loss) in order to further manage the hearing impairment.

2.7 Summary

This chapter discussed ASSR as an audiometric procedure, defining related terms and explaining the underlying physiological and audiological concepts. An historical overview was given to ensure the delineation of the path of the procedure. The electronic and mathematical techniques that were implemented to aid the process of recording were briefly discussed. The influential variables were highlighted as well as the characteristics of ASSR as a whole and the different methods of stimulus presentation. A further comparison to other similar procedures was provided. The clinical application of the ASSR conditions and the results of current clinical research were discussed and integrated. The chapter was concluded with an overview of the current literature and highlighted the lack of research in the area.

3

Research Methodology

This chapter aims to provide the methodological approach implemented in the conducting of the empirical research component of this study.

3.1 Introduction

> “Research is not an academic banality; it is a vital and dynamic force that is indispensable to modern progress. “ (Leedy, 1993, p5)

In chapters 1 and 2 the research question and the setting in which it originated was discussed. Based on the literature review, this chapter aims to describe the methods and procedures used for realizing the aims of this study. This chapter serves as the core of the research process in delineating the experimental procedures implemented (Johnson & Pennypacker, 1993; Leedy, 1993).

3.2 Aim of study

The aims of this research project have been formulated as follows:

3.2.1 Main aim

The main aim of this study was to establish the accuracy of monotic single ASSR in estimating pure tone behavioural thresholds for a group of normal hearing and hearing-impaired subjects.

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

3.2.2 Sub Aims

- To collect normative data in 30 normal hearing ears, controlled for age and gender, across 0.5, 1, 2 and 4 kHz in the pure tone behavioural audiometry and auditory steady state response (ASSR) conditions.

- To collect data obtained from 29 hearing-impaired ears controlled for degree and configuration of hearing loss, using monotic single ASSR across 0.5, 1, 2 and 4 kHz.

- To compare the results of this study to those in the literature with regard to the accuracy in threshold estimation of the ASSR condition in similar testing conditions.

3.3 Research Design

In order to achieve the aims of this study a **comparative experimental research design** was selected. To explain the rationale behind the selection of this design, reference has to be made to the “true” or classical experimental design (Neuman, 1997).

When an experiment is conducted it consists of several components namely, the independent variable, the dependant variable, the pre-test, the post-test, the experimental group, the control group and the random assignment of subjects (Neuman, 1997). If in the proposed research endeavour one or more of these components cannot be included, then the design selected is a variation on the classical or "true" experimental design (Neuman, 1997). In this study experiments were performed and their effects observed. Different independent variables' effects on dependent variables were compared to substantiate a hypothesis. Subsequently the variation on the classical experimental design would be the difference in the implementation of the tests and the comparison made between them. The disadvantage of this variation would be that the validity of the study in comparison to the classical design might be compromised, since some of the components would not be included and could cause the strength of the comparison to be attenuated. However, this variation enables the design to appropriately fit the architectural plan of the study.

According to Leedy (1993), in an experimental design the researcher controls the independent variables and examines its effects on the dependent variables. The matter of control is fundamental to the experimental method (Leedy, 2001). The independent[1] variable is the variable the researcher will be able to manipulate in order to obtain results in the experiment. The dependent[2] variable is the result of the influence of the independent variable (Leedy, 2001; Johnson & Pennypacker, 1993). In this experimental setting certain variables have to be kept constant, and prevented from varying for the independent variable to manipulate the dependent variable. This variable is referred to as the constant (Graziano & Raulin, 2000). In the present study the researcher will be able to manipulate the independent variables in an experimental setting where certain variables are kept constant in order to record the effect the independent variables has on the subjects.

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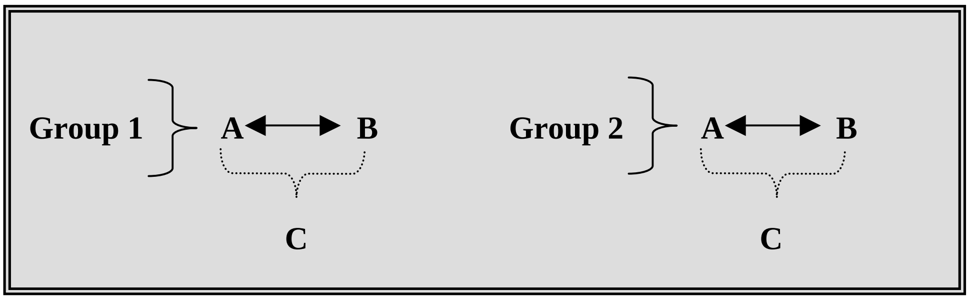
[1] Independent variable: A variable that is actively manipulated by the researcher to see what the impact will be on other variables (Graziano & Raulin, 2000).

[2] Dependent variable: The variable that we hypothesize will be affected by the independent-variable manipulation (Graziano & Raulin, 2000).

Subsequently as stated before a **comparative experimental research design** was implemented for this study. Figure 3.1 is an attempt to graphically summarize the intended research design. In Figure 3.1 two groups are illustrated, within each group a test was performed (A) that served as a basis against which another test (B) could be compared. A comparison was made to relevant literature and especially studies that made use of the same subjects and the same type of comparison (A – B) but with another test as (B). Subsequently both (B) tests can be compared in the end, although this is not the focus of the study. The current study revolves around the comparison between tests (A) and (B), where these tests serve as the independent variables that are manipulated to effect the dependent variables enabling the researcher to measure the outcome of the effect.

Figure 3.1: Comparative Experimental Design



With regard to the present study Figure 3.1 is representative of the following:

Group 1	Group of subjects with **hearing impairment**
Group 2	Group of subjects with **normal hearing**
Test A	Thresholds obtained using **pure tone behavioural audiometry**
Test B	Thresholds obtained using **monotic single ASSR**
Comparison C	– Comparison to relevant literature with regard to threshold estimation using ASSR

The variables of this study are as follows:

Manipulated or independent variables:

- Pure Tone Behavioural Thresholds (PTBT) Audiometry
- Monotic single Auditory Steady State Responses

Measured or dependent variables:

- Pure tone behavioural thresholds at 0.5, 1, 2 and 4 kHz in normal hearing ears.
- Pure tone behavioural thresholds at 0.5, 1, 2 and 4 kHz in hearing-impaired ears.
- Monotic single ASSR thresholds at 0.5, 1, 2 and 4 kHz in normal hearing ears.
- Monotic single ASSR thresholds at 0.5, 1, 2 and 4 kHz in hearing-impaired ears.
- Recording time for the monotic single ASSR technique for each subject.

Controlled or constant variables:

- Experimental setting – the test environment was simulated to resemble the test environment depicted in the relevant literature. To enable valuable comparisons to be made. Where possible the exact same rooms and equipment were used.
- Selection criteria – the selection criteria of subjects were, where possible, kept the same as those in the literature to which data is compared to eliminate significant variance in subjects.

3.4 Subject Description

29 Hearing-impaired ears[3] (15 subjects) were selected for the experimental group, as well as 30 normal hearing ears (15 subjects) for the normal control group. The subjects with normal hearing were colleagues and friends that voluntarily participated in the experiment. All the subjects with a hearing impairment had previously identified sensory neural hearing losses, which ranged in category between mild and profound as stated in Table 3.2 and a configuration of that loss as stated in Table 3.3. The classification of each subject according to the degree and configuration of their hearing impairment is stipulated in Table 3.1. The hearing-impaired group consisted of pupils at a residential school for hearing-impaired learners. The emphasis in this particular school is placed on the auditory-oral method, where learners are encouraged to make optimal use of their residual hearing with the help of appropriate amplification.

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[3] In the group of subjects with hearing impairment the odd number of 29 ears can be attributed to the fact that one of the subjects had a cochlear implant implanted to one ear, just preceding the study.

In this study the sample of subjects for both the normal hearing and hearing-impaired group can be described as follows:

- **30 normal hearing ears**, (15 subjects) were selected of whom **8** were **male** and **7** were **female**. These subjects ranged in age between **17** and **36 years of age**. The **central tendencies** (excluding the modus) of the subjects' age were **25 for the mean** and **25 for the median**. The **standard deviation from the mean was 6**.
- **29 hearing-impaired ears**, (15 subjects) with hearing impairment of whom **6** were **male** and **9** were **female** were selected. These subjects range in age between **13** and **22 years of age**. The **central tendencies** (excluding the modus) of the subjects' age were **17 for the mean** and **17 for the median**. The **standard deviation from the mean was 2**.

To illustrate the age and gender distribution of the subjects, reference is made to Figure 3.2 and Figure 3.3.

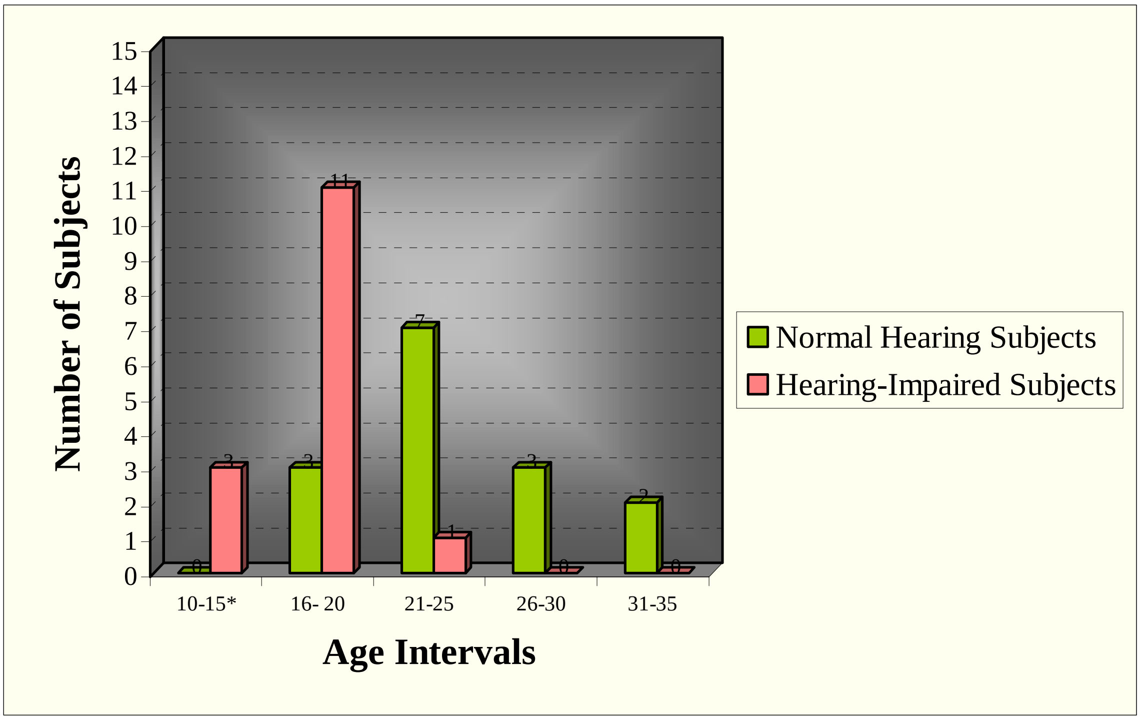

Figure 3.2 Age distributions of both groups of Subjects

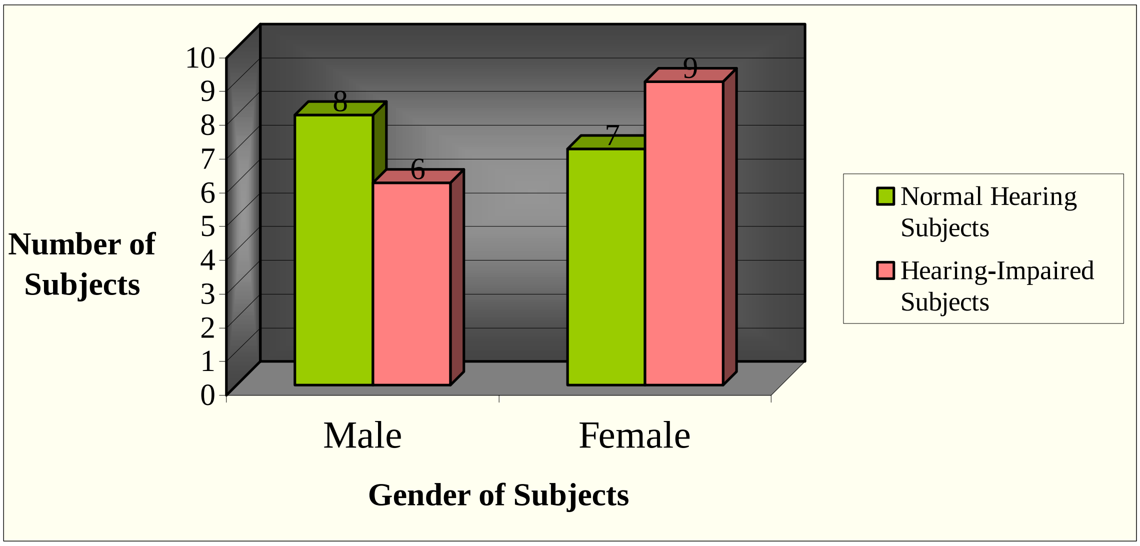

Figure 3.3 Gender distribution of both groups of Subjects

In the following Table 3.1 the distribution of the degree and configuration of each subject's hearing ability is stipulated. Table 3.2 and Table 3.3 will follow this table where the relevant degree and configuration is delineated separately and terms used in Table 3.1 will be defined. An important note is the classification of normal hearing ears in a table referring to hearing impairment. Table 3.1 is representative of the whole sample of subjects and as in Table 3.2 normal hearing abilities are also classified.

Table 3.1 Distribution of degree and configuration of hearing loss in 59 ears

Classification of degree and configuration	Ears with normal hearing (0-25 dB)	Ears with mild HI (26-40 dB)	Ears with moderate HI (41-55 dB)	Ears with moderately-severe HI (56-70 dB)	Ears with Severe HI (71-90 dB)	Ears with Profound HI (90< dB)
Flat configuration	30	-	3	1	3	2
Sloping configuration	1	-	3	1	1	2
Low frequency configuration	-	3	-	-	-	-
Ski-slope configuration	-	1	-	1	3	-
High frequency configuration	1	1	-	-	-	-
Notch and Inverted notch configuration	-	-	-	-	2	-

Another important factor is the classification of two “normal” ears with a configuration of hearing loss. These two ears are hearing impaired with a ski-slope hearing loss configuration, but on average the pure tone thresholds are classified as within normal ranges. They are however considered as part of the hearing-impaired group.

3.4.1 Subject Selection Criteria

Subjects were selected according to the following criteria:

3.4.1.1 Subject Age

Subjects were required to be between 15 and 40 years of age. The reason for this age criteria was that subjects could reliably and accurately respond to pure tone behavioural audiometry, as well as understand instructions given. Adult subjects also eliminated the possibility that the recording of responses could be influenced by neural pathways and neural transmitters that have not matured (Lins et al. 1996). It is also representative of a large age group. Furthermore auditory evoked potentials can be elicited from any person regardless of their age, newborn to the age of ninety (Hecox & Galambos, 1974). Although age has an effect on the amplitudes and general configuration of latencies (Goldstein & Aldrich, 1999), for the purposes of this study, amplitudes and general configuration of latencies do not significantly impact on the recording of ASSR.

3.4.1.2 Subject Gender

For the purposes of this study an even gender distribution was acquired. Some investigators revealed that head size and the length of the basilar membrane (which differs between genders) could have a possible influence (Goldstein & Aldrich, 1999; John & Picton, 2000), but not to the extent that is a significant consideration. Nevertheless, statistical analyses were performed on the results in order to exclude any effect of gender, age and different ears on the recording of ASSR.

3.4.1.3 Normal Middle Ear Function

Subjects were required to have normal middle ear function. Evaluation of the middle ear is deemed important in the selection of subjects for the purposes of research into the hearing abilities as any condition caused by middle ear pathology has a significant influence on the accuracy of the pure tone thresholds and responses of the ASSR (Hall & Mueller, 1997). Subsequently if a conductive hearing loss was identified, the subject was not included in the study.

3.4.1.4 Hearing Ability

Subjects with normal hearing were required to have pure tone thresholds within the range 0 - 25 dB (referred to as “normal” hearing abilities) as listed in Table 3.2. Subjects with a hearing impairment were required to have hearing thresholds in the hearing categories mild to profound as listed in Table 3.2 and a configuration of that hearing loss as listed in Table 3.3. For this study the criteria for hearing ability is important, as this is the emphasis of the study. Subsequently the criteria will be illustrated in Table 3.2 and Table 3.3 and further elaborated upon thereafter.

Table 3.2 Degree of Hearing Loss Categories

Categorization of Degree of Hearing Loss	Hearing Thresholds (dB)
Normal	0-25
Mild	26-40
Moderate	41-55
Moderately-Severe	56-70
Severe	71-90
Profound	90<

(Adapted from Goodman, 1965; Northern & Downs, 1991)

Previous studies (Jerger & Johnson, 1988) showed that there is a correlation between evoked potential morphology and the behavioural audiogram configuration. This correlation is clear from the relationship between the behavioural audiogram configuration and ABR latencies (Hall, 1992).

Table 3.3 Criteria for Audiogram Configuration

Term	Description
Flat	Little or no change in thresholds across all frequencies
Sloping	As frequency increases, the degree of hearing loss increases
Low frequency	As frequency increases, the degree of hearing loss decreases
Ski-slope	Very sharp increase in the hearing loss between octaves
High frequency	The hearing loss is limited to the frequencies above the speech range (2 – 3 kHz)
Notch and Inverted notch	Notched shaped loss around 1–3 kHz, also inverted

(Derived from Roeser, Valente & Hosford-Dunn, 2000)

As this study attempts to determine the accuracy of ASSR in the prediction of hearing thresholds, subjects were chosen to reflect different types of hearing loss. This was done to examine the prediction, of not only the thresholds using ASSR but also the prediction of the configuration of the hearing loss. A representative sample of low, middle and high frequency hearing loss across the degree of hearing loss range are listed in Table 3.3 (Roeser et al. 2000).

3.4.2 Subject Selection Procedures

To select subjects for this study a research proposal was submitted to the University of Pretoria Research and Ethics Committee to obtain permission for the research to be implemented (Appendix A). Once permission was obtained to conduct the study, letters of informed consent were distributed. The letters were distributed at the hearing-impaired school to all the subjects that have participated in previous research by the Department of Communication Pathology, University of Pretoria (Appendix B). The current study intended to compare some of the results obtained to results obtained in a similar study by Schmulian (2002) using dichotic multiple ASSR in hearing-impaired subjects. Therefore the subjects used for that study formed part of the sample subjected to the selection criteria for this study. This was done to draw comparisons between the different methods of ASSR stimulus presentation. This comparison is however not the focus of the study and will therefore not be further elaborated upon, although it did influence the selection of subjects.

Letters of informed consent were also distributed to subjects from the University of Pretoria's Speech, Language, Voice and Hearing clinic's client base, as well as to friends and colleagues (Appendix C). Approximately 25 possible participants were approach and 19 agreed to participate. Once consent was obtained from the subjects, subjects were randomly selected based upon the results of the selection criteria (Neuman, 1997). This selection approach enables the researcher to first identify categories of people (hearing-impaired subjects from University of Pretoria client base, after they have given their consent to participate) and then randomly select people out of the groups based on the convenience or accessibility to participate (Neuman, 1997, Montgomery, 1984). Subjects who consented to participate in this study were required to undergo two examinations and one form of audiometric testing in order to be selected for the research proposed. The selection procedures are illustrated in Figure 3.4.

3.4.2.1 Otoscopic Examination

The first criterion was that of otoscopic examination. Preceding the otoscopic examination, the subject was questioned regarding any existing external or middle ear pathology and informed about the data collection procedures. An otoscopic examination was performed by a qualified Audiologist on each of the subjects in both ears, to determine if the external canal of the ear was clear of any obstructions and/or obstacles that could affect the conduction of sound to the tympanic membrane (Martin, 1997; Silman & Silverman, 1991). The condition of the tympanic membrane was also viewed to determine if any inflammation or any obvious abnormalities were visible, as well as whether a light reflex was present suggesting a healthy tympanic membrane (Martin, 1997; Silman & Silverman, 1991). In the cases where abnormalities or pathologies were observed or identified, the subject was verbally advised to consult a general practitioner for consultation.

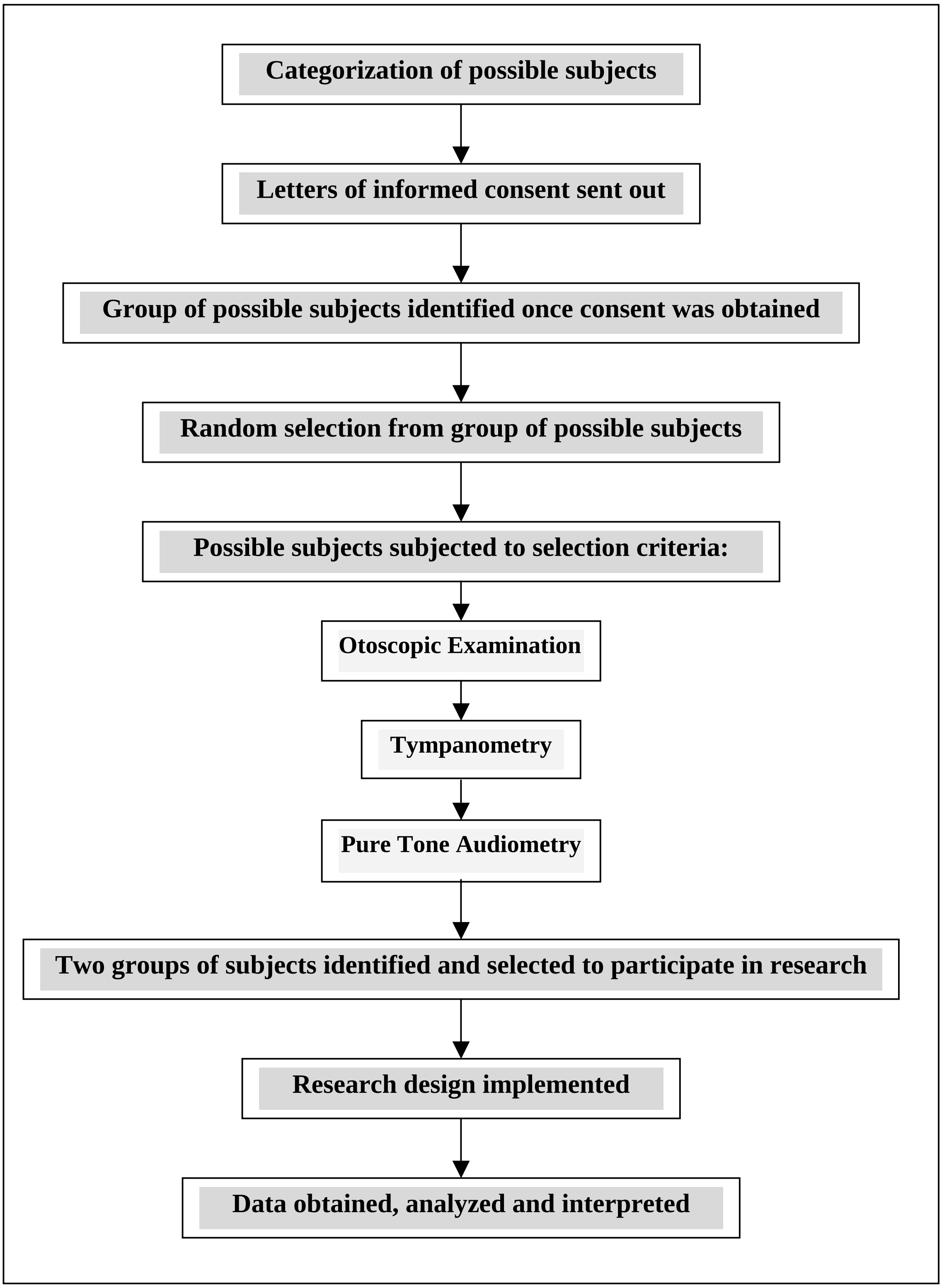

Figure 3.4 Illustration of Subject Selection Procedures

3.4.2.2 Tympanometry

Once subjects met the otoscopic criterion, tympanometry commenced. With this procedure middle ear functioning was determined (Hall & Mueller, 1997). The results of each subject included in the study were required to fall within the normal ranges as presented in Table 3.4 and subsequently the results had to be classified as a Type A tympanogram (Silman & Silverman, 1991).

Table 3.4 Tympanometry normative data

Parameters	Norms
Compliance	0.50 -- 1.75 cc
Volume	1.0 -- 1.4 ml
Pressure	-50 -- +50 daPa
Gradient Type	Type A

(Silman & Silverman, 1991)

A type A tympanogram suggests normal function of the middle ear (Hall & Mueller, 1997; Silman & Silverman, 1991). Again, similar to the otoscopic examination, if a gradient type not indicative of normal middle ear function was recorded, the subject was verbally advised to consult a general practitioner.

3.4.2.3 Pure Tone Audiometry

After it was established that each subject had normal middle ear function, subjects were required to respond behaviourally to pure tone audiometry. The data obtained from the pure tone behavioural audiograms were used to determine if the subjects that were selected for the normal group had normal pure tone thresholds and if the subjects selected for the hearing-impaired group had a hearing impairment, that was consistent with the relevant literature to which some of the results will be compared (Schmulian, 2002). Thresholds were determined for the frequencies 0.5, 1, 2, and 4 kHz as these frequencies are representative of the speech frequency range (Stach, 1998) and are also the frequencies assessed by the ASSR software (Schmulian, 2002; Swanepoel, 2001).

The pure tone results were used as the basis to which the ASSR thresholds were compared. In the case of the normal hearing group, if a subject was tested and found not to meet the criteria for normal hearing abilities (0 – 25 dB across the frequency range of 0.5, 1, 2 & 4 kHz) again they were advised of the appropriate action to be taken for management of the hearing loss and not included in the study.

As the hearing-impaired subjects have already been diagnosed with a certain degree of hearing loss (stipulated in Schmulian, 2002), the aim of this specific procedure was to exclude any deterioration to the extent that the hearing loss had to be re-categorized with regard to the degree or configuration of the hearing loss. No subject showed any signs of significant deterioration. If any subject did show deterioration in the hearing thresholds they would not have been included in the study and advised of the appropriate procedures to follow towards management of the hearing loss.

3.5 Apparatus

Data was obtained at two separate locations. The hearing-impaired group, of whom all were scholars, was tested on the school premises as agreed upon when consent was given. The normal hearing group was tested on location at the University of Pretoria. The locations will now be described.

3.5.1 Subject Selection Apparatus

Specific equipment was used to select the subjects. An important factor regarding the selection of subjects was that selection proceeded at two separate locations with some of the equipment being different. **Location A** was a residential school for the hard of hearing located in Pretoria. Testing facilities located in the audio-visual department of the school were equipped with soundproof rooms and appropriate apparatus. Verbal consent was obtained from the school principal and applicable staff members to make use of the facilities **ocation B** was the Speech, Voice, Language and Hearing clinic at the University of Pretoria. The clinic is equipped with standardized apparatus used for student training and research purposes. The specific equipment used will be discussed with regard to the different locations.

Location A:

- The otoscopic examination of the external ear canal and tympanic membrane was performed with a **Heine mini 2000 otoscope**.
- The tympanometric evaluation of the middle ear was performed with a **GSI 33** Tympanometer, calibrated in January 2002; testing proceeded in February 2002.
- Pure tone threshold audiometry was performed using the **GSI 16 Clinical Audiometer.** Fitted with **TDH 39 supra-aural headphones** in a **sound proof booth** within a **sound-treated room.** The apparatus met the requirements set out by the SABS (South African Bureau of Standards, 1998) and were calibrated in December 2001.

Location B:

- The otoscopic examination of the external ear canal and tympanic membrane was performed with a **Heine mini 2000 otoscope**.
- The tympanometric evaluation of the middle ear was performed with a **GSI 33** Tympanometer, calibrated in January 2002; testing proceeded in February 2002.
- Pure tone threshold audiometry was performed using the **GSI 60 Clinical Audiometer**. This audiometer is fitted with **TDH 39 supra-aural headphones** in a **sound proof booth** within a **sound-treated room**. The apparatus met the requirements set out by the SABS (South African Bureau of Standards) and were calibrated in January 2002.

3.5.2 Data Collection Apparatus

Similar to the subject selection procedure, the data collection procedures were also obtained at two separate locations, as previously explained. Pure tone behavioural thresholds were obtained using:

- The **GSI 60 Clinical Audiometer** calibrated January 2002. Pure tone stimuli were presented in steady tones through **TDH 39 supra-aural headphones** in a **double walled soundproof booth** within a **sound-treated room**.
- The **GSI 16 Clinical Audiometer.** Pure tone stimuli were presented in steady tones through **TDH 39 supra-aural headphones** in a **double walled soundproof booth** within a **sound-treated room.** Calibrated in December 2001.

Monotic single ASSR thresholds were obtained with the GSI Audera system (School of Audiology, University of Melbourne in Australia). This equipment consists of a specialized software component connected to a Pentium Laptop Computer, a serial cable, an ERA system Unit, a fibre-optic cable, an EEG amplifier, tube phones and electrodes. The system is accompanied and operated by means of computer software specifically designed for the recording and analysis of ASSR at various frequencies (0.5 – 4 kHz) and intensity levels. The ERA system was also designed for simultaneous analysis of patient EEG activity for evidence that an evoked potential has occurred. Calibration of the ERA system was performed in January 2002. The ASSR measurements were obtained in a **single walled soundproof booth** on both occasions, using **Bio-Logic E-A-R Link Foam Ear Tips** for **Insert Earphones** to present acoustic signals while the subjects were lying on a bed in a dark room.

3.6. Data Collection Procedures

To illustrate the procedures used in the collection of the research data reference is made to Figure 3.5. (page 57). In this figure it is illustrated that some of the procedures used in the selection of subjects also formed part of the research data. Two groups of subjects were identified as potential research subjects: a group of normal hearing subjects and a group of previously identified hearing-impaired subjects. A suitable date and time of day was arranged with the potential subjects for the testing to proceed. A time frame of approximately two hours was given. Prior to the appointment, the informed letter of consent that explained to the subjects the procedures and the aims of the session was returned. The potential subjects were questioned about his/her hearing ability, history or recurrence of any kind of external or middle ear pathology. The procedures were discussed again and instructions were given to enable the potential subjects to fulfil his/her part in the procedures, especially during the behavioural pure tone testing. The selection criteria were implemented and research subjects were identified.

Pure tone behavioural thresholds were obtained during the selection of subjects and this data was collected in a controlled test environment. The test environment was in accordance with the test environment of researchers Schmulian (2002) and Swanepoel (2001) to enable comparisons to be made later in this study. Each selected subject was prepared for the monotic single ASSR testing. Firstly the possible experience was discussed and the subjects were advised to be relaxed and attempt to sleep if possible. These two sets of data were collected within the same session in a controlled test environment. Pure tone behavioural thresholds were obtained first, as part of the selection criteria, followed by the monotic single ASSR recording. Data collection was performed at locations A and B, as stipulated under heading 3.5.1.

3.6.1 Preliminary study

To determine clinical feasibility of the study, a preliminary study was conducted with two subjects from each group that complied with the selection criteria. The purpose of the preliminary study was to determine whether the experimental setting (testing conditions and apparatus parameters) were suitable and appropriate with regard to the subjects. The experimental setting used for the preliminary study was stipulated in the proposal accepted by the University of Pretoria Ethics and Research committee. The stimuli and subject parameters are briefly summarized in Table 3.5 according to the pre-described parameters and appropriate alterations. Following the preliminary study, alterations to the parameters were minimal, due to the fact that the stimulus and subject parameters were based on parameters used in the literature (Schmulian, 2002; Swanepoel, 2001). Certain recommendations were made with regard to the subjects and the conditions of the experimental setting. During the ASSR procedure it is important for the subject to be as relaxed as possible. Optimally subjects should be sleeping but this was not always possible due to the time of day, for this reason more care was taken to keep subjects relaxed. The lights were switched off outside the soundproof booth and an attempt was made to accommodate subjects regarding their preference to temperature inside the booth by providing blankets and manipulating the air-conditioning system. The time of day the test was conducted was also scheduled to accommodate subjects at a time when they knew they would be relaxed.

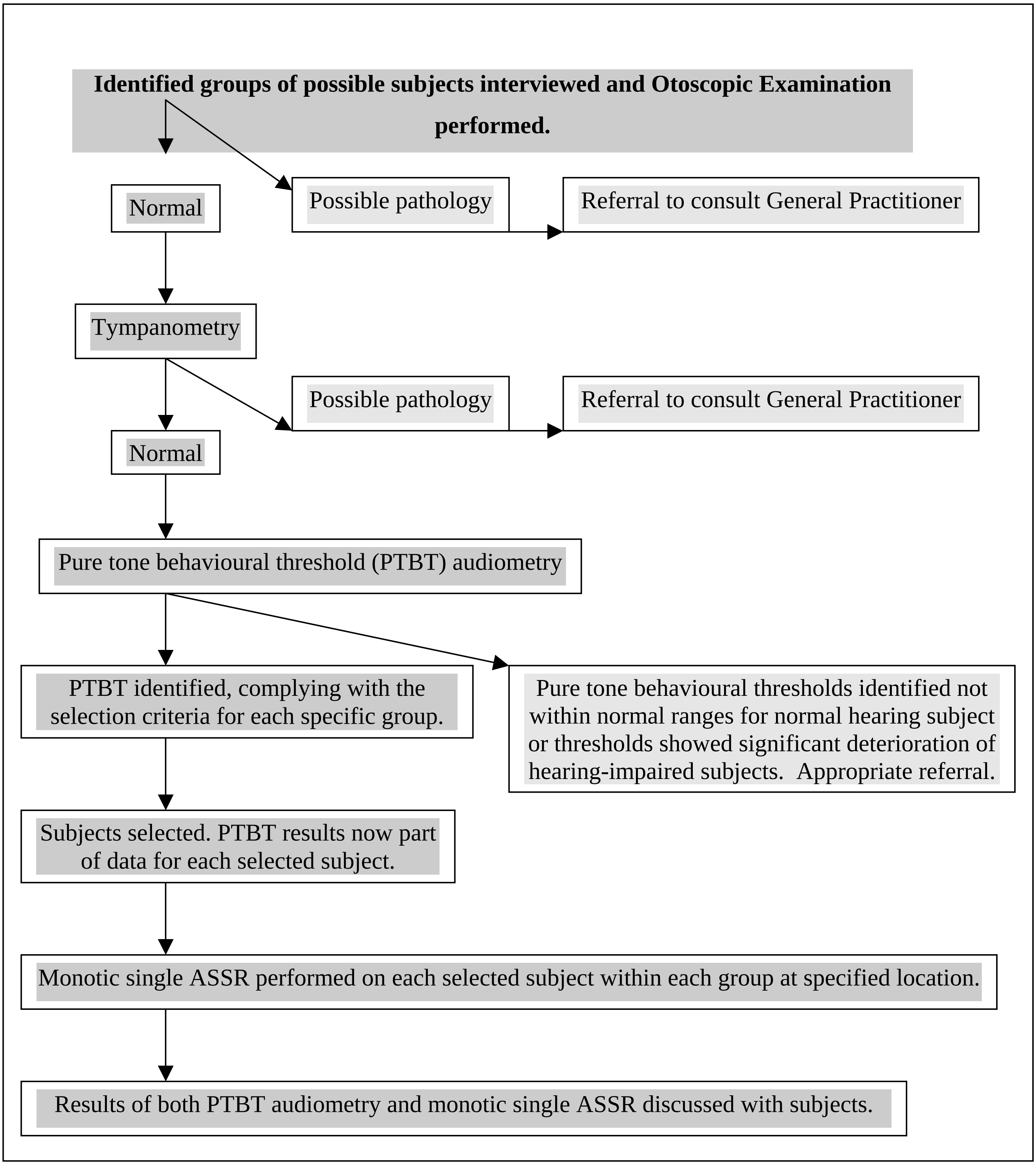

Figure 3.5 Illustration of Data Collection Procedures

The following descriptions will give insight into the procedures used in the collection of data.

Table 3.5 Stimulus and Subject Parameters

Parameters	**Subjects with Normal hearing**		**Subjects with Impaired hearing**	
	Pure Tone Audiometry	Monotic ASSR	Pure Tone Audiometry	Monotic ASSR
Frequencies	0.5, 1,2 & 4 kHz	0.5, 1,2 & 4 kHz	0.5, 1,2 & 4 kHz	0.5, 1,2 & 4 kHz
Stimuli	Pure tone Stimuli	Modulated Stimuli	Pure tone Stimuli	Modulated Stimuli
Clinical setting	Speech, Voice and Hearing Clinic at the University of Pretoria	Speech, Voice and Hearing Clinic at the University of Pretoria	Audio-Visual Clinic at Residential School	Audio-Visual Clinic at Residential School
Test Environment	Single-walled, soundproof booth	Single-walled, soundproof booth	Double-walled, soundproof booth	Double-walled, soundproof booth
Patient positioning	Subject sitting upright in a light room in a chair facing clinician from behind glass window	Subject lying in a dark room on bed, with head supported by pillow.	Subject sitting upright in a light room in a chair facing clinician from behind glass window	Subject lying in a dark room on bed, with head supported by pillow.
Patient Status	Patient awake and attentive, behaviourally responding to sound	Patient relaxed or asleep, not behaviourally responding to sound	Patient awake and attentive, behaviourally responding to sound	Patient relaxed or asleep, not behaviourally responding to sound
Apparatus	GSI 61 Clinical audiometer. TDH 39 supra-aural headphones.	GSI Audera system for the recording of ASSR (portable system)	GSI 16 Clinical audiometer. TDH 39 supra-aural headphones.	GSI Audera system for the recording of ASSR (portable system)

3.6.2 Data Collection using pure tone behavioural audiometry

Pure tone behavioural thresholds were obtained by means of a steady tone presented to each ear at 0.5, 1, 2, and 4 kHz. These frequencies correspond with the data from the ASSR protocols. A pure tone air conduction audiogram was obtained for each subject once the otoscopy and tympanometry confirmed normal middle ear functioning (with reference to Table 3.3).

Thresholds will be determined using a descending intensity (10 dB) and an ascending intensity protocol (5 dB) until responses had been validated for a specific decibel hearing level (dB HL). This threshold seeking technique is known as the Hughson-Westlake ascending method (Carhart & Jerger, 1959). For a response to be valid it had to be confirmed, meaning that the subject had to behaviourally respond at least 50% of the time to that specific intensity level. A subject’s hearing was considered normal if it was equal or less than 25 dB HL and for the subjects with a hearing impairment any degree of hearing loss above 25 dB HL would be considered a hearing loss (with reference to Table 3.1).

3.6.3 Data Collection using ASSR

The ASSR thresholds and the time it took to obtain these thresholds at 0.5, 1, 2 and 4 kHz, were the second set of data obtained.

3.6.3.1 Stimulus Parameters for monotic single ASSR

- **Frequency Parameters**

Four frequencies (0.5, 1, 2 and 4 kHz) were used and these carrier frequencies were either amplitude modulated between 80 and 110 Hz or between 30–50 Hz. The rate implemented depended on the subject’s state of consciousness and no significant threshold shift was evident between the slower and faster rates, unless the subject was sleeping (Lins et al. 1996; Picton et al. 1998). The amplitude of responses decreases with the lower modulation rates if a subject is asleep. Depending on the subject’s state of consciousness, the relevant rate would be implemented. Since the subjects were encouraged to sleep, the higher modulations rates were implemented most of the time. Only one modulated tone per ear is presented with the monotic single ASSR technique, subsequently the tones were presented sequentially. The carrier frequencies were amplitude and frequency modulated, referred to as mixed modulation. Each ear was tested separately in no specific order.

- **Intensity parameters**

Monotic single ASSR stimulus intensity for this study commenced at 20 dB HL above the hearing threshold estimated by the pure tone audiometry of the subjects. A descending threshold seeking procedure was used (in 10 dB HL steps) until no response was present. The intensity was then raised in 5 dB increments until a response was recorded at each specified frequency. The ASSR threshold could only be considered valid if a "random" response was recorded 5 dB lower than the recorded response. This means that the recorded response was at the minimum response level (MRL) and not just because a high signal-to-noise ratio prevented the measurement of recording responses. Taking into consideration that ambient and internal noise can have a significant effect on the recording of responses, the subjects were constantly reminded of the importance of the quietude of the setting in order for accurate responses to be recorded. If a subject was especially noisy during the testing while being asleep, the subject was carefully woken up, offered nourishment if necessary and asked to be calm and try to sleep again. Only two subjects were treated in this way and these actions did not have a significant effect on the recording of ASSR. If a subject became restless because of the duration of the test, the subject was given some time to recuperate and a second attempt was made at obtaining ASSR thresholds.

3.6.3.2 Recording procedure for monotic single ASSR

Directly after the subject met the criteria for subject selection the ASSR recordings commenced.

- For electrode placement three areas on the skull were prepared namely the high forehead and behind the ears on the area of the mastoid bone. This was done by means of abrasive scrub and a cotton ear bud. Electrode discs of Ag/AgCI were fixed to the scalp by means of electrolytic paste after the skin was prepared, on the scalp Fz (positive), the test ear (negative) and the non-test ear (positive). This method of placement ensures equal distance between the electrode placement and both ears, which ensures symmetrical recordings.
- Impedance values were kept below 3000 Ohms.
- The bio-electric activity was amplified with a gain of 100 000 and analogue filtered between 30 and 300 Hz.
- Bio-Logic E-A-R Link Foam Ear Tips insert earphones were used to present the stimuli.
- Subjects were asked to lie on a bed in a soundproof booth within a sound-treated room and were encouraged to relax as much as possible or sleep. The nature of the stimuli was explained to the subjects. Stimuli were presented monotically

(separate ears) and sequentially at supra threshold intensities, as determined by the pure tone thresholds that were obtained previously.

- The Notch filter was activated at 50 Hz to avoid any line interference.
- 64 Samples were averaged in a response and no response was recorded after 40 epochs.
- The F-test was implemented for response detection. This was done by testing the amplitude of the spectrum at each modulation frequency against the 120 adjacent bins to determine significant amplitude differences.
- Rejection level (noise) of 50 micro Volts was specified with subsequent responses with greater amplitude being rejected.
- Thresholds were established in descending intensity steps of 10 dB until no response was present.
- A no-response, however, could only be determined after 40 epochs had been collected and averaged and no response was recorded. The minimum response level (lowest obtained response) for specific frequencies in each ear was taken as the threshold.
- The researcher used a stopwatch to record the testing time, excluding preparation time.

3.7 Data Analysis Procedures

The data obtained from the completed procedures were organized onto spreadsheets, suitable for analysis. This was done using Excel software on the Microsoft Word 2000 Program.

- Hearing threshold estimation: the pure tone behavioural thresholds functioned as the base against which the ASSR thresholds were compared. Therefore, consistency in recording protocol was important. The measure of all thresholds was in decibel (dB) hearing level (HL), throughout the study. The results from the pure tone behavioural threshold audiometry and the monotic single ASSR was analyzed by the researcher and two other qualified audiologists and interpreted according to the hearing abilities of the subjects with reference to Table 3.2 and 3.3 (Goodman, 1965; Northern & Downs, 1991; Roeser et al. 2000).

- Test time: the time measured was that of the pure tone audiometry and monotic single ASSR conditions. The time lapse was measured by using a stopwatch. The testing time for each subject was represented in minutes.
- The raw data as well as the processed data on the spreadsheets was subjected to statistical analysis techniques. The behavioural and estimated thresholds of each frequency of each test procedure were analysed for central tendencies; the **mean** which is the arithmetic average and the **median** which is the middle score in a distribution, the mode of the data was not calculated, as it was not deemed applicable (Graziano & Raulin, 2000). Measures of variability was also determined, for this study the **standard deviation** (SD) which is a measure of the variability of a set of scores around the mean (Graziano & Raulin, 2000). **Correlation** between test procedures was ascertained to determine the extent to which the two compared variables are related. An applicable correlation technique for this study was the **Spearman Correlation,** subsequently the correlation between the different techniques and the effect variables like the gender of subjects or the configuration of the hearing loss might have on results, were investigated (Graziano & Raulin, 2000; Myers & Well, 1991). An independent non-parametric statistical procedure known as the Mann-Whitney test was implemented. The Mann-Whitney independent observation test is where a comparison is made between two variables in a set environment. Further statistical analysis involved the use of **ANOVA: Analysis of Variance**. This depended on the number of comparisons that needed to be done between test procedures. ANOVA allows for testing the differences between more than two means (Leedy, 2001; Graziano & Raulin, 2000; Myers & Well, 1991).

3.8 Summary

This chapter described the method that was used to accomplish the aim of the study. The architectural plan was laid out that stipulated the procedures that were followed and apparatus that were used to accomplish the main aim of this study. The apparatus used in the selection of subjects, as well as collection of data was discussed and relevant literature supporting the methods used was highlighted.

4

Results and Discussions

This chapter aims to present the collected and processed data as a result of the empirical research done and to demarcate the findings and the significance of these findings.

4.1 Introduction

> “ Measurements extend human senses. It lets us observe things that were once unseen and unknown but were predicted by theory.”
>
> – Neuman (1997, page: 132-133)

In the first part of this study the rationale and relevant literature surrounding the research question have been described. This body of knowledge forms a source from which the researcher can extract information in order to compare, describe and predict relationships between variables and identify patterns in the data (Montgomery, 1984).

In this chapter the results of this study are presented, interpreted, compared and discussed in relation to relevant literature. The results under each sub aim will be presented to address the main aim of this study namely: **Establishing the accuracy of monotic single ASSR in estimating pure tone behavioural thresholds for normal hearing and hearing-impaired subjects.** The sub aims were formulated to fulfil the main aim of the study and are stipulated in chapter three, the methodology of the study.

4.2 Results from normal hearing ears in the Pure Tone and Monotic single ASSR conditions

In this sub aim data was obtained from 30 normal hearing ears using pure tone audiometry and monotic single ASSR. This was compared to relevant literature regarding threshold estimation using the same ASSR condition. The normative data obtained with this sub aim contributed to a growing body of normative data with regard to ASSR (Herdman & Stapells, 2001; Swanepoel, 2001) and subsequently served as a reference basis with regard to stimulus and subject parameters.

4.2.1 Central tendencies and Standard Deviation values for the PTA and ASSR conditions

The central tendencies for the current study did not include the mod of the results, only the mean and median of the results. The central tendencies and standard deviation (SD) of the PTBT and monotic single ASSR thresholds at 0.5, 1, 2 and 4 kHz are tabulated in Table 4.1.

Table 4.1 Threshold values in 30 normal hearing ears in PTA and ASSR conditions

Relevant Frequency	PTBT in dB HL			ASSR thresholds in dB HL		
	Mean	Median	SD	Mean	Median	SD
0.5 kHz	6	5	± 6	35	40	± 14
1 kHz	2	0	± 6	29	30	± 12
2 kHz	3	5	± 5	27	25	± 11
4 kHz	3	0	± 8	30	30	± 13

The PTBT recorded were within normal ranges as stipulated by the selection criteria, described in Table 3.2 as between 0 – 25 dB HL (Goodman, 1965; Northern & Downs, 1991). It is evident from Table 4.1 that most of the mean thresholds are less than 10 dB HL and close to 0 dB HL. The standard deviations around the PTBT mean of 4 dB HL were on average ± 6 dB (calculated across the frequency range of 0.5 – 4 kHz), indicating a PTBT range of –3 to 10 dB HL. In this range of PTBT 92.5% of the thresholds were equal to or less than 10 dB HL and approximately 75.8% equal to or less than 5 dB HL, the thresholds obtained represents the upper range of normality and indicate reliable testing measurements as the standard deviation (SD) of the PTBT were on average 6 dB (Katz, 1985). ASSR responses were recorded from the same subjects while they were relaxed or sleeping, implementing a modulation rate between 70 and 110 Hz. As tabulated in Table 4.1 the mean of the monotic single ASSR thresholds were 35, 29, 27 and 30 dB HL respectively across the frequency range (0.5, 1, 2 & 4 kHz). An average of 28 dB HL (calculated across the frequency range of 0.5 – 4 kHz) with a standard deviation average of 12 dB was calculated. This indicates that the range of thresholds were between 15 and 40 dB HL. The distribution of ASSR thresholds across the frequency range is further illustrated in Figure 4.1. It is evident from the figure that for 0.5 kHz the highest percentage (36.6 %) of thresholds were at 40 dB HL, for 1 and 2 kHz the highest percentage (30% and 43.3 % respectively) of ASSR thresholds were at 20 dB HL and for 4 kHz the highest percentage (50%) was at 30 dB HL. In this particular way the frequencies 0.5 and 4 kHz shows greater deviation from the behavioural thresholds than 1 and 2 kHz.

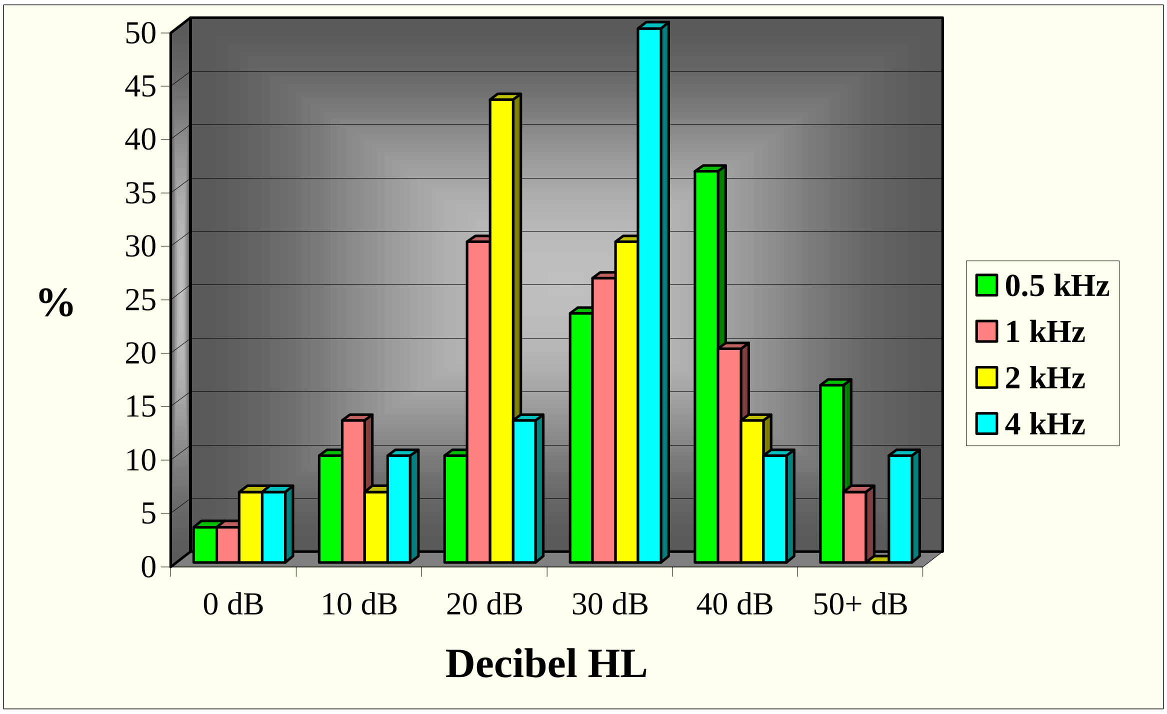

Figure 4.1 Frequency distribution of ASSR thresholds in 30 normal hearing subjects.

The PTBT mean (4 dB HL) in relation to the monotic single ASSR threshold mean (28 dB HL) indicates a difference in threshold prediction of on average 24 dB HL (ASSR thresholds 24 dB greater than that of the PTBT). The difference between the PTBT and the monotic single ASSR thresholds is further illustrated in Figure 4.2.

The mean values of 30 normal hearing ears are presented in audiogram format and illustrate the relationship between thresholds using different procedures in the same ears.

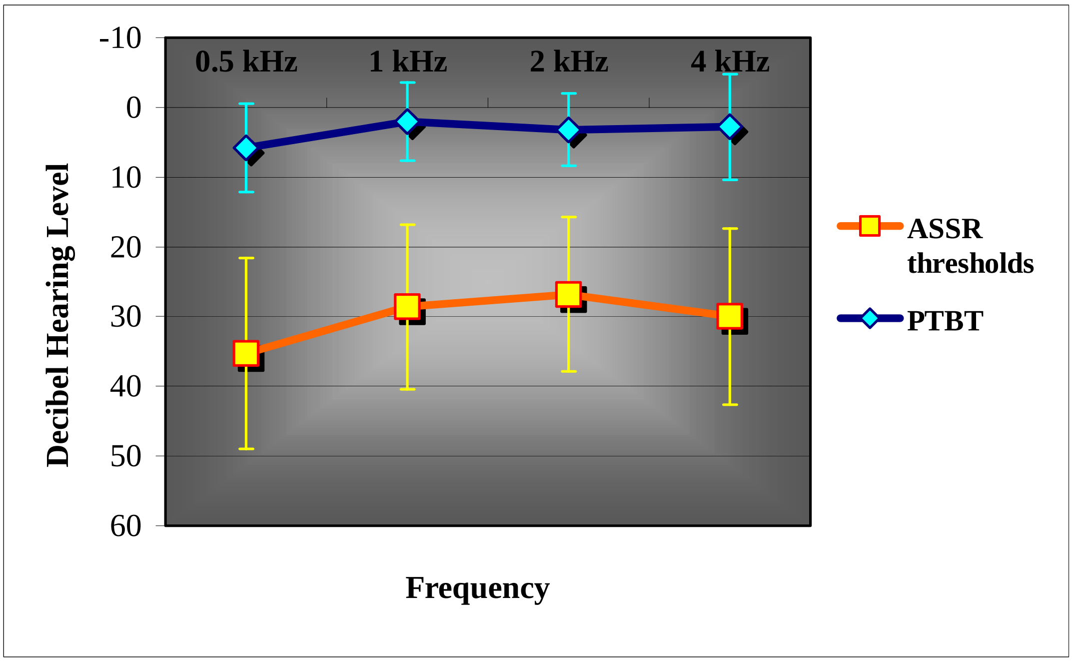

Figure 4.2 Threshold means of PTBT and Monotic single ASSR across 0.5, 1, 2 and 4 kHz (n = 30 ears)

A number of studies using monotic single ASSR substantiated the results obtained in the current study (Rickards et al. 1994; Rance et al. 1995; Herdman & Stapells, 2001). From the literature 2 factors in particular are highlighted that can impact on the inherent differences in thresholds between the two procedures. They are the effect of **acoustic ambient noise levels** and the **modulation of stimuli**, on the recording of responses.

As with all AEP procedures, ambient noise in the recording of evoked potentials is an important factor. For instance Picton and colleagues (1998) attributed higher thresholds obtained with ASSR compared to PTBT, partly to the acoustic environment in which testing proceeded. The **acoustic ambient noise levels** can have a significant effect on estimated thresholds, mimicking a mild sensory neural hearing loss with recruitment (Picton et al. 1998). A mild sensory neural hearing loss with recruitment implies that the ASSR thresholds signify a mild hearing loss. A mild hearing loss that is not due to any conductive components creating a hearing loss (as this possibility was eliminated by the selection criteria procedures) but a sensory pathology in the cochlea referring to the recruitment part of the statement. This mild sensory neural hearing loss with recruitment was manifested in the current study's results, where the ASSR thresholds showed a mild degree of hearing loss (reference to Figure 4.1 where on average of 28 dB HL were calculated) in subjects with normal hearing and normal middle ear function. Picton and colleagues (1998) further refers to the signal-to-noise ratio, which is especially evident in normal hearing subjects as the intensity of the input stimulus is significantly lower and can possibly be masked by the ambient noise levels in the testing environment.

In a study by Herdman and Stapells (2001), the influence of noise on the recording of responses was not necessarily explored but some conclusions were formed regarding the influence of noise. In that particular study, ambient noise levels were kept to a minimum (10–12 dB SPL) with sound attenuated testing environments and subsequently the estimated thresholds more closely approximated PTBT (the ASSR thresholds were measured between 15 and 25 dB SPL). Their study showed that if ambient noise levels are kept to a minimum, ASSR thresholds that closely correlate the PTBT could be obtained. In the current study measurements with regard to the ambient noise levels in the acoustic testing environment were done preceding the testing and were 16.6, 22, 18.2 and 13.1 dB SPL for 0.5, 1, 2 and 4 kHz respectively (thus between 13 and 22 dB SPL). In the current study careful consideration was taken to keeping noise levels to a minimum (single walled sound proof booth within a sound treated room) and yet the results indicate ASSR thresholds that were significantly higher than the results obtained by Herdman and Stapells (2001). This leads us to other possibilities that could have attributed to better correlation between thresholds. Herdman and Stapells mainly attributed the close correlations between thresholds to the low levels of noise but the fact that 12 to 48 EEG recording sweeps were averaged for each stimulus intensity taking approximately between 3 and 13 minutes per intensity, could also attribute to the results obtained. Prolonged recording time and significant averaging of responses is not always a feasible option in a clinical setting (Bachman & Hall, 2001).

The influence of noise on the recording of responses is further reflected in the study of Perez-Abalo and colleagues (2001). They recorded ASSR thresholds between 32 and 42 dB HL in an acoustic environment with ambient noise levels between 65 and 71 dB SPL. It can be concluded that little control was exerted over the ambient noise levels and this is reflected in the ASSR thresholds that are significantly higher than those obtained by Herdman and Stapells (2001) and the current study (ASSR threshold means were between 27 and 35 dB HL).

Obtaining the ambient noise levels of the acoustic environment preceding testing is a definite consideration and in hindsight should be deemed more important as it can significantly influence the obtainment of ASSR thresholds. Presently there seems to be a lack in research done with regard to the guidelines and measures of noise levels when recording responses. The test environment suffers variability and cannot be seen as a constant and should rather lean heavily on ANSI equivalent specifications as with any audiometric procedure (Schmulian, 2002).

The above-mentioned studies did not highlight any dissimilarity regarding the influence of ambient noise levels between single or simultaneous presentation of stimuli. Comparisons between the different ASSR conditions will be drawn in the last sub aim of this chapter (paragraph 4.4).

The second possibility regarding the elevation of ASSR thresholds in normal hearing subjects refers to the **modulation of stimuli**. The modulated tone consists of a carrier frequency and two side bands (50 % in amplitude of the carrier frequency). Responses can only be obtained by amplitude modulation, but the amplitude modulation actually decreases the intensity and responses can only be recorded when the side bands are audible (Picton, 1998). This suggests that for the response to be recorded, the modulated tone has to be audible and thus be presented above threshold level. This further implies that feasibility of obtaining near threshold levels using the ASSR procedure is decreased significantly and that ASSR thresholds will always to some extent manifest a certain level of elevation from behavioural thresholds. Picton and colleagues (1998) also stated that at near threshold intensities (within 10 dB HL of actual hearing threshold) no recognizable responses could be recorded because of too much latency jitter. This limitation however can possibly be bridged as the study by

Herdman and Stapells (2001) showed when ASSR thresholds were obtained near threshold (within 10 dB of behavioural thresholds). It is difficult to directly compare the proximity of ASSR thresholds towards PTBT between studies, as the protocols differ and subsequently has a significant effect on the outcomes of the study. In actual fact it is these protocols that can probably be responsible for the difference in thresholds. The study by Herman and Stapells (2001) showed that low background noise levels and possibly prolonged averaging, maximum EEG sweeps and prolonged testing time (approximately 164 ± 22 min for the monotic single ASSR condition) can significantly alter the outcome of a study. The prolonged averaging can significantly reduce the effects of internal noise on the recording of responses. Internal noise can be just as intruding as ambient noise on the detection of responses using ASSR. The prolonged averaging and testing time as well as maximum EEG sweeps can impact on outcomes to the extent that thresholds can be obtained within the clinically significant 10 dB range (Picton et al. 1998). However as stated before, prolonged recording time and significant averaging of responses is not always a feasible option in a clinical setting (Bachmann & Hall, 2001). In conclusion the possibility that other variables, at this stage not extensively explored, could be responsible for the variation in the estimation of ASSR thresholds.

4.2.2 Effects of variables on the recording of responses in normal hearing ears

The possible effect that **gender and different ears** (left or right) has on the prediction and recording of responses in normal hearing subjects has also been explored. The influence of the age of subjects has been explored in the literature (Lins et al. 1996; Rickards et al. 1994) but unfortunately this could not be done in the current study, as the age distribution was not representative of the whole age spectrum. Statistical testing was impractical as the normal hearing subjects ranged between 17 and 36 years of age, representative only of an early adult age group (reference is made to chapter, Figure 3.2). Although the age distribution of this study was limited, this actually prohibits the possibility that age could have had an effect on the recording of responses, since variability in the recording of responses was reported only in the newborn population (Lins et al. 1996; Rickards et al. 1994).

Gender and different **ear** effects were explored using the Mann Whitney non-parametric analysis. The gender distribution was approximately equal (reference is made to chapter 3, Figure 3.3) and therefore a representative sample. The p-values of the male and female subjects for each testing condition (PTA and ASSR) were measured against 5% and 1% level of comparison. The result of the analysis showed no statistical significant differences as the p-values were all above 10% significance value. The statistical analyses of the effect of gender are illustrated in Appendix D at the end of this study.

The effect of different ears (left and right) on the recording of responses in normal hearing subjects were also analysed and the p-values for the PTA and ASSR procedures were 0.4083 and 0.8057 respectively. This was measured against 5% and 1% strength of evidence against the null hypothesis. The result showed no statistical difference and subsequently no effect on the responses of either procedure. The statistical analyses of the effect of ears are illustrated in Appendix E at the end of this study.

4.2.3 Time efficiency of the monotic single ASSR condition

The time efficiency in any AEP procedure is of clinical importance, seeing as these kinds of test procedures are mostly designed for the “difficult-to-test” population where time constraints are a definite consideration. The duration of the test invariably affects the amount of information that can be gathered, especially in the paediatric population (Bachmann & Hall, 2001). In the current study consenting adults participated, they were familiar with the testing procedures and co-operation was optimal. The duration of the two test conditions will be highlighted and elaborated upon.

Firstly the **pure tone audiometry** test battery: The otoscopic examination, tympanometry and the giving of instructions were not included in the calculation, only the recording of behavioural thresholds. The recording of thresholds included air conduction thresholds at four designated frequencies (0.5, 1, 2 & 4 kHz) sequentially at varying intensities (descending in 10 dB steps and ascending in 5 dB steps) in each ear separately. The average time for the recording of behavioural thresholds was 19 minutes

Monotic single ASSR condition: The preparation of the subjects, electrode placement, impedance checks and stabilization of the test environment were not included in the calculations. The duration of the ASSR procedure consisted of threshold estimation at four frequencies (0.5, 1, 2 & 4 kHz) sequentially, at varying intensities (descending in 10 dB steps and ascending in 5 dB steps) in each ear separately. The average time for the recording of monotic single ASSR thresholds in both ears was 99 minutes with a standard deviation of 11 minutes. These results in comparison to other studies implementing the monotic single ASSR condition are tabulated in Table 4.2.

Table 4.2 The mean recording time of the monotic single ASSR condition in comparison to Herdman and Stapells (2001)

Studies	**Mean recording time (in minutes)**
Current study	99 ± 11
Herdman and Stapells (2001)	164 ± 22

Table 4.2 shows that the recording time for the current study was significantly shorter than the time stated by Herdman and Stapells (2001). There is a difference of approximately 65 minutes between the current study and that of Herdman and Stapells (2001). The possible reason for this time difference has already been discussed under paragraph 4.2.1, where it was stated that the averaging procedure utilized by these researchers prolonged the testing time but could have attributed to the fact that thresholds were obtained within 10 dB of behavioural thresholds. The time efficiency of a procedure remains a clinical issue, referring to an ongoing debate between the accurate estimation of thresholds and the clinical utility of the test (Schmulian, 2002).

4.3. Results from 29 hearing impaired ears controlled for degree and configuration of hearing loss in the PTA and ASSR conditions

In this sub aim the focus will be on the data obtained from the hearing-impaired ears in the related PTA and monotic single ASSR conditions. The thresholds are compared with reference to the degree and configuration of the hearing impairment. Literature relevant to the estimation of hearing impaired thresholds using either ASSR technique are integrated. The central tendencies and standard deviation from the mean are graphically illustrated and the results discussed. The graphic illustrations will facilitate comparisons and conclusions regarding the threshold estimation capabilities of the monotic single ASSR condition in hearing-impaired ears.

4.3.1 Central tendencies and Standard Deviation values for the PTA and ASSR conditions

The central tendencies and standard deviation of the PTBT at 0.5, 1, 2 and 4 kHz and of monotic single ASSR at 0.5, 1, 2 and 4 kHz are tabulated in Table 4.3.

Table 4.3 Threshold values in 29 hearing-impaired ears in the PTA and ASSR conditions

Relevant Frequency	**PTBT in dB HL**			**ASSR thresholds in dB HL**		
	Mean	Median	SD	Mean	Median	SD
0.5 kHz	54	50	± 28	80	90	± 26
1 kHz	63	60	± 32	78	75	± 24
2 kHz	69	73	± 31	84	90	± 28
4 kHz	73	73	± 30	90	93	± 27

As tabulated in Table 3.2 (chapter 3) the degree of hearing loss is categorized from normal hearing to a profound hearing loss ranging from 0 – 120 dB. In this sub aim, as already mentioned, the results are indicative of 29 hearing-impaired ears. The mean average for the PTBT is 65 dB HL, as it is evident from Table 4.3, with an average standard deviation of approximately 30 dB. The great standard deviation can be directly attributed to the fact that the whole spectrum of hearing loss is represented, from 26 dB HL to 90 dB HL and above. The mean estimated thresholds obtained from the monotic single ASSR condition were 80, 78, 84 and 90 dB HL respectively across the frequency range of 0.5, 1, 2 and 4 kHz.

In order to determine the correlation between ranks (in the current study that would refer to the frequencies of the PTA and ASSR conditions), a statistical test, the Spearman correlations coefficient, was employed. The means of thresholds at each frequency are matched in order to determine the highest correlation; optimally the corresponding frequency (example 0.5 kHz matched to 0.5 kHz) should show significant correlation.

Table 4.4 Spearman correlation coefficient statistical representation

Pure Tone Behavioural Audiometry	Monotic single ASSR			
	0.5 kHz	1 kHz	2 kHz	4 kHz
0.5 kHz	0.14	0.28	0.41	0.43
1 kHz	0.73	0.79	0.61	0.30
2 kHz	0.29	0.52	0.86	0.62
4 kHz	0.10	0.26	0.64	0.81

It is evident from Table 4.4 that the corresponding frequencies, (cells are marked in dark yellow) showed significant correlation, except at 0.5 kHz, where there was a significant correlation between 0.5 and 1 kHz (cell marked in light yellow). The significant correlations obtained for the frequencies 1 – 4 kHz between the means obtained for each frequency in the PTA and ASSR conditions with the exception of 0.5 kHz, will be discussed later on in this chapter under paragraph 4.3.2. The significant correlation for the rest of the frequencies implies accurate prediction of the specific frequency by the monotic single ASSR procedure, without interference from surrounding frequency points, with regard to the frequency specific pure tone behavioural procedure.

4.3.2 Results obtained in hearing-impaired ears with regard to the degree and configuration of the hearing loss

The thresholds obtained in the PTA and ASSR conditions are presented in audiogram format in Figure 4.3.

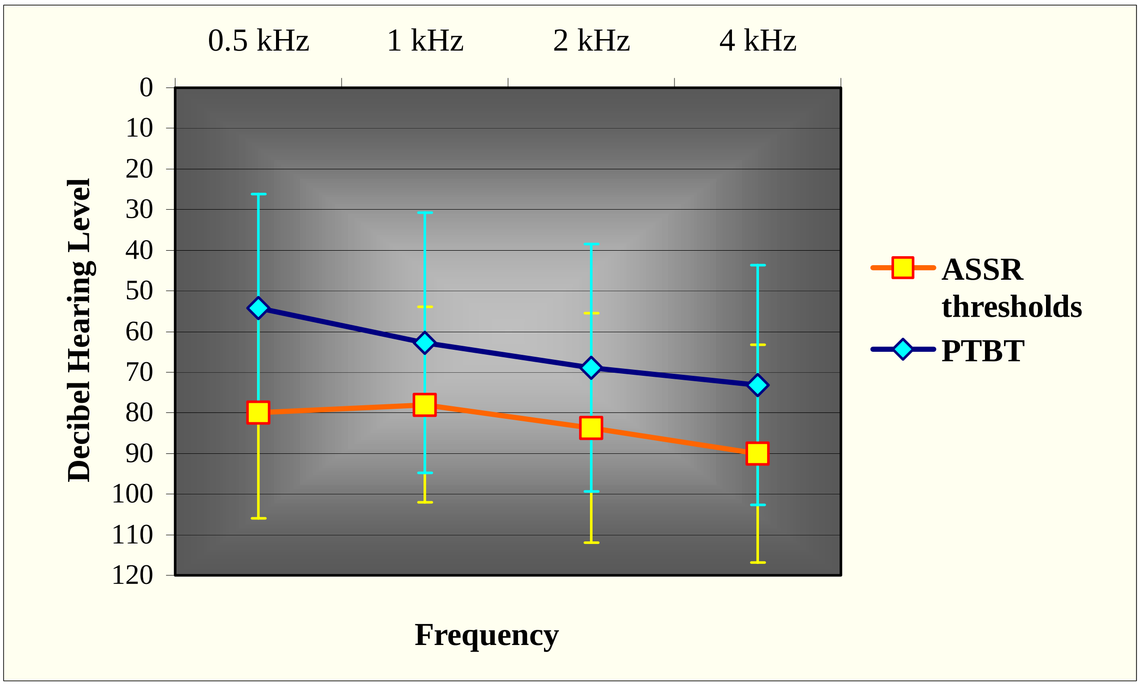

Figure 4.3 Threshold means of PTBT and monotic single ASSR across 0.5, 1, 2 and 4 kHz (n = 29 ears)

The PTBT in this figure represents a moderately severe flat hearing loss (56 – 70 dB HL, with little or no change in the thresholds across the frequencies) with regard to the degree and configuration of the hearing loss. The ASSR thresholds manifest a severe flat hearing loss, which in comparison to the PTBT shows a significant difference in thresholds but the same configuration of hearing loss. These differences in thresholds across the frequency range are tabulated in Table 4.5 and show that they (15 – 26 dB) are significantly smaller than the differences in thresholds across the frequencies in the normal hearing subjects (24 – 29 dB).

Table 4.5 Difference in threshold at comparative frequency points

	0.5 kHz	1 kHz	2 kHz	4 kHz
PTBT vs. ASSR in dB HL	**26 dB**	**15 dB**	**15 dB**	**17 dB**

The closer correlation of ASSR thresholds and PTBT in the hearing-impaired subjects can be influenced by a number of possibilities, such as the signal-to-noise ratio and loudness recruitment. The signal-to-noise ratio can influence the recording of responses but more so while testing normal hearing ears because the signal is mostly greater than the noise in hearing impaired subjects. In the current study the testing environment was also sufficiently quiet for this not to have a significant impact.

The other possibility according to Picton and colleagues (1998) can be attributed to **loudness recruitment** associated with hearing impairment. The physiological response increase in amplitude more steeply with increasing intensity when there is a hearing loss, and reach a recognizable level at an intensity level closer to the hearing threshold of the hearing impaired subject. The fact that ASSR thresholds were closer to the PTBT in hearing-impaired subjects than in normal hearing subjects were substantiated by Lins and colleagues (1996) and were also attributed to loudness recruitment that is present in the damaged cochlea. Thus, better correlation between ASSR and PTBT are evident in mild to profound hearing losses more than in normal hearing ears, possibly implying that the ASSR procedure “favours pathology” (John & Picton, 2000).

Picton and colleagues (1998) further stated that the better correlation between ASSR thresholds and PTBT in hearing-impaired ears can be attributed to the recruitment (as stated before) and the abnormal tuning curves present in the damaged cochlea. Loudness recruitment is defined as the abnormally rapid growth of loudness with the increase of intensity, creating a smaller dynamic range (Hallpike & Hood, 1960). It has been attributed to the increased firing rate once the neural threshold of the damaged cochlea has been exceeded. This was substantiated by Jastreboff (1990) with regard to the perception of tinnitus in the presence of a hearing loss. He explained that there might be an increased evoked response in the vicinity of the neural edge, meaning that a hearing loss produces a region of increased gain within the central auditory system. The theory of recruitment is related to the abnormal tuning curves in the damaged cochlea. The tuning curves lack the high sensitivity tip at a particular frequency and now resembles a shape similar to a Bekesy traveling wave, effecting the low frequencies more than the high frequencies (Picton et al. 1998). The distorted tuning curves keep their high frequency cut-off slopes, so that the use of multiple ASSR stimuli can cause interference of the low frequencies. This phenomenon is present in normal cochlea at high intensities but occur in ears with sensory neural hearing loss close to threshold (Picton et al. 1998). The age of subjects could also be responsible for the recruitment, as older individuals show greater sensitivity to high intensity sounds than younger individuals (John & Picton, 2000). However, Hood (1998) reported that only individuals in their fourth stage of life (after 60 years of age) showed some influence. For the purposes of this study no subjects was over 36 years of age, subsequently dismissing the possibility that age was responsible for the recruitment.

In the current study single ASSR stimuli were implemented and this was recommended by Picton and colleagues (1998) who stated that response amplitudes are better represented at high intensities when implementing a single modulated stimulus than the presentation of multiple ASSR stimuli. The current study showed that the mean differences between thresholds show higher correlation between ASSR and pure tone thresholds in the hearing-impaired ears.

A further observation is that the correlation between the ASSR thresholds and PTBT is better in the higher frequencies than in the lower frequencies, such as 0.5 kHz. This is also evident from Table 4.4, where the Spearman correlation coefficient shows no significant correlation at 0.5 kHz between the PTA and ASSR conditions. In a study by Rance and colleagues (1995) regarding the prediction of hearing thresholds in sleeping adults using monotic single ASSR, they described **difficulties in predicting thresholds especially in low frequencies**. The underestimation of the PTBT in the lower frequencies was attributed to the larger spatial extent of activation on the basilar membrane with regard to lower frequencies (0.25, 0.5 & 0.75 kHz) than with higher frequencies. This was in its turn influenced by the abnormal tuning curves in the impaired cochlea, causing the impaired system to have place and frequency specificity discrepancies for lower and higher intensity stimuli, effecting the lower frequencies more (Picton, 1998). Regions of the cochlea designated for the higher frequencies may represent the lower frequencies, subsequently influencing the spread of energy on the basilar membrane and reducing the frequency specificity of especially the lower frequencies (Picton, 1998).

This is corroborated in the literature where it is stated that responses originating from regions of the cochlea more basal than those associated with the nominal frequencies can be difficult to record (Cohen et al. 1991; Rance et al. 1995). The relevance to the current study is proven by the variability of 0.5 kHz throughout the results, but more so in the hearing-impaired ears than in the normal hearing ears. The differences between ASSR and behavioural thresholds related between frequencies therefore showed greater differences at 0.5 kHz in relation to the other frequencies in the hearing-impaired ears than in the normal hearing ears.

The difficulty in predicting thresholds in the lower frequencies was further substantiated by John and Picton (2000). They stipulated that physiological responses to auditory stimuli of high frequencies occur at earlier latencies than that of low frequencies. This was possibly attributed to the fact that the auditory stimuli initiate a “traveling wave” in the basilar membrane of the cochlea. Subsequently a **frequency-related delay** that effects lower frequencies more than higher frequencies is stipulated. A raw conclusion can be reached that if in the time-domain, latency delays in the lower frequencies effects the recording of responses and the time-domain is converted to the frequency domain (by means of the FFT, discussed in chapter 2), there is likely to be discrepancies in the estimation of thresholds in the said lower frequencies.

At this point, the ability of monotic single ASSR to accurately predict the degree and configuration of a hearing loss will be explored. Subsequently each relevant degree and configuration category will be presented in audiogram form, accompanied by related literature. Reference is made to Table 3.1, 3.2 and 3.3 in the methodological chapter of this study (chapter 3), where the distribution and categorization of relevant degrees and configurations of hearing loss were delineated.

Firstly, the **degree of hearing loss** for each subject was calculated across the frequency spectrum (0.5, 1, 2 & 4 kHz), and an average of the behavioural thresholds across the frequencies were classified in a severity category. Ears with the same degree of hearing loss were grouped and tabulated in Table 4.7 and represented in audiogram format in Figure 4.4.

Secondly, the effect that the degree of the hearing loss as a variable had on the data was statistically explored through implementing the Analysis of Variance (ANOVA) measure (Hicks, 1973). The p-value of the comparison was measured against 5% and 1% strength of evidence against the null hypothesis, at the nominated frequencies of 0.5 – 4 kHz. As could be expected, the significant differences between the monotic single ASSR and behavioural thresholds ensured that statistically significant differences were recorded across the frequency range. All the p-values representing the different frequencies measured significantly smaller than 0.5 or even 0.1 level of measurement. The results of this statistical analysis are tabulated in Table 4.6.

Table 4.6 Statistical representation of the effect of degree on responses in hearing-impaired subjects.

Frequencies in kHz	PTA vs. ASSR	Statistical significance differences	
	P-values	P <= 0.05	P <= 0.01
0.5 kHz	**0.000626**	✓	✓
1 kHz	**0.000014**	✓	✓
2 kHz	**0.000105**	✓	✓
4 kHz	**0.009923**	✓	✓

Table 4.7 is representative of only 27 ears, attributed to the fact that two ears were categorized with normal hearing even though there was a hearing loss present in the very high frequencies.

Table 4.7 Mean values in dB HL of 27 hearing-impaired ears grouped in relation to the degree of hearing loss

Categorization of degree of hearing loss	Pure Tone Behavioural Thresholds				Monotic single ASSR			
	0.5 kHz	1 kHz	2 kHz	4 kHz	0.5 kHz	1 kHz	2 kHz	4 kHz
Mild	32	33	41	38	62	58	54	60
Moderate	58	45	52	56	77	75	76	91
Mod-Severe	45	48	77	82	58	57	83	88
Severe	68	83	92	92	98	101	112	109
Profound	104	115	112	115	110	117	119	112

From Table 4.7 it can be seen that certain means do not fall within the specified category (ex. 82 dB HL at 4 kHz in the moderately severe category which ranges from

56 – 70 dB HL). This can be attributed to the fact that there was an unequal distribution of subjects across the severity categories. Also the configuration of the hearing loss may have an influence at certain frequencies, as a sloping loss may show a severe loss in the high frequencies but normal thresholds in the low frequencies and subsequently an average that categorizes the hearing loss as being of a moderate degree. The discrepancies will be highlighted when each of the degrees of hearing loss is discussed individually. Each severity category has been represented in audiogram format and will be briefly discussed and accompanied by relevant literature.

In the mild hearing loss category, 5 ears were grouped with this degree of severity. The differences in thresholds between the PTBT and the estimated thresholds of the monotic single ASSR condition were 30, 25, 13 and 22 dB respectively across the frequency range 0.5, 1, 2 and 4 kHz. It is evident from these numbers that the greatest difference was at 0.5 kHz. The elevation of ASSR thresholds especially at 0.5 kHz has already been highlighted by a number of studies (Rance et al. 1995; Cohen et al. 1991; Lins et al. 1996; John & Picton, 2000). The best correlation was at 2 kHz, where a mean difference of 13 dB was recorded. At 2 kHz the hearing loss reached a peak in the severity of the hearing loss. As it was stated by Picton and colleagues (1998), the recruitment of hearing loss becomes more evident with increase in severity of the hearing loss, and with recruitment the differences between the ASSR estimated thresholds and the PTBT becomes smaller.

In the moderate hearing loss category, 6 ears were grouped with this degree of hearing loss. Mean threshold differences between the PTBT and ASSR thresholds were identified as 19, 30, 24 and 35 dB respectively across the frequency spectrum (0.5, 1, 2 & 4 kHz). The most significant difference in thresholds was recorded at 4 kHz, the difference being 35 dB. Lins and colleagues (1996) reported significant elevation of the physiological thresholds in babies and normal hearing adults to be at 0.5 and 4 kHz. The slight variability of the physiological estimation of thresholds at 4 kHz has been corroborated in similar studies (Herdman & Stapells, 2001; Perez-Abalo et al. 2001) and especially at high intensities and in the dichotic multiple ASSR condition (Picton et al. 1998).

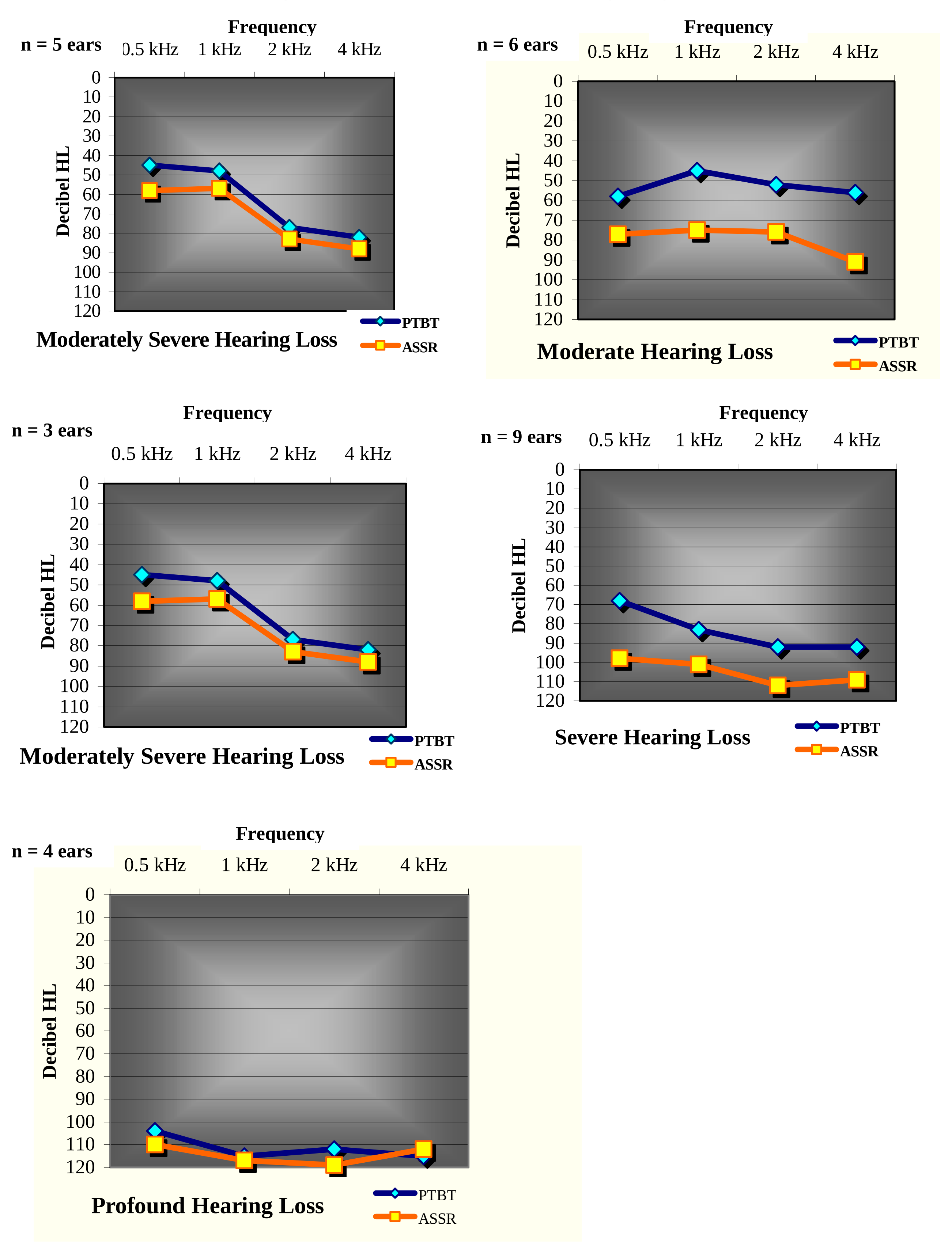

Figure 4.4 Illustrations of different degrees of hearing loss

In the Moderately Severe category the difference between the monotic single ASSR thresholds and PTBT were 13, 9, 6 and 6 dB across the frequency range (0.5 – 4 kHz). The number of ears represented by this category was three ears. A reasonably high correlation between the behavioural and physiological thresholds was established and is also representative of the configuration of this degree of severity. Subsequently reliable estimation by the monotic single ASSR condition of the behavioural thresholds is evident from this graph in Figure 4.4.

From the audiogram representing the severe category of hearing loss, it becomes clear that the ASSR means in the higher frequencies were closer to the behavioural thresholds than that of the means at 0.5 kHz, the differences respectively being 30, 18, 20 and 17 dB across the frequency range (0.5, 1, 2 & 4 kHz). This implicates that the differences were all 20 dB or less, except at 0.5 kHz and that the configuration of the hearing loss was well represented at each frequency, except that of 0.5 kHz. Again variability in predicting behavioural thresholds using the ASSR procedure at 0.5 kHz is established. Rance and colleagues (1995) found similar discrepancies with regard to 0.5 kHz at high intensity levels, using monotic single ASSR. It is important to note that with the presentation of multiple stimuli this becomes even more evident as the activation of the basilar membrane can possibly crossover at levels above 60 dB SPL (approximately 70 dB HL). The variability of 0.5 kHz was corroborated by Lins and colleagues (1996), Picton and colleagues (1998) and Perez-Abalo and colleagues (2001).

In the profound hearing loss category, the prediction of behavioural thresholds using monotic single ASSR were significantly closer than that of hearing losses of lesser severity. This can be attributed to the loudness recruitment of a profound hearing loss and the limited dynamic range of residual hearing (Picton, 1998). This is evident from Figure 4.4 where the differences between the physiological thresholds and the behavioural thresholds were 7 dB or less (6, 2, 7 & -3 dB respectively) across the frequency range. There was a marginal elevation of ASSR thresholds at 0.5 and 2 kHz, but the elevation was still well within the 10 dB range of the behavioural thresholds. At 4 kHz the PTBT were overestimated by 3 dB HL, also marginal and within a 10 dB range. Evidently accurate prediction of PTBT by the monotic single ASSR condition was recorded in the profound hearing loss category.

In the **second instance**, the **configuration of a subject's hearing loss** is determined by a preset configuration classification set out early in the history of audiology. Reference is made to Table 3.3 in chapter 3, where a classification table was drawn up as recently stipulated by Roeser et al (2000). The described configurations serve as a basis and alternative hearing loss configurations are described on a daily basis in the field of audiology. For the purpose of this study certain relevant configurations have been stipulated and will be used in the comparison between thresholds obtained in the PTA and ASSR conditions. In the current study, to classify a configuration of a hearing loss, the behavioural pure tone thresholds of the 29 hearing-impaired ears across the frequency range of 0.5 - 4 kHz were defined and a certain configuration was identified. The monotic single ASSR estimated thresholds of the same ear were grouped under the same configuration as the PTBT. This data is tabulated in Table 4.8 and each configuration will subsequently be represented in audiogram format.

Table 4.8 Mean values in dB HL for 29 hearing-impaired ears grouped according to the configuration of the hearing loss

Categorization of the configuration of hearing loss	Pure Tone Behavioural Thresholds				Monotic single ASSR			
	0.5 kHz	1 kHz	2 kHz	4 kHz	0.5 kHz	1 kHz	2 kHz	4 kHz
Flat	74	81	76	76	98	95	94	93
Sloping	50	56	65	76	65	58	82	89
Low Frequency	48	45	30	23	77	60	42	43
Ski-slope	40	54	93	100	60	72	93	109
High Frequency	13	15	28	53	53	53	50	78
Notch shaped	65	95	88	78	100	105	105	113

The statistical effect that the configuration of the hearing loss as the variable had on the data was measured by a statistical procedure, the Analysis of Variance (ANOVA) (Hicks, 1973). These results are tabulated in Table 4.9 and the p-value of the comparison was measured against 5%, as well as 1% strength of evidence. Implicating that in this analysis where $p < 0.05$, it is representative of moderate evidence against the null hypothesis and that where $p < 0.01$ it is strong evidence against the null hypothesis. When the p-value is measured against 1% the comparison is statistically stricter with little leeway for variation. In Table 4.8 statistical significant differences were marked with a tick (✓) and where no statistically significant difference was recorded, it was marked with a cross (✗). In this instance no statistical differences were recorded across the frequency region of 1 - 4 kHz but a statistically significant difference was recorded at 0.5 kHz. This indicates a high level of variance between the variables (PTBT and ASSR thresholds) at 0.5 kHz. This trend is in co-ordinance with the already discussed variability in the estimation of behavioural thresholds using the ASSR procedure with regard to 0.5 kHz. In conclusion the configuration of the hearing loss was not significantly affected at 1% comparison level by any of the relevant frequencies in the estimation of thresholds but only at 5% comparison level. This will be highlighted in the relevant illustrations and discussion that follow.

Table 4.9 Statistical representation of the effect of configuration on responses in hearing-impaired subjects.

Frequencies in kHz	PTA means vs. ASSR means	Statistically significant difference	
	P-values	P <= 0.05	P <= 0.01
0.5 kHz	0.040236	✓	✗
1 kHz	0.122675	✗	✗
2 kHz	0.171287	✗	✗
4 kHz	0.828875	✗	✗

In Figure 4.5 each configuration category has been represented in audiogram format in 6 different graphs under the following titles (reference is made to Table 3.3, chapter 3):

- **Flat configuration of hearing loss –** Little or no change in thresholds across all frequencies
- **Sloping configuration of hearing loss** – As frequency increases, the degree of hearing loss increases
- **Low Frequency configuration of hearing loss** – As frequency increases, the degree of hearing loss decreases
- **Ski-slope configuration of hearing loss** – Very sharp increase in the hearing loss between octaves
- **High Frequency configuration of hearing loss** – The hearing loss is limited to the frequencies above the speech range (2000 – 3000 Hz)
- **Notched Shaped configuration of hearing loss** – Notched shaped loss around 1 – 3 kHz can also be inverted

In the graph representing the **flat configuration** of hearing loss, 9 ears were represented. The differences between the PTBT and the estimated thresholds obtained using the monotic single ASSR condition across the frequency range of 0.5, 1, 2 and 4 kHz was 24, 14, 18 and 17 dB respectively. This indicates threshold differences of less than 20 dB, except for the greater difference at 0.5 kHz. Discrepancies in the estimation of thresholds using any ASSR condition have already been highlighted from the literature (Lins et al. 1996; Rance et al. 1995) Although the thresholds at 0.5 kHz were slightly more elevated, the configuration prediction using monotic single ASSR was accurate enough for appropriate management of the hearing loss.

The graph showing the **sloping hearing loss configuration** 8 ears were represented and the monotic single ASSR predicted behavioural thresholds with differences across the frequency range (0.5, 1, 2 & 4 kHz) of 15, 2, 17 and 13 dB. These differences are at most 17 dB and come as close as 2 dB at 1 kHz. Regarding this configuration of hearing loss monotic single ASSR accurately predicted the gradual slope of these hearing losses.

In predicting the **low frequency hearing loss configuration** with monotic single ASSR, only 3 ears were represented. The variability was at 0.5 kHz where a difference of 29 dB was recorded. This high elevation is significant in comparison to the frequencies 1, 2 and 4 kHz where the predictions were all at 20 dB and below. The prediction of low frequency configuration hearing losses could possibly be ambiguous as the incidence of sensory neural low frequency hearing losses is not very high. This is mainly because low frequency deprivation of acoustic information is usually attributed to conductive pathologies (Hall, 1992) Conductive hearing losses mostly caused by chronic middle ear pathology can cause low frequency hearing losses. These low frequency conductive losses can to an extent be treated medically (Hall, 1992). Another possibility of low frequency variability is the influence of the abnormal tuning curves in the impaired cochlea, causing the impaired system to have place and frequency specificity discrepancies for lower and higher intensity stimuli, having a greater effect on the lower frequencies (Picton, 1998).

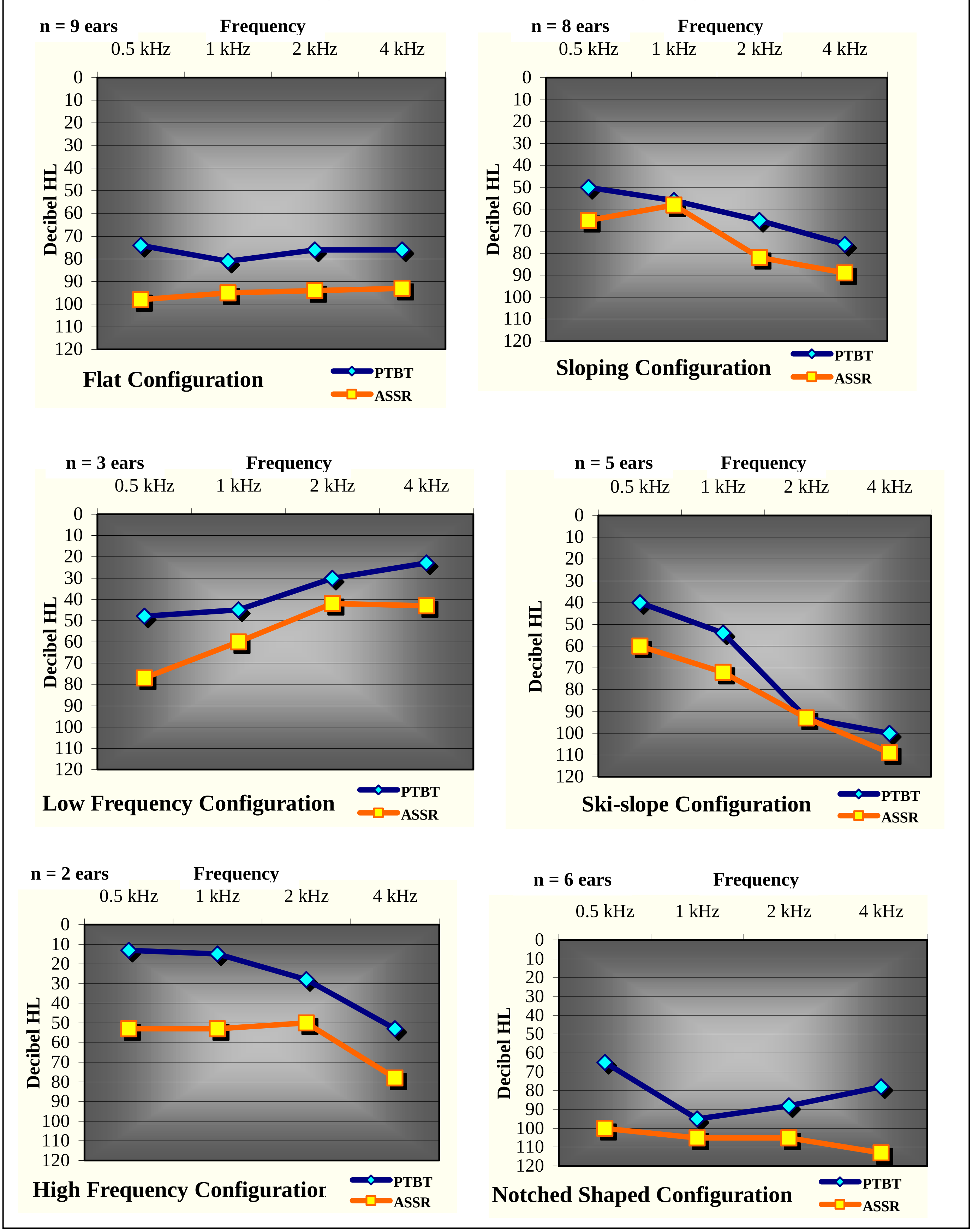

Figure 4.5 Illustrations of different configurations of hearing loss

Regions of the cochlea designated for the higher frequencies may represent the lower frequencies. Subsequently influencing the spread of energy on the basilar membrane and reducing the frequency specificity of especially the lower frequencies (Picton, 1998).

In the prediction of the **ski-slope hearing loss configuration,** 5 ears were represented and the mean differences between the behavioural and physiological (thresholds obtained using the monotic single ASSR condition) thresholds were 20, 18, 0 and 9 dB respectively across the frequency range (0.5 – 4 kHz). This shows better threshold prediction in the high frequencies (2 and 4 kHz), which is likely to be the result of loudness recruitment as stated by Picton and colleagues (1998). The higher frequency thresholds were at higher intensity levels and, as stated earlier in this chapter, the more severe the hearing loss, the likelihood of accurate behavioural threshold prediction increases using the ASSR procedure.

The **high frequency hearing loss configuration** shows better correlation between ASSR and behavioural thresholds in the higher frequencies than in the lower frequencies. However, from the range of differences in threshold across the frequencies (0.5, 1, 2 & 4 kHz) which was 40, 28, 22 and 25 dB, significantly greater differences were recorded in comparison to the other configurations. A possible explanation could be the fact that only 2 ears were classified with a high frequency hearing loss and that both ears had normal or near normal low frequency hearing abilities. However even though significant differences between ASSR and behavioural thresholds were recorded, the configuration of the monotic single ASSR estimated thresholds did follow a high frequency slope, which could possibly be predictive of a high frequency hearing loss configuration.

In the last graph a **notched shaped hearing loss configuration** was illustrated with only 2 ears being represented. Differences between thresholds were 35, 10, 17 and 35 dB respectively in the frequency range 0.5 – 4 kHz. Again only two ears represented this kind of configuration, which cannot be seen as a representative sample and subsequently not a representative prediction of the configuration using monotic single

ASSR. At both the low and high frequencies (0.5 and 4 kHz) the ASSR technique was insensitive to the behavioural threshold configuration.

In conclusion the ASSR thresholds were predictive of the behavioural threshold configuration in approximately 4 out of 6 represented configurations and as the statistical correlation showed on a strict level, the ASSR technique correlated with the pure tone behavioural thresholds across the frequency range of 0.5 – 4 kHz.

4.3.3 Effects of variables on the recording of responses in hearing-impaired ears

The possible effect that **age, gender and different ears** (left or right) has on the prediction and recording of responses in hearing-impaired ears will now be elaborated upon. The **age** distribution in the hearing-impaired subjects ranged between 13 and 22 years, representative of an adolescent and early adult age group (reference is made to chapter three, Figure 3.2). Unfortunately the age distribution was not representative of the whole age spectrum and subsequently statistical testing was not practical. Although it was not representative of a wide age range, this actually limits the possibility that age could have had an effect on the recording of responses, since that variability was only recorded in the newborn population (Lins et al. 1996; Rickards et al. 1994).

To analyse the data concerning the gender of subjects and the different ears, an independent non-parametric statistical procedure known as the Mann-Whitney test was implemented. The Mann-Whitney independent observation test is used to make a comparison between two variables in a set environment (in this case the technique used). With regard to the **gender** of the subjects, the p-value was compared to 0.05 % and a statistically significant difference was noted at 4 kHz in both the PTA and ASSR conditions, whereas if it was compared to 0.01 % no statistically significant difference was noted. Reference is made to Table 4.10 for a tabulated version of the results. Statistically significant differences are indicated with a tick (✓) and if no statistically significant difference is noted it will be indicated with a cross (✗).

Table 4.10 Statistical representation of the effect of gender on responses in hearing-impaired subjects

Technique	Female	Male	P-value	%	
PTA	Mean			>= 0.05	>= 0.01
0.5 kHz	57.5	49.1	0.8923	×	×
1 kHz	63.6	61.4	0.9281	×	×
2 kHz	63.5	77.3	0.1717	×	×
4 kHz	63.2	88.6	0.0263	✓	×
ASSR					
0.5 kHz	79.4	81.7	0.8271	×	×
1 kHz	76.9	82.2	0.4253	×	×
2 kHz	82.2	86.7	0.7959	×	×
4 kHz	80.0	107.5	0.0123	✓	×

It is evident from Table 4.10 that the gender of subjects may have an effect on the responses at 4 kHz (marked in yellow) with the difference leaning towards the male subjects. It is not certain whether the length of the basilar membrane, which is slightly longer in males, could cause this outcome. John and colleagues (2000) reported that locations of frequency specific regions on the basilar membrane of the cochlea may vary because the length of the basilar membrane varies between subjects and more so between male and female subjects. Goldstein and Aldrich (1999) also reported that possible variation exists between genders with regard to the recording of physiological responses due to the fact that head size can differ dramatically. This trend has not been investigated further but is a possible recommendation for further research. However this does not impact on the accuracy of the current study, since the differences were only on a moderate significance level.

The different ears (left or right) showed not to have any statistically significant effect on the recording of responses. Subsequently the statistical data is represented in Appendix F at the end of this study.

4.3.4 Time efficiency of the monotic single ASSR condition

As stated before, the duration of the test is a critical component in the clinical setting and has a direct influence on the quality and quantity of results. In the current study consenting adults participated, they were familiar with the testing procedures and co-operation was optimal. The duration of the two test conditions will be highlighted and elaborated upon.

Firstly the **pure tone audiometry** test battery: The otoscopic examination, tympanometry and the giving of instructions were not included in the calculation, only the recording of behavioural thresholds. The recording of thresholds included air and bone conduction thresholds at four designated frequencies (0.5, 1, 2 and 4 kHz) sequentially at varying intensities (descending in 10 dB steps and ascending in 5 dB steps) in each ear separately. The average time for the recording of behavioural thresholds in both ears was 19 minutes.

Monotic single ASSR condition: The preparation of the subjects, electrode placement, impedance checks and stabilization of the test environment were not included in the calculations. The duration of the ASSR procedure consisted of threshold estimation at four frequencies (0.5, 1, 2 & 4 kHz) sequentially, at varying intensities (descending in 10 dB steps and ascending in 5 dB steps) in each ear separately. The average time for the recording of monotic single ASSR thresholds in both ears was 96 minutes with a standard deviation of 8 minutes.

These results showed little comparison to other relevant studies, when implementing monotic single ASSR. Rance and colleagues (1995) reported testing time of between 30 and 60 minutes per subject, depending on the signal-to-noise ratio. In a later study by Rance and colleagues (1998), the testing time was not discussed, making comparisons difficult. It seems that time efficiency in using the monotic single ASSR procedure has not been extensively explored. This may be because dichotic multiple ASSR has ruled the time efficiency domain. Nevertheless, the time efficiency of a procedure remains a clinical issue, referring to an ongoing debate between the accurate estimation of thresholds and the clinical utility of the test (Schmulian, 2002).

4.4 Accurate estimation of thresholds using the ASSR technique.

Neuman (1997) stated that the key to all research is the achievements of comparisons in the research endeavour, subsequently the third and last sub aim of this chapter highlights the comparison between the monotic single and dichotic multiple ASSR, in normal hearing and hearing-impaired subjects. The estimated thresholds obtained using monotic single ASSR are compared to the threshold estimation ability of dichotic multiple ASSR. This is achieved through comparisons to relevant literature but more importantly the current study forms part of a research endeavour where dichotic multiple ASSR was implemented in the same normal and hearing-impaired subjects. These previously obtained results (Schmulian, 2002; Swanepoel, 2001) using the same hearing impaired subjects, makes comparisons between the two different ASSR conditions possible. This sub aim will subsequently provide a holistic view to current relevant literature and the comparison between the two conditions and their ability to accurately predict behavioural thresholds.

The source of extraction for the comparisons to be made will comprise of the current study's results, the previously obtained results using dichotic multiple ASSR (Schmulian, 2002; Swanepoel, 2001) and a number of selected, current and relevant studies where various ASSR conditions were implemented in normal hearing and hearing-impaired subjects. The selection of relevant studies was based on the use of ASSR techniques, how recent the publication date of the study's article was and the focus of the study. Studies published in approximately the last 10 years regarding the use of ASSR were considered and the inclusion was established if the focus of the study was on threshold estimation in either hearing-impaired or normal hearing subjects using either single or multiple presentation of steady state stimuli. The studies selected and their connection to the current study is illustrated in Figure 4.6. and they are tabulated in Table 4.11.

Table 4.11. Summary of research focusing on threshold estimation using ASSR in normal hearing and hearing impaired subjects

Researchers and year of publication	Title of study	Type of ASSR condition	Hearing ability of subjects
D. Schmulian, 2002	The prediction of hearing thresholds with Multiple Frequency Steady State Evoked Potentials compared to an Auditory Brainstem Response protocol.	Dichotic multiple ASSR	Normal hearing and hearing-impaired subjects
De Wet Swanepoel, 2001	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	Dichotic multiple ASSR	Normal hearing subjects
G. Rance, F.W. Rickards, L. T. Cohen, S. De Vidi & G. Clark, 1995	The automated prediction of hearing thresholds in sleeping subjects using Auditory Steady State Evoked Potentials.	Monotic single ASSR	Normal hearing and hearing-impaired subjects
G. Rance, R. C. Dowell, F. W. Rickards, D. E. Beer & G. Clark, 1998	Steady State Evoked Potentials in a group of children with absent click-evoked Auditory Brainstem Response	Monotic single ASSR	Hearing-impaired subjects
A. T. Herdman & D. R. Stapells, 2001	Thresholds determined using the monotic and dichotic multiple auditory steady-state response technique in normal hearing subjects.	Monotic single and multiple ASSR and Dichotic multiple ASSR	Normal hearing subjects
O.G. Lins, T. W. Picton, B. L. Boucher, A. Durieux-Smith, S. C. Champagne, L. M. Moran, M. C. Perez-Abalo, V. Martin & G. Savio, 1996	Frequency-Specific Audiometry using Steady-State Responses.	Dichotic multiple ASSR	Normal hearing and hearing-impaired subjects
T. W. Picton, A. Durieux-Smith, S. C. Champagne, J. Whittingham, L. M. Moran, C. Giguere & Y. Beauregard, 1998	Objective Evaluation of aided thresholds using Auditory Steady-State Responses	Dichotic multiple and Monotic single ASSR	Normal hearing and hearing-impaired subjects
M.C. Perez-Abalo, G. Savio, A. Torres, V. Martin, E. Rodriquez & L. Galan, 2001	Steady State Responses to Multiple Amplitude Modulated Tones: An optimised method to test frequency-specific thresholds in hearing-impaired children and normal hearing subjects	Dichotic multiple ASSR	Normal hearing and hearing-impaired subjects

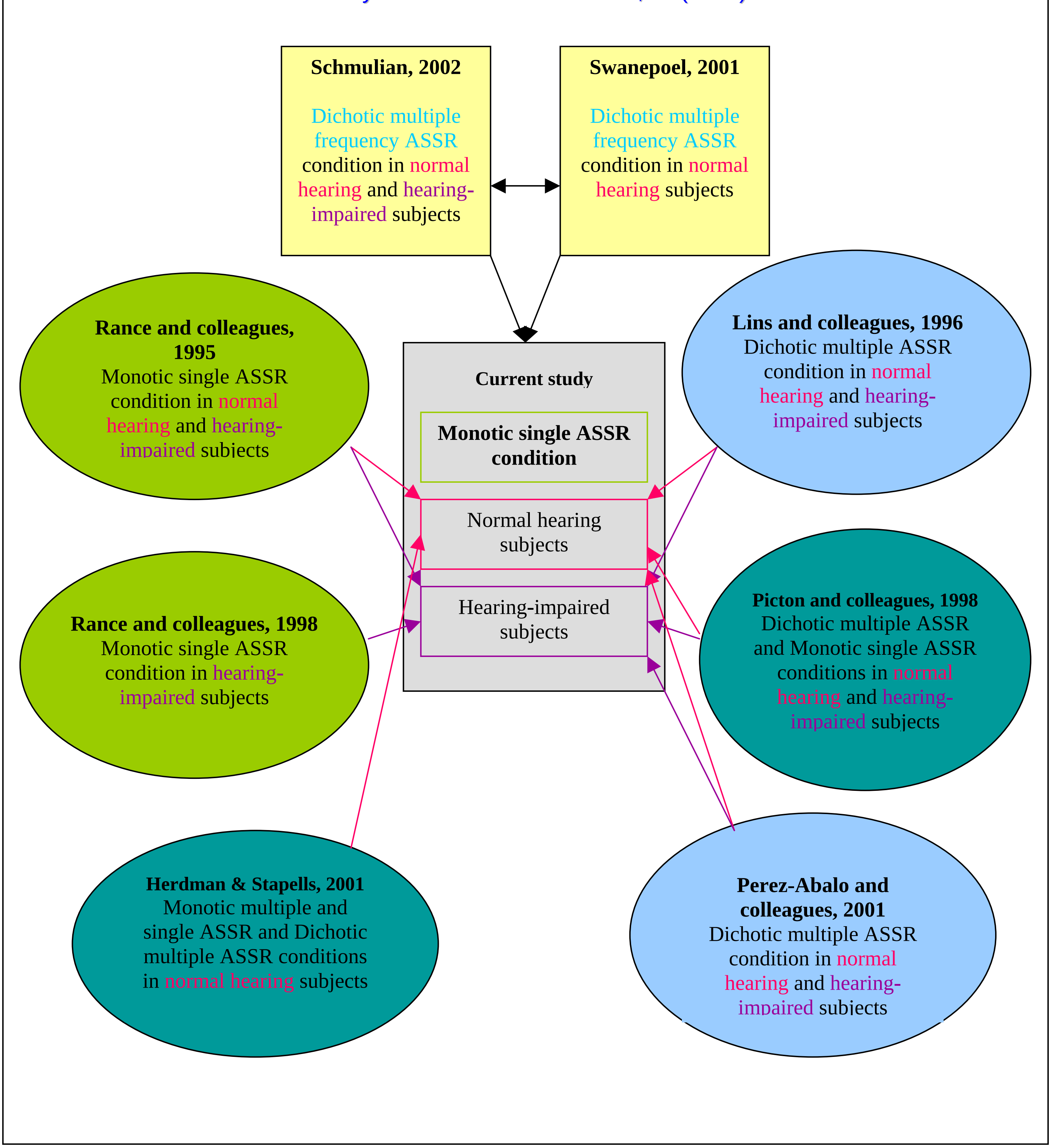

Figure 4.6 Illustration of comparative literature

Firstly, a discussion of monotic single ASSR employed in the current study, compared to the results of the relevant literature (Rance et al. 1995; Rance et al. 1998; Herdman & Stapells, 2001; Picton et al. 1998) will follow. In these studies monotic ASSR has been implemented, presenting single stimuli either sequentially (as it was done in the current study) or multiple stimuli simultaneously (referred to as monotic multiple ASSR) in normal hearing subjects and/or subjects with hearing impairment. In a study done by Rance and colleagues (1995) normal hearing and hearing-impaired subjects were used in a study where thresholds were obtained using monotic single ASSR. The results suggested that the standard deviation decreased with increasing frequency and increasing degree of hearing loss. For the normal hearing subjects in the particular study the ASSR thresholds were approximately 17 – 35 dB HL greater than the pure tone behavioural thresholds. This range correlates with the range of 15 – 40 dB HL for ASSR thresholds in relation to the PTBT, found in the current study.

In another study by Rance and colleagues (1998) the focus shifted more towards the hearing-impaired subjects. The focus was more specifically on the role of ASSR in threshold estimation with regard to management of the hearing loss. They substantiated that with the increase of frequency and degree of hearing loss, the correlation between the physiological (ASSR) thresholds and behavioural thresholds increases. They also found that 99% of ASSR thresholds were within 20 dB of the behavioural thresholds and that better responses were obtained in the severe to profound hearing loss categories. They attributed these reliable, large response amplitudes to the loudness recruitment accompanying a hearing impairment, especially in the severe to profound hearing loss category.

Picton and colleagues (1998) corroborated these findings, that at high intensity levels, possibly due to recruitment, better prediction of behavioural thresholds are achieved in the severe to profound hearing loss range. However in the particular study they describe variability at 4 kHz for high intensity levels when presenting multiple stimuli simultaneously but obtained clear responses when presenting the specific stimuli alone. Subsequently implying that at high intensities, the presentation of monotic single ASSR stimuli provides more reliable results.

This inclination can only be investigated when comparing the different means of stimulus presentation. Reference is made to a study done in normal hearing subjects comparing monotic single ASSR, monotic multiple ASSR and dichotic multiple ASSR by Herdman & Stapells (2001). The mean monotic single ASSR threshold range recorded across 0.5 – 4 kHz were from 18 – 20 dB SPL (8 – 10 dB HL according to ANSI standards, 1996), which is significantly "better" than the results obtained in the normal hearing subjects in the current study. Herdman and colleagues also stated that no significant differences for ASSR thresholds between the three stimulus conditions or techniques or the four frequencies were recorded. These results are also significantly better than results obtained in the related studies by Lins and colleagues (1996), Picton and colleagues (1998) and Perez-Abalo and colleagues (2001) and were attributed to the low ambient noise levels maintained during the testing procedures. The prolonged testing time and increased amount of averaging implemented in the study by Herdman and Stapells (2001) could also possibly have had an effect and is not always a feasible option in a clinical setting. Unfortunately the inclination of threshold estimation variability at high intensities, using the dichotic multiple ASSR was not investigated by Herdman and Stapells (2001). Even though responses can be recorded from normal hearing subjects at high intensity levels, results regarding the performance of the different stimulus techniques using ASSR would have been more conclusive if hearing-impaired subjects were used.

In the study by Lins and colleagues (1996) normal hearing as well as hearing-impaired subjects were tested using mostly the multiple simultaneous presentation of stimuli. In the normal hearing subjects, elevated thresholds (on average 12 dB) were recorded and a comparison between the multiple and single presentation of stimuli was made. It was stated that no significant differences in threshold prediction were recorded. However in the hearing-impaired subjects responses showed signs of an over activated basilar membrane with overlapping of low frequencies activation areas into high frequencies activation areas at high intensity levels. This can be overcome by separating the modulation frequencies by at least an octave or through masking, yet some studies still report some affect on the recording of responses at high intensities when presenting multiple stimuli (Picton et al. 1998; Picton et al. 2002).

These findings were corroborated by Picton (1998) when he stated that in normal hearing subjects no differences were obtained between ASSR stimulus condition, but that in some hearing-impaired subjects thresholds were more elevated when presenting the multiple stimuli than with the single stimuli, at high intensity levels. Picton and colleagues (1998) also stated that the proximity of physiological thresholds to behavioural thresholds increased with the increase in intensity and frequency.

However, a later study by Perez-Abalo and colleagues (2001) showed different results with regard to hearing-impaired subjects. In their study they tested normal hearing as well as hearing-impaired subjects using dichotic multiple ASSR. Their findings showed no significant influences of intensity levels on the recording of responses when implementing the multiple simultaneous stimuli. Subsequently they reported accurate threshold estimation using dichotic multiple ASSR in both normal hearing and hearing-impaired subjects. However their study showed significant ambient noise levels, approximately 65 – 71 dB SPL, these high noise levels are more than likely to influence the accuracy and reliability of their results. Yet, the reliability of the study was regained when the amount of subjects are taken into consideration, they included 43 hearing-impaired children (86 ears) and 40 normal hearing adults (80 ears). The same results were recorded in most of the subjects, establishing reliable results and subsequently accurate estimation of thresholds using dichotic multiple ASSR in normal hearing and hearing-impaired adults.

The focus of this sub aim was the comparison between monotic single ASSR and dichotic multiple ASSR in the estimation of thresholds. This was done by comparing the results of the current study to the relevant literature, but more important was the comparison between the previously obtained data by researchers Schmulian (2002) and Swanepoel (2001). The same hearing-impaired subjects and the same criteria for the normal hearing subjects were implemented in this study, the main difference being the use of dichotic multiple ASSR instead of monotic single ASSR.

Results are tabulated in Table 4.12 and it can be concluded that in the normal hearing subjects little or no differences were recorded in the prediction of thresholds between the monotic single and dichotic multiple presentation of ASSR stimuli. Monotic single ASSR showed slightly better prediction at 1 and 2 kHz than dichotic multiple

ASSR. Furthermore the insignificant differences between the two ASSR conditions are substantiated in the relevant literature.

Table 4.12 Comparative estimated thresholds using different ASSR conditions in the same subjects.

	Normal hearing subjects				**Hearing-impaired subjects**			
	0.5 kHz	1 kHz	2 kHz	4 kHz	0.5 kHz	1 kHz	2 kHz	4 kHz
Current study, 2003 in dB HL	**35 ± 14**	**29 ± 12**	**27 ± 11**	**30 ± 13**	**80 ± 26**	**78 ± 24**	**84 ± 28**	**90 ± 27**
Swanepoel, 2001 in dB HL	**33 ± 11**	**34 ± 11**	**32 ± 11**	**30 ± 11**				
Schmulian, 2002 in dB HL					**66 ± 23**	**74 ± 24**	**78 ± 24**	**77 ± 24**
Differences in thresholds	2 dB	-5 dB	-5 dB	0 dB	14 dB	4 dB	6 dB	13 dB

In the hearing-impaired subjects on the other hand there are significant differences, especially at 0.5 and 4 kHz (frequencies already identified as showing variability). Schmulian (2002) stated that no inaccuracies were found in recording any degree of hearing loss using dichotic multiple frequency ASSR. This substantiated the findings of Perez-Abalo and colleagues (2001), that accurate thresholds can be obtained at high intensities using the dichotic multiple ASSR procedure. Yet, research has shown that the single presentation of stimuli is better equipped to establish thresholds at high intensities and from Table 4.12, there seem to be discrepancies.

This can be attributed to the distribution of subjects, in the current study the same subjects were used as in the study by Schmulian (2002), but not the same amount of subjects. There was a significant difference in the distribution of subjects with regard to the degree and configuration of hearing loss. This discrepancy and other possible differences will be highlighted between the two procedures. In the introductory chapter of this study it was stated that in order for a procedure to effectively measure the hearing abilities of the “difficult-to-test” population (with regard to further management of the hearing loss) it has to accurately predict the degree and configuration of hearing impairment. The accurate prediction of the degree and configuration of the hearing impairment will form the basis of the comparison between monotic single and dichotic multiple ASSR. Reference is made to Figure 4.7, where the threshold means across the frequencies (0.5, 1, 2 & 4 kHz) of each study, will be illustrated in audiogram format. The time-efficiency of the ASSR procedure with regard to the different measures will be highlighted at the end of this sub aim.

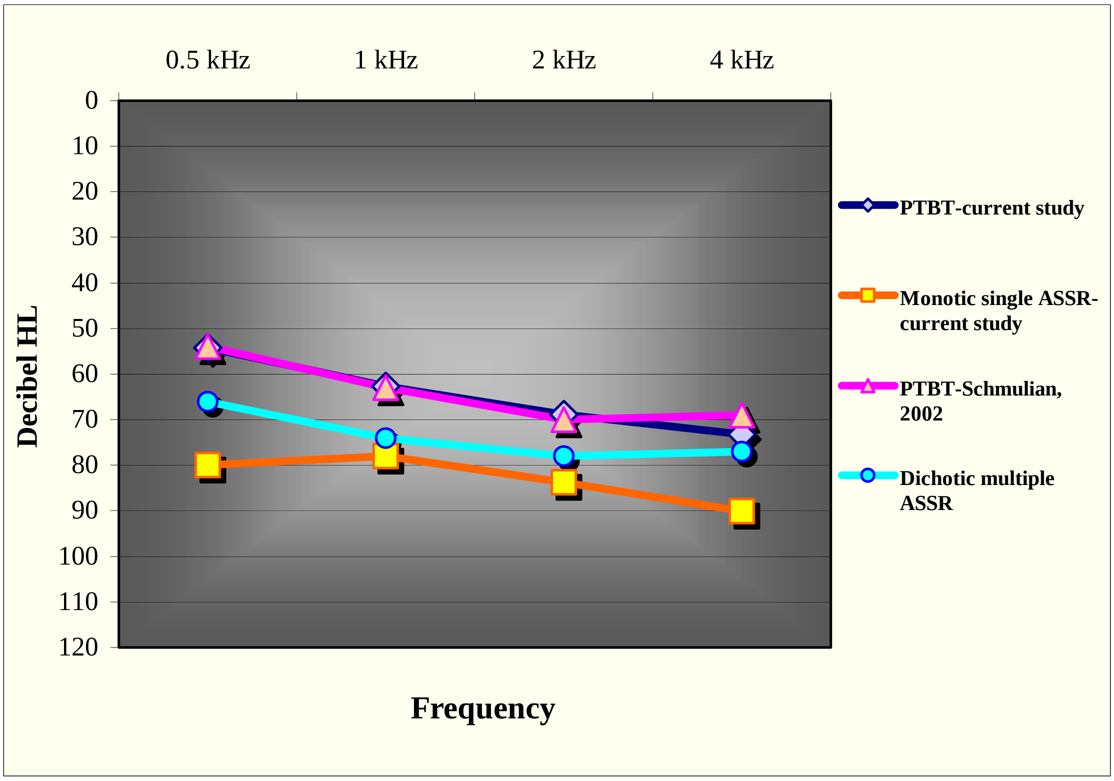

Figure 4.7. Means across frequencies of PTBT and ASSR thresholds of current study and study of Schmulian (2002).

In Figure 4.7, the results of the current study are representative of 29 hearing-impaired ears and the results of Schmulian's study were representative of 50 hearing-impaired ears. From Figure 4.7 it can be seen that the monotic single ASSR results are reasonably predictive of the degree and configuration of the pure tone behavioural thresholds, except for slight deviation at 0.5 kHz (variability of 0.5 kHz has already been discussed previously in this chapter). The dichotic multiple ASSR results accurately predicted the degree and configuration of the pure tone behavioural thresholds.

A number of factors could have contributed to the slightly better prediction of behavioural thresholds using dichotic multiple ASSR.

- The acoustic environment: no formal measurements were done in the study by Schmulian, subsequently little comparison can be made but with regard to hearing-impaired individuals, this factor is not of significant influence. This is mainly the case because the signal-to-noise ratio is of such variance (signal significantly higher than noise in most instances) that the acoustic noise could not have had such a significant influence. Especially so, because the pure tone behavioural thresholds were as expected and subsequently ambient noise did not influence the reliability of the measurements.

- Type of transducer used: The same transducers were used, namely insert earphones (reference is made to chapter three, paragraph 3.5.2). The implication is that the type of transducer could not have had such a significant influence on the recording of responses.
- Stimulus presentation: The stimulus presented differed, seeing as that is the main difference between monotic single ASSR and dichotic multiple ASSR. Subsequently the duration and complexity of the stimulus differed, but the influence of these factors, as well as the stimulus frequency and intensity, have been discussed (reference is made to chapter two, paragraph 2.3.3).
- Adequate averaging: In the current study approximately 40 epochs were completed before a no-response was recorded and in the other study between 16 and 24 epochs were averaged for a response. This amount of averaging is adequate in relation to the different software that was used and the different testing techniques.
- Sample size: This sample size can have a significant influence on the reliability of results, as was evident with the study conducted by Perez-Abalo and colleagues (2001) where the sample size probably contributed to the reliability of the results within an environment subjected to high levels of noise. As it was stated previously, the current study included a sample size of 29 ears and the study by Schmulian (2002) included a sample size of 50 ears. This difference in sample size could have effected the results significantly enough that dichotic multiple ASSR showed better threshold estimation abilities than monotic single ASSR.

The time efficiency of the dichotic multiple ASSR has been emphasized in the literature by numerous studies (Picton et al. 2002; Herdman & Stapells, 2001; Perez-Abalo et al. 2001; Picton et al. 1998; Lins et al. 1996) and in comparison to the time efficiency of monotic single ASSR in the current study, was the following:

- Testing time for both ears using Monotic single ASSR in the current study – 96 min ± 8 min
- Testing time for both ears using Dichotic multiple ASSR from the previously obtained data (Schmulian, 2002; Swanepoel, 2001) – 12 to 52 min

In conclusion dichotic multiple ASSR is significantly more time efficient than monotic single ASSR due to the fact that stimuli are presented simultaneously and not sequentially, and to both ears at the same time, not each ear individually.

4.5 Summary

This chapter stipulated the results obtained, while implementing the method of the study. The data was discussed in accordance with the sub-aims presented in chapter three and the relevant data was graphically presented. Each result was followed by an interpretation of the data and discussion of the relevance with regard to the literature. The chapter was concluded with a summary of the content.

5

Conclusion of Study

This chapter aims to draw conclusions and discuss the implications from the represented results, critically evaluate the study and recommend further research possibilities

5.1 Introduction

The field of Audiology evolved as technology expanded, from a practice ruled by otologists, post World War II, to a dynamic field where hearing sensitivity can be determined while an individual is sleeping (Martin, 2000). Physiological measures have assumed an essential role in clinical practice and is testimony to the direction in which audiology is heading (Ferraro & Durrant, 1994). Research in this arena, constantly broadens the scope of clinical practice and subsequently introduces new, improved and relevant procedures that ultimately aims to benefit the hearing-impaired individual (Martin, 2000).

Such is the case with the Auditory Steady State Response (ASSR), a new clinical procedure that aims to obtain a frequency-specific audiogram without any response from the individual. This procedure is finding its place in the existing field of audiology and needed to contribute to the existing framework of procedures. Furthermore within the scope of ASSR different presentations of stimuli provide a few different means of acquiring ASSRs, each with its own strengths and weaknesses. Each of these stimulus presentation techniques has to establish their applicability, for the ASSR procedure to establish its place in the existing field of audiology.

The current study centred on monotic single ASSR in its ability to accurately estimate frequency-specific hearing thresholds in normal hearing and hearing-impaired subjects, across the range of hearing sensitivity. A level of comparison was subsequently drawn between the results of the current study and relevant literature focusing on estimated thresholds using dichotic multiple ASSR, to obtain a holistic view of the ASSR procedure's abilities.

To draw conclusions from the results of the current study, monotic single ASSR must be subjected to scrutiny to determine the specific usefulness in a particular setting. Underlying reference will be made to the reliability (dependability or repeatability of the measurement), validity (how well a procedure measures what it is suppose to measure), sensitivity (the accurate prediction of the pathology by the procedure) and specificity (accurate elimination of pathology in the presence of normal abilities) of each ASSR condition (Martin, 1997).

In this chapter the purpose will be to draw conclusions from the results represented and discussed in chapter 4 under each sub aim, and provide the clinical and theoretical implications of this study. A critical evaluation of the study is subsequently provided to identify the inherent and methodological limitations, followed by recommendations for further future research. Finally a conclusion and summary is provided.

5.2 Conclusions of sub aims

The comparative experimental research design that was implemented in this study enables the researcher to draw a direct conclusion between the dependant variables of each sub aim (reference is made to chapter three, where the methodology of the study was discussed). To be able to answer the hypothetical question asked in the introductory chapter of this study. The conclusions will be discussed according to each sub aim.

5.2.1 To collect normative data in 30 normal hearing ears, subject group controlled for age and gender, across 0.5, 1, 2 and 4 kHz in the pure tone behavioural audiometry and auditory steady state response (ASSR) conditions

In this sub aim data was obtained in 30 normal hearing ears using Pure Tone Audiometry and monotic single ASSR. This was done to determine the accuracy of behavioural threshold prediction when using monotic single ASSR. Ninety three percent of the normal hearing subjects were identified with hearing abilities in the upper range of normality (0-10 dB HL according to Northern & Downs, 1991) and the ASSR results indicated an elevation of 29, 27, 24 and 27 dB across the frequencies 0.5, 1, 2 and 4 kHz, respectively. The possible reasons for the elevated thresholds were discussed with regard to relevant literature and the conclusion was reached that the ambient noise levels and the modulation of the stimuli presented could account for the elevation (Herdman & Stapells, 2001; Lins et al. 1996; Picton et al. 1998). Thus **frequency-specific thresholds were estimated reasonably accurately** with an average standard deviation of 12 dB. This implies that the monotic single ASSR condition can obtain thresholds at specified frequencies (0.5, 1, 2 & 4 kHz), reasonably close to the behavioural thresholds in normal hearing subjects.

However, the feasibility of obtaining near threshold levels using either ASSR condition (monotic single or dichotic multiple ASSR) is decreased because of the latency jitter close to threshold level especially for normal hearing subjects (Picton et al. 1998). Currently for the ASSR procedure to be clinically applicable, it will have to form part of the audiometric test battery in order to be reliably accurate and sensitive to the subject's hearing abilities. This is known as the cross-check principle, which ensures appropriate management of the hearing loss if a disability is identified. In the case of normal hearing individuals this is even more important as inappropriate management can cause significant harm (Jerger & Hayes, 1976). In the normal hearing group of subjects the effect that the gender and different ears (left and right) could possibly have on the recording of responses were also investigated. No statistically significant effects were identified in this group of subjects in this regard.

5.2.2 To collect data obtained from 29 hearing impaired ears controlled for degree and configuration of hearing loss using monotic single ASSR across 0.5, 1, 2 and 4 kHz

In this sub aim the focus was on the data obtained from the hearing-impaired ears in the related pure tone behavioural and monotic single ASSR conditions. The thresholds were compared with reference to the degree and configuration of the hearing impairment. This was done in order to determine the accuracy of threshold prediction using monotic single ASSR in hearing-impaired subjects, across the range of hearing sensitivity. The difference between the ASSR estimated thresholds and the behavioural thresholds across the frequency range of 0.5, 1, 2 and 4 kHz, was 26, 15, 15 and 17 dB, respectively. This was a significantly closer estimation than the results obtained in the normal hearing subjects. A number of researchers attribute the fact that in hearing-impaired individuals the more accurate estimation of pure tone behavioural thresholds using ASSR could be attributed to loudness recruitment in the damaged cochlea (Picton, 1998; Rance et al. 1995; Rance et al. 1998).

Statistical correlation between the PTBT and the estimated thresholds of the monotic single ASSR condition showed significant correlation at all the frequencies except at 0.5 kHz. This trend was substantiated by relevant literature stating that variability in the estimation of thresholds at 0.5 kHz is evident and can possibly be attribute to the larger spatial extent of activation on the basilar membrane with lower frequencies (0.25, 0.5 & 0.75 kHz) than it is with higher frequencies. This influence can be attributed to the abnormal tuning curves in the impaired cochlea (Cohen et al. 1991; Rance et al. 1995; Picton et al. 1998). Subsequently behavioural thresholds were accurately predicted using monotic single ASSR, with the exception of 0.5 kHz.

The sensitivity of monotic single ASSR was measured with regard to the degree and configuration of the hearing loss (accurate identification of the pathology). In the mild and moderate categories of hearing loss reasonably accurate estimation of behavioural thresholds were obtained using monotic single ASSR, except for thresholds at 0.5 and 4 kHz. This was corroborated by similar studies referring to variability in threshold estimation at these frequencies (Herdman & Stapells, 2001; Lins et al. 1996; Perez-Abalo et al. 2000). Evident from the results was the trend identified by a number of researchers (Picton et al. 1998; Rance et al. 1995) namely that as the recruitment of hearing loss becomes more evident with increased severity, the differences between the ASSR estimated thresholds and the PTBT become smaller. In the moderately severe and profound hearing loss categories, the ASSR thresholds were on average within a 10 dB range of the behavioural thresholds. **The ASSR condition provided accurate estimation of the behavioural thresholds for impaired ears.**

This was however contradicted in the severe hearing loss category where the ASSR thresholds were not an accurate prediction of the behavioural thresholds. This was attributed to individual discrepancies in the threshold estimation of participating subjects. This finding was unexpected and factors that attributed to the results in this category will be discussed under the limitations of this study, later in this chapter.

With regard to the configuration of the hearing loss and the effect on the estimation of behavioural thresholds using monotic single ASSR, no statistically significant differences were found, except at 0.5 kHz. Again this variability of 0.5 kHz in the estimation of behavioural thresholds has been corroborated in the literature by a number of similar studies (Lins et al. 1996; Rance et al. 1995). Six configurations were defined (adapted from Roeser et al. 2000) of which four of the six configurations were accurately predicted using the ASSR technique. Variability was as before evident at 0.5 and 4 kHz and subsequently some configurations indicated inaccurate prediction at one or both of these frequencies. All the ASSR thresholds of all the configurations were within 20 dB of the behavioural thresholds, except at the prediction of the high frequency and notched shaped hearing loss configurations, where a significantly limited sample of subjects were classified. This implicates an inaccurate representation of the specific configuration of hearing loss and an in accurate representation of the ability of monotic single ASSR to predict the configuration of the loss. However, in general the statistical correlation showed on a strict level (measured against p>= 0.01), that there was a high level of correlation between the ASSR technique and the pure tone behavioural thresholds across the frequency range of 0.5 – 4 kHz, with regard to the prediction of the configuration of the hearing loss. On a moderate level of comparison (p>= 0.05), the statistical analysis did not indicate a significant correlation between ASSR thresholds and behavioural thresholds.

In the hearing-impaired group of subjects the effect that the gender and different ears (left and right) could possibly have on the recording of responses were also investigated. No statistically significant effects were identified in this group of subjects, on a strict level of representation.

5.2.3 To compare the results with trends in the literature with regard to the accuracy in threshold estimation using the ASSR condition in similar testing conditions

In this sub aim the focus was on the comparison between the two different means of stimulus presentation relevant to ASSR in normal hearing and hearing-impaired subjects. The estimated thresholds obtained using monotic single ASSR were compared to threshold estimation using dichotic multiple ASSR. This was achieved through comparisons to relevant literature, but more importantly, the current study formed part of a research endeavour where dichotic multiple ASSR was implemented in the same normal and hearing-impaired subjects (Schmulian, 2002; Swanepoel, 2002).

In the first instance the results obtained in the normal hearing and hearing-impaired ears using the monotic single ASSR condition was compared with relevant literature. It was found that thresholds obtained corroborated with other relevant studies and substantiated the findings that with increasing frequency and increasing degree of hearing loss the difference between physiological and behavioural thresholds decreased (Rance et al. 1995; Rance et al. 1998; Picton et al. 1998). When comparing the threshold estimation abilities of the different ASSR conditions, the current study's results were compared to two previous studies and to relevant literature. **The findings suggested that no significant differences were evident between the threshold estimation abilities of either monotic single or dichotic multiple ASSR techniques in the normal hearing subjects.** This is also substantiated in the literature by several relevant studies (Lins et al. 1996; Picton et al. 1998; Perez-Abalo et al. 2001) but especially the study done by Herdman and Stapells (2001). In that specific study comparisons using several different ASSR conditions were made in normal hearing subjects and no significant differences were recorded.

However, when it comes to hearing-impaired individuals, up until recently, the literature was in favour of monotic single ASSR in estimation thresholds at very high intensities. Nevertheless, recent studies showed that with accurate modulation and threshold estimation criteria, responses could be recorded as efficiently at high intensities using any ASSR technique (Perez-Abalo et al, 2001; Schmulian, 2002). In the comparison between the current study’s results and that of the previously obtained results (Schmulian, 2002), dichotic multiple ASSR showed better thresholds than that of the monotic single ASSR. This was attributed to a limited number of subjects used in the current study with subsequent poor representation of the different degree and configuration of hearing losses. **In conclusion little difference has been established between the estimation of thresholds using either monotic single ASSR or dichotic multiple ASSR.**

5.3 Critical Evaluation of Research Study

Just like new audiometric procedures have to fit into an existing audiology framework for them to function effectively, the same principles apply to research. Each new research project fits into an existing framework of research that may either require contribution or be saturated. Nevertheless, each study‘s results do not only reside in its contribution, but also highlighting the strengths and weaknesses of the endeavour (Neuman, 1997). This enables research that follows to improve upon the existing research and in so doing build into a strong research framework. A critical evaluation of the current study, where certain limitations will be discussed, will follow. Distinction can be made between the test environment, the participating subjects and the relevant audiometric procedure to ascertain the weaknesses of the study.

In the test environment, previous research has shown that keeping the **ambient noise levels** to a minimum can have significant influence on the recording of responses (Herdman & Stapells, 2001; Perez-Abalo et al. 2001; Picton et al. 1998). In the study by Herdman and Stapells (2001) the ASSR thresholds were obtained on average within 10 dB of the behavioural thresholds and this was to an extent, attributed to the low ambient noise levels. In the current study, behavioural thresholds were obtained in a double walled, sound attenuated booth within a sound treated room but the ASSR thresholds were obtained in a single walled, sound attenuated booth within a sound treated room.

The acoustical ambient noise levels were measured in the ASSR test environment and careful consideration was taken to keep acoustic ambient noise levels to a minimum. However this was not the focus of the study and subsequently the influence of noise on the recording of responses cannot be eliminated as a possible influential factor.

Research subjects contribute to a certain amount of variables in any study through age, gender and hearing abilities. The researcher controls these aspects as much as possible but unfortunately other variables like the emotional state of a subject can have a significant influence on the research and little control can be exerted. This is significant when it comes to the restlessness of the subject and the internal noise artefacts that are recorded. When the recording time is limited, constant **internal noise artefacts** sometimes caused by a restless, stressed subject can prevent the recording of responses at low intensities, proven to be audible to the subject by the behavioural testing. In the current study, the clinical set-up in which the testing of subjects proceeded prevented prolonged testing time and averaging of responses, which could have provided better prediction of the behavioural thresholds using the ASSR procedure.

Another consideration with regard to the participating subjects is the **sample size** implemented in the study. According to Neuman (1997) the size of the subject sample depends on the kind of data analysis the researcher plans. A large sample with a poor sampling frame does not guarantee a representative sample. The same applies to a small sample with a good sampling frame. In the current study the rule of thumb was used, using the same amount of subjects that proved to be a representative sample in previous studies (Neuman, 1997). Thirty subjects were randomly selected after they have met the selection criteria and according to availability. This sample size proved to be representative of threshold estimation using monotic single ASSR, but detailed comparisons between different ASSR techniques with regard to the degree and configuration of the hearing loss was not sufficiently represented. The distribution of subjects between each degree and configuration of hearing loss in comparison to the previous study (Schmulian, 2002) was not sufficiently represented and this was evident in the results of the current study.

Another consideration was the **age distribution** of the subjects in the current study (reference is made to chapter three, Figure 3.2). The most represented age group was between 16 and 25 years of age, with lesser representation in the age groups 10 – 15 and 26 – 35 years of age. This limits the generalization that can be drawn from the results with regard to the possible effect of age on the recording of ASSR responses.

The last aspect identified in the critical evaluation of this study is lack of **threshold estimation criteria**. As stated previously in this section, the internal noise artefacts of a subject can have a significant influence on the recording of responses close to threshold. Accompanied by a limited time frame for the testing of the subjects, this contributed to a lack of threshold estimation criteria. The signal-to-noise ratio should be included to determine the amount of averaging that needs to be done to obtain a reliable response. This will also have an effect on the test-retest reliability of the ASSR procedure as inter and intra subject variability could possibly decrease.

5.4 Recommendations for further research

The contribution of a single study not only depends on the results of the study but also the questions that arose in answering the one question at hand. From the critical evaluation of the current study a number of limitations were highlighted that subsequently related into recommendations for future researchers. These suggestions follow.

- In order to obtain reliability of an audiometric procedure, repeatability is important (Neuman, 1997). This implicates the correlation of results from different measures using the same procedure. A number of variables have been determined using the ASSR procedure and there seems to be a lack in research concerning test-retest ability. This will contribute significantly towards establishing the stability of the procedure and subsequently any of the different conditions of the ASSR procedure. Presently, the preliminary findings of a study exploring the test-retest ability of ASSR seem favourable (Van der Merwe, 2002).

- The second recommendation for further research is in relation to the evaluation of ASSR in the existing framework of electrophysiological procedures. This will ascertain the function and place of each procedure in the test battery of objective diagnostic audiometry. A number of studies have already reported on comparisons between ASSR and ABR (Swanepoel, 2001; Schmulian, 2002) but the focus should not only be on ABR but also on other electrophysiological procedures, namely early latency, middle latency and late latency response measurements. Valuable information regarding complimentary relationships between certain measures will aid in extensive diagnostic information regarding an individual‘s hearing capabilities.

- The third recommendation centres on ASSR’s ability to obtain thresholds at very high intensities. Diagnostically ASSR has already been implemented in identifying cochlear implant candidates (Rance et al. 1998; Picton et al. 1998). Another possibility for further research is the ASSR procedures’ ability to obtain aided thresholds from the patient with a cochlear implant. This can result in clinicians implementing ASSR in the rehabilitation process of the candidates already implanted.

- The last recommendation for further research involves the test environment. Using the same subjects but manipulating the ambient noise levels should contribute to the influence noise has on threshold estimation using the ASSR procedure. This will enable the researcher to set out criteria for threshold estimation with regard to the amount of averaging that needs to be done according to the estimated signal to noise ratio.

5.5 Final comments

The final comments on the threshold estimation abilities of the ASSR procedure can be related to the reliability, validity, sensitivity and specificity of the procedure (Martin, 1997). The reliability of the procedures has been established to an extent, since reasonably accurate results were obtained when the measurement was repeated. The reliability of the procedure is evident from the small standard deviations that were recorded with regard to the normal hearing subjects (it is not applicable to the hearing impaired-subjects, as the standard deviations represent the whole range of severity). These deviations from the mean compared favourably with the deviations from the behavioural means, implicating dependable results with every measure.

The frequency specificity of the ASSR procedure and its ability to accurately predict the degree and configuration of the hearing loss were established through this study and strongly implicates the positive validity of the procedure. Since the validity refers to how well a procedure measures what it is intended to measure (Martin, 1997). The accurate prediction of the degree and configuration of the hearing loss further implicates that the procedure accurately identifies the possible pathology. Subsequently the ASSR procedure is sensitive to the accurate prediction of pathology. A procedure should not only be able to identify pathology but also be able to accurately eliminate pathology if none exist and normal hearing abilities need to be identified. This was done when ASSR predicted normal hearing thresholds within 20 dB of the behavioural thresholds. Previous studies (Herdman & Stapells, 2001) even predicted normal hearing thresholds within 10 dB of behavioural thresholds, with prolonged testing time and averaging of responses.

The different ASSR stimulus presentation techniques have contributed to applicability of the ASSR procedure in the existing field of audiometry. Yet it is perhaps a time for cautious optimism. There is always room for improvement and ASSR is no exception. The results are favourable and reasonably close estimation of the behavioural results has been established, but a certain extent of elevation still exists and should be accounted for. Clinicians should also be educated with regard to ASSR, as it is new to the field and will provoke some scepticism or overzealous application. Picton and colleagues (1998) stated that much still needs to be done with regard to ASSR. Nonetheless it is a promising procedure that is broadening the existing field of audiometry.

5.6 Summary

In this chapter conclusions had been drawn from the results obtained. Significant results were highlighted and their contribution to the literature was discussed. A conclusion regarding the aim of the study was formulated to answer the question the study originally posed. A critical evaluation of the study highlighted its limitations and subsequent recommendations for further research were provided.

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Appendix A

Approval letter from University of Pretoria Research and Ethics Committee

Appendix B

Letter of Consent to parent/guardian of potential subjects

February 2002

Dear Sir / Madam

Thank you for showing interest in this research project being conducted at the Hearing Clinic, Department of Communication Pathology at the University of Pretoria. We are aware of the fact that the study done in 2001 was successful and we would like to continue in the same manner. We hope that this new technique will become part of all audiometric procedures in the near future.

As you may know, what makes this procedure different is the fact that we do not need any response from the child in order to obtain hearing thresholds. The University is privileged to have this kind of equipment because it is not yet available elsewhere in the world.

The testing involves the following:

1. A normal hearing test will be done to get a general idea of the child's hearing abilities. In the case of the child making use of amplification, we will only determine unaided thresholds.
2. Then the same testing will be done on the new equipment but without any response from the child. The child will be asked to lie down on a bed with three electrodes attached to their head and insert earphones in both ears.
3. The whole procedure will last ± 2 hours. Both procedures are non-invasive and only one procedure requires subjective responses. At your request, a copy of the results will be made available to you. Thank you for your assistance.

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

Yours sincerely

______________________	______________________	______________________
Prof. René Hugo	Dr. Dunay Schmulian	Me Riëtte Bosman
Head of Department	Research Supervisor	Researcher

REPLY SLIP

University of Pretoria

Department of Communication Pathology

Surname: ____________________________	Name: ______________________
Date of Birth: ________________________	Age: _______________________
First language: _______________________	Contact numbers: ____________
	_____________________________
	_____________________________

Please be so kind to fill in the reply slip and bring it with on the day of testing.

I, __________________________________, parent/guardian/caretaker of ____________________________________ hereby give permission that he/she may participate in this project. I am aware that we can at any stage of the study withdraw from participating. I also understand that the information will be used for research purposes only and is confidential.

___________________________	___________________________
Signature	Date

Appendix C

Letter of Consent to potential subjects

February 2002

Dear Sir / Madam

Thank you for showing interest in this research project being conducted at the Hearing Clinic, Department of Communication Pathology at the University of Pretoria. We are aware of the fact that the study done in 2001 was successful and we would like to continue in the same manner. We hope that this new technique will become part of all audiometric procedures in the near future.

As you may know, what makes this procedure different is the fact that we do not need any response from you in order to obtain hearing thresholds. The University is privileged to have this kind of equipment because it is not yet available elsewhere in the world.

The testing involves the following:

1. A normal hearing test will be done to get a general idea of your hearing abilities. In the case of you making use of amplification, we will only determine unaided thresholds.
2. Then the same testing will be done on the new equipment but without any response from you. You will be asked to lie down on a bed with three electrodes attached to your head and insert earphones in both ears.
3. The whole procedure will last ± 2 hours. Both procedures are non-invasive and only one procedure requires subjective responses. At your request, a copy of your results will be made available to you. Thank you for your assistance.

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

Yours sincerely

Prof. René Hugo	Dr. Dunay Schmulian	Me Riëtte Bosman
Head of Department	Research Supervisor	Researcher

REPLY SLIP

University of Pretoria

Department of Communication Pathology

Surname: ____________________________	Name: ______________________
Date of Birth: _________________________	Age: ________________________
First language: ________________________	Contact numbers: _____________ _____________________________ _____________________________

Please be so kind to fill in the reply slip and bring it with on the day of testing.

I, __________________________________ (state full name) hereby consent to participate as a research subject in this project at the Hearing Clinic, Department of Communication Pathology at the University of Pretoria. I understand that the information will be used for research purposes only and is confidential.

___________________________	___________________________
Signature	Date

Appendix D

Statistical representation of the effect of gender on the responses of normal hearing subjects

Statistical representation of the effect of gender on responses in normal hearing subjects

Technique	Female	Male	P-value	%	
PTA	**Mean**			**>= 0.05**	**>= 0.01**
0.5 kHz	**6.8**	**5.0**	**0.3358**	✗	✗
1 kHz	**3.2**	**0.9**	**0.2360**	✗	✗
2 kHz	**3.2**	**3.1**	**0.9141**	✗	✗
4 kHz	**2.5**	**3.1**	**0.8258**	✗	✗
ASSR					
0.5 kHz	**37.9**	**33.1**	**0.5705**	✗	✗
1 kHz	**30.4**	**27.2**	**0.5423**	✗	✗
2 kHz	**25.4**	**28.1**	**0.1065**	✗	✗
4 kHz	**33.6**	**26.9**	**0.1449**	✗	✗

Appendix E

Statistical representation of the effect of different ears on responses in normal hearing subjects

Statistical representation of the effect of different ears on responses in normal hearing subjects

Technique	Left	Right	P-value	%	
	Mean			>= 0.05	>= 0.01
PTA	**4.1**	**2.8**	**0.4083**	✗	✗
M(s)ASSR	**29.7**	**30.6**	**0.8057**	✗	✗

Appendix F

Statistical representation of the effect of different ears on responses in hearing impaired subjects

Statistical representation of the effect of different ears on responses in hearing impaired subjects.

Technique	Left	Right	P-value	%	
	Mean			>= 0.05	>= 0.01
PTA	60.8	68.5	0.2488	✗	✗
M(s)ASSR	78.9	87.4	0.3624	✗	✗