Slow Cortical Auditory Evoked Potentials and Auditory Steady-State Evoked Responses in adults exposed to occupational noise

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I hope I have made you proud....

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LIST OF ABBREVIATIONS

ABR	**-**	**Auditory Brainstem Response(s)**
AEP	**-**	**Auditory Evoked Potential(s)**
Ai	**-**	**Ipsilateral Earlobe**
AM	**-**	**Amplitude Modulation**
AM/FM	**-**	**Amplitude and frequency modulated (stimuli)**
AMFR	**-**	**Amplitude Modulated Following Response**
ASSR	**-**	**Auditory Steady State Evoked Response(s)**
Cz	**-**	**Midline**
dBeHL	**-**	**Decibel estimated hearing level**
dBHL	**-**	**Decibel hearing level**
dBnHL	**-**	**Decibel normal hearing level**
dBSPL	**-**	**Decibel sound pressure level**
Diff	**-**	**Difference score (AEP threshold – behavioural PT threshold)**
EEG	**-**	**Electroencephalogram**
FFT	**-**	**Fast Fourier Transform**
FM	**-**	**Frequency Modulation**
Fz	**-**	**Midline High Forehead**
GSI	**-**	**Grason-Stadler Incorporated**
HL	**-**	**Participants with hearing loss**
Hz	**-**	**Hertz**
ILO	**-**	**International Labour Organisation**
ISO	**-**	**International Standards Organisation**
kHz	**-**	**Kilo Hertz**
kΩ	**-**	**Kilo Ohms**
m	**-**	**Meters**
min	**-**	**Minutes**
ms	**-**	**Miliseconds**
n	**-**	**Number of participants unless otherwise specified**
N	**-**	**Participants with normal hearing**
N/A	**-**	**Not applicable**

NIHL	**-**	**Noise induced hearing loss**
OAE	**-**	**Otoacoustic Emissions**
PT	**-**	**Pure Tone**
r	**-**	**Correlation score**
$\mathbf{R^2}$	**-**	**R-squared correlation**
s	**-**	**Seconds**
SANS	**-**	**South African National Standard**
SCAEP	**-**	**Slow Cortical Auditory Evoked Potential(s)**
SH	**-**	**Participants with simulated hearing loss**
std dev	**-**	**Standard Deviation**
µV	**-**	**MicroVolts**

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ABSTRACT

TITLE:	**Slow Cortical Auditory Evoked Potentials and Auditory Steady-State Evoked Responses in Adults Exposed to Occupational Noise**
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In individuals claiming compensation for occupational noise induced hearing loss, a population with a high incidence of nonorganic hearing loss, a reliable and valid behavioural pure tone (PT) threshold is not always achievable. Recent studies have compared the accuracy of behavioural PT threshold estimation using the slow cortical auditory evoked potentials (SCAEP) and auditory steady-state responses (ASSR) but there is no consensus regarding recommended technique. A review of the literature indicated that no comparison has been completed on the use of SCAEP and a single frequency ASSR technique.

A research project was therefore initiated with the aim of comparing the clinical effectiveness (accuracy) and clinical efficiency (time required) of SCAEP and ASSR for behavioural PT threshold estimation in adults exposed to occupational noise. Adult participants were divided into a group with normal hearing (behavioural PT thresholds $\leq$ 20 dBHL; n = 15) and a group of participants with hearing loss (n = 16 adults), the latter of which were recruited from individuals referred for audiometric screening, as part of hearing conservation programs, and who were, therefore, exposed to occupational noise. The GSI Audera electrophysiological system was used for both SCAEP and ASSR threshold measurement at 0.5, 1, 2 and 4 kHz. Use was made of tone burst stimuli for the SCAEP (rise and fall of 10 ms with 80 ms plateau), while amplitude and frequency modulated (AM/FM) stimuli was used during ASSR testing. The system's 40 Hz protocol was chosen for use during ASSR recording while participants slept because this led to lower noise levels, and because the long assessment session promoted sleep in all of the participants. ASSR thresholds could not be measured in two of the three sleeping participants in the preliminary study using an 80 Hz modulation rate due to excessive noise.

The mean SCAEP difference scores (SCAEP threshold minus behavioural PT threshold) for both participant groups were -0.2±10.2, 2.8±10.1,5.8±9.7, 0.5±10.4 at 0.5, 1, 2, and 4 kHz respectively, while ASSR difference scores were 25.3±12.8, 21.7±11.3,32.3±12.2, 27.1±13.8. The SCAEP correlations with behavioural PT thresholds across frequencies (r = 0.85) were also stronger than ASSR correlations (r = 0.75). Therefore, with regard to proximity of auditory evoked potentials (AEP) to behavioural PT thresholds and consistency of this relationship, the SCAEP, rather than ASSR, is the AEP of choice. However, the SCAEP took on average 10.1 minutes longer to complete than the ASSR. Clinical effectiveness was given comparably more weight than the clinical efficiency of the AEP technique to estimate behavioural PT thresholds due to the impact on overcompensation for occupational noise induced hearing loss. As such, the study acknowledged the SCAEP as the AEP of choice for the purpose of behavioural PT thresholds in adults exposed to occupational noise.

It is important to note that the conclusion reached in the current study arose from the comparison of the SCAEP with a specific ASSR technique. Accuracy of ASSR estimation of behavioural PT thresholds is strongly influenced by stimulus and recording parameters of the system used, and by the participant variables.

Keywords: *occupational noise induced hearing loss, nonorganic hearing loss, auditory steady state responses (ASSR), slow cortical auditory evoked potentials (SCAEP), auditory evoked potentials, clinical effectiveness, clinical efficiency, stimulus and recording parameters.*

CHAPTER ONE

INTRODUCTION AND ORIENTATION

1.1 INTRODUCTION

Non-organic[#] and *exaggerated hearing loss* are terms used to describe the apparent loss of hearing sensitivity without obvious pathology to explain the loss or its extent (Martin, 1981). Alberti, Hyde and Riko (1987) also list factors other than deliberate exaggeration that may cause volunteered behavioural pure tone (PT) thresholds to be worse than true behavioural PT hearing thresholds, including poor comprehension of the test, high criterion for response, and fatigue. Martin (2002) adds physical or emotional incapacity for appropriate responses, or an unconscious motivation to the reasons for a lack of cooperation during hearing evaluations. This is further complicated by the fact that many individuals with exaggerated behavioural PT thresholds have nonorganic aspects superimposed on an organic hearing loss (Martin, 2002). The audiologist's function is to determine the extent of the organic component.

A high incidence of nonorganic behavioural PT hearing thresholds in individuals claiming compensation for occupational noise induced hearing loss has been reported, from 8 to 26% of sample sizes ranging from 238 to 2528 individuals (Alberti et al., 1987; Alberti, Morgan, & Czuba, 1978; Hone, Norman, Keogh, & Kelly, 2003; Rickards & De Vidi, 1995). The considerable financial gain resulting from exaggeration of behavioural PT thresholds since implementation of laws regarding hearing safety in the workplace, may account for the high incidence of nonorganic hearing loss in this population (Hone et al., 2003; Martin, 2002).

Noise induced hearing loss is the most common form of occupational hearing loss, and remains one of the most prevalent occupational conditions (American College of Occupational and Environmental Medicine [ACOEM], 2002). The ACOEM (2002) suggests that this is partly due to the fact that noise is one of the most pervasive occupational hazards found in a wide range of industries. Murray-Johnson et al. (2004)

[#] Definitions of terms in the text are marked using italic font style.

state that noise induced hearing loss is the second most self-reported occupational illness or injury. Nelson, Nelson, Concha-Barrientos and Fingerhut (2005) estimate that 16% of hearing loss in adults worldwide is attributable to occupational noise. Of relevance to South Africa, Nelson et al. (2005) also state that the occupational noise induced hearing loss burden is much greater in the developing world.

South Africa has more than 8.2 million workers who spend at least eight hours per day in formal employment in factories, mines, farms and other places of work (South African Department of Health, 1997). By affecting the health of the large working population, occupational injuries and diseases have profound effects on productivity and the economic and social well-being of workers, their families and dependants (South African Department of Health, 1997). Noise induced hearing loss has therefore been recognised as a major occupational health risk in South African industries such as the mining industry (Zinsser, 2004).

The South African Occupational Diseases in Mines and Works Amendment Act, no. 60 of 2002 (2003) requires benefit (compensation) examinations of not only current but also former employees. However, access to benefit examinations is poor in historically under-served areas, notably the Eastern Cape, Northern Province and KwaZulu-Natal (South African Department of Health, 1997). Consequently, a backlog exists and many thousands of both current and former employees may suffer from unidentified compensable diseases, including occupational noise induced hearing loss.

Reliable and valid audiometric results are crucial in determining hearing disability compensation. Without accurate testing, there will be inaccurate compensation for noise induced hearing loss claims (Rickards & De Vidi, 1995). Even small deviations from true behavioural PT thresholds can translate into a significant difference in financial outcome (Coles, Lutman, & Robinson, 1991; Alberti et al., 1987). Inaccurate compensation is of particular concern in South Africa, where cost-efficacy is a key element in the transformation of the health system (South African Department of Health, 1997).

One of the aims stipulated in the White Paper for the Transformation of the Health System in South Africa, is to diagnose disabilities as early as possible (South African Department of Health, 1997). Behavioural PT audiometry has remained the gold standard to compute the amount of compensation for individuals claiming compensation for noise induced hearing loss (Melnick & Morgan, 1991; Martin, 2002). For most patients and most purposes, behavioural PT audiometry is the most definitive of all audiometric procedures capable of evaluating the entire auditory system at specific frequencies (Cope, 1995; Goldstein & Aldrich, 1999). Hall (1992), however, cautions that no single auditory measure consistently and adequately evaluates all aspects of hearing differentially. This cross-check principle is motivated by the goal of increased accuracy of identification and quantification of hearing loss (Jerger & Hayes, 1976; Stach, 1998). The behavioural PT threshold determination is therefore always supplemented by other behavioural measures, such as speech audiometry, as well as objective audiometric measures, such as immittance and auditory evoked potentials (AEP; Hall & Mueller, 1997).

Objective measures serve to confirm the behavioural PT thresholds and are useful in site-of-lesion differentiation due to their neurophysiologic bases (Burkard & Secor, 2002). With regard to identification of occupational noise induced hearing loss, and in a population where the incidence of nonorganic hearing loss is high, the goal of early and accurate diagnosis can be challenging. However, when reliable and valid behavioural PT thresholds are not achievable for certain populations, the audiologist is forced to place increased emphasis on objective measures such as AEP. Several audiometric measures are available for the identification of nonorganic hearing loss and for the determination of true behavioural PT thresholds.

1.2 AUDIOMETRIC PROCEDURES FOR NONORGANIC HEARING LOSS

In a population exposed to occupational noise and at risk for noise induced hearing loss, a variety of behavioural indices have been described to assist in identifying individuals presenting with a nonorganic component to their hearing loss. These include variable audiometric response, poor test-retest reliability, a flat audiometric configuration, a threshold of greater than 50 dBHL (decibel hearing level) at 0.5 kHz, hearing ability (as observed during personal communication) better than the behavioural PT thresholds, discrepancies between tests, and violations of anatomical or acoustical relationships, for example, absence of a shadow curve with unilateral loss (Alberti et al., 1987; Martin, 1981; Stach, 1998). Audiometric tests such as the Lombard voice intensity test, Békésy audiometry, descending lengthened off-time (DELOT) Békésy test, short increment sensitivity index (SISI), delayed auditory feedback test, Doerfler-Stewart test, and speech audiometry are all used to rule out the presence of a nonorganic component to a hearing loss (Alberti et al., 1978; Chaiklin, 1990; Hall & Mueller, 1997; Kumpf, 1975; Martin, 1981; Stach, 1998). However, these tests do not quantify the magnitude of the feigned component. Thresholds can be determined using Stenger and speech Stenger tests, but these are appropriate for use only in cases of unilateral hearing loss (Hall & Mueller, 1997; Martin, 1981).

For a population at risk for occupational noise induced hearing loss, identification of a nonorganic component to hearing loss alone is not sufficient. Compensation for occupational noise induced hearing loss is awarded for the amount of disability (Sataloff & Sataloff, 1987). The International Labour Organisation (ILO; 1983) classifies disability as the conversion of medical impairment into an entitlement or monetary award. Disability is calculated from the percentage loss of hearing according to current South African legislation (South African Compensation for Occupational Injuries Act, no 130 of 1993 [COIDA], 2001; Occupational Health and Safety Act, no 85 of 1993, 2003). For the purposes of determining the percentage loss of hearing, frequency specific behavioural PT hearing thresholds at 0.5, 1, 2, 4 kHz need to be quantified.

Certain audiometric measures are capable of objective quantification of behavioural PT hearing thresholds. Physiological measures capable of accurate behavioural PT threshold estimation offer a unique approach for defining true hearing sensitivity level in nonorganic hearing loss (Hall, 1992). Acoustic reflexes, otoacoustic emissions (OAE), and AEP are considered physiological measures of the auditory system.

There have been repeated claims in literature that behavioural PT hearing thresholds can be estimated by means of acoustic reflex threshold measurements (Feldman, 1963; Hall, 1978; Jerger, 1970; Terkildsen & Scott-Nielsen, 1960). The acoustic stapedial reflex, however, can only be measured in the absence of middle ear pathology (Hall & Mueller, 1997; Stach, 1998). In South Africa, individuals at risk of occupational noise induced hearing loss will frequently present with middle ear pathology due to the large percentage of mine workers that test positive for HIV (human immunodeficiency virus; Bam, Kritzinger, & Louw, 2003; Hoffmann, Rockstroh, & Kamps, 2007; Robinson, Nel, Donald, & Schaaf, 2007; Swanepoel, 2000). Prevalence studies report that 25 to 45% of mine workers are HIV positive (Davies, de Bruin, Deysel, & Strydom, 2002; Pelser & Redelinghuys, 2006; Stevens, Apostolellis, Napier, Scott, & Gresak, 2006). The mining industry is the single largest employer in South Africa (Davies et al., 2002). Bam et al. (2003) and Swanepoel (2000) report an 85 and 68% prevalence of otitis media in children who are HIV positive respectively. There is, according to Robinson et al. (2007), a five times higher prevalence of otitis media in children who are HIV positive than in children who are HIV negative. Therefore, a considerable percentage of the target population present with middle ear pathology. Use of acoustic reflexes to estimate behavioural PT hearing threshold would therefore not be possible for these individuals. For the individuals without middle ear pathology, acoustic reflexes would be measurable. An extensive investigation into the use of acoustic reflexes to estimate behavioural PT thresholds utilizing a sample of 1207 adult patients with sensorineural hearing loss, was undertaken by Hyde, Alberti, Morgan, Symons and Cummings (1980). Results indicated significant variability in accuracy and a poor average statistical correlation between acoustic reflex threshold and behavioural PT thresholds. The study therefore concluded that acoustic reflex thresholds used to estimate behavioural PT thresholds were inadequate for medico-legal assessment and probably not sufficiently accurate for clinical use in adults.

Another physiological technique for assessing auditory integrity is OAE testing. *OAE* are sounds measured in the external ear canal that are produced due to the motility of the normal functioning outer hair cells of the cochlea (Kemp, 2002; Norton, 1992). The OAE are the result of nonlinear, biomechanical processes of the cochlea responsible for the high sensitivity, sharp tuning, and wide dynamic range of the normal cochlea (Norton, 1992). Outer hair cell movement, either spontaneous or in response to a stimulus, generates vibrations which sustain and amplify the travelling wave within the cochlea. This sound energy becomes part of the forward travelling wave but a small amount is transmitted back, due to nonlinearities in the cochlea, through the middle ear and tympanic membrane and is then converted to an acoustic signal in the ear canal (Kemp, 2002). OAE can be measured with a microphone in the ear canal of an individual with an absence of middle ear pathology and normal cochlear outer hair cell function. Behavioural PT hearing threshold is a property of the inner hair cells and nerve synapse, which play no part in the creation of OAE. OAE, being specific to the outer hair cells, can therefore not be used to estimate behavioural PT hearing threshold, or quantify any degree of sensory hearing loss in the absence of middle ear pathology (Hall & Mueller, 1997; Kemp, 2002). OAE merely indicate the presence of middle ear and/or cochlear pathology. In addition the high incidence of middle ear pathology in individuals who are HIV positive and exposed to occupational noise in South Africa (Bam et al., 2003; Hoffmann et al., 2007; Robinson et al., 2007; Swanepoel, 2000) means that OAE testing would indicate an absence of emissions due to the presence of middle ear pathology alone (Kemp, 2002; Hall & Mueller, 1997; Norton, 1992). Therefore the influence of middle ear pathology on OAE and the inability of OAE to quantify behavioural PT thresholds, yield them an inappropriate choice for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise.

In contrast to acoustic reflexes and OAE, AEP are capable of accurate behavioural PT threshold estimation. The clinical use of AEP for this purpose has been reported on extensively (including Alberti et al., 1987; Davis, 1976; De Koker, 2004; Hall, 1992; Hayes & Jerger, 1982; Herdman & Stapells, 2001; Hone et al., 2003; Hood, 1998; Laureano, Murray, McGrady, & Campbell, 1995; Lins et al., 1996). As such, AEP play a critical role in the assessment of hearing in individuals who cannot or will not participate actively in standard hearing assessment procedures, as well as in infants and young children (Sinninger & Cone-Wesson, 2002).

AEP are recordings of synchronous neural activity within the auditory system (the auditory nerve or auditory regions of the central nervous system) in response to external auditory stimulation (Hall, 1992; Hood, 1998). AEP are not measures of hearing as such but are highly correlated with hearing thresholds (Davis, 1976; Hall, 1992; Hood, 1998, Sinninger & Cone-Wesson, 2002). It is for this reason that the phrase 'estimation of behavioural PT auditory thresholds' is used. Therefore AEP thresholds can be used to estimate behavioural PT hearing sensitivity (organic, psychophysical hearing thresholds). A discrepancy between behavioural PT thresholds and AEP threshold intensity (AEP indicating better hearing sensitivity) in a population suspected of nonorganic hearing loss, is strong evidence that behavioural PT threshold findings are invalid (Hall, 1992).

Several AEP classification systems exist (Cacace & McFarland, 2002; Davis, 1976; Jacobson, 1999; Stapells, 2002). AEP may be classified according to their presumed site of generation, their latency relative to stimulus onset, or their relationship to the stimulus (Jacobson, 1999; Stapells, 2002). One of the earliest and the most widely accepted classification systems is that of Davis (1976), who proposed that AEP be classified by latency, the time at which they typically occur after stimulus presentation. In so doing, four components are recognized, namely early, middle, slow and late AEP. Early AEP occur at a latency of 0 to 20 ms, and comprise of the the auditory brainstem response (ABR) and electrocochleography. Middle AEP occur at 10 to 100 ms, and refer to the middle latency AEP and the auditory steady-state response (ASSR)*. Although the latter two AEP categories are often considered together as 'late' AEP, the current study maintains the original 'slow' and 'late' classifications as delineated by Davis (1976) and recommended by Stapells (2002). The slow cortical auditory evoked potential or SCAEP occurs at 50 to 300 ms latency following stimulus onset, while late AEP refers to AEP occurring at 150 to 1000 ms. Late cortical AEP include the mismatch negativity, P300, N400 and P600 responses (Davis, 1976; Stapells, 2002).

In order to identify the AEP most applicable for the purpose of behavioural PT threshold estimation for individuals at risk of noise induced hearing loss, the literature on the clinical use of each of the AEP available needs to be critically evaluated. A review of the AEP therefore follows with reference to adults exposed to occupational noise.

1.3 CRITICAL REVIEW OF THE USE OF AEP FOR ADULTS EXPOSED TO OCCUPATIONAL NOISE

Early AEP include the ABR and electrocochleography. The ABR is the most widely used AEP. The *ABR* is defined as a far-field recording of neuroelectric activity of the eighth nerve and brainstem auditory pathways that occurs over the first 10 to 15 ms after an abrupt stimulus (Ruth & Lambert, 1991). The ABR is characterized by five to seven vertex-positive peaks representing synchronous neural discharge from dipole generators

* ASSR have also been referred to as amplitude modulated following response (AMFR). The ASSR can, however, be elicited by amplitude or frequency modulated stimuli or by a combination hereof. The term steady-state evoked potential or SSEPs has lost favour as the acronym SSEP may mistakenly be perceived as referring to somatosensory evoked potentials. The outcome is that the acronym ASSR or auditory steady-state evoked response has been adopted (Cone-Wesson, Dowell, Tomlin, Rance, & Ming, 2002).

located along the auditory pathway to the inferior colliculus of the midbrain (Hood, 1998; Ruth & Lambert, 1991). Each peak is labelled by consecutive roman numerals (Jewett, 1970). ABR is used as an objective diagnostic tool for otoneurologic disorders and for estimation of auditory sensitivity.

Participant attention to stimuli, or the lack thereof, also has little or no effect on these short latency responses (Kuk & Abbas, 1989; Lukas, 1981), resulting in robust, repeatable recordings despite differences in participant state of consciousness. ABR does require that individuals lie quietly with minimal movement in order to reduce artefacts and sedation is sometimes required for adults or children who will not comply herewith. Despite this, the stability of these potentials over participant state, the relative ease with which they may be recorded, and their sensitivity to dysfunctions of the peripheral and brainstem auditory systems make them well suited for clinical use (American Speech-Language-Hearing Association [ASHA], 1987). This has led to the almost universal application of ABR for behavioural PT threshold estimation for children and infants too young to be tested using standard behavioural measures (Vander Werff, Brown, Gienapp, & Schmidt Clay, 2002).

Synchronous firing of multiple neurons, which is the general physiological foundation of the ABR, is dependent on an abrupt stimulus onset (Hood, 1998). It is for this reason that the abrupt onset click stimulus is routinely used in clinical ABR recordings. A typical 100 μs square wave click has a broad frequency spectrum with equal energy from 0.1 to 6 kHz (Hall, 1992). The click stimulus therefore activates a wide area of the basilar membrane. As a consequence hereof, click-evoked ABR provides little information regarding the slope of the audiometric configuration or sensitivity at a particular frequency (Ruth & Lambert, 1991). There is widespread belief that the greatest agreement between the click-evoked ABR and behavioural PT thresholds is in the 2 to 4 kHz frequency range (Coats & Martin, 1977; Davis, 1976; Hall, 1992; Hall & Mueller, 1997; Hood, 1998; Ruth & Lambert, 1991). This is true on average and across a large group of individuals with hearing loss, but is not true for individual participants, especially when hearing loss is restricted to certain frequencies (Stapells, 2002). The click-evoked ABR is virtually independent of low frequency hearing sensitivity (Hall, 1992). A normal ABR may therefore be recorded in individuals with hearing loss with only isolated regions of residual normal hearing sensitivity in the 2 to 4 kHz region (Hall, 1992; Stapells, Picton, Perez-Abalo, Read, & Smith, 1985). Masking techniques to improve frequency specificity using click stimuli have not been proven to limit cochlear activation (Hall, 1992). Both ASHA (1987) and Hall (1992) highlight concerns regarding the extent and effect of masking noise spread into the stimulus region. The clinical application of these and the derived response ABR methods, also used in an attempt to improve frequency specificity, are limited, as they are technically demanding and may be more time consuming (ASHA, 1987; Hall, 1992).

The click-evoked ABR remains important as an indication of the integrity of the auditory nerve and the brainstem auditory pathways, and provides a tool for screening for hearing loss in infants (Stapells, 2002). The lack of frequency specific behavioural PT threshold information offered by click-evoked ABR is, however, a significant limitation for use with adults exposed to occupational noise (and consequently at risk of developing a high frequency hearing loss), for which frequency specific behavioural PT threshold estimation is required to determine percentage loss of hearing in accordance with South African legislation on occupational noise exposure (COIDA, 2001).

ABR to brief tones can be used to obtain more frequency specific threshold information than is available from the click-evoked ABR. However, the abrupt rise-fall times of the tone burst ABR stimuli (relative to the longer stimulus envelope of the tone bursts utilized for SCAEP), although necessary to best elicit the ABR, negatively influences frequency specificity and increases spectral splatter (ASHA, 1987; Hall, 1992; Stapells, 2002). The ability to obtain a place specific response is constrained by neural synchrony and the travelling wave mechanics of normal cochlear function (Cone-Wesson, Dowell et al., 2002). As a consequence hereof, some authors have found poor correlates of low frequency behavioural PT threshold estimation using tone burst ABR (Hayes & Jerger, 1982; Gorga, Kaminski, Beauchaine, & Jesteadt, 1988). Tone burst ABR waveforms, especially for low frequency stimuli, tend to be less distinct and more difficult to identify than the click or high frequency tone burst ABR (ASHA, 1987). As subjective response detection is required for tone burst ABR, clinician experience is a critical variable in accuracy of behavioural PT threshold estimation.

Studies including those by Picton, Ouellette, Hamel and Smith (1979), Purdy and Abbas (1989), and Stapells, Picton and Durieux-Smith (1994), concluded that steeply sloping high frequency hearing losses (i.e. with 40 dB difference in behavioural PT threshold between adjacent octaves) may be underestimated, due to brief tone burst's spectral splatter which stimulates the better hearing sensitivity at the adjacent frequency. Stapells et al. (1985) recommend the use of ipsilateral notched noise when testing with high intensity tone bursts in order to limit the region of the basilar membrane which can contribute to the response, increasing the frequency and place specificity of the tone burst ABR. Software with the option of ipsilateral notched noise is, however, limited and not currently widely utilized in clinical practice. Output limitations are also a concern with tone burst stimuli, particularly for low frequency tone bursts for which ABR thresholds are often elevated relative to behavioural PT threshold (Vander Werff et al., 2002).

The brief review of current knowledge of click and tone burst ABR has highlighted certain limitations of the ABR, specifically when dealing with a sloping, high frequency hearing loss, as is typically the case with noise induced hearing loss. The accuracy of behavioural PT threshold estimations from ABR may be influenced by clinician experience, especially at low frequencies, while the accuracy of high frequency thresholds may be affected by spectral splatter of the ABR tone burst stimuli. Inaccurate estimations of behavioural PT thresholds result in incorrect determination of percentage loss of hearing in accordance with South African legislation on hearing disability and compensation (COIDA, 2001; South African Occupational Health and Safety Act, 2003). This in turn negatively affects the cost efficacy of national occupational health programs. Cost efficacy is important in South Africa as the development of the economy is the second of the three major objectives of the Reconstruction and Development Program (South African Department of Health, 1997).

In addition to the ABR, electrocochleography is classified as an early latency AEP. Electrocochleography is primarily used clinically in the evaluation of Ménière's Disease or endolymphatic hydrops, identification of ABR wave I, and intraoperative monitoring (Ferraro, 2007). The application of electrocochleography for the estimation of behavioural PT hearing thresholds has been reported (Laureano et al., 1995). Ferraro and Ferguson (1989) found no significant differences between the thresholds obtained with electrocochleography using a transtympanic electrode and conventionally recorded ABR thresholds in individuals with normal hearing. Electrocochleography using an extratympanic electrode does not require sedation or anaesthetic and results in minimal discomfort, but behavioural PT threshold estimations are not as reliable as those obtained using the transtympanic technique (Probst, 1983). However, despite this, both ASHA (1987) and Ferraro (2007) state that it is unlikely that electrocochleography will emerge as a routine clinical tool for estimating hearing sensitivity as other electrophysiological approaches are easier, less invasive and take less time to administer.

The *middle latency AEP* is an electrophysiological recording of the electrical activity of the auditory thalamus and early auditory cortex (Ruth & Lambert, 1991). It occurs from 10 to 80 ms after click or tone burst stimulus onset. The waveform consists of four positive waves (Po, Pa, Pb, Pc) and three negative waves (Na, Nb, Nc; Musiek, Geurkink, Weider, & Donnelly, 1984). Wave Pa is the most prominent and most robust component of the middle latency response. Generators in the auditory thalamus and early primary auditory cortex contribute to the Pa component of the response (Hall, 1992). Middle latency AEP, therefore, evaluates the auditory pathway in practically its entirety. With behavioural PT audiometry as the gold standard and most comprehensive audiometric procedure, the extent of the auditory pathway evaluated by the middle latency response constitutes an advantage over earlier latency AEP such as the ABR and electrocochleography. In addition, several authors report agreement between middle latency AEP and behavioural PT responses (Hall, 1992; Oates & Stapells, 1997; Xu, De Vel, Vinck, & Van Cauwenberge, 1995). However, as a consequence of the central anatomic origins of the middle latency AEP response, sleep and sedation affect the response by reducing the amplitude of the Pa (Musiek et al., 1984). This is a disadvantage for the purpose of assessment of infants and children.

Hall (1992), Musiek et al. (1984), and Oates and Stapells (1997) advocate the use of middle latency AEP due to good frequency specificity. However, Cacace and McFarland (2002) caution against the use of middle latency AEP for behavioural PT threshold estimation in patients with steeply sloping, high frequency hearing loss. Middle latency AEP may underestimate the magnitude of high frequency hearing loss due to the spread of excitation to lower stimulus frequencies as intensity is increased (Cacace & McFarland, 2002). The use of middle latency AEP may therefore not be the ideal AEP tool for use in a population typically at risk of a high frequency hearing loss, as is the case with individuals exposed to occupational noise.

This review of the theoretical and clinical knowledge of AEP used for the purpose of behavioural PT threshold estimation has therefore identified certain limitations of the ABR, electrocochleography and middle latency AEP which may affect the accuracy of behavioural PT threshold estimations with individuals that present with a steeply sloping high frequency hearing loss. Several authors have, however, named SCAEP as the measure of choice for individuals exposed to occupational noise and at risk of developing a high frequency hearing loss (Alberti et al., 1987; Coles & Mason, 1984; Hone et al., 2003; Hyde, 1997; Hyde, Alberti, Matsumoto, & Li, 1986; Lightfoot & Kennedy, 2006; Prasher, Mula, & Luxon, 1993; Rickards & De Vidi, 1995; Stapells, 2002; Tsui, Wong, & Wong, 2002). Stapells (2002) states that the SCAEP is ideal for use when an objective estimate of behavioural PT hearing thresholds are required for a patient who is likely to be passively cooperative and alert.

The *SCAEP* is a transient scalp potential complex evoked by any change in the perceived auditory environment that is sufficiently abrupt (Hyde, 1997). This AEP occurs at 50 to 300 ms following stimulus onset, and follows the cochlear and eighth cranial nerve responses, the ABR and the middle latency AEP in the time domain (Stapells, 2002). The SCAEP is characterized by a P1-N1-P2 sequence of waveforms. Hall (1992) states that SCAEP is the ideal response for frequency specific electrophysiological auditory assessment from a stimulus perspective due to the reduced spectral splatter and increased frequency specificity. This frequency specificity is achieved because the SCAEP can be evoked by tone bursts of relatively long rise-fall times and duration in comparison with the abrupt rise-fall times required to elicit ABR using toneburst stimuli (Ferraro & Durrant, 1994). Better frequency specificity results in AEP thresholds that are closer to behavioural PT thresholds in a variety of audiometric configurations. The susceptibility of this response to state of arousal renders SCAEP unsuitable for use with infants and young children (Hood, 1998). However, with co-operative adults exposed to occupational noise, the population targeted in the present study, the sensitivity of the SCAEP to state of arousal does not constitute a disadvantage. Reading or mental alerting tasks are sufficient to ensure that adults remain alert without the decrease in response amplitude and increase in threshold intensity associated with sleep and drowsiness (Hyde, 1997; Stapells, 2002). The SCAEP response is also more resilient to electrophysiologic noise arising from small movements than are the earlier AEP (Stapells, 2002).

Hone et al. (2003) listed the advantages of SCAEP, stating that SCAEP is non-invasive, are recorded from a higher auditory level than electrocochleography or ABR, and are therefore less likely to be affected by neurologic disorders. Stapells (2002) states that the SCAEP is representative of the complete auditory system. The author further explains that the presence of N1 to a stimulus provides physiologic evidence of the arrival of the stimulus at the auditory cortex. The N1 therefore reflects the presence of the audible stimulus. The N1 is the vertex negative peak with a latency of approximately 100 ms, which, together with the P2 positive peak, comprises the most prominent component of the SCAEP.

Middle ear pathology will affect the latency of the components of the SCAEP. The presence of middle ear pathology, as is often found in individuals who are HIV positive (Bam et al., 2003; Hoffmann et al., 2007; Robinson et al., 2007; Swanepoel, 2000), which constitutes a large portion of the working population in South Africa (Davies et al., 2002; Pelser & Redelinghuys, 2006; Stevens et al., 2006), will result in a delayed N1 and P2 latency. Yet increased response latency is likely to have a minimal effect on response amplitude and threshold intensity (Hyde, 1997). Therefore middle ear pathology has no effect on the SCAEP thresholds and behavioural PT threshold estimation from SCAEP thresholds.

Numerous studies have demonstrated that the SCAEP thresholds and behavioural PT thresholds are typically measured within 10 dBHL (decibel hearing level) of each other (Alberti et al., 1987; Hyde, 1997; Hyde et al., 1986; Stapells, 2002). It has been reported that SCAEP thresholds can provide a closer estimate of behavioural PT thresholds than ABR thresholds (Hyde, 1997). Tsui et al. (2002) point out that the larger SCAEP response amplitude results in fewer averages being needed to yield a noise free repeatable waveform than ABR. Behavioural PT threshold estimation is consequently time efficient. A recent study by Lightfoot and Kennedy (2006) reported that, by using an efficient test protocol that automates certain tasks, a six threshold estimate of behavioural PT threshold using SCAEP took on average only 20.6 minutes to complete. It is logical to conclude from the preceding discussion regarding AEP that SCAEP is appropriate for the purpose of behavioural PT threshold estimation in an adult population exposed to occupational noise and at risk of noise induced hearing loss. Despite this, SCAEP is rarely utilized for this population in South Africa. The limited availability of the equipment required to perform SCAEP in the past, the cost of the equipment and the lack of clinicians experienced in the interpretation of SCAEP threshold responses may be the reason for this.

Over the past decade, a new clinically available AEP technique, the ASSR has been proposed as an alternative AEP for behavioural PT threshold estimation (De Koker, 2004; Dobie & Wilson, 1998; Herdman & Stapells, 2003; Hyde et al., 1986; Hsu, Wu, & Liu, 2003; Lins et al., 1996; Rance, Rickards, Cohen, De Vidi, & Clark, 1995; Vander Werff et al., 2002; Van Maanen & Stapells, 2005). The *ASSR* is a brain potential evoked by continuous stimuli characterized by periodic modulations in amplitude of a carrier frequency (Jerger, 1998; Vander Werff et al., 2002). It yields a waveform closely following the time course of the stimulus modulation and a response specific to the frequency of the carrier (Cohen, Rickards, & Clark, 1991; Jerger, 1998). The response is generated when the stimulus tones are presented at a rate that is sufficient to cause an overlapping of transient potentials (Rance, Dowell, Rickards, Beer, & Clark, 1998). By varying the intensity of the eliciting stimulus, one can seek the threshold response (Jerger, 1998).

ASSR testing, using continuous modulated tones, offers significant advantages over techniques that require transient stimuli (Rance et al., 1998). As the tones are continuous, they do not suffer the spectral distortion problems associated with brief tone bursts or clicks. As such, they are comparatively more frequency specific than responses to transient stimuli (John & Picton, 2000). This specificity allows testing across the audiometric frequency range, including sloping high frequency hearing losses, reducing the possibility of underestimation of high frequency behavioural PT thresholds due to poor frequency specificity for this audiometric configuration (Lins et al., 1996; Herdman & Stapells, 2001; Rance, Rickards, Cohen, Burton, & Clark, 1993; Rance et al., 1995).

Assessment at high intensity levels (i.e. up to 120 dBHL) is possible, due to the continuous nature of the ASSR stimuli and hence the absence of calibration corrections to account for temporal summation differences between short and long duration signals associated with stimuli such as tone bursts and clicks (Rance et al., 1998, 2005).

Initially, the most widely studied ASSR was evoked by stimuli presented at rates near 40 Hz (Galambos, Makeig, & Talmachoff, 1981; Schimmel, Rapin, & Cohen, 1974; Stapells, Linden, Suffield, Hamel, & Picton, 1984). In sleeping or sedated adults, 40 Hz ASSR amplitudes are smaller than in the awake state (Aoyagi et al., 1993; Galambos et al., 1981; Linden, Campbell, Hamel, & Picton, 1985). ASSR to tones modulated at frequencies between 80 and 100 Hz, however, are minimally affected by sleep or maturation (Cohen et al., 1991; Levi, Folsom, & Dobie, 1993; Lins & Picton, 1995; Rance et al., 1995) and can therefore be recorded in children and infants (John & Picton, 2000). Another advantage of the ASSR is that multiple frequencies can be evaluated simultaneously, in one or both ears, without significant loss in the amplitude of any of the responses, provided each stimulus has a different modulating rate and the carrier frequencies differ by one octave or more (John & Picton, 2000; John, Lins, Boucher, & Picton, 1998; John, Dimitrijevic, Van Roon, & Picton, 2001; John, Purcell, Dimitrijevec, & Picton, 2002; Lins & Picton, 1995; Picton, Dimitrijevic, John, & Van Roon, 2001). This may reduce the testing time required to obtain behavioural PT threshold estimation.

Clinical use of the ASSR is greatly facilitated by the objective response detection which is measured in either the time or frequency domain using various statistical methods (Picton, John, Dimitrijevic, & Purcell, 2003). Errors that result from observer bias or from poor inter-observer and intra-observer reliability, are therefore eliminated by the objective response detection (Gans, Del Zotto, & Gans, 1992; Rose, Keating, Hedgecock, Schreurs, & Miller, 1971). In addition, an experienced tester is not required to report ASSR threshold findings, as no subjective interpretation of waveforms is required. The objective response detection of an ASSR response can control bias, perform with stable and known sensitivity, and can outperform human observers (Arnold, 1985; Champlin, 1992; Dobie & Wilson, 1995; Valdes-Sosa et al., 1987).

1.4 RATIONALE

Several characteristics of the ASSR suggest that this AEP may also be applicable for clinical use for behavioural PT threshold estimation in individuals exposed to occupational noise and at risk for noise induced hearing loss. The accuracy of behavioural PT threshold estimation, potentially better frequency specificity of continuous rather than transient tonal stimuli, independence of participant attention or state of arousal, and ability to obtain higher output levels, all suggest that ASSR may be an appropriate tool for behavioural PT threshold estimation in this population (Vander Werff et al., 2002). In addition, the objective nature of response determination makes ASSR attractive in a clinical setting.

Despite the possible suitability of the ASSR for behavioural PT threshold estimation in adults exposed to occupational noise, only five studies were found that address the clinical use of ASSR for this population (De Koker, 2004; Herdman & Stapells, 2003; Hyde et al., 1986; Hsu et al., 2003; Van Maanen & Stapells, 2005). Studies by Hyde et al. (1986) and Hsu et al. (2003) were executed, using participants that presented with a noise induced sensorineural hearing loss, although Hyde et al. (1986) merely reported on preliminary results with ASSR. The majority of the participants of the studies by De Koker (2004), Herdman and Stapells (2003) and Van Maanen and Stapells (2005) presented with a sloping hearing loss and were in the process of claiming workmen's compensation for occupational hearing loss, and, as such, were likely to have a history of noise exposure. The studies by Herdman and Stapells (2003), Hyde et al. (1986), Hsu et al. (2003) and Van Maanen and Stapells (2005) found ASSR thresholds to be significantly correlated with behavioural PT thresholds ($r = 0.65$ to 0.95), while the configuration of the typical sloping audiogram was closely matched, without underestimation. De Koker (2004) reported mean differences between behavioural PT threshold and ASSR threshold of no greater than 10 dB (range: 0.3 to 7.4 dB). These studies suggest that the ASSR is an appropriate method of estimating behavioural PT thresholds in a population exposed to occupational noise.

If you consider the amount of individuals exposed to occupational noise in South Africa alone, the amount of studies that explore the use of the ASSR technique for the purpose of estimating behavioural PT thresholds, is inadequate. In South Africa the mining industry is the single largest employer (Davies et al., 2002). The prevalence of compensable noise induced hearing loss is higher in the mining industry than in most other industries, as machinery is confined in highly reverberant underground work places (Franz & Phillips, 2001). Franz and Phillips (2001) estimated that between 68 and 80% of workers in the mines are exposed to a time weighted average of 85 dBA or greater, indicating risk for noise induced hearing loss for the majority of the industry's personnel. Noise induced hearing loss constitutes 12 to 14% of all occupational injury claims in the mining industry, yet accounts for 40% of the amount of compensation awarded (Franz & Phillips, 2001). Noise induced hearing loss is also the most common occupational disease outside the mining industry with a prevalence of 56% (Franz & Phillips, 2001). Noise induced hearing loss therefore poses a risk to economic sustainability that South Africa, as a developing country, can ill afford. The accuracy of audiometric measures that provide estimates of behavioural PT thresholds, in accordance with which compensation is calculated, is therefore critical. Therefore, despite the encouraging data reported by the aforementioned five studies on the use of ASSR for behavioural PT thresholds for individuals exposed to occupational noise, the amount of research is insufficient.

Prior to the introduction of ASSR into clinical use, SCAEP, although not widely used in South Africa, was widely considered the AEP of choice for use in behavioural PT threshold estimation for adults exposed to occupational noise, and in whom a nonorganic hearing loss is suspected (Alberti et al., 1987; Coles & Mason, 1984; Hone et al., 2003; Hyde, 1997; Hyde et al., 1986; Rickards & De Vidi, 1995; Stapells, 2002; Tsui et al., 2002). Recent studies have compared the accuracy of behavioural PT threshold estimation using SCAEP and ASSR (Kaf, Durrant et al., 2006; Tomlin, Rance, Graydon, & Tsialios, 2006; Van Maanen & Stapells, 2005; Yeung & Wong, 2007). The studies by Tomlin et al. (2006) and Yeung and Wong (2007) concluded that SCAEP provided more accurate estimates of behavioural PT thresholds, while Van Maanen and Stapells (2005) and Kaf, Durrant et al. (2006) advocated the use of ASSR rather than SCAEP for the purpose of threshold estimation. There is therefore disagreement regarding the choice of behavioural PT threshold estimation in adults. The researcher is aware of only one comparative study on the use of SCAEP and the ASSR for the purpose of behavioural PT threshold estimation in the same population as is targeted in this study, namely in adults exposed to occupational noise. The study by researchers Van Maanen and Stapells (2005) compared the use of the multiple ASSR technique using both 40 and 80 Hz modulation frequencies and SCAEP to estimate behavioural PT threshold in adults claiming compensation for occupational hearing loss. There are, to the researcher's knowledge, as yet no comparative studies on the use of SCAEP and a single frequency ASSR technique for the population in question.

1.5 RESEARCH QUESTION

In light of the lack of comparative research on SCAEP and single stimulus ASSR, the following question arises: How effective and how efficient is the clinical use of a single stimulus ASSR technique as compared to SCAEP for behavioural PT threshold estimation in adults exposed to occupational noise?

The formulation of this question has instigated the proposal of the research project aiming to obtain an answer based on empirical evidence. The growing need to ascertain comparative clinical efficiency of procedures is a result of rapid technical advancement in the field of AEP over the past three decades (Hall, 1992). The continued inclusion of new test procedures in the standard audiometric test battery is a product of advancement in knowledge and technology (Hall & Mueller, 1997). Audiologists therefore have an obligation to evaluate new procedures and technology to compare the effectiveness thereof with the more established measures, in order to provide the best possible service to clients. Goodman (2004) states that health technology assessment considers the effectiveness, appropriateness and cost of technologies. This is achieved by asking whether the technology works, for whom, at what cost, and how it compares with alternatives. Without effectiveness studies, we cannot easily judge the degree to which patient outcomes are optimized (Brook & Lohr, 1985).

The South African Department of Health states that even the best proven diagnostic procedure must continuously be challenged through research for its effectiveness, efficiency, accessibility and quality (South African Department of Health, 2000). *Effectiveness* is defined as the benefit (e.g. to health outcomes) of using a technology for a particular problem under general or routine conditions (Goodman, 2004). The concise Oxford dictionary (1967) defines *efficiency* as the ratio of useful work performed to the total energy expended. A clinical procedure needs to be evaluated, according to Stapells (2002), in terms of the following: sensitivity and specificity of the measure for detecting and diagnosing dysfunction; the time the test requires; and whether there is an equally good or better test available that may be faster or less expensive. In keeping with the preceding recommendations of the South African Department of Health (2000) and Stapells (2002) the current study will compare the clinical effectiveness and efficiency of the AEP currently advocated for use in behavioural PT threshold estimation in adults exposed to occupational noise, namely SCAEP, to that of the single stimulus ASSR technique. The addition of a comprehensive cost analysis comparing the effectiveness of the two technologies in terms of the economic impact of each would fulfil all the requirements recommended by Stapells (2002) for the evaluation of a clinical procedure, but is beyond the scope of the current study. The topic will however be briefly revisited at the conclusion of the project. ***For the purpose of this research project, clinical effectiveness was defined as the accuracy of behavioural PT threshold estimation, while clinical efficiency was determined by the amount of time necessary for acquisition of the threshold AEP responses.***

1.6 CHAPTER DELINEATION

Chapter 1 provides the background, context and motivation for the research project, culminating in the research question. This is followed by an outline of the contents of the chapter and the declaration of terminology.

Chapter 2 presents a critical review of SCAEP and ASSR in adults exposed to occupational noise. SCAEP and ASSR techniques are each discussed in terms of existing theoretical knowledge and the characteristics of each, which make them suitable for the population in question in the context of current South African legislation on compensation for occupational noise induced hearing loss.

Chapter 3 begins with the delineation of the main and sub aims formulated in order to answer the research question posed. The research methodology is then described with reference to the design, the participant selection criteria, apparatus, data collection and analysis procedures which are applied, in order to generate the answers to each sub aim and ultimately the main research aim.

Chapter 4 presents the results of the statistical analysis of the collected data with regard to each sub aim.

Chapter 5 discusses and evaluates the results by drawing on and integrating previous research. This discussion is realized within the framework of the target population and South African health system.

Chapter 6 clarifies the conclusions drawn from the results with reference to the definitions of clinical effectiveness and efficiency. The clinical implications of the research are examined and recommendations for further study are acquired through a critical review of the research project.

1.7 DEFINITION OF TERMS

Slow cortical auditory evoked potentials (SCAEP)

Hyde (1997) described the SCAEP as a transient scalp potential evoked by any change in the perceived auditory environment that is sufficiently abrupt. Audiometrically, the SCAEP is recorded by averaging 20 to 50 tone bursts presented regularly at one per s or one half per s, with a vertex-mastoid derivation (Hyde, 1997; Stapells, 2002). The SCAEP is therefore classified as a slow AEP (Davis, 1976). Näätänen and Picton (1987) describe cortical sources that contribute to the SCAEP.

Auditory steady-state evoked response (ASSR)

The ASSR is a brain potential evoked by continuous amplitude modulated (AM) stimuli of a carrier frequency (Jerger, 1998; Vander Werff et al., 2002). It yields a waveform closely following the time course of the stimulus modulation and a response specific to the frequency of the carrier (Cohen et al., 1991; Jerger, 1998). The response is generated when the stimulus tones are presented at a rate that is sufficient to cause an overlapping of transient potentials (Rance et al., 1998). The ASSR is classified as a middle AEP by virtue of the response latency (Davis, 1976). By varying the intensity of the eliciting stimulus, one can seek the threshold response (Jerger, 1998).

One of the most defining characteristics of the ASSR is its relationship with the rate at which the stimuli are presented (Picton et al., 2003). Clinically, use is typically made of either a low modulation rate, namely at or near 40 Hz, or a high modulation rate, namely 80 to 100 Hz. For simplicity, the present study also makes use of the term 40 Hz ASSR when referring to the low modulation rate ASSR technique, while the high modulation rate ASSR is additionally referred to as the 80 Hz ASSR technique.

Efficacy

This refers to the probability of benefit to individuals in a defined population from a medical technology applied for a given medical problem **under ideal conditions** of use within the protocol of a carefully managed randomized control trial (Brook & Lohr, 1985; Goodman, 2004).

Effectiveness

Effectiveness is the benefit (e.g. to health outcomes) of using a technology for a particular problem under **general or routine conditions**, for example, by a physician in a community hospital or by a patient at home (Goodman, 2004). Similarly, Brook and Lohr (1985) define effectiveness by stating that effectiveness has all the attributes of efficacy except one: it reflects performance under ordinary conditions by the average practitioner for the typical patient. In quality-of-care terms, what the health care professional does for an individual in the daily course of events is measured in terms of effectiveness.

Efficiency

The Oxford dictionary (1967) defines efficiency as the ratio of useful work performed to the total energy expended. Therefore it is the extent to which time is well spent for the intended task.

Threshold

The current study makes use of the terms SCAEP / ASSR threshold to describe the lowest intensity at which each specific AEP response is recognized. Use of the term estimated behavioural PT threshold is used if an estimation of behavioural PT thresholds is made from the SCAEP or ASSR thresholds.

Estimated behavioural PT threshold

Estimated behavioural PT thresholds need to be further qualified, since the estimation can be derived from the AEP threshold, a regression equation or from subtraction of the main difference between AEP and behavioural PT thresholds (Picton et al., 2003). As a result of the conclusion drawn in sub aim one, regarding the statistically significant difference between behavioural detection of the stimuli used for SCAEP and ASSR techniques, and behavioural PT thresholds, estimated behavioural PT thresholds were derived from the subtraction of behavioural tone burst thresholds (for SCAEP), or from behavioural amplitude and frequency modulated (AM/FM) thresholds (for ASSR) from the SCAEP or ASSR thresholds respectively.

Difference score

The difference score is the difference (in dB) between SCAEP or ASSR threshold and behavioural PT threshold at a particular frequency. It is therefore equivalent to dB sensation level above behavioural PT threshold. The difference score is calculated by subtracting the behavioural PT threshold from the SCAEP or ASSR threshold.

Comparable difference scores

When comparing the difference scores (difference between SCAEP or ASSR threshold and behavioural PT threshold) reported by the current study with those recounted in previous studies, the term comparable difference scores is used when scores fell within 5 dB of each other.

1.8 SUMMARY

The preceding chapter explained the need for objective measures of behavioural PT thresholds in adults exposed to occupational noise, who could claim compensation for noise induced hearing loss. The inability of a variety of audiometric tools to quantify hearing loss in individuals unable or unwilling to provide reliable behavioural PT thresholds, was explored. Although AEP could be identified as the optimal audiological tool for this purpose, caveats for certain AEP techniques were highlighted which may affect the accuracy of estimates of behavioural PT thresholds. SCAEP was acknowledged as the method of choice for behavioural PT threshold estimation in adults exposed to hearing loss. In contrast to this, ASSR was proposed as equally appropriate, yet minimally researched for the population in question. The lack of comparative studies of the SCAEP and single frequency ASSR for behavioural PT threshold estimation in adults exposed to occupational noise was discussed, leading to the formulation of the research question, concluding with definitions of clinical effectiveness and clinical efficiency.

CHAPTER TWO

SCAEP AND ASSR IN ADULTS EXPOSED TO OCCUPATIONAL NOISE: A CRITICAL REVIEW

2.1 INTRODUCTION

Reliable and valid audiometric results are crucial in determining hearing disability compensation. This is especially relevant in the context of South Africa, a developing country with more than 8.2 million workers in formal employment in factories, mines, on farms and other places of work (South African Department of Health, 1997). However, a high incidence of nonorganic hearing thresholds in individuals claiming compensation for occupational noise induced hearing loss has been reported (Alberti et al., 1987, 1978; Hone et al., 2003; Rickards & De Vidi, 1995). Many individuals with exaggerated hearing thresholds have nonorganic aspects superimposed on an organic hearing loss (Martin, 2002). In this population, reliable and valid behavioural pure tone (PT) thresholds are not always achievable and the audiologist is forced to place increased emphasis on objective measures.

The various audiometric procedures used in assessing nonorganic hearing loss were discussed in the preceding chapter. In contrast to acoustic reflexes and otoacoustic emissions, AEP (auditory evoked potentials) are able to quantify hearing loss through estimation of behavioural PT thresholds. A review of the theoretical and clinical knowledge of AEP used for the purpose of behavioural PT threshold estimation, identified certain limitations of the auditory brainstem response (ABR), electrocochleography and middle latency AEP for use with adults exposed to occupational noise and at risk of developing a noise induced hearing loss. However, several authors have named the slow cortical auditory evoked potential (SCAEP) as the measure of choice for the population in question (Alberti et al., 1987; Hone et al., 2003; Hyde, 1997; Hyde et al., 1986; Lightfoot & Kennedy, 2006; Prasher et al., 1993; Rickards & De Vidi, 1995; Stapells, 2002; Tsui et al., 2002). Over the past decade, a new clinically available AEP technique, the ASSR (auditory steady-state evoked response) has been proposed as an alternative AEP for behavioural PT threshold estimation (Hyde et al., 1986; Hsu et al., 2003; Dobie & Wilson, 1998; Lins et al., 1996; Rance et al., 1995; Vander Werff et al., 2002; Van Maanen & Stapells, 2005).

The current chapter will be dedicated to a review of current knowledge and research with regard to the use of SCAEP and ASSR for adults exposed to occupational noise. The review will include a discussion of the neural generators, morphology, participant variables and clinical uses of the SCAEP and the ASSR. The chapter will conclude with a summary of the suitability of the two AEP techniques for the target population and a critical review of available literature, comparing clinical use of SCAEP and ASSR. In so doing, the lack of comparative research on SCAEP and single stimulus ASSR that resulted in the formulation of the research question is highlighted.

2.2 SLOW CORTICAL AUDITORY EVOKED POTENTIALS (SCAEP)

The *SCAEP* is a transient scalp potential complex evoked by any change in the perceived auditory environment that is sufficiently abrupt (Hyde, 1997). The components of the SCAEP consist of sequential peaks labelled by N (negative voltage) or P (positive voltage), including P1, N1, P2, N2, as recorded with a vertex electrode (Hall, 1992). The SCAEP is referred to in literature by numerous other terms, including averaged evoked electroencephalogram (EEG) audiometry, slow vertex potential, auditory late response, cortical audiometry and 'on-effects in the waking human brain to acoustic stimuli', the term initially used to describe the response (Davis, 1976; Hall, 1992; Hyde, 1997; Ruth & Lambert, 1991). The current study makes use of the term ‘slow cortical auditory evoked potential’ or SCAEP as recommended by Davis (1976) in his latency-based classification system.

2.2.1 Historical overview of SCAEP

Hall (1992) points out that the SCAEP was the first auditory electrical response to be recorded from the central nervous system. Hallowell Davis attributes the first recordings of SCAEP to his wife and colleague, Pauline Davis, in 1939 (Davis, 1976). These were described as an on-response to sound in the EEG (Hall, 1992). The availability of computers and signal averaging in the early 1960s yielded an intensive period of research into SCAEP and the technique's potential clinical use (Davis, 1976; Hall, 1992).

Several papers on SCAEP as a clinical procedure for objective auditory assessment followed (Alberti et al., 1987; Boniver, 2002; Coles & Mason, 1984; Hone et al., 2003; Hyde et al., 1986; Prasher et al., 1993; Rickards & De Vidi, 1995; Tsui et al., 2002; Van Maanen & Stapells, 2005). Hall (1992) states, however, that interest in this procedure declined sharply following the first clinical reports on ABR in the mid 1970s. The reason for the decline in interest is due to the effect of sedation and state of arousal on the recording of SCAEP, while the ABR was robust, despite state of consciousness, which offered a distinct advantage for the paediatric population. Thereafter, clinical application of slow cortical AEP centred on estimation of behavioural thresholds for adults and children over the age of eight years, and differential diagnosis of site of auditory lesion.

2.2.2 SCAEP neural generators

The neuroanatomic origin of the SCAEP has for many years been the subject of study and debate. Näätänen and Picton (1987) describe SCAEP as a series of temporally overlapping waves which in combination produce the scalp recorded response. As such, several cortical sources contribute to the SCAEP. Combined high-resolution magnetic resonance imaging scans and magnetoencephalographic recordings localize N1 to the primary auditory cortex and associated areas (Alain, Woods, & Covarrubias, 1997; Pantev et al., 1990; Picton et al., 1999; Vaughan & Ritter, 1970). A number of authors have postulated that a series of discrete generators in close proximity to each other comprise the N1 (Davis, 1976; Hyde, 1997; Jacobson, 1999; Näätänen & Picton, 1987; Stapells, 2002). Each of these generators may be affected by changes in the stimulation paradigm used to elicit the N1 (Davis, 1976; Jacobson, 1999).

Hall (1992) summarized the evidence attained from scalp and intracranial recordings in participants with normal hearing and studies of participants with temporal lobe lesions, naming the generators of the SCAEP as the posterior portion of the superior temporal plane (as initially suggested by Vaughan & Ritter, 1970), the lateral temporal lobe, and the adjacent parietal lobe regions. Authors Picton, Hillyard, Krausz and Galambos (1974) initially hypothesized that the third generation site was possibly the frontal motor and/or premotor cortex, but this theory was refuted by Knight, Hillyard, Woods and Neville (1980), the same laboratory that first proposed the idea. Hall (1992) postulates that although there does not appear to be a SCAEP generator in the frontal cortex, portions of this region may modulate the response in some way. This may explain why participant attention to the stimulus increases SCAEP amplitude. The reticular formation and ventral lateral nucleus of the thalamus are also thought to influence the auditory N1 (Näätänen & Picton, 1987).

Conflicting findings exist in the literature with regard to laterality of the SCAEP. Laterality refers to whether the response following monaural stimulation originates from the ipsilateral or contralateral side of the brain, or from both sides of the brain (Hall, 1992). Early studies in certain animal models report dominance of the contralateral auditory pathways (Kimura, 1961). Investigations of laterality in humans yielded findings that include no amplitude difference between hemispheres for verbal stimuli, and shorter latency values for SCAEP recorded from the hemisphere contralateral to the stimulus (Näätänen & Picton, 1987; Pantev, Lütkenhöner, Hoke, & Lehnertz, 1986).

The number of SCAEP studies on individuals with pathology of the central nervous system, are limited. The study by Knight et al. (1980) is one of the most comprehensive. These researchers found that the N1 component of the SCAEP was not decreased by frontal lobe pathology, yet appeared to be larger with contralateral stimulation, supporting theories of dominance of the contralateral pathways. The amplitude of the N1 was reduced by more than half in individuals with posterior temporoparietal pathology of either hemisphere. In contrast, anterior and middle temporal lobe lesions did not affect the N1. This study therefore provides further evidence of the contralateral posterior temporoparietal source of the SCAEP.

Knowledge of the neural generators of an AEP is essential in understanding not only the effect of neurological pathology on the measured response, but also the effect of patient state of consciousness. AEP generated by lower or distal neurological centres are more independent of an individual's state of consciousness than higher, more central neural generators. When comparing the relative contribution of AEP as clinical tools in the assessment of the auditory system, as the researcher is doing in the current study, the extent to which an AEP evaluates the auditory pathway is significant. AEP assessment of the auditory pathway is more comprehensive if the AEP is generated by higher or more central sources in the central nervous system. Identification of the primary auditory cortex and associated areas as generators of the SCAEP (Pantev et al., 1990; Vaughan & Ritter, 1970) therefore constitutes a limitation in terms of susceptibility to an individual's state of consciousness, but is also advantageous as the auditory system is evaluated in its entirety (Stapells, 2002).

2.2.3 Properties and components of the SCAEP

Hyde (1997) describes the SCAEP as a transient scalp potential complex evoked by any change in the perceived auditory environment that is sufficiently abrupt. Audiometrically, the SCAEP is recorded by averaging 20 to 50 tone bursts presented regularly at one or one half per second, with a vertex-mastoid derivation (Hyde, 1997; Stapells, 2002).

The SCAEP is comprised of four identifiable waveforms, namely P1, N1, P2 and N2 (Davis, 1976). The N1 and P2 form the primary and most prominent components of the SCAEP as the P1 and N2 occur less consistently (Hall, 1992). The N1 is a vertex-negative AEP of cortical origin, with a typical latency in adults of about 100 ms, usually followed by a vertex-positive wave, P2, at about 175 ms (Hyde, 1997). The N2 negative peak occurs at approximately 250 ms (Davis, 1976). The smaller, less significant P1 precedes these at about 50 ms (Davis, 1976). The SCAEP can be evoked by transient sounds, such as clicks, noise bursts, tone bursts and speech elements. This AEP can also be elicited by abrupt changes in the loudness, pitch, quality or perceived point of origin of continuous sounds (Davis, 1976; Hyde, 1997).

The N1 wave is thought to reflect conscious perception of a sound and may represent detection or an attention-triggering process (Stapells, 2002). However, it does not represent the first arrival of neural input to the cerebral cortex (Davis, 1976). The gross stimulus-response dynamics resemble a time differentiation of the acoustic environment. The presence of the P1-N1-P2 in response to frequency shifts during an ongoing sound, is thought to reflect the physiologic detection of the frequency and intensity changes at the level of the auditory cortex, which in turn may be related to frequency and intensity discrimination abilities (Harris, Mills, & Dubno, 2007; Harris, Mills, He, & Dubno, 2008). Hyde (1997) notes that the functional significance of the N1 and P2 peaks may differ. Each subcomponent of the SCAEP may therefore be differently affected by dysfunction.

Davis (1976) states that, although the average SCAEP response is stable, the individual responses may vary considerably in amplitude or waveform. The main inter-participant waveform variation is the relative magnitude of N1 and P2 (Hyde, 1997). Latencies are more stable than amplitudes within participants (Hyde, 1997). Davis (1976) attributes much of the variability to interaction with the ongoing spontaneous electrical activity. The characteristics of the SCAEP are affected by the features of the stimuli utilized to elicit the response.

2.2.4 SCAEP stimulus effects

Various stimuli can be used to elicit the SCAEP. Tone burst stimuli are used for the purpose of frequency specific behavioural PT threshold estimation. Stimulus characteristics have an effect on the response amplitude, latency and morphology. The stimulus envelope, frequency and intensity are therefore critical variables in determining the accuracy and frequency specificity of behavioural PT threshold estimation.

2.2.4.1 Effect of stimulus envelope on SCAEP

The SCAEP is associated with a change in acoustic energy that remains constant for at least a short period of time (Stapells, 2002). Consequently the slope or abruptness of onset of the change determines the latency and amplitude of the N1 peak. The amplitude of the response is calculated from the trough of the N1 to the peak of the P2. The N1 amplitude increases with a tone burst stimulus duration up to approximately 30 ms and decreases with duration times of longer than 50 ms (Onishi & Davis, 1968; Stapells, 2002). Stimuli with very slow onsets of about 500 ms do not elicit the N1 (Hyde, 1997). Hyde (1997) cautions against the use of abrupt stimulus onsets with short stimulus duration as this results in energy spread (spectral splatter) and consequently to reduced frequency specificity. This then leads to incorrect threshold estimates, especially for sloping audiometric configurations. Stimulus duration is therefore an important factor for estimation of behavioural PT thresholds in a population exposed to occupational noise and at risk of developing a sloping high frequency hearing loss. In terms of frequency specificity and generation of maximum response amplitude for a given stimulus level, Hyde (1997) recommends the use of a 5- to 10-cycle rise-fall time. Hall (1992) and Onishi and Davis (1968) suggest optimal SCAEP stimuli with 20 to 30 ms rise-fall times. In this condition, both Lightfoot, Mason and Stevens (2002), and Onishi and Davis (1968) found that the plateau duration was immaterial for the purpose of evoked response audiometry. These authors recommended stimulus duration of 200 to 300 ms, significantly longer than the 60 to 90 ms duration advocated by Hall (1992).

A tone burst stimulus has an energy peak at 5 to 6 Hz (Davis, 1976), with little energy below about 2 Hz or above 10 Hz (Hyde, 1997). For this reason Hyde (1997) advocates a recording bandwidth of 1 to 15 Hz or narrower, in order to maximize signal to noise ratio for the purpose of behavioural PT threshold estimation. Recording with a high-pass filter that is lower than 1 Hz is problematic, due to the resulting high physiologic noise levels. The narrow recording bandwidth results in phase distortion, but this is irrelevant for response detection.

The SCAEP is highly dependent on interstimulus interval (Davis, 1976; Hall, 1992; Stapells, 2002). Hall (1992) suggests that interstimulus interval is the more appropriate method of describing the rate factor rather than simply the number of stimuli per second. The interstimulus interval has a significant effect on N1-P2 amplitude (Stapells, 2002) and is therefore an important consideration for threshold estimation. The N1-P2 amplitude increases as interstimulus level increases from less than 1 to 8 s (Hall, 1992) or 10 s (Stapells, 2002). Davis (1976) reported a 10% increase in average response amplitude when interstimulus interval was varied between 0.5 and 4 s. Hyde (1997) and Stapells (2002) recommend a 1 to 2 s interstimulus interval (i.e. 1 to 0.5/s stimulus rate) for optimal signal to noise ratio within a given time period. Hall (1992) recommends a marginally faster rate of 1.1/s stimulus rate. A randomized interstimulus interval is advocated by Lightfoot et al. (2002) and Lightfoot and Kennedy (2006) in order to avoid participant habituation to stimuli. Despite these differences in opinion regarding the optimal interstimulus interval, a 1 to 2 s interval is typically accepted for the purpose of behavioural PT threshold estimation (Stapells, 2002). The effect of stimulus intensity and stimulus frequency on the SCAEP is less contentious.

2.2.4.2 Effect of stimulus intensity and frequency on SCAEP

As stimulus intensity increases, the amplitude of the SCAEP response increases (Onishi & Davis, 1968). An increase in intensity produces a nonlinear increase in response amplitude. That is, the amplitude increases rapidly just above the response threshold (to 20 dB sensation level), but more gradually for higher intensity levels (Davis, 1976; Hyde, 1997). Latency for N1 and P2 systematically decreases as stimulus intensity increases, according to Adler and Adler (1989). Hall (1992) reports considerable intra- and interindividual variability of the amplitude-intensity relationship. Hyde (1997) suggests that this variability may be partly attributable to effects of attention. Therefore participant and stimulus variables are inextricably connected and equally important factors in the assessment of behavioural PT threshold estimation using SCAEP.

At higher stimulus levels, Davis (1976) states that the middle frequencies (i.e. 1 and 2 kHz) provide slightly larger responses. However, Stapells (2002) found a greater suprathreshold N1 amplitude in response to 0.25 to 1 kHz than to stimuli of 2 to 4 kHz (Stapells, 2002). Wunderlich and Cone-Wesson (2001) support this statement, adding that the latency of the N1 response also decreased as frequency increased. These authors also noted that the P2 amplitude, but not the latency, decreased as stimulus frequency increased. Waveforms at middle and higher frequencies are also sharper in morphology than at 0.25 and 0.5 kHz (Davis, 1976). Stapells (2002), however, states that there is no significant effect of stimulus frequency on N1 amplitude near threshold. Therefore, when making use of SCAEP for behavioural PT threshold estimation, as in the present study, no SCAEP threshold response at a single frequency was expected to be any closer to behavioural PT threshold than at another frequency.

Stimulus envelope, intensity and frequency are therefore central to the response characteristics. Specifically, response repeatability and amplitude are modulated by stimulus characteristics. Waveform repeatability and amplitude in turn determine threshold intensity and the accuracy of behavioural PT threshold estimation. Participant variables affect the response characteristics and accuracy of behavioural PT threshold estimation of the SCAEP in the same way.

2.2.5 Effects of participant variables on SCAEP

Attention and state of consciousness significantly affects response amplitude and waveform (Hyde, 1997). Dependence on an individual's state of consciousness is largely due to the neural generators of the SCAEP. AEP generated by lower or distal neurological centres are more independent of an individual's state than higher, more central neural generators. The primary auditory cortex and its associated cortical areas are the neural generators of the SCAEP (Pantev et al., 1990; Vaughan & Ritter, 1970). In physiological terms, the individual's state of arousal relates to the level of EEG background activity (Davis, 1976). During sleep, latency is increased, threshold response elevates by approximately 20 to 30 dB, and amplitude becomes more variable (Picton & Hillyard, 1974). Sleep also differentially affects the SCAEP components, with N2 showing a marked increase in amplitude (Picton & Hillyard, 1974). Hyde (1997) suggests that variation of response amplitude and waveform due to attention is due to changes in adaptation or habituation. Such effects demonstrate intra- and inter-individual fluctuations. N1 and P2 amplitude is larger when the participant attends to the stimuli (Stapells, 2002), although each of these waves may not be equally affected hereby (Hyde, 1997). Amplitude changes due to attention are most marked near threshold (Hyde, 1997). The accuracy of behavioural PT threshold estimation is therefore influenced by participant attention. Maintaining participant attention during SCAEP threshold determination was therefore a critical factor for the current study.

An individual's hearing sensitivity is another important variable which affects the SCAEP. Hyde (1997) reports that a conductive hearing loss alters the slow cortical response amplitude and latency "in a manner equivalent to change in effective stimulus level" (Hyde, 1997, p. 288). This implies a reduction in amplitude and an increase in latency of the N1 and P2 waves in the presence of middle ear pathology. For a cochlear hearing loss, the amplitude and latency input-output function slope magnitude usually increases, with rapid convergence to normal values at raised sensation levels of 30 dB and higher (Davis, 1976; Hyde, 1997). This is comparable to loudness recruitment. Individuals with a noise induced hearing loss present with a cochlear site of lesion (Sataloff & Sataloff, 1987; Stach, 1998). Therefore, the participants in the present study with hearing loss and exposed to occupational noise, were expected to demonstrate this steep increase in amplitude of the SCAEP response above the threshold response.

The SCAEP undergoes substantial changes during maturation, and these changes appear to continue into teenage years (Stapells, 2002; Sussman, Steinschneider, Gumenyuk, Grushko, & Lawson, 2008). According to Onishi and Davis (1968), the most pronounced alterations occur within the first year of life. Stapells (2002) states that latency of the SCAEP decreases and amplitude increases as a function of age during childhood, up until 10 years. This finding is refuted by Wunderlich, Cone-Wesson and Sheperd (2006), who found relatively stable component latencies from birth to six years. Hall (1992) states that age differentially affects the N1 and P2 as well as the other components of the SCAEP in children. N2 and P1 decrease in amplitude, while N1 and P2 increase in amplitude from birth to adulthood (Wunderlich et al., 2006). These authors also report immature tonotopic organisation of the generators when responses from infants and young children are compared to those of adults. The SCAEP response obtained in a child is characterized by a relatively large P1 wave which may be followed by a N1 wave (Stapells, 2002). By ages eight to 11 years the P1 and N2 components dominate the waveform while the N1 is the dominant SCAEP component in adults (Sussman et al., 2008). Wave identification and quantification of maturational changes in young children are complicated by significant response variability and changes with attention, state of arousal and stimulation paradigms (Hyde, 1997). The changes in maturation were, however, not a variable in the present study, as only adults of 18 to 65 years of age were included as participants.

Both Hall (1992) and Hyde (1997) comment on the lack of research relating to gender effects on the SCAEP. Onishi and Davis (1968) did, however, note a tendency of SCAEP amplitude to be larger and the amplitude-versus-intensity function steeper for females than for males. The larger amplitudes noted in female individuals may therefore result in lower mean thresholds if both male and female participants are included in behavioural PT threshold estimation studies.

Both stimulus and participant variables are therefore modulators of the response characteristics and ultimately the accuracy of behavioural PT threshold estimation. Analysis and detection of an AEP response is a further determinant of the accuracy of behavioural PT threshold estimation. Although AEP response detection can be done either subjectively or objectively, clinical response detection of the SCAEP is subjective.

2.2.6 SCAEP response detection/analysis

The determination of threshold SCAEP response is usually based on the visual inspection of the recordings by an evaluator and identification of the N1 and P2, the primary components of the SCAEP, within 80 to 200 ms latency of the response (Prasher et al., 1993). Yeung and Wong (2007) demonstrated consistent interpretations of SCAEP thresholds between two experienced audiologists, with 96% of judgments of threshold response intensities between two experienced clinicians falling within 5 dB of each other. The evaluator's experience in SCAEP threshold identification and any bias the evaluator may have, play a role in the inter-evaluator and intra-evaluator reliability (Gans et al., 1992; Rose et al., 1971). Hoth (1993) states that objective response detection is desirable to avoid variability. Hoth (1993) proposes a computer aided evaluation technique, which was demonstrated, to be able to accurately predict hearing threshold. The technique is, however, based on a parameter of which the value increases with better perceptibility. Therefore response detection by this method is not truly objective. A widely accepted and clinically proven objective response technique for objective SCAEP response identification is currently not available. Consequently, visual response detection remains standard clinical practice.

There are advantages of subjective response detection. Abnormal neural function that may result in changes in response morphology or latency would be identified by an experienced evaluator. An abnormal response would be indicated by an absence of N1-P2 waveform that is larger than the background electroencephalogram within 15 dB of the behavioural PT threshold or by the presence of the N1-P2 response at a latency of greater than 200 ms (Prasher et al., 1993). Objective response detection may not recognise these atypical waveforms as a response and would not identify auditory neural dysfunction. Estimation of behavioural PT thresholds may still be possible in this case by subjective response detection by taking response changes into consideration. The advantages and limitations of response detection methods may therefore vary with each clinical application of the SCAEP.

2.2.7 Clinical use of SCAEP

The clinical use of the SCAEP includes behavioural PT threshold estimation, auditory discrimination and speech perception, as well as objective measurement of benefit from cochlear implantation, auditory training or amplification (Cone-Wesson & Wunderlich, 2003). Stapells (2002) is of the opinion that SCAEP is underutilized, having been replaced by the ABR in clinical practice. This is true, despite the increased frequency specificity, the better resilience to electrophysiological noise and the more complete evaluation of the auditory system offered by SCAEP. Unlike ABR or middle latency AEP, SCAEP may also be elicited by complex stimuli, such as speech sounds, providing functional information on auditory processing ability (Stapells, 2002).

Table 2.1 displays a summary, in chronological order, of the studies on the accuracy of SCAEP for the purpose of behavioural PT threshold estimation. Although some of the listed studies included children as participants, studies using children and infants only were omitted from the summary.

TABLE 2.1 SCAEP studies reporting differences between SCAEP thresholds and behavioural PT thresholds (difference score in dBnHL = SCAEP threshold minus behavioural PT threshold), correlation scores and participant numbers

Study	**500 Hz**			**1000 Hz**			**2000 Hz**			**4000 Hz**		
	diff	**r**	**n**	**diff**	**r**	**n**	**diff**	**r**	**n**	**diff**	**r**	**n**
Coles & Mason (1984)	0 ± 10	-	14 N+HL	0 ± 6	-	129 N+HL	0 ± 11	-	95 N+HL	0 ± 7	-	18 N+HL
Prasher et al. (1993)	-	-	-	0 ± 11 2 ± 8	0.79 0.9	62 HL NIHL 27 N+HL Ménière's	-	-	-	1 ± 10 1 ± 8	0.89 0.89	62 HL NIHL 27 N+HL Ménière's
Tsui et al. (2002)	-	-	-	-2 ± 11	-	204 N+HL	-1 ± 9	-	204 N+HL	-	-	-
Van Maanen & Stapells (2005)	20 ± 6	0.81	46 N+HL	20 ± 9	0.82	46 N+HL	20 ± 12	0.80	46 N+HL	-	-	-
Kaf, Durrant et al. (2006)	-	-	-	-	-	-	10 ± 6 8 ± 6	0.89	16 N 16 SH	-	-	-
Lightfoot & Kennedy (2006)	-	-	-	11 ± 6	-	48 N+HL	10 ± 10 *(3 kHz)*	-	48 N+HL	-	-	-
Tomlin et al. (2006)	13 ± 6 8 ± 7	0.95	36 N 27 HL	-	-	-	-	-	-	12 ± 4 13 ± 12	0.96	36 N 20 HL
Yeung & Wong (2007)	6 ± 9	0.96 (r^2)	34 N+HL	8 ± 7	0.98 (r^2)	34 N+HL	8 ± 8	0.97 (r^2)	34 N+HL	-2 ± 15	0.97 (r^2)	34 N+HL
Average	**9.4 ± 7.5**	**-**	**-**	**5.6 ± 7.9**	**-**	**-**	**7.9 ± 7.0**	**-**	**-**	**4.2 ± 6.6**	**-**	**-**

(dBnHL = decibel normal hearing level; diff = difference score; r = correlation; n = number of participants; N = participants with normal hearing; HL = participants with hearing loss; NIHL = participants with noise induced hearing loss; Ménière's = participants with Ménière's disease; SH = participants with simulated hearing loss)

A calculation of the mean difference between SCAEP threshold and behavioural PT threshold of the studies presented in Table 2.1 indicated scores of 9.4, 5.6, 7.9 and 4.2 dB at 0.5, 1, 2 and 4 kHz respectively, all of which fall below 10 dB. The summary presented in Table 2.1 therefore supports the criteria for the identification of individuals presenting with a nonorganic hearing loss utilized in various studies, namely a difference between behavioural PT thresholds and SCAEP thresholds of greater than 10 dB at the test frequencies (Alberti et al., 1987*; Coles & Mason, 1984; Hone et al., 2003; Hyde et al., 1986*; Prasher et al., 1993). The correlation co-efficients of 0.79 to 0.98 indicate a strong positive correlation between SCAEP threshold and behavioural PT threshold. The test-retest reliability correlation of the SCAEP is also high, with studies measuring correlations of 0.91 to 0.99 (Jacobson, McCaslin, Smith, Elisevich, & Mishler, 1999; Kaf, Sobo, Durrant, & Rubinstein, 2006; Pekkonen, Rinne, & Näätänen, 1995). The high test-retest reliability and the mean difference of less than 10 dB between SCAEP threshold and behavioural PT threshold confirm that the SCAEP technique is capable of consistently and accurately estimating behavioural PT thresholds in co-operative adults. This is in keeping with the statements of Hyde (1997), Hyde et al. (1986) and Stapells (2002) that state that SCAEP is the measure of choice when an AEP estimate of behavioural PT hearing threshold is required for any patient who is likely to be passively co-operative and alert, namely for most older children and adults.

A clinical AEP tool must not only be accurate and reliable, but must also enable rapid acquisition of threshold responses at the relevant frequencies. A report by Hyde et al. (1986) states that a four frequency SCAEP threshold acquisition in both ears typically takes 1.5 hours. More recently, however, a study by Lightfoot and Kennedy (2006) made use of a SCAEP system with online averaging and random interstimulus intervals in addition to automation of various classically manual tasks during SCAEP assessment. Lightfoot and Kennedy (2006) established that with this system, a six threshold estimate took on average 20.6 min to complete with a mean error in behavioural PT threshold estimation of 6.5 dB. The SCAEP is therefore capable of both accurate and time efficient behavioural PT threshold estimation, two important elements for clinical use. The time

* Alberti et al. (1987) and Hyde et al. (1986) are two publications that reported on findings of the same research.

efficiency was an aspect compared in the present study in addition to the accuracy of the SCAEP and ASSR techniques.

With regard to further clinical application, SCAEP is affected by listening experience and attention, and is therefore effectively used to gauge the effects of aural habilitation (Cone-Wesson & Wunderlich, 2003). Prolonged latency of the N1 and P2 components may also be used to indicate an auditory processing disorder (Jirsa & Clontz, 1990). Harris et al. (2007, 2008) state that auditory processing can be evaluated using the SCAEP, as the presence of the P1-N1-P2 response reflects the physiologic detection of the frequency and intensity changes at the level of the auditory cortex, which in turn may be related to frequency and intensity discrimination abilities. Harris et al. (2007, 2008) made use of the P1-N1-P2 response as an index to measure preattentive levels of auditory processing in young and older participants. The authors found that older participants demonstrated significantly decreased sensitivity to small changes in frequency and intensity (by higher P1-N1-P2 thresholds). The SCAEP was therefore able to provide objective information on auditory processing ability.

Not only is the SCAEP sensitive to changes in frequency and intensity, but by making use of speech stimuli the SCAEP may also be used to assess cortical ability to discriminate changes within speech stimuli (Martin & Boothroyd, 1999). Presenting speech stimuli to aided participants allows for a functional measure of hearing aid benefit using the SCAEP technique (Aiken & Picton, 2008; Beynon, Snik, & Van den Broek, 2002; Kurtzberg, 1989; Stapells, 2002). The SCAEP is also useful in demonstrating higher-level, cortical responsivity to sound when earlier, lower-level responses (such as ABR) suggest neuropathy (Gravel & Stapells, 1993; Kurtzberg, 1989). Absence or abnormality of SCAEP in the presence of earlier responses suggests higher-level, central dysfunction (Hood, Berlin, & Allen, 1994; Stapells, 2002).

The SCAEP therefore provides an accurate and time efficient measure of aided and unaided behavioural PT threshold estimation, provides information on auditory processing ability and on site of lesion in cases of auditory neuropathy or dysynchrony. The present study was, however, concerned only with the ability of the SCAEP technique to estimate behavioural PT thresholds in individuals with normal hearing, and in individuals with hearing loss who were exposed to occupational noise. Previous literature referencing SCAEP use with individuals exposed to occupational noise was therefore reviewed in more detail.

2.2.8 Use of SCAEP for behavioural PT threshold estimation in adults exposed to occupational noise

Several studies have successfully made use of the SCAEP for the assessment of individuals with noise induced hearing losses (Alberti et al., 1987; Boniver, 2002; Coles & Mason, 1984; Hone et al., 2003; Hyde et al., 1986; Prasher et al., 1993; Rickards & De Vidi, 1995; Tsui et al., 2002; Van Maanen & Stapells, 2005). The study by Prasher et al. (1993) evaluated the ability of the SCAEP method to estimate behavioural PT thresholds in a population of adults with noise induced hearing loss. Prasher et al. (1993) did this by comparing a group of individuals with noise induced hearing loss with individuals with Ménière's disease, using the latter as a reference to determine the accuracy of SCAEP behavioural PT threshold estimation. The study found SCAEP thresholds within 10 dB of behavioural PT thresholds for 94 and 97% at 1 and 4 kHz respectively for the participants with noise induced hearing loss, and within 92% of behavioural PT thresholds for participants with Ménière's disease. The results of this study confirm that behavioural PT threshold estimation using SCAEP is accurate in adults with noise induced hearing loss as compared to another population of adults with sensorineural hearing loss.

The percentage distribution score reported by Prasher et al. (1993) is similar to that reported by Alberti et al. (1987) and Hyde et al. (1986). Alberti et al. (1987) and Hyde et al. (1986) performed SCAEP on 1168 individuals claiming compensation for occupational hearing loss. Of the individuals considered to present with organic hearing loss, 96.4% of SCAEP thresholds were measured within 10 dB of behavioural PT thresholds. When the difference between SCAEP thresholds and behavioural thresholds was 15 dB or more, the individual was identified as presenting with a non organic component to the hearing loss. The criterion for identification of non organic hearing loss is the same as that used by Coles and Mason (1984) and Tsui et al. (2002).

Hone et al. (2003) made use of a similar criteria when using SCAEP to identify individuals with a non organic hearing loss. A non organic hearing loss was considered to be present when the behavioural PT average was more than 10 dB worse than the average of SCAEP threshold at 0.5, 1, 2 and 4 kHz. Of the 673 individuals claiming compensation for occupational noise induced hearing loss, 13% were found to present with a non organic hearing loss. The disadvantage of making use of the average of four frequencies to indentify non organic hearing loss is that only half the participants underwent SCAEP testing at all four frequencies.

The criteria used by Alberti et al. (1987), Coles and Mason (1984), Hyde et al. (1986) and Tsui et al. (2002) in order to identify individuals with a non organic hearing loss, namely behavioural PT thresholds which were greater than SCAEP thresholds by 15 dB or more at individual frequencies, receives further support from the body of literature on use of the SCAEP for the purpose of behavioural PT threshold estimation. As can be seen from Table 2.1, all but one study reports SCAEP thresholds within 15 dB of behavioural PT thresholds (Coles & Mason, 1984; Kaf, Durrant et al., 2006; Lightfoot & Kennedy, 2006; Prasher et al., 1993; Tomlin et al., 2006; Tsui et al., 2002; Yeung & Wong, 2007). The studies of Coles and Mason (1984), Kaf, Durrant et al. (2006), Prasher et al. (1993), Tsui et al. (2002) and Yeung and Wong (2007) reported mean difference scores (between SCAEP threshold and behavioural PT thresholds) of 10 dB or less. Lightfoot and Kennedy (2006) measured difference scores of 11 and 10 dB at 1 and 3 kHz respectively. Although Lightfoot and Kennedy (2006) did include participants with some degree of hearing loss, the participants predominantly presented with normal hearing. The slightly larger mean difference scores for individuals with normal hearing than with hearing loss, are consistent with previous literature (Kaf, Durrant et al., 2006; Tomlin et al., 2006; Yeung & Wong, 2007). Hyde (1997) states that for a cochlear hearing loss, the magnitude of the SCAEP amplitude and latency input-output function slope usually increases, with rapid convergence to normal values at raised sensation levels. This is comparable to loudness recruitment. The difference between SCAEP thresholds and behavioural PT thresholds for individuals with hearing loss is therefore smaller than for individuals with normal hearing. The greater number of participants with normal hearing is also likely to be the reason why the mean differences between SCAEP and behavioural PT thresholds in the study by Tomlin et al. (2006; viz. mean difference score = 11 dB at 0.5 and 4 kHz) were greater than 10 dB.

The findings of Van Maanen and Stapells (2005) are in obvious contrast to existing literature displayed in Table 2.1 on SCAEP used to estimate behavioural PT thresholds. Van Maanen and Stapells (2005) displayed a mean difference between SCAEP threshold and behavioural PT threshold of approximately 20 dB. Van Maanen and Stapells (2005) made use of a male only population, with 40 out of 46 participants claiming compensation and consequently, frequently presenting with a noise induced high frequency hearing loss. The population from which participants were drawn was therefore identical to the studies by Coles and Mason (1984), Prasher et al. (1993) and Tsui et al. (2002). The protocol and participant state of attention was also the same. Van Maanen and Stapells (2005) ascribed the reason for the elevated SCAEP thresholds to the calibration method utilized. SCAEP stimuli were calibrated in dBeHL (dB estimated hearing level), so that a 20 dBeHL SCAEP threshold was equivalent to a 20 dB behavioural PT threshold. Van Maanen and Stapells (2005) suggest that the SCAEP thresholds reported would have been approximately 9 dB smaller, had the typical normal hearing level calibration (nHL) been used instead of the dBeHL scale selected. A 9 dB decrease in SCAEP thresholds would bring the mean difference scores between SCAEP thresholds and behavioural PT thresholds to less than 15 dB, which is in keeping with the studies listed in Table 2.1. The study by Van Maanen and Stapells (2005) therefore reflects poorly on the accuracy of the SCAEP for behavioural PT threshold estimation, but is incongruent with previous research.

The accuracy of the SCAEP is the reason why the SCAEP is still widely considered the AEP of choice for adults exposed to occupational noise. Hyde et al. (1986) state that the experience and data collected by the Department of Veterans Administration in Toronto, Canada, indicate that SCAEP is an excellent tool for quantitative verification of behavioural PT thresholds in individuals claiming compensation for occupational hearing loss. The comments made by Hyde et al. (1986) regarding the use of SCAEP are relevant to the current situation in South Africa. The authors are of the opinion that research suggests that the limited acceptance of SCAEP in North America (and by extension, in South Africa) is unfortunate and inappropriate. The limitation, according to Hyde et al.

(1986) is that behavioural PT threshold estimation using SCAEP is dependant on subjective judgement of response presence or absence.

Over the past 15 years, a new clinically available AEP technique which makes use of objective response detection, namely the ASSR, has been proposed as an alternative AEP for behavioural PT threshold estimation (Dobie & Wilson, 1998; Lins et al., 1996; Rance et al., 1995; Vander Werff et al., 2002). As new clinical tools become available, comparisons are necessary in order to determine whether the newer tools are more accurate or more cost effective than the ones advocated at the time. There are, however, only a limited number of studies exploring the use of ASSR for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise (De Koker, 2004; Herdman & Stapells, 2003; Hyde et al., 1986; Hsu et al., 2003; Van Maanen & Stapells, 2005). Third party payers of compensation due to occupational diseases, such as noise induced hearing loss, are demanding efficacy in research, documenting the effectiveness of diagnostic and therapeutic protocols in controlled clinical experiments prior to reimbursement (Johnson & Danhauer, 2002). In order to effectively undertake a research project comparing two diagnostic AEP techniques, a review of current knowledge of both is required. An appraisal of ASSR and the suitability thereof, for the purpose of behavioural PT threshold estimation in adults with normal hearing, and with hearing loss and exposed to occupational noise, therefore follows.

2.3 AUDITORY STEADY-STATE RESPONSE (ASSR)

The ASSR is a brain potential evoked by continuous stimuli characterized by periodic amplitude modulation of a carrier frequency (Jerger, 1998; Vander Werff et al., 2002). It yields a waveform closely following the time course of the stimulus modulation and a response specific to the frequency of the carrier (Cohen et al., 1991; Jerger, 1998). The response is generated when the stimulus tones are presented at a rate that is sufficient to cause an overlapping of transient potentials (Rance et al., 1998). By varying the intensity of the eliciting stimulus, one can seek the threshold response (Jerger, 1998).

The terminology used to refer to ASSR has changed since its introduction by Galambos et al. (1981), who referred to the ‘40 Hz auditory potential’. Various other terms were also later used, namely frequency following response amplitude modulation following response or AMFR (Aoyagi et al., 1993, 1994, 1996, 1999; Cebulla, Stürzbecher, & Wernecke, 2001; Lynn, Lesner, Sandridge, & Daddario, 1984; Van der Reijden, Mens, & Snik, 2001, 2006), auditory steady-state potentials (Champlin, 1992; Cohen et al., 1991; Linden et al., 1985; Pethe, Von Specht, Mühler, & Hocke, 2001; Rickards et al., 1994; Stapells et al., 1984), 40 Hz middle latency response (Dauman, Szyfter, De Sauvage, & Cazals, 1984; Hyde et al., 1986) and the 40 Hz event related potential (eg. Sammeth & Barry, 1985; Spydell, Pattee, & Goldie, 1985). In recent years however, the majority of studies are in agreement that the preferred term is auditory steady steady-state response or ASSR.

2.3.1 Historical overview of ASSR

Human steady-state evoked responses were originally recorded in response to visual stimuli (Regan, 1966). Steady-state responses in response to acoustic stimuli were not recognizable in the ongoing EEG until the development of averaging procedures to attenuate the background EEG. Schimmel et al. (1974) mentioned that the auditory responses with peak latencies between 20 and 40 ms could be efficiently recorded at stimulus rates of 40 to 45 Hz. These researchers were the first to suggest automated analysis of the response through use of Fourier analysis of the amplitude of the response at the frequency of the stimulation and the amplitude of the response at adjacent frequencies. Extensive research into the potential clinical application of ASSR followed the description of the ‘40 Hz AEP’ by Galambos et al. (1981). These authors described ASSR at these rates as a superposition of transient middle latency responses. The authors also demonstrated the attenuating effect of sleep on the response amplitude and that the response could be recorded at intensities near hearing threshold. In addition, there was also interest in the possible neurodiagnostic value of ASSR for evaluation of the status of the central nervous system above the level of the brainstem (Hall, 1992).

Investigations into the effect of different response rates followed, including the discovery by Cohen et al. (1991) that sleep did not attenuate the response at modulation rates of greater than 70 Hz. This finding instigated research of the application of ASSR for behavioural PT threshold estimation for the paediatric population (Cone-Wesson, Rickards et al., 2002; Luts, Desloovere, & Wouters, 2006; Perez-Abalo et al., 2001; Pethe, Mühler, Siewert, & Von Specht, 2004; Rance & Tomlin, 2006; Rance & Briggs, 2002; Rance & Rickards, 2002; Rance et al., 1993, 1998; Sininger & Cone-Wesson, 2002; Small & Stapells, 2006; Stueve & O'Rourke, 2003; Swanepoel, Hugo, & Roode, 2004; Vander Werff et al., 2002). The use of ASSR for the purpose of behavioural PT threshold estimation in the paediatric population continues to generate the majority of interest and research with this technique.

For both the paediatric population and the adult population, knowledge of the neural generators of an AEP (auditory evoked potential) is essential in understanding both the advantages and limitations of the technique. Recommendations for clinical use of the ASSR for each population are developed on the basis of this information.

2.3.2 ASSR neural generators

Galambos et al. (1981) proposed that the 40 Hz modulation rate ASSR results from a superposition of middle latency response components. The study by Pantev, Roberts, Elbert, Ross and Wienbruch (1996) evaluated this hypothesis and found the sources of the 40 Hz ASSR and middle latency AEP to differ, however. Cortical ASSR sources, determined for different carrier frequencies, were found to display a medial tendency tonotopy resembling that of the N1, which is opposite to the lateral tendency tonotopy displayed with the middle latency waveform. Pantev et al. (1996) identified the generators of 40 Hz stimuli within the supratemporal gyrus of the auditory cortex. Reyes et al. (2004) expanded on this, identifying not only generators of the 40 Hz response in the primary auditory cortex (ipsilaterally and contralaterally), but outside of this in the cingulate and frontal lobes.

The first study to suggest that modulation rate affected the source of the ASSR, was that by Mauer and Döring (1999, as cited in Herdman et al., 2002), who found that both brainstem and cortical (temporal lobe) sources were active during ASSR, once modulation rate was varied between 24 to 120 Hz. Herdman et al. (2002) demonstrated that the brainstem was consistently active at stimulation rates of 12, 39 and 88 Hz, whereas cortical sources were more active at slower rates, 39 Hz in particular. At 39 Hz, both cortex and brainstem sources are activated simultaneously. These findings are supported by the Rickards et al. (1994) study of sleeping neonates, using modulation frequencies ranging from 35 to 185 Hz, indicating a systematic decrease in response latency with increasing modulation rate. The latency of the response (calculated from the response phase) using a 65 to 100 Hz rate, occurred at 11 to 14 ms, suggesting that ASSR at these high modulation rates are generated by the brainstem. The neural generators of the low and high modulation rate ASSR therefore differ, with the low modulation rate ASSR being generated by the primary and secondary auditory cortices, in addition to some brainstem activation, while the brainstem is the primary neural generator when a high modulation rate is utilized.

Herdman et al. (2002) state in summary of their findings, that a participant evaluated with ASSR using amplitude modulated (AM) tones modulated between 70 and 110 Hz, would suggest normal auditory function to the level of the brainstem. Dysfunction further along the auditory pathway may only be resolved by use of a slower modulation rate (i.e. 40 Hz). In addition, although central cortical lesions (Herdman et al., 2002) and upper brainstem lesions (Spydell et al., 1985) will disrupt the recording of the 40 Hz ASSR, unilateral cortical lesions do not alter the phase of these responses (Spydell et al., 1985). The ASSR would therefore, in keeping with this finding, be present in individuals with a unilateral cortical lesion. On review of the research by Reyes et al. (2005), one realises that this statement needs to be clarified. The ASSR may only be present if the unilateral cortical lesion is present ipsilaterally. The aforementioned study reports a larger, contralateral, temporal-parietal response than the ipsilateral temporal response. Yet Reyes et al. (2005) did find both ipsilateral and contralateral activation with AM stimuli modulated at 40 Hz, in a widely distributed network of cortical sites including regions of the temporal and frontal lobes. Confirmation of right hemispheric dominance for 40 Hz AM tones by Ross, Herdman and Pantev (2005) and Wollbrink and Pantev (2007), would further restrict the conclusion drawn by Spydell et al. (1985).

Knowledge of the neural generators of the high and low modulation rate ASSR was important, as the current study aimed at comparing the ASSR technique with the SCAEP technique, which is known to be generated in the primary auditory cortex and associated areas (Alain et al., 1997; Pantev et al., 1990; Picton et al., 1999; Vaughan & Ritter, 1970).

A within participant comparison of the accuracy of SCAEP and ASSR would require the use of an ASSR modulation rate, that resulted in a response that was generated by the same or similar neural sources. The low modulation rate ASSR meets this requirement as the neural generators have been identified as the primary and secondary auditory cortices (Herdman et al., 2002; Pantev et al., 1996; Reyes et al., 2004). With the ideal ASSR modulation rate for the present comparative study identified, the ASSR is further discussed in terms of its properties and components.

2.3.3 Properties and components of the ASSR

Picton et al. (2003) describe the ASSR as an evoked potential of which the components remain constant in amplitude and phase over a period of time longer than the duration of a single stimulus cycle. Transient responses are evoked by stimuli that occur infrequently, whereas ASSR are evoked by stimuli that occur when the stimulus rate is sufficiently rapid that the transient response to one stimulus overlaps with the responses of succeeding stimuli (Picton et al., 2003). Hall (1992), with reference to the key publication of Galambos et al. (1981), provides an explanation of the ASSR waveform. A stimulus rate of approximately 40/s produces an evoked response waveform with a peak every 25 ms, or 40 peaks/s (i.e. 40 Hz). This occurs as the major components of the auditory middle latency AEP occur at intervals of 25 ms. With a stimulus rate of 40 ms and an adequately long analysis time (greater than or equal to 25 ms), the AEP will occur approximately 40/s and the auditory middle latency AEP components will be in phase and hence superimposed.

With reference to the neurological significance of the ASSR response, Picton et al. (2003) state that ASSR demonstrate how the brain follows a periodically presented stimulus or, conversely, how the stimulus drives the response. In so doing, ASSR provides objective demonstration that sounds have been processed by the brain. It is for this reason that the ASSR is able to be used to estimate behavioural PT thresholds. Picton et al. (2003) clarified this statement by adding that ASSR recorded using low modulation rates may correlate more closely with cortical processing. Higher modulation rates may provide objective indication that auditory information has been processed through the brainstem for presentation to the cortex. Picton et al. (2003) also suggest that ASSR demonstrates the ability of the auditory system to process rapid temporal changes required in order to discriminate speech. Boettcher, Madhotra, Poth and Mills (2002) state that ASSR using frequency modulated stimuli (FM stimuli) may reflect the neural correlate of the ability to detect modulation in stimulus frequency. Knowledge of the neural correlate of the ASSR therefore determines the value of the technique and facilitates the development of clinical applications.

During clinical use of the ASSR, responses need to be distinguished from noise. The ASSR threshold intensity will vary with the size of the response, the amount of electrical noise in the recording, and the time taken to reduce this noise, by averaging or increasing the sweep of the FFT (fast Fourier transform) analysis (Picton et al., 2003). Any behavioural PT threshold estimation is consequently made with reference to the noise level at which a response is judged to be present or absent. The noise levels will determine both the accuracy with which the ASSR can estimate behavioural PT threshold and the time required to estimate them. Noise levels are in turn influenced by stimulus and participant variables.

2.3.4 ASSR stimulus variables

Continuous PT have maximum acoustic specificity, meaning that energy within the stimulus is concentrated within certain frequencies in a spectrum (Picton et al., 2003). The most commonly utilized ASSR stimuli are continuous sinusoidally AM tones. AM tones are acoustically frequency specific, with spectral energy only at the stimulus or carrier frequency and two sidebands at a frequency separation equal to the modulation rate (Picton et al., 2003). The amplitude of the ASSR response increases as the depth of modulation increases, and the amplitude saturates as modulation depth reaches 50% (Lins, Picton, Picton, Champagne, & Durieux-Smith, 1995). Cohen et al. (1991) and John et al. (2001) reported the simultaneous modulation of both amplitude and frequency (AM/FM stimulus) evokes larger responses than amplitude modulation alone. Stimulus variables such as the modulation rate, the rate at which the stimulus is modulated, is named as one of the most defining characteristics of the ASSR (Picton et al., 2003).

2.3.4.1 Effect of modulation rate on ASSR

The modulation rate is one of the most defining characteristics of the ASSR (Picton et al., 2003). Initially, the most widely studied ASSR was evoked by stimuli presented at rates near 40 Hz (Galambos et al., 1981; Schimmel et al., 1974; Stapells et al., 1984). Galambos et al. (1981) first identified the maximal response amplitude at a rate of 35 to 45/s for alert adults. In sleeping or sedated adults, 40 Hz ASSR amplitudes are smaller than in the awake state (Aoyagi et al., 1993; Galambos et al., 1981; Linden et al., 1985). Many studies examined the effect of modulation rate on the amplitude and detectability of the ASSR response, including Aoyagi et al. (1999), Cohen et al. (1991), Dobie and Wilson (1998), Lins et al. (1995), and Rees, Green and Kay (1986). The aforementioned studies found the amplitude of the response decreased with increasing modulation rate. In addition to this general decline, these studies reported an increase in the amplitude around 40 Hz and again around 90 Hz. The ASSR to stimuli presented at rates of 70 to 110 Hz, are two to three times smaller in amplitude than those of the 40 Hz response in alert individuals (Cohen et al., 1991; Levi et al., 1993; Lins et al., 1995). Herdman et al. (2002) compared the amplitude of the ASSR response modulated at different rates in alert adults measured, using a 1 kHz AM stimulus and presented at 70 dBSPL (decibel sound pressure level) stimulus intensity. The response, when using a 39 Hz modulation rate, was five times larger than when making use of 88 Hz modulation rate.

In order to discuss optimal modulation rate for the purpose of objective assessment of hearing threshold, the reliability of the statistical verification of the presence of a response must be taken into account. The reliability hereof is influenced by the signal to noise ratio as an expression of both response amplitude and residual noise (Pethe et al., 2004). Considering amplitude alone, would lead to the incorrect conclusion being drawn. Several authors report significantly lower background electroencephalogram noise levels at 80 Hz modulation rate than at a 40 Hz modulation rate (Cohen et al., 1991; Pethe et al., 2004; Picton et al., 2001, 2003). Muscle activity, however, is also an important source of noise (Dimitrijevic et al., 2002) and the 80 Hz ASSR response is more influenced by myogenic activity than is the 40 Hz response (Pethe et al., 2004). Consequently, due to the decreased myogenic noise levels when participants are asleep, the threshold response, although smaller in amplitude at 40 Hz in sleeping individuals than when alert, may become more detectable (i.e. identifiable at a lower intensity; Dobie & Wilson, 1998). This statement is supported by the findings of Linden et al. (1985) who found no difference in the 40 Hz ASSR threshold values in awake versus sleeping adults. An opposing opinion is presented by Jerger, Chmiel, Frost and Coker (1986) who found that the use of 40 Hz modulation rate on sleeping adults causes an elevation in ASSR threshold intensities. Authors such as Luts and Wouters (2005) and Van Maanen and Stapells (2005) also report excessive noise levels when using the 80 Hz ASSR despite participants' restful or sleeping states. Luts and Wouters (2005) found that selection of a low modulation rate reduced the high noise levels. The choice of modulation rate is therefore often, as in the case of the present study, dependant on noise levels. In a population of adults referred for objective assessment due to (typically) wilful exaggeration of behavioural PT thresholds and are liable to be rather anxious about the outcome of the assessment, high myogenic noise levels are likely to be measured. In this population, the use of a 40 Hz modulation rate is likely to reduce myogenic noise.

Modulation rate is intrinsically linked to an individual's state of consciousness. Authors such as Aoyagi et al. (1993) and Levi et al. (1993) found that, using moderate stimulus intensity levels, sedated adults demonstrated larger response amplitudes at 80 Hz than at 40 Hz modulation rate. A study by Griskova, Morup, Parnas, Ruksenas and Arnfred (2007) also made use of moderate stimulus intensities to investigate the effect of a high arousal condition (participants sat upright reading a book) and low arousal condition (participants were sitting reclined with eyes closed and lights turned off) on the ASSR using a click stimulus and a 40 Hz modulation rate. Griskova et al. (2007) found that the amplitude and phase precision of the ASSR were significantly larger during the low arousal state compared to the high arousal condition. By detection of the focal ASSR component and extraction of the noise component of the ASSR, it was also demonstrated that the increased ASSR amplitude during drowsiness was not due to activity in the postauricular muscles as was suggested by Picton et al. (2003). However, in light of the clinical application of ASSR, namely threshold determination, the use of moderate intensity stimuli limits the value of the aforementioned studies. On recognition of this shortcoming, Dobie and Wilson (1998) completed an experimental study on the effect of state and stimulus rate on the detectability of an ASSR at low stimulus intensity levels by comparing the intensities of the ASSR threshold responses. Dobie and Wilson (1998) concluded that ASSR at low intensities in adults are best recorded in either the awake or sleeping state using a modulation rate of 40 to 50 Hz rather than a high modulation rate. The findings of the study by Dobie and Wilson (1998) and Linden et al. (1995) were vital, when deciding on the ASSR modulation rate used for estimation of behavioural PT threshold estimation in the present study. As both studies suggested that the testing of sleeping participants reduced myogenic noise levels, and threshold intensity of the ASSR response was not negatively influenced, a 40 Hz modulation rate was chosen for evaluation of adult participants who were either sleeping or lying relaxing with their eyes closed. The effect of different modulation rates at different stimulus or carrier frequencies and at different stimulus intensities, is discussed in greater detail below.

2.3.4.2 Effect of carrier frequency and stimulus intensity on ASSR

The effects of carrier frequency are different for stimuli modulated at rates at 40 Hz and at 80 Hz. Picton et al. (2003) state that these effects of modulation rate are not large in adults. Galambos et al. (1981) first reported that 40 Hz ASSR amplitude was greater for low frequency stimuli and decreased with increasing frequency. This statement was supported by Rodrigués, Picton, Linden, Hamel and Laframboise (1986), Picton, Skinner, Champagne, Kellett and Maiste (1987), and Ross, Draganova, Picton and Pantev (2003), the latter of whom stating that the amplitude at 0.25 kHz was three times larger than the amplitude at 4 kHz for low modulation rate ASSR.

There are several examples of contradicting findings in research on the effects of carrier frequency and high modulation rate on ASSR responses. Cohen et al. (1991), and Rance et al. (2005) noted that high frequency stimuli elicit comparatively larger ASSR amplitudes in sleeping adults using high modulation frequencies. Similarly, Lins et al. (1996) and Rance et al. (1995) found that ASSR thresholds were obtained at significantly lower intensity levels for high frequency stimuli than low frequency stimuli with high modulation rates. In contrast to the aforementioned studies, larger amplitudes were measured at 1 and 2 kHz than for either higher or lower frequencies for 80 to 100 Hz ASSR by John et al. (2001). John and Picton (2000) found no significant interaction between high modulation frequencies (namely 78 to 96 Hz) and carrier frequency. A study that included these researchers later found, however, that when multiple stimuli are presented simultaneously, the responses at the lower carrier frequencies may be slightly attenuated (John et al., 2002).

As with carrier frequency, research on the effect of intensity on ASSR indicates different findings for low and high modulation rates. For continuous AM stimuli modulated at a rate of 40 Hz, the intensity of the stimulus increases, the amplitude of the response increases and the latency decreases (Picton et al., 1987). At higher modulation rates, the response amplitude is smaller and therefore the amplitude change with intensity is correspondingly less for intensities below 70 dBSPL (Lins et al., 1995). At intensities above 70 dBSPL the amplitude of the responses increases to a greater extent with increasing intensity (Lins et al., 1995). Picton et al. (2003) postulates that the greater amplitude changes with intensity at a lower modulation rate may be due to a combination of the increased number and synchronicity of the responding cells (in the cortex) and the shorter distance between the cells and the recording electrodes. John and Picton (2000) report that the decrease in latency with increasing intensity is similar across carrier frequency.

Rance et al. (1998) states that ASSR testing, using continuous modulated tones, offers advantages over techniques that require transient stimuli. The continuous AM/FM tones do not suffer the spectral distortion problems associated with brief tone bursts or clicks. As such, AM/FM tones are comparatively more frequency specific than responses to transient stimuli (John & Picton, 2000). The frequency specificity allows testing across the audiometric range, including sloping high frequency hearing losses, as is typical of the population targeted by the current study (Lins et al., 1996; Herdman & Stapells, 2001; Johnson & Brown, 2005; Rance et al., 1995). In addition, assessment at high intensity levels (i.e. up to 120 dBHL, decibel hearing level) is possible, due to the continuous nature of the ASSR stimuli and hence the absence of calibration corrections to account for temporal summation differences between short and long duration signals associated with stimuli such as tone bursts and clicks (Rance et al., 1998, 2005).

When determining the ASSR threshold intensity at various frequencies, the response recording duration is a key determinant of the proximity of ASSR threshold to behavioural PT threshold. The comparison of the difference scores between ASSR thresholds and behavioural PT thresholds, was used to determine the comparative accuracy of the SCAEP and ASSR techniques in the present study.

2.3.4.3 Effect of response recording duration on ASSR

The length of the response recording determines the resulting amount of residual noise in the recording. When responses are recorded over a shorter period of time, there is more residual noise in the recording and the response will not be recognised (and threshold determined) until the intensity and response amplitude increases (Picton et al., 2003). The study by Luts and Wouters (2004) examined the effect of test duration in terms of accuracy of estimation of behavioural PT thresholds with ASSR. They found that increasing the length of recordings of individual frequencies from 5 to 15 min, increased the accuracy of estimation of behavioural PT thresholds (in terms of difference between ASSR threshold and behavioural PT threshold, the standard deviation of this difference and the correlation between the ASSR threshold and behavioural PT threshold), independently of the test frequency. Therefore a system that allows for a longer response duration is advantageous as it will yield ASSR thresholds closer to behavioural PT thresholds.

In individuals with a sensorineural hearing loss, the response amplitude increases more rapidly as the intensity increases above threshold, than for individuals with normal hearing (Picton et al., 2003). This amplitude-intensity function is similar to recruitment. At high intensities it is easy to recognize a response near behavioural PT threshold in adults with sensorineural hearing loss. In adults with a mild hearing loss or with normal hearing, Picton et al. (2003) state it was often necessary to lengthen recording times to 10 min or more in order to recognize the small responses at threshold intensity. If brief recording times are used (eg. 90 s), the ASSR threshold will be higher and the difference between ASSR threshold and behavioural PT threshold greater than if a longer recording time (eg. 15 min) is used (Picton et al., 2003). Consequently, when comparing average ASSR threshold data between studies, aberrant data can often be explained by examining response recording length.

When considering the two clinical ASSR systems which are most widely used in South Africa, namely the Biologic MASTER ASSR system (John et al., 1998) and the GSI (Grason-Stadler Incorporated) Audera ASSR system (GSI, 2003), different response recording times are evident. The Biologic MASTER system allows for ASSR response to be recorded for up to 15 min or 900 s, in order to improve the signal to noise ratio of recordings (John et al., 1998). This long recording duration is in contrast to the response recording duration of only 89 s of the GSI Audera ASSR system (GSI, 2003). Therefore, the difference between ASSR thresholds and behavioural PT thresholds are likely to be greater when using the GSI Audera than when using the Biologic MASTER system. The GSI Audera compensates for the elevated ASSR thresholds, by using regression equations suggested by Rance et al. (1995) that relate the behavioural PT threshold to the ASSR threshold (GSI, 2003). ASSR research that utilizes the GSI Audera system generally refers to ASSR thresholds without correction by the regression equations. As clinical use of the ASSR technique is being evaluated by the present study, reference is made to GSI Audera corrected ASSR thresholds (applying the Rance et al., 1995, regression equations) and uncorrected ASSR threshold, when reporting thresholds obtained using the GSI Audera.

The Biologic MASTER and GSI Audera ASSR systems differ not only in response recording duration, but also with respect to method of presentation of ASSR stimuli. The GSI Audera ASSR presents stimuli in a monotic, single frequency manner (GSI, 2003), while the Biologic MASTER ASSR system makes use of dichotic, multiple frequency ASSR stimuli (John et al., 1998).

2.3.4.4 Use of dichotic stimuli and multiple frequency ASSR stimuli

Lins and Picton (1995) were the first to describe the possibility of using multiple ASSR to assess hearing at different frequencies and in both ears simultaneously. ASSR evoked by simultaneously presented multiple AM tones can be measured by examining the spectral components in the recording that correspond to the different carrier frequencies, each of which are modulated at different rates (John et al., 1998; John & Picton, 2000; Lins & Picton, 1995; Lins et al., 1995. 1996; Stapells, Makeig, & Galambos, 1987; Rance et al., 1995). This multiple ASSR technique can be recorded simultaneously, in one or both ears, without significant loss in the amplitude of any of the responses, provided the carrier frequencies differ by one octave or more (John et al., 1998; Lins & Picton, 1995). This finding is supported by that of Herdman and Stapells (2001) that found no significant differences between monotic and dichotic stimulus conditions in high modulation ASSR thresholds in adults with normal hearing. John et al. (1998) also recommend using modulation frequencies between 70 and 110 Hz as there is less interaction between stimuli than at lower modulation frequencies of 30 to 50 Hz.

When considering multiple frequency ASSR using low modulation rates, John et al. (1998) reported that the multiple frequency ASSR technique (viz. Biologic MASTER ASSR system) was not significantly better than the single frequency ASSR technique. This contradicts the findings of the Van Maanen and Stapells (2005) study that recommended the use of a low modulation rate with the Biologic MASTER system, due to the smaller difference scores measured when compared to that of the 80 Hz Biologic MASTER protocol. There is thus no consensus in terms of the optimal clinical ASSR tool for behavioural PT threshold estimation.

A study by Luts and Wouters (2005) compared the monotic single frequency ASSR technique with that of the multiple ASSR technique. This was done using the two most widely used clinically available ASSR systems, namely the GSI Audera (monotic single frequency ASSR) and the Biologic MASTER (dichotic multiple frequency ASSR). Both the single and multiple frequency ASSR thresholds were highly correlated with behavioural PT thresholds. For the total participant group, the multiple frequency technique displayed smaller difference scores between ASSR threshold and behavioural PT thresholds with smaller standard deviations. Both techniques, however, performed equally well with participants with hearing loss. One may deduce that a dichotic multiple frequency ASSR technique provides more accurate estimates of behavioural PT thresholds than a monotic single frequency ASSR system. The results of the study may well have been predicted by examining the response recording duration of each technique alone. A longer response recording time will yield ASSR thresholds closer to behavioural PT thresholds in individuals with normal hearing, as the small threshold response is only distinguishable from noise given sufficient recording time (Picton et al., 2003). The Biologic MASTER ASSR system allows for a response recording duration of up to 15 min (John et al., 1998), while the GSI Audera ASSR system allows for a maximum response recording duration of only 89 s (GSI, 2003). It is therefore logical to predict that ASSR thresholds obtained, using the Biologic MASTER system, would be found at a lower sensation level than with the GSI Audera. The rapid increase in ASSR amplitude above threshold in individuals with a sensorineural hearing loss, accounts for the conclusion by Luts and Wouters (2005) that the two ASSR systems were able to provide estimates of elevated behavioural PT threshold equally well. The rapid increase in amplitude above threshold makes ASSR threshold responses recognizably more rapidly and at a lower intensity level in individuals at sensorineural hearing loss than those without (Aoyagi et al., 1993; Lins et al., 1996; Perez-Abalo et al., 2001). Luts and Wouters (2005) state that response duration was a very important factor in explaining the results of their study. However, the GSI Audera and Biologic MASTER ASSR systems differed on many other parameters, namely number of frequencies simultaneously assessed, monotic or dichotic stimulus presentation, calibration method, modulation rate, response detection algorithm and electrode montage (GSI, 2003). The presence of these different variables in commercially available ASSR systems, makes the drawing of conclusions regarding superiority of a single frequency versus a multiple frequency ASSR system very difficult. The Luts and Wouters study (2005) focused on the different stimulus variables used by the two ASSR systems. Participant variables, however, also have a significant effect on the ASSR.

2.3.5 Effects of participant variables on ASSR

As with other AEP techniques, the ASSR is affected by various participant variables. In contrast to the effect of participant attention on SCAEP, studies by Alegre et al. (2008) and Linden, Picton, Hamel and Campbell (1987) found no significant effect of attention on 40 Hz ASSR response amplitude. In addition, Alegre et al. (2008) found no difference in intertrial coherence (using both a high and low modulation rate ASSR) between measurement with participants attending to the stimuli and when engaged in a reading task. The ASSR is, however, affected by participant state of consciousness, degree of hearing loss, maturation and age.

2.3.5.1 Effect of state of consciousness on ASSR

The ASSR modulation rate and the effect of an individual's state of consciousness are closely linked. The low modulation rate ASSR is affected by state of consciousness, while the high modulation rate ASSR is largely independent of state of consciousness (Cohen et al., 1991; Dobie & Wilson, 1998; Levi et al., 1993; Linden et al., 1985; Lins & Picton, 1995; Lins et al., 1995, 1996; Rickards et al., 1994; Aoyagi et al., 1993; Galambos et al., 1981; Linden et al., 1985). This is the result of the difference in neural generators between the high and low modulation rate ASSR. The low modulation rate ASSR is generated by the primary and secondary auditory cortices in addition to some brainstem activation, while the brainstem is the primary neural generator when a high modulation rate is utilized (Herdman et al., 2002; Galambos et al., 1981; Pantev et al., 1996; Reyes et al., 2004; Rickards et al., 1994). For a review of the effect of state of consciousness on the ASSR, the reader is referred to section 2.3.4.1, which discusses this, together with the effect of modulation rate on the ASSR. As is typical of any AEP technique, the degree of hearing loss affects the resulting amplitude and threshold intensity of the ASSR response.

2.3.5.2 Effect of degree of hearing loss on ASSR

Several authors have found that individuals with a hearing loss present with smaller difference scores between ASSR thresholds and behavioural thresholds than those with normal hearing (Aoyagi et al., 1993; Lins et al., 1996; Perez-Abalo et al., 2001; Rance et al., 1995). This phenomenon is likely to be related to recruitment (Lins et al., 1996). The physiological response increases in amplitude more steeply with increasing intensity when there is a hearing loss. This will make the ASSR responses for adults with a sensory hearing loss recognizably closer to threshold intensity.

Rance et al. (1995, 1998) found that the error of estimation of behavioural PT threshold is less with increasing degree of hearing loss. Rance et al. (2005) emphasized that ASSR testing cannot reliably differentiate between individuals with normal hearing and those with mildly elevated hearing thresholds. This is in line with the finding by Scherf, Brokx, Wuyts and Van de Heyning (2006) who found large variations in ASSR threshold estimation of behavioural PT hearing thresholds of less than 40 dBHL. Rance and

Rickards (2002) report lower correlations between ASSR thresholds and behavioural PT thresholds for infants and children with normal to mild hearing losses of 0.54 to 0.74, than for children with a greater degree of hearing loss. While the majority of studies present threshold data for a single group with a variety of degrees of hearing loss, the study by Swanepoel and Erasmus (2007) evaluated the ability of the dichotic multiple ASSR technique to estimate behavioural PT thresholds for a moderate degree of sensorineural hearing loss (n = 12). Swanepoel and Erasmus (2007) reported a strong correlation coefficient (r = 0.78) for behavioural PT thresholds of greater than or equal to 60 dBHL, but a poor correlation (r = 0.21) for thresholds of less than 55 dB. This prompted a caution from the authors when using ASSR for estimation of behavioural PT thresholds of less than 60 dBHL. Divergent results were, however, reported by Ahn, Lee, Kim, Yoon and Chung (2007). Using the same 80 Hz multiple frequency ASSR technique, but a considerably larger cohort of participants (n = 111), Ahn et al. (2007) report identical correlations between moderate and severe to profound degrees of hearing loss (r = 0.91). The study did, however, agree with previous findings that ASSR thresholds were less strongly correlated with normal behavioural PT thresholds (r = 0.62). The contrary findings in literature, with reference to the ability of the ASSR to estimate mild to moderate degrees of hearing loss, warrants further investigation.

The GSI Audera ASSR system makes use of regression formulae in order to generate an estimated behavioural PT audiogram based on single frequency ASSR thresholds (GSI, 2003). These regression formulae were proposed by Rance et al. (1995) in a study that aimed at examining the relationship between 80 Hz ASSR and behavioural PT thresholds in 60 sleeping adults and children (aged 10 months to 82 years). Standard deviations values between estimated behavioural PT thresholds generated from the ASSR thresholds and actual behavioural PT thresholds were calculated for each frequency and for three categories of hearing loss. The three categories of hearing loss were separated as follows: for behavioural PT thresholds of 0 to 55 dBHL; 60 to 85 dBHL; and 90 dBHL and greater. Rance et al. (1995) reported correlation coefficients of 0.97 for all frequencies, implying a very strong positive relationship between behavioural PT thresholds and ASSR thresholds. The strength of the relationship increased with increasing frequency and increasing degree of hearing loss, while the standard deviation of the error of estimation of behavioural PT thresholds from ASSR threshold decreased with increasing frequency and degree of hearing loss. Rance et al. (1995) included participants of various ages. The study concluded that the regression formulae were applicable to individuals of all ages as they found no significant age effect at any frequency.

Rance et al. (1995) regression formulae are used by the GSI Audera to ASSR thresholds generated using a 40 Hz modulation rate. Yet Rance et al. (1995) based the regression formula on the correlation between ASSR thresholds using a high modulation rate (viz. 90 Hz) and behavioural PT thresholds. The validity of the use of the Rance et al. (1995) regression formula for the estimation of behavioural PT thresholds from 40 Hz ASSR thresholds may therefore be questioned, especially when the neural generators of the high and low modulation ASSR techniques differ. Van Maanen and Stapells (2005) and Van der Reijden et al. (2006) both found ASSR thresholds closer to behavioural PT thresholds when using a 40 Hz rather than an 80 Hz multiple frequency ASSR technique. Although early studies compared single frequency 40 Hz and 80 Hz detectibility, and response amplitudes within subjects (eg. Cohen et al., 1991; Dobie & Wilson, 1998; Levi et al., 1993), to the author’s knowledge, there are no studies that compare behavioural PT thresholds estimated from ASSR thresholds at different modulation rates within the GSI Audera ASSR system.

Rance and Rickards (2002) tested the validity of the Rance et al. (1995) regression formulae to estimate behavioural PT thresholds, using infants of one to eight months of age with normal hearing and with varying degrees of hearing loss. Rance and Rickards (2002) found that the Rance et al. (1995) regression formulae can be applied to babies for the purpose of behavioural PT thresholds estimation, provided that the ASSR thresholds were 60 dB or greater. For infants with normal or near normal hearing, the Rance et al. (1995) formulae estimated behavioural PT thresholds which were 10 to 15 dB above their true behavioural PT thresholds. Given the weaker correlation between ASSR thresholds and behavioural PT thresholds for adults reported by Scherf et al. (2007) and Swanepoel and Erasumus (2007), one wonders whether the aforementioned finding of the Rance and Rickards (2002) study is related to degree of hearing loss, rather than to the population employed. Although it is postulated that degree of hearing loss may have a greater effect on ASSR thresholds than the effect of participant age, the effect of maturation and age on the ASSR warrants further discussion.

2.3.5.3 Effect of maturation and age on ASSR

As with other AEP, the ASSR is also affected by maturation and age. The amplitude of the infant ASSR decreases with increasing rate of stimulation, without the enhancement of the amplitude around 40 Hz, as is typical in adults (Levi et al., 1993). Due to the reduced ASSR amplitude, Levi et al. (1993) concluded that the 40 Hz ASSR cannot be reliably recorded in alert infants. In addition, as with adults, sleep further attenuates the 40 Hz ASSR response in infants (Aoyagi et al., 1993). Picton et al. (2003) hypothesized that the aforementioned studies indicate that the immature infant cortex is probably unable to process a sustained rhythmic response at rapid rates. The 40 Hz ASSR increases in amplitude with increasing age (Pethe et al., 2004). By 14 years of age, the 40 Hz response becomes similar in amplitude to ASSR responses recorded in adults (Aoyagi et al., 1994).

The study by Dobie and Wilson (1998) was the first to demonstrate the advantage of using a high modulation rate of greater than 60 Hz for sleeping infants. Cohen et al. (1991) and Rickards et al. (1994) supported this finding. Studies by both Lins et al. (1996) and Aoyagi et al. (1994) indicate that the amplitude of responses in infants, using a high modulation rate, was 50% of the amplitude in adults. Levi et al. (1993) demonstrated the largest phase coherence values for young infants using AM tones, regardless of carrier frequency, for 80 Hz ASSR. Aoyagi et al. (1994) came to the same conclusion when testing sedated children and infants of four years of age and younger.

Rance and Tomlin (2006) reported on a longitudinal study on 80 Hz ASSR changes for 20 full term neonates at the age of zero, two, four and eight weeks of age. The authors found that the mean ASSR threshold intensity decreased by approximately 10 dB between week zero and week six. Furthermore, at six weeks of age, Rance and Tomlin (2006) demonstrated that the ASSR thresholds in infants with normal hearing were still elevated and therefore not yet mature. Clinical use of the 80 Hz ASSR procedure for infants needs to take the developmental changes noted in the aforementioned study into account.

Clinical use of the ASSR is greatly facilitated by the objective response detection which is measured using various statistical methods (Picton et al., 2003). The objective nature of response determination makes ASSR attractive in a clinical setting.

2.3.6 ASSR response detection/analysis

Visual detection of AEP near threshold can be difficult for human observers. Problems with inter-evaluator and intra- evaluator reliability (Rose et al., 1971), and with evaluator bias have been documented (Gans et al., 1992). Dobie and Wilson (1995) found that experienced evaluators of ASSR responses did not perform better than inexperienced evaluators. Use of an objective response detection methods can control bias, perform with stable and known sensitivity, and can outperform human evaluators (Arnold, 1985; Champlin, 1992; Dobie & Wilson, 1995; Valdes-Sosa et al., 1987). The ASSR response can be objectively measured in either the time or frequency domain. In the time domain, a recording can be measured by selecting peaks and troughs, and calculating their amplitudes and latencies (Picton et al., 2003). However, noise can distort the peak measurements, and small changes in phase between harmonics can alter the peaks. ASSR are therefore generally measured in the frequency domain. Dobie (1993) states that, in general, time domain analysis is preferable for impulsive responses (temporally narrow, spectrally broad), whereas frequency-domain analysis is more appropriate for tonal responses (spectrally narrow, temporally broad).

A robust noise power estimate in the frequency domain requires a fast Fourier transform, which allows the response to be easily visible in the spectrum at the frequency of stimulation (Picton et al., 2003). To simplify this, subaverages are used instead of performing the fast Fourier transform on every sweep. For example, the grand average containing 2000 sweeps could be divided into 10 subaverages containing 200 sweeps each. The ratio of grand average power to averaged subaverage power is statistically equivalent to magnitude squared coherence (Picton et al., 2002). Phase coherence has also been used for objective response detection for ASSR (Dobie, 1993). This again involves the division of grand average response into multiple subaverages. The degree of dispersion of the phases is taken as a measure of dispersed or random versus a true clustered response. The most widely utilized monotic single frequency ASSR device, namely the GSI Audera, makes use of phase coherence to objectively detect an ASSR response (GSI, 2003). The dichotic multiple frequency Biologic MASTER ASSR device makes use of an F-ratio which compares the fast Fourier components at the stimulus modulation frequencies to the 120 adjacent frequencies (60 bins above and 60 bins below the frequency), to determine if the difference is significantly different ($P < 0.05$) from the background noise (John et al., 1998). Other statistics that are applied for frequency domain objective response detection include the Hotelling T^2 test, F-test, T^2 test and variants thereof (Dobie, 1993; Lins et al., 1996; Valdes et al., 1997).

Several authors have tried to determine whether one statistical method is preferable to another for objective response detection for ASSR. Picton, Vajsar, Rodrigués and Campbell (1987) found Hotelling T^2 to perform similarly to phase coherence in participants with normal hearing listening to 0.5 kHz tone bursts presented at 40 Hz modulation rate. Tucci, Wilson and Dobie (1990) compared visual detection by trained observers of ASSR responses to magnitude squared coherence. The use of the objective response detection was superior with thresholds 7 to 10 dB better than could be obtained with visual inspection. This finding was supported by a study by Champlin (1992), who also demonstrated magnitude squared coherence superiority over phase coherence and to an amplitude statistic based on comparing ASSR response amplitude to neighbouring frequency amplitudes. Magnitude squared coherence superiority over phase coherence was found to be so considerable by Dobie and Wilson (1992) that a two to four times longer data collection time is necessary to achieve an equivalent statistical power. The studies by Picton et al. (2001) and Cebulla et al. (2001) suggest a small but clear advantage for measurements combining amplitude and phase data. Valdes et al. (1997) compared coherence synchrony and a variant of the Hotelling T^2 method with more novel statistical indicators like circular T^2 and the F-test for hidden periodicity. Valdes et al. (1997) found no significant differences in their capability to predict behavioural PT thresholds. In contrast, a comparison of the F-test and the T^2 by Lins et al. (1996) found the F-test to be more effective. Picton et al. (2003) support this finding by stating that the F-test has certain advantages over tests based on repeated measurements of the response (like phase coherence). Firstly, the number of adjacent frequency bins, to which the signal response is compared, can be increased beyond the number of separate measurements made. Secondly, the technique can be adapted to omit certain frequency bins to eliminate line noise or responses by other frequencies during multiple stimuli ASSR. There is, therefore, no consensus on the best statistical method for objective ASSR response detection. Several studies have, however, suggested that other statistical methods of objective response detection may be superior to phase coherence, the method utilized by the GSI Audera ASSR software. Exploration of the accuracy of the phase coherence objective response detection method used by the GSI Audera ASSR, the system employed in the current study, was, however, beyond the scope of the study. Rather, clinical use of the ASSR technique versus the SCAEP technique using the GSI Audera was assessed with relevance to the accuracy of behavioural PT threshold estimation and the time efficiency. The clinical applications of the ASSR procedure, in addition to behavioural PT threshold estimation, are elaborated on below.

2.3.7 Clinical use of ASSR

Galambos et al. (1981) were the first to estimate behavioural PT hearing thresholds using ASSR at modulation rates near 40 Hz. This study and several subsequent studies made use of tone burst stimuli and, for the majority, relied on visual response detection (Chambers & Meyer, 1993; Dauman et al., 1984; Kankkunen & Rosenhall, 1985; Klein, 1983; Lynn et al., 1984; Milford & Birchall, 1989; Rodrigués et al., 1986; Sammeth & Barry, 1985; Stapells, Makeig, & Galambos, 1987; Szyfter, Dauman & De Sauvage, 1984). Table 2.2 presents, in chronological order, the behavioural PT threshold estimation data for 40 Hz ASSR studies on adults that made use of continuous AM or AM/FM stimuli. Although certain of the studies listed included children as participants, studies with children and infants only as participants were omitted from the summary.

TABLE 2.2 40 Hz ASSR studies reporting differences between ASSR thresholds and behavioural PT thresholds (difference score in dBnHL = ASSR threshold minus behavioural PT threshold), correlation scores and participant numbers

Study	ASSR stimulus technique	500 Hz			1000 Hz			2000 Hz			4000 Hz		
		diff	r	n	diff	r	n	diff	r	n	diff	r	n
Aoyagi et al. (1993)	SF	11 ± 10 8 ± 7	-	15 N 18 HL	11 ± 11 9 ± 6	-	15 N 18 HL	13 ± 10 13 ± 8	-	15 N 18 HL	18 ± 12 12 ± 6		15 N 18 HL
De Koker (2004) * *40 + 80 Hz single frequency*	SF	8	-	23 HL	6	-	23 HL	-	-	-	-	-	-
Van Maanen & Stapells (2005)	MF	14 ± 7	0.70	23 N+HL	11 ± 6	0.92	23 N+HL	12 ± 14	0.73	23 N+HL	0 ± 9	0.93	23 N+HL
Scherf et al. (2006)	SF	-	0.86	63 N+HL	-	0.91	62 N+HL	-	0.83	60 N+HL	-	0.82	59 N+HL
Tomlin et al. (2006)	SF	17 ± 10 11 ± 9	0.84	36 N 30 HL	-	-	-	-	-	-	42 ± 14 24 ± 8	0.85	36 N 30 HL
Van der Reijden et al. (2006)	MF	10 ± 0	-	11 N	-	-	-	10 ± 0	-	11 N	-	-	-
Yeung & Wong (2007)	SF	11 ± 10	0.96 (r^2)	34 N+HL	14 ± 10	0.97 (r^2)	34 N+HL	12 ± 10	0.97 (r^2)	34 N+HL	4 ± 12	0.95 (r^2)	34 N+HL
Average		**11.7 ± 2.9**	**-**	**-**	**11.3 ± 2.1**	**-**	**-**	**12.0 ± 1.2**	**-**	**-**	**16.7 ± 5.2**	**-**	**-**

(diff = difference score; r = correlation; n = number of participants; SF = single frequency ASSR technique; MF = multiple frequency ASSR technique; N = participants with normal hearing; HL = participants with hearing loss; * = 28 of 41 participants tested with 40 Hz ASSR*)*

Table 2.2 displays the calculation of the mean difference between ASSR thresholds and behavioural PT thresholds for 40 Hz ASSR studies, using AM or AM/FM stimuli, indicating difference scores of 11.7, 11.3, 12 and 16.7 dB at 0.5, 1, 2 and 4 kHz respectively. The mean discrepancy between ASSR threshold and behavioural PT threshold is greatest at 4 kHz. Picton et al. (1998) are of the opinion that the elevated ASSR thresholds at 4 kHz can be attributed to abnormally broad tuning curves of the auditory neurons in individuals with hearing loss (Picton et al., 1998).

The data reported by De Koker (2004) reported on single frequency ASSR using a low modulation rate for 28 participants and a high modulation rate for 13 of the participants. The data was reported in Table 2.2 as the majority of the participants were evaluated using the 40 Hz modulation rate ASSR technique.

Use of the high modulation rate for behavioural PT threshold estimation was first explored by Aoyagi et al. (1994). The bulk of the literature which followed focused on behavioural PT threshold estimation in infants and children due to the independence of the technique on the individual’s attention and state of consciousness. Lins and Picton (1995) were the first to describe the possibility of using multiple frequency stimuli presented in both ears simultaneously. Table 2.3 provides a review of high modulation rate ASSR studies on behavioural PT threshold estimation in adult participants (the majority of which used the multiple frequency ASSR technique). The studies are listed in chronological order and studies using children only as participants were again excluded.

TABLE 2.3 80 Hz ASSR studies reporting differences between ASSR thresholds and behavioural PT thresholds (difference score in dBnHL = ASSR threshold minus behavioural PT threshold), correlation scores and participant numbers

Study	ASSR stimulus technique	500 Hz			1000 Hz			2000 Hz			4000 Hz		
		diff	r	n	diff	r	n	diff	r	n	diff	r	n
Aoyagi et al. (1994)	SF	34 ± 15	-	20 N	29 ± 14	-	20 N	30 ± 15	-	20 N	9 ± 14	-	20 N
Lins et al. (1995)	MF	-	-		16 ± 8	-	8 N	-	-	-	-	-	-
*Rance et al. (1995)**	SF	20 ± 7	0.97	60 N+HL	13 ± 6	0.98	60 N+HL	16 ± 5	0.99	60 N+HL	10 ± 4	0.99	60 N+HL
Lins et al. (1996)	MF	14 ± 11	-	56 N	12 ± 11	-	56 N	11 ± 8	-	56 N	13 ± 11	-	56 N
Picton et al. (1998)	MF	21 ± 9	-	10 N	26 ± 13	-	10 N	18 ± 13	-	10 N	20 ± 10	-	10 N
Herdman & Stapells (2001)	MF	14 ± 10	-	10 N	8 ± 7	-	10 N	8 ± 9	-	10 N	15 ± 9	-	10 N
Perez-Abalo et al. (2001)	MF	12 ± 11	-	40 N	13 ± 9	-	40 N	10 ± 10	-	40 N	13 ± 10	-	40 N
Dimitrijevic et al. (2002)	MF	14 ± 11	0.85	45 N+HL	5 ± 9	0.94	45 N+HL	5 ± 9	0.95	45 N+HL	9 ± 10	0.95	45 N+HL
Herdman & Stapells (2003)	MF	14 ± 13	0.75	26 HL	8 ± 9	0.89	29 HL	10 ± 10	0.88	27 HL	3 ± 10	0.85	28 HL
Hsu et al. (2003)	SF	18 ± 4	0.86	11 HL	19 ± 3	0.92	11 HL	17 ± 3	0.94	11 HL	12 ± 5	0.95	11 HL
De Koker (2004)	MF	14	-	23 HL	9	-	23 HL		-	-	-	-	-
*Johnson & Brown (2005)**	MF	-	0.87	10 N+HL	19 13.5	-	14 N 20 HL	14 5.5	0.98	14 N 20 HL	-	0.95	10 N+HL

*(diff = difference score; r = correlation; n = number of participants; SF = single frequency ASSR technique; MF = multiple frequency ASSR technique; N = participants with normal hearings; HL = participants with hearing loss; SH = simulated hearing loss; * = includes data from both adults and children; # = included data from both adults and children over 12 years of age*

Study	ASSR stimulus technique	500 Hz			1000 Hz			2000 Hz			4000 Hz		
		diff	**r**	**n**	**diff**	**r**	**n**	**diff**	**r**	**n**	**diff**	**r**	**n**
Luts & Wouters (2005) ***40+80 Hz single frequency***	SF	48 ± 21 20 ± 8	0.54	10 N 10 HL	40 ± 21 14 ± 7	0.72	10 N 10 HL	33 ± 10 13 ± 7	0.92	10 N 10 HL	30 ± 20 14 ± 13	0.85	10 N 10 HL
Luts & Wouters (2005) ***Dichotic multiple frequency***	MF	24 ± 11 17 ± 12	0.83	10 N 10 HL	17 ± 9 12 ± 8	0.95	10 N 10 HL	14 ± 7 17 ± 8	0.97	10 N 10 HL	21 ± 11 19 ± 12	0.93	10 N 10 HL
Picton, Dimitrijevic, Perez-Abalo & Van Roon (2005)	MF	21 ± 8 11 ± 18	-	10 N 10 HL	7 ± 8 -4 ± 9	-	10 N 10 HL	10 ± 6 3 ± 11	-	10 N 10 HL	13 ± 7 5 ± 12	-	10 N 10 HL
Schmulian, Swanepoel & Hugo (2005)[#]	MF	14 ± 16	0.88	25 HL	18 ± 18	0.84	25 HL	15 ± 13	0.91	25 HL	14 ± 15	0.86	25 HL
Van Maanen & Stapells (2005)	MF	17 ± 11	0.65	23 N+HL	15 ± 7	0.91	23 N+HL	19 ± 9	0.90	23 N+HL	4 ± 10	0.87	23 N+HL
Attias, Buller, Rubel & Raveh (2006)*	MF	13 ± 13 2 ± 12	0.86	18 N 29 HL	10 ± 8 0 ± 7	0.93	18 N 29 HL	3 ± 7 0 ± 10	0.94	18 N 29 HL	3 ± 7 -2 ± 8	0.93	18 N 29 HL
Kaf, Durrant et al. (2006)	MF	17 ± 12 17 ± 10	0.53	16 N 16 SH	13 ± 8 9 ± 8	0.75	16 N 16 SH	10 ± 5 3 ± 5	0.93	16 N 16 SH	12 ± 8 6 ± 10	0.75	16 N 16 SH
Van der Reijden et al. (2006)	MF	18 ± 10	-	11 N	-	-	-	12 ± 4	-	11 N	-	-	-
Ahn et al. (2007)	MF	-	0.94	111 N+HL	-	0.95	111 N+HL	-	0.94	111 N+HL	-	0.92	111 N+HL
Swanepoel & Erasmus (2007)	MF	8 ± 10	-	7 HL	2 ± 7	-	7 HL	5 ± 8	-	7 HL	5 ± 8	-	7 HL
D'haenens et al. (2008)	MF	19 ± 11	-	29 N	13 ± 10	-	29 N	10 ± 9	-	29 N	13 ± 10	-	29 N
Average	MF	**17.9 ± 9.3**	**-**	**-**	**14.3 ± 9.1**	**-**	**-**	**12.8 ± 8.2**	**-**	**-**	**11.5 ± 7.5**	**-**	**-**

*(diff = difference score; r = correlation; n = number; SF = single frequency ASSR technique; MF = multiple frequency ASSR technique; N = participants with normal hearings; HL = participants with hearing loss; SH = simulated hearing loss; * = includes data from both adults and children; # = included data from both adults and children over 12 years of age)*

The data displayed in Table 2.3 of the study by Luts and Wouters (2005) requires further clarification. The study compared behavioural PT threshold estimation, using a monotic single stimulus ASSR technique, with that of a dichotic multiple frequency ASSR technique. An adaptive protocol was utilized for the single stimulus ASSR assessment, whereby a high modulation rate was used unless excessive noise was measured. Nine out of the 20 participants were tested using a low, 40 Hz modulation rate. The data was presented in Table 2.3 because the majority of the sleeping participants were therefore evaluated, using a high modulation rate during assessment with the single frequency ASSR technique. The study by Luts and Wouters (2005) is listed a second time immediately below the first citation. This represents the results for the assessment with the dichotic multiple ASSR method using a high modulation rate only.

A review of studies of behavioural PT threshold estimation using 80 Hz modulation rate ASSR, as presented in Table 2.3, indicates a mean difference between ASSR threshold and behavioural PT threshold of 16.5, 13.3, 12.5 and 11.4 dB at 0.5, 1, 2 and 4 kHz respectively. Similar to the 40 Hz ASSR studies, the majority of studies found 80 Hz ASSR thresholds within 15 dB of behavioural PT thresholds. In contrast to the mean data presented for 40 Hz ASSR studies in Table 2.2, where the largest mean difference score was measured at 4 kHz, the largest mean difference between ASSR threshold and behavioural PT threshold for 80 Hz ASSR studies was measured at 0.5 kHz. In addition, mean ASSR thresholds at 0.5 kHz were closer to behavioural PT thresholds for the 40 Hz ASSR studies than for the 80 Hz ASSR studies, but 4 kHz ASSR thresholds were closer to behavioural PT thresholds for the 80 Hz studies than for the 40 Hz studies. This observation was supported by Cone-Wesson, Dowell et al. (2002) who compared thresholds in sleeping adults for tone burst ABR to single frequency ASSR at different modulation rates. The mean ASSR threshold at 0.5 kHz for the low modulation rate ASSR was closer to the behavioural PT threshold (viz. 23 dB sensation level), than that for 74 Hz modulation rate (viz. 40 dB sensation level). This finding was reversed at 4 kHz where the threshold for the high modulation rate was better (lower) than when using the low modulation rate ASSR techniques (viz. 16 and 33 dB sensation level ASSR thresholds for the high and low modulation rate ASSR techniques respectively). The majority of the 80 Hz studies listed in Table 2.3, used multiple frequency stimuli presented simultaneously, with the exception of only four out of the 20 studies, which presented stimuli individually, namely Aoyagi et al. (1994), Rance et al. (1995), Hsu et al. (2003), Luts and Wouters (2005; marked '40 Hz + 80 Hz single frequency'). Picton et al. (1998) demonstrated a masking effect of the lower frequency stimuli when simultaneously presenting high frequency stimuli, as was done in the majority of the studies in Table 2.3. This explains the elevated ASSSR threshold at 0.5 kHz compared to thresholds at the mid and high frequencies with use of the 80 Hz dichotic multiple frequency ASSR technique.

Several authors have found that individuals with a hearing loss demonstrate less of a difference between ASSR thresholds and behavioural PT thresholds than in individuals with normal hearing (Aoyagi et al., 1993; Attias et al., 2006; Hsu et al., 2003; Kaf, Durrant et al., 2006; Lins et al., 1996; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Picton et al., 2005; Rance & Rickards, 2002; Rance et al., 1995, 2005; Swanepoel & Erasmus, 2007; Tomlin et al., 2006). This phenomenon is attributed to recruitment (Lins et al., 1996). Hsu et al. (2003) remarked that the strength of the relationship between ASSR threshold and behavioural PT threshold increased with increasing frequency and increasing degree of hearing loss. One can therefore conclude that the ASSR method provides good estimates of degree and configuration of sensorineural hearing loss in adults.

When the results of the research using a high modulation rate, as presented in Table 2.3, are compared to the research using a low modulation rate presented in Table 2.2, it is evident that the large majority of the difference scores between 80 Hz ASSR thresholds and behavioural PT thresholds at each frequency (for both participants with normal hearing and with hearing loss) were smaller than the difference between the 40 Hz ASSR thresholds and behavioural PT thresholds. Not only did the studies in Table 2.3 use a high modulation rate ASSR technique but the majority (viz. Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Hsu et al., 2003; Kaf, Durrant et al., 2006; Lins et al., 1995, 1996; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Picton et al., 1998; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van der Reijden et al., 2006; Van Maanen & Stapells, 2005), with the exception of Aoyagi et al. (1994), Hsu et al. (2003), and Rance et al. (1995), used a specific dichotic multiple frequency ASSR system, namely the Biologic MASTER ASSR system. The Biologic MASTER system allows for a single ASSR to be recorded for up to 15 min or 900 s in order to improve the signal to noise ratio of recordings (John et al., 1998). This is in comparison with the monotic single frequency GSI Audera ASSR system, which allows a maximum recording duration of 89 s (GSI, 2003). The GSI Audera does not allow lengthening of data collection time, irrespective of noise levels. A single recording can only be repeated in the event of high noise levels. Recording duration is a key factor in determination of accuracy of an ASSR technique (Picton et al., 2005). ASSR responses need to be distinguished from noise, as threshold identification is made with reference to the noise level at which a response is judged to be absent. The accuracy hereof will vary with the size of the response, the amount of electrical noise in the recording, and, importantly, the time taken to reduce this noise by averaging or increasing the sweep of the FFT analysis (Picton et al., 2003). The long recording duration offered by the Biologic MASTER ASSR system is therefore an advantage.

The opinion of Picton et al. (2005) that the duration of a single response recording is a major factor in ASSR threshold determination, was supported by Luts and Wouters (2004, 2005). Luts and Wouters (2004, 2005) found that increasing the stimulus duration resulted in a decrease in difference between ASSR threshold and behavioural PT threshold, and a decrease in standard deviations. These statements obtained further verification from the research done by Attias et al. (2006) on sleeping adults with normal hearing and with hearing loss, using the Biologic MASTER ASSR system. Attias et al. (2006) reported using a response recording duration of up to 17 min, longer than is typically reported. The long recording duration is likely the reason why Attias et al. (2006) measured the smallest difference between ASSR threshold and behavioural PT threshold of the studies listed in Table 2.3 (mean difference score for both participants with normal hearing and with hearing loss = 3.6 dB).

The difference scores between ASSR threshold and behavioural PT threshold for 80 Hz single frequency ASSR studies (viz. for Aoyagi et al., 1994; Rance et al., 1995; Hsu et al., 2003), were larger than was reported for the majority of research using 80 Hz dichotic multiple frequency ASSR (Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Kaf, Durrant et al., 2006; Lins et al., 1996; Perez-Abalo et al., 2001; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van der Reijden et al., 2006; Van Maanen & Stapells, 2005). One may therefore conclude that the application of the multiple stimulus technique resulted in improved proximity of ASSR thresholds to behavioural PT thresholds when compared to a single stimulus ASSR technique. The dichotic multiple stimulus ASSR technique used in these studies, namely the Biologic MASTER ASSR system, makes use of a significantly longer recording duration (maximum of 15 min; John et al., 1998) in comparison to that of the monotic single stimulus ASSR methods, the recording durations of the latter varying between 51 and 300 s. The longer recording duration offered by the Biologic MASTER is likely to be the cause of the closer proximity of the ASSR threshold to behavioural PT thresholds therefore rather than the stimulus presentation condition. By the same token, the similarities between proximity of 40 and 80 Hz monotic single frequency ASSR thresholds to behavioural PT thresholds is liable to be due to similar recording durations, rather than due to the method of presentation of stimuli. There is a consensus of results in literature indicating that ASSR thresholds generated by both the single frequency ASSR technique (Aoyagi et al., 1994, 1999; Hsu et al., 2003; Rance et al., 1995, 1998; Rance & Briggs, 2002) and the multiple frequency ASSR technique (Dimitrijevic et al., 2002; Herdman & Stapells, 2001; Lins et al., 1995; Luts & Wouters, 2004; Perez-Abalo et al., 2001) are highly correlated with behavioural PT thresholds.

Luts and Wouters (2005) examined the use of a single versus a multiple stimuli ASSR system. Luts and Wouters (2005) compared the ability of a commercially available monotic single stimulus ASSR system (viz. GSI Audera) with that of a commercially available dichotic multiple frequency ASSR system (viz. Biologic MASTER) to estimate behavioural PT thresholds in adults. Luts and Wouters (2005) attempted to render the two ASSR systems comparable with respect to the considerable difference in duration of a single recording. This was done by measuring the total time taken to acquire four ASSR thresholds, using recordings of a maximum of 16, 24, 32 and 48 sweeps with the Biologic MASTER system, and using a short and long test protocol with the GSI Audera. A short test protocol was defined as a single low noise recording per frequency and stimulus level. A long test protocol involved repetitions of recordings below the threshold ASSR response. In the event of a statistically significant response on repetition of a recording, the intensity level was decreased until a new threshold ASSR response was defined. The total test time of the 24 sweep Biologic MASTER protocol and the short test protocol of the GSI Audera were most similar. ASSR thresholds using the aforementioned test protocols were therefore compared. Despite this, it is the opinion of the author of the present research that, due to the longer recording duration of a single recording allowed by the Biologic MASTER ASSR system, noise levels of the 24 sweep Biologic MASTER protocol would still be lower than with the short GSI Audera ASSR protocol. The effect of the longer response recording duration offered by the Biologic MASTER ASSR system, was evident when comparing the difference between behavioural PT thresholds and ASSR thresholds obtained by the two ASSR systems. Similar difference scores between ASSR threshold and behavioural PT threshold were reported by the two systems with the participants with hearing loss. The effect of recruitment for individuals with a sensory hearing loss, means that ASSR thresholds in close proximity to behavioural PT thresholds can be obtained in a relatively short time (Picton et al., 2003). The Biologic MASTER, however, yielded ASSR thresholds closer to behavioural PT thresholds for the participants with normal hearing, and consequently, with the participants with normal hearing and with hearing loss grouped together. With adults with a mild hearing loss or with normal hearing, Picton et al. (2003) state it was often necessary to lengthen recording times to 10 min or more in order to recognize the small responses at threshold intensity. By performing statistical comparisons within each ASSR system, Luts and Wouters (2005) found that prolongation of the recording duration improved the correlation between ASSR threshold and behavioural PT thresholds in both the single and multiple frequency technique.

Luts and Wouters (2005) made use of an alternative test protocol when testing with the GSI Audera in the event of excessive noise levels. ASSR assessment of sleeping adults began using a high modulation rate for both the dichotic multiple frequency ASSR technique, and for the monotic single frequency ASSR technique. Luts and Wouters (2005), however, found that many participants with hearing loss could not be assessed using the 80 Hz protocol of the GSI Audera, due to excessive noise levels, despite the fact that participants were asleep. This then necessitated a change to the 40 Hz modulation rate for a total of nine out of 20 sleeping participants. The disparity in modulation rates complicated the interpretation of the results, as modulation rate influences the cerebral generator activated (Herdman et al., 2002), the size of ASSR response and the effect of sleep or drowsiness (Cohen et al., 1991). Furthermore, the differences in both ASSR recording duration and modulation rate used by the two ASSR systems, made it difficult to draw conclusions on the comparative accuracy (proximity of ASSR thresholds to behavioural PT thresholds and the consistency of this relationship) of single versus multiple ASSR techniques.

The data in Table 2.3 presents the findings for studies that used adult participants. As high modulation rate ASSR are, however, only minimally affected by sleep, they have the advantage over the slower modulation rate ASSR in that they can be recorded in infants (Cohen et al., 1991; Dobie & Wilson, 1998; Lins & Picton, 1995; Lins et al., 1996; Rickards et al., 1994). Various studies have demonstrated the ability of ASSR to predict behavioural PT hearing thresholds in infants and children as ASSR thresholds were found to be highly correlated with behavioural PT thresholds (including Aoyagi et al., 1993, 1996, 1999; Cone-Wesson, Parker, Swiderski, & Rickards, 2002; Cone-Wesson, Rickards et al., 2002; Lins et al., 1996; Picton et al., 1998; Rance & Tomlin, 2006; Rance et al., 1995, 1998, 2005; Rance & Rickards, 2002; Rickards et al., 1994; Sininger & Cone-Wesson, 2002; Stroebel, Swanepoel, & Groenewald, 2007; Swanepoel & Steyn, 2005).

When a decision must be made on whether an infant or child is a candidate for cochlear implantation, the ASSR allows for the assessment of these individuals with minimal amounts of residual hearing and, consequently, absent click and tone burst ABR (Attias et al., 2006; Ménard et al., 2004; Rance et al., 1993, 1995, 1998; Stueve & O'Rouke, 2003; Swanepoel, Hugo et al., 2004). Assessment with high intensity levels (up to 120 dBHL) is possible due to the continuous nature of the ASSR stimuli and hence the absence of calibration corrections to account for temporal summation differences between short and long duration signals associated with transient stimuli such as tone bursts and clicks (Rance et al., 1998, 2005).

In addition to behavioural PT threshold estimation for adults, children and individuals with profound hearing loss, ASSR can also be used as an objective evaluation of aided behavioural PT thresholds. This is achieved by presenting single or multiple frequency stimuli through a soundfield speaker (Picton et al., 1998; Stroebel et al., 2007). The continuous nature of the ASSR stimuli means that stimuli are more stable over time than brief transients and they can therefore be more reliably transferred through free field speakers and hearing aids (Picton et al., 2002). There is also less distortion from the amplifiers, as there are no abrupt changes over time (Lins et al., 1996). The studies undertaken by Picton et al. (1998) and Stroebel et al. (2007) indicated moderate to strong correlations of aided threshold with aided behavioural thresholds in infants and children (r = 0.55 to 0.81). Yang, Chen and Hwang (2008) were also able to demonstrate that the ASSR was able to accurately predict aided behavioural PT hearing thresholds in children with cochlear implants, using the regression formulae proposed by Rance and Rickards (2002).

Although the objective response detection of the ASSR facilitates clinically aided and unaided behavioural PT threshold estimation, objective response detection also means that ASSR testing cannot differentiate between peripheral hearing losses and those related to neural transmission or retrocochlear abnormalities (Rance et al., 2005; Rance & Briggs, 2002). The statistical response detection method may not recognize a response that occurs at a delayed latency, or that presents with abnormal waveform morphology. Any attempt to estimate behavioural PT hearing levels on the basis of ASSR results, is based on the assumption that the individual's auditory pathway is normal. ASSR thresholds obtained from an individual with neurological abnormalities cannot therefore be used to estimate behavioural PT hearing thresholds (Rance et al., 2005).

The ASSR is capable of providing information on not only behavioural PT hearing thresholds, but also on auditory processing at suprathresholds levels. Dimitrijevic, John, Van Roon and Picton (2001) investigated, using the ASSR to evaluate the ability of the auditory system to process differences in frequency and intensity at supra-threshold intensities. This was done by determining the ability to detect an AM tone and an FM tone. The study confirmed that the ability to detect these stimuli relates well to the ability of the adult participant to discriminate words. This application is useful in the clinical investigation of the participant's ability to understand speech, in the selection and monitoring of hearing aids and in studying disorders of auditory perception (Dimitrijevic et al., 2001).

The ASSR not only provides information about auditory function, but the 40 Hz ASSR also provides a reliable marker of anesthetic-induced unconsciousness (Gilron, Plourde, Marcantoni, & Varin, 1998; Plourde, 2008; Plourde & Boylan, 1991). This is possible as the 40 Hz ASSR arises from cortical and subcortical generators. The absence of the ASSR is therefore indicative of the depth of unconsiousness induced by the anaesthetic agents.

The ASSR can therefore be used for behavioural PT threshold estimation in adults and children with varying degrees of hearing loss, for objective assessment of benefit from amplification, for assessing auditory processing skills and is useful as a measure of level of consciousness. The current study is concerned with one particular clinical use of the ASSR for a specific population though. The current study aims to evaluate the clinical effectiveness and efficiency of the ASSR to estimate behavioural PT thresholds in adults exposed to occupational noise.

2.3.8 Use of ASSR for behavioural PT threshold estimation in adults exposed to occupational noise

Several characteristics of the ASSR suggest that this AEP may also be applicable for clinical use for behavioural PT threshold estimation in adults exposed to occupational noise and at risk for noise induced hearing loss. The accuracy of behavioural PT threshold estimation, potentially better frequency specificity of continuous rather than transient tonal stimuli, independence of participant attention or state of arousal, and ability to obtain higher output levels, all suggest that ASSR may be an appropriate tool for behavioural PT threshold estimation in the population in question (Vander Werff et al., 2002). In addition, the objective nature of response determination makes ASSR attractive in a clinical setting. There are five studies that have investigated the use of ASSR for this purpose (De Koker, 2004; Herdman & Stapells, 2003; Hyde et al., 1986; Hsu et al., 2003; Van Maanen & Stapells, 2005).

The earliest of these studies, namely that of Hyde et al. (1986), made use of 40 Hz ASSR in cases when an excessively rhythmic EEG was measured during SCAEP evaluation (in 21 out of 1168 individuals claiming compensation for occupational noise induced hearing loss). Although no ASSR threshold data was presented by Hyde et al. (1986) the authors remarked that further validation of the technique was required, especially for sloping audiograms.

Herdman and Stapells (2003) assessed 23 individuals claiming compensation for occupational hearing loss. Participants were divided into two groups, the first presenting with a steeply sloping hearing loss defined as a fall in behavioural PT thresholds of greater than or equal to 30 dB per octave and the second group presenting with a change in behavioural PT thresholds of less than 30 dB. A monotic multiple frequency ASSR protocol was used with high modulation rates. In addition, a frequency of interest was also presented individually at one frequency for certain participants. Participants slept or relaxed during the ASSR assessment. Results indicated that behavioural PT thresholds and multiple ASSR thresholds were significantly correlated (r = 0.75 to 0.89). ASSR thresholds were measured within 3 to 14 dB of the behavioural PT threshold. Herdman and Stapells (2003) therefore concluded that the multiple frequency ASSR protocol using a high modulation frequency was able to accurately estimate the degree and configuration of hearing loss, including steeply sloping hearing losses, as is typical of individuals with a noise induced hearing loss. Frequency specificity of the multiple ASSR method was confirmed, as high frequency behavioural PT thresholds were not underestimated, even with steeply sloping hearing losses. In addition, the results of the study indicated that the difference between ASSR thresholds measured at individual frequencies and those measured using a multiple frequency protocol were neither statistically nor clinically significant. Herdman and Stapells (2003) also recorded the mean time required to acquire ASSR thresholds at four frequencies in one ear, namely 47 min. The strict noise criterion employed in the study contributed to the longer test time than was reported by Perez-Abalo et al. (2001) who spent 21 min on average in order to obtain a four frequency ASSR estimation in each ear. Herdman and Stapells (2003) postulated that dichotic testing would only minimally increase test time if the hearing sensitivity in each ear was symmetrical.

Hsu et al. (2003) were able to confirm, as did Herdman and Stapells (2003), that the high modulation rate ASSR technique was able to accurately provide an estimate of behavioural PT thresholds in adults with a noise induced sensorineural hearing loss. Whereas Herdman and Stapells (2003) used the Biologic MASTER ASSR system and a multiple frequency protocol for the majority of the ASSR thresholds measured, Hsu et al. (2003) made use of the ERA ASSR system, a single frequency ASSR system and the predecessor of GSI Audera ASSR system. The 11 participants presented with a noise induced hearing loss and were evaluated while relaxed but not sedated. The authors did not specify whether certain participants slept during the evaluation. The results indicated a strong correlation between ASSR threshold and behavioural PT thresholds at 0.5, 1, 2, and 4 kHz, ranging from 0.86 to 0.95. The correlation increased with increasing frequency and increasing degree of hearing loss.

In contrast to the high modulation rate, ASSR technique used by Herdman and Stapells (2003), Hsu et al. (2003) and De Koker (2004) evaluated the use of the ASSR technique using various protocols in a population of South African adult mineworkers with noise induced hearing loss. De Koker (2004) compared single and multiple frequency ASSR techniques, high and low modulation ASSR techniques, and the accuracy and time efficiency of ASSR with participants who received sedation, versus participants who did not receive sedation. De Koker (2004) reported mean ASSR thresholds (using both single and multiple frequency ASSR techniques, as well as high and low modulation rates) within 10 dB of behavioural PT thresholds, indicative of the accuracy offered by ASSR for the purpose of estimating behavioural PT thresholds in adults with noise induced hearing loss. Difference scores between ASSR thresholds and behavioural PT thresholds were statistically greater with the dichotic multiple frequency ASSR technique (high modulation frequency), than for the monotic single frequency technique (high and low modulation frequency) at 0.5 kHz. This is in contrast with existing literature using the Biologic MASTER ASSR system, as was used by De Koker (2004). Previous research typically reports multiple frequency ASSR thresholds closer behavioural PT thresholds than single frequency ASSR thresholds, as demonstrated by Tables 2.2 and 2.3 and reported by Luts and Wouters (2005). Luts and Wouters (2005) also compared the Biologic MASTER ASSR system using a high modulation rate and the GSI Audera ASSR system using both a high and low modulation rate. Difference scores between ASSR thresholds and behavioural PT thresholds were smaller when evaluating using the Biologic MASTER ASSR system, presumably due to the longer recording duration offered, compared to the GSI Audera ASSR (the single frequency ASSR system used by De Koker, 2004). The use by De Koker (2004) of both high and low modulation rates, and different participant states of attention for the single frequency ASSR data, does complicate the interpretation of the results. Existing literature does report 40 Hz ASSR thresholds closer to 0.5 kHz behavioural PT thresholds than 80 Hz ASSR thresholds (Cone-Wesson, Dowell et al., 2002; Van Maanen & Stapells, 2005). Although De Koker

(2004) used both high and low modulation rates for the single frequency ASSR technique, the majority of participants (28 out of 41 participants) were evaluated using a low modulation rate. The modulation rate, rather than the ASSR stimulus presentation method (i.e. single or multiple frequency technique), is therefore likely to be the reason why the single frequency ASSR thresholds were on average closer to behavioural PT thresholds than the multiple frequency ASSR thresholds were.

Of note was the finding by De Koker (2004) that sedation did not improve the accuracy of behavioural PT threshold estimation, nor did it improve the time efficiency. The single frequency ASSR technique was, however, more time efficient than the dichotic multiple frequency ASSR technique. The steeply sloping audiometric configuration of the participants, as is typical of individuals with noise induced hearing loss, meant that a uniform intensity protocol could not be set for 0.5 to 4 kHz. Testing of 0.5 kHz was done separately, lengthening the test time.

De Koker (2004) also tested a group of 29 adults who presented with a nonorganic hearing loss. De Koker (2004) was able to make use of ASSR to provide an estimation of true behavioural PT thresholds on all but one individual, due to excessive noise levels. The costing exercise completed by De Koker (2004) demonstrated considerable cost savings by using ASSR in order to estimate behavioural PT thresholds for individuals employed by a mine and suspected of presenting with a non organic hearing loss. Despite the cost of the ASSR system and time required to complete the assessment, costs relating to overcompensation, repeated behavioural PT audiometry and loss of production time were reduced.

Van Maanen and Stapells (2005) made use of the ASSR to evaluate individuals who were in the process of claiming compensation for occupational hearing loss, the majority of which were likely to have been exposed to occupational noise and to present with a noise induced hearing loss. Van Maanen and Stapells (2005) was the first of only two studies the researcher is aware of that used a 40 Hz dichotic multiple frequency ASSR technique for the purpose of behavioural PT threshold estimation in adults (the second being Van der Reijden et al., 2006). Van Maanen and Stapells (2005) investigated the accuracy and the time required for the multiple frequency ASSR for behavioural PT threshold estimation in adults with normal hearing and with hearing loss, using ASSR with 80 and 40 Hz modulation rates and compared these to the SCAEP. Forty-six males participated in the study. All the participants bar one underwent SCAEP testing, while half were tested using the 40 Hz ASSR technique and half were evaluated using the 80 Hz ASSR technique. Van Maanen and Stapells (2005) indicated that the 40 Hz multiple ASSR provided an estimation of behavioural PT thresholds, which was significantly better than the 80 Hz multiple frequency ASSR and the SCAEP (based on proximity of AEP threshold to behavioural PT threshold). The mean difference between the behavioural PT thresholds and the 40 Hz ASSR thresholds ranged from 0.4 dB at 4 kHz to 14 dB at 0.5 kHz. Difference scores of 4 to 19 dB and 20 to 22 dB were reported for the 80 Hz ASSR and SCAEP respectively. The difference scores reported between SCAEP and behavioural PT thresholds were markedly greater than is reported elsewhere in literature (eg. by Alberti et al., 1987; Coles & Mason, 1984; Hone et al., 2003; Hyde et al., 1986; Kaf, Durrant et al., 2006; Tomlin et al., 2006; Tsui et al., 2002). Van Maanen and Stapells (2005) attribute the large mean difference between SCAEP thresholds and behavioural PT thresholds to the calibration method used, suggesting that SCAEP thresholds reported would have been approximately 9 dB smaller, had the typical nHL been used instead of the dBeHL scale selected. Correlations were similar for all three AEP measures, rendering behavioural PT thresholds estimated, using regression formulae similarly accurate for 40 Hz ASSR, 80 Hz ASSR and SCAEP. The SCAEP did take less time to estimate behavioural PT thresholds than either multiple frequency ASSR method, although not significantly less than the 40 Hz multiple frequency ASSR. Van Maanen and Stapells (2005) named the subjective threshold identification required for identification of SCAEP responses as a disadvantage due to the difficulty in obtaining training and experience. Consequently, Van Maanen and Stapells (2005) concluded that the 40 Hz dichotic multiple frequency ASSR technique was the AEP of choice for the purpose of estimation of behavioural PT thresholds, due to the proximity of the ASSR thresholds to the behavioural PT thresholds and the time taken to complete the assessment. The study by Van der Reijden et al. (2006) also found, as did Van Maanen and Stapells (2005), a closer proximity of ASSR threshold to behavioural PT thresholds when using a 40Hz multiple frequency ASSR modulation rate, than with a 80 Hz multiple frequency ASSR modulation rate.

There is, therefore, no consensus on ASSR stimulus presentation method and modulation rate for the purpose of behavioural PT thresholds estimation in adults that are exposed to occupational noise and at risk of presenting with a noise induced hearing loss. Yet previous research is in agreement that the ASSR is capable of providing an accurate and objective estimate of behavioural PT thresholds for the aforementioned population. The previously named AEP of choice for behavioural PT threshold estimation in adults exposed to occupational noise, namely the SCAEP, has been compared to the ASSR technique in recent years.

2.4 COMPARISON BETWEEN SCAEP AND ASSR FOR BEHAVIOURAL PT THRESHOLD ESTIMATION IN ADULTS EXPOSED TO OCCUPATIONAL NOISE

Several studies have named the SCAEP as the AEP of choice for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise (Alberti et al., 1987; Hone et al., 2003; Hyde, 1997; Prasher et al., 1993; Rickards & De Vidi, 1995; Stapells, 2002; Tsui et al., 2002). With the advent of the ASSR as a clinical tool for behavioural PT threshold estimation, it is apparent that the ASSR offers certain features which would be appealing for use within a population of adults exposed to occupational noise. Table 2.4 compares these features of the ASSR with those of the SCAEP.

TABLE 2.4 Features of SCAEP and ASSR techniques that facilitate utility for behavioural PT threshold estimation in adults exposed to occupational noise

FEATURE	SCAEP	ASSR
Accurate behavioural PT threshold estimation in adults	✓ Extensively researched.	✓ Established but not as extensively.
Frequency specific	✓ Achieved using tone burst stimuli with longer (than ABR tone burst stimuli) rise-fall times.	✓ Achieved using continuous AM / FM stimuli.
Resistant to state of consciousness	✕ Participants must be awake and alert. Sleep or drowsiness attenuates the response amplitude, increasing the intensity of threshold responses.	✓ 40 Hz modulation rate may be used for alert or sleeping participants while 80 Hz modulation rate is used with sleeping participants.
Evaluates complete auditory pathway due to central generators	✓	✓ With the 40 Hz modulation rate only. The faster 80 Hz modulation rate is generated by more peripheral sources.
Objective response measurement	✓	✓
Objective response detection	✕	✓
Dichotic testing possible	✕	✓
Simultaneous multiple frequency assessment possible	✕	✓
Clinical tool	✓ Established use	✓ Newer clinical tool
Time efficient	✓	✓ Dichotic and multiple frequency testing may shorten assessment time further

The SCAEP has been used extensively for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise and claiming compensation for occupational hearing loss (Hyde, 1997; Stapells, 2002). The review in the preceding section of existing research, regarding the use of the ASSR for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise and/or presenting with a noise induced hearing loss, confirms that the technique is capable of providing accurate estimations of frequency specific behavioural PT thresholds (De Koker, 2004; Herdman & Stapells, 2003; Hyde et al., 1986; Hsu et al., 2003; Van Maanen & Stapells, 2005). In contrast to the SCAEP, which can only be recorded with alert individuals, the ASSR can be used with adults who are alert or relaxed and asleep (Cohen et al., 1991; Dobie & Wilson, 1998; Levi et al., 1993; Linden et al., 1985). Both the SCAEP and ASSR techniques are capable of objectively providing estimates of behavioural PT thresholds, although response detection methods differ.

The objective response detection offered by the ASSR technique is an appealing feature in clinical use. Detecting AEP near threshold can be difficult for human observers. Problems with inter-observer and intra-observer reliability (Rose et al., 1971) and with observer bias have been documented (Gans et al., 1992). Objective response detection methods can control bias, perform with stable and known sensitivity, and can outperform human observers (Arnold, 1985; Champlin, 1992; Dobie & Wilson, 1995; Valdes-Sosa et al., 1987). Authors such as Van Maanen and Stapells (2005) are of the opinion that subjective response detection is a disadvantage in a clinical setting, as clinicians experienced in SCAEP response identification are required. It was, however, demonstrated by Yeung and Wong (2007) that interpretations of SCAEP thresholds between two experienced audiologists were consistent. Judgements of threshold intensity of the two audiologists were identical for 86.5% of the data, were within 5 dB for 96% of judgments and never differed by more than 10 dB. In addition, Kaf, Durrant et al. (2006) also demonstrated that the objective response detection performs at least as well as the classical visual detection limit method of SCAEP scoring by a skilled examiner. Therefore, judgment of SCAEP threshold by an experienced clinician can result in consistent threshold detection that performs as well as objective response detection methods. There are, therefore, divergent opinions on the preferred method of AEP response detection, although consistency of threshold judgements have been established using both objective and subjective methods.

The dichotic and multiple frequency ASSR techniques are advantageous in clinical use, if the protocol reduces the time required to acquire estimates of behavioural PT thresholds without affecting accuracy. Several studies have confirmed that the dichotic multiple frequency ASSR technique is capable of accurate estimates of behavioural PT thresholds (eg. D'haenens et al., 2008; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Schmulian et al., 2005). John et al. (2002), however, states that recording responses to eight stimuli simultaneously does not make threshold estimation eight times faster. The recording time required to measure a threshold response for an individual with normal hearing is lengthened, as the smallest of the responses at each frequency becomes significantly larger than the noise (Picton et al., 2003). It will also take longer to decide that an ASSR response is absent, which is relevant for individuals with a sloping hearing loss, as with the target population in the current study (De Koker, 2004; Picton et al., 2003). Several increments in stimulus intensity are required for the high frequencies, leading to an increase in total recording time. A third factor which affects time efficiency is the noise criterion which is used. An ASSR response is judged to be absent based on the noise levels (Dimitrijevic et al., 2002). The lower the noise criterion used, the longer it will take to identify that a response is absent. These factors all reduce the advantage of the multiple frequency ASSR technique. John et al. (2002) has, however, recommended adjusting the intensities of the stimuli at different frequencies. By doing so, the time efficiency of the multiple frequency ASSR technique can be improved to two to three times faster than when presenting stimuli individually. Accuracy of the procedure remains, however, paramount and would take precedence over a faster, less accurate AEP technique.

In recent years, a few studies have emerged regarding the comparative accuracy of behavioural PT threshold estimation using SCAEP and ASSR (Kaf, Durrant et al., 2006; Tomlin et al., 2006; Van Maanen & Stapells, 2005; Yeung & Wong, 2007). The study by Van Maanen and Stapells (2005) compared multiple frequency ASSR with SCAEP in adults claiming workmen's compensation for occupational hearing loss (Van Maanen & Stapells, 2005). Contrary to the aforementioned reports, the study by Van Maanen and Stapells (2005) found significantly smaller difference scores between the dichotic multiple frequency 40 Hz ASSR technique than for either the dichotic multiple frequency 80 Hz ASSR or SCAEP techniques. The difference scores reported for the SCAEP technique are, however, considerably higher than reported elsewhere in literature (difference scores =

19.8 to 22.2 dB). SCAEP studies typically report difference scores of 0 to 15 dB (Alberti et al., 1987; Boniver, 2002; Coles & Mason, 1984; Hone et al., 2003; Hyde et al., 1986; Prasher et al., 1993; Rickards & De Vidi, 1995; Tsui et al., 2002). The elevated SCAEP thresholds and the similar time required to complete behavioural PT threshold estimation using the SCAEP and 40 Hz ASSR techniques, led to the recommendation of the use of the 40 Hz multiple frequency ASSR technique for the purpose of behavioural PT threshold estimation in adults claiming compensation for occupational hearing loss.

Kaf, Durrant et al. (2006) compared the accuracy of multiple frequency ASSR thresholds (at four frequencies) obtained, using a high modulation rate to SCAEP thresholds at 2 kHz only. This was done by using 16 female participants with normal hearing and filtered masking noise to simulate sensorineural hearing loss. The simulated hearing loss of different degrees was shaped with a notch at 2 kHz. The results indicated that the proximity of ASSR and SCAEP thresholds to behavioural PT thresholds was the same for the group of participants with normal hearing, but ASSR thresholds were closer to behavioural PT thresholds than SCAEP thresholds at 2 kHz in participants with a simulated sensorineural hearing loss. It is postulated that the longer response recording time allowed by the Biologic MASTER ASSR system resulted in a reduction of noise levels and, consequently, in ASSR thresholds closer to behavioural PT thresholds than SCAEP thresholds. Kaf, Durrant et al. (2006) were able to establish strong correlations between ASSR thresholds and behavioural PT thresholds at 1 to 4 kHz ($r = 0.75$ to 0.93) to within 10 dB. A statistically significant but weaker correlation ($r = 0.53$) was measured between ASSR thresholds and behavioural PT thresholds at 0.5 kHz. Luts and Wouters (2005) reported the same correlation between single frequency ASSR thresholds at 0.5 kHz and behavioural PT thresholds. Several studies have noted that the correlation between ASSR thresholds and behavioural PT thresholds was weaker at 0.5 kHz than at higher frequencies (Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2003; Hsu et al., 2003; Van Maanen & Stapells, 2005). Kaf, Durrant et al. (2006) liken the greater variability of ASSR thresholds at 0.5 kHz to that with use of tone burst ABR. Kaf, Durrant et al. (2006) suggest that the possible underlying mechanism that results in the increased variability at 0.5 kHz, includes the adverse effects of higher background noise at lower than higher frequencies; the greater effect of the masking noise used to simulate hearing loss at lower frequencies; the poorer neural synchronization at low frequencies;

and the effects of basalward spread of cochlear excitation during AEP assessment. Despite the greater variability of behavioural PT threshold estimation from the multiple frequency ASSR at 0.5 kHz, Kaf, Durrant et al. (2006) state that this relationship is, however, statistically significant, and the ASSR technique is a valid and accurate technique for behavioural PT threshold estimation, capable of following audiometric patterns well. Kaf, Sabo et al. (2006) extended the research project to investigate the test-retest reliability of the 80 Hz multiple frequency ASSR technique. The same participants (16 females with normal hearing) were used and hearing losses of different degrees were again simulated using filtered masking noise. Similarly to the evaluation of ASSR accuracy and validity by Kaf, Durrant et al. (2006), Kaf, Sabo et al. (2006) demonstrated moderately-strong test-retest reliability at 1 to 4 kHz (r = 0.83 to 0.93) with a weaker correlation of 0.75 at 0.5 kHz. Therefore, despite certain limitations, the studies found the 80 Hz multiple frequency ASSR technique to be an accurate, valid and reliable means of estimating behavioural PT thresholds.

In contrast to the finding of better accuracy of the ASSR technique reported by Kaf, Durrant et al. (2006), Tomlin et al. (2006) concluded that, with reference to both proximity to behavioural PT thresholds and variability of this relationship, the SCAEP technique demonstrated a clear advantage over the 40 Hz ASSR. Tomlin et al. (2006) compared SCAEP with the 40 Hz ASSR technique, using 36 adults with normal hearing and 30 adults with a sensorineural hearing loss. SCAEP and ASSR thresholds were measured at 0.5 and 4 kHz while participants were alert. Correlation co-efficients between ASSR thresholds and behavioural PT thresholds were 0.84 and 0.85 at 0.5 and 4 kHz respectively. A closer relationship between SCAEP thresholds and behavioural PT thresholds was evident, with correlations of 0.95 and 0.96 at 0.5 and 4 kHz respectively. Mean differences between SCAEP or ASSR and behavioural PT thresholds ranged from 10.3 to 15.9 dB for SCAEP and from 10.0 to 42.2 dB for ASSR. The largest difference score between ASSR thresholds and behavioural PT thresholds was measured at 4 kHz for individuals with normal hearing. The use by Tomlin et al. (2006) of the GSI Audera ASSR system meant that the maximum duration of a single ASSR recording was limited to 89 s (GSI, 2003). Picton et al. (2003) state that a recording duration of over 10 min is often required to identify threshold ASSR responses in close proximity to behavioural PT thresholds for individuals with normal hearing. The effect of the short recording duration offered by the GSI Audera ASSR system is therefore evident by the large difference score at 4 kHz. Tomlin et al. (2006) also demonstrated that ASSR threshold sensation levels were lower in individuals with greater degrees of hearing loss but that SCAEP did not demonstrate the same pattern.

Yeung and Wong (2007) were able to demonstrate closer proximity of not only ASSR thresholds, but also SCAEP thresholds to behavioural PT thresholds with increasing degree of hearing loss. The participants (63 ears) of the study by Yeung and Wong (2007) were divided into three groups on the basis of degree of hearing loss. Nineteen ears presented with normal hearing, 24 ears presented with a mild to moderately severe degree of hearing loss ($\leq$ 70 dBHL) and 20 ears presented with a severe to profound hearing loss. The ASSR thresholds were closest to behavioural PT thresholds at 4 kHz, as was reported by Herdman and Stapells (2003), Hsu et al. (2003), and Van Maanen and Stapells (2005; for both the 40 and 80 Hz ASSR techniques). Yeung and Wong (2007) reported a mean difference score for the total participant group between ASSR thresholds and behavioural PT thresholds at 4 kHz of 4 dB with a standard deviation of 12 dB. Mean difference scores of 17.1 dB were reported for ears with normal hearing at 4 kHz, decreasing to -1.7 dB for ears with a profound degree of hearing loss. It is interesting to note that the participants in the studies by Herdman and Stapells (2003), Hsu et al. (2003), and Van Maanen and Stapells (2005) all presented with a sloping sensorineural hearing loss. The small difference scores between ASSR thresholds and behavioural PT threshold were, therefore, measured at the frequency that represented the greatest degree of sensorineural hearing loss. This is consistent with the effect of recruitment on ASSR amplitude (Lins et al., 1996).

With respect to the comparison between the ability of the SCAEP and ASSR technique to estimate behavioural PT thresholds, Yeung and Wong (2007) concluded, similarly to Tomlin et al. (2006), that the SCAEP technique estimated behavioural PT thresholds more accurately than the ASSR did, albeit only slightly. A mean difference of 10 dB was measured between ASSR threshold and behavioural PT threshold across the four frequencies evaluated compared to a mean difference score of 5 dB using the SCAEP technique. The mean difference score between ASSR thresholds and behavioural PT thresholds at 4 kHz reported by Yeung and Wong (2007) is, however, considerably smaller than that reported by Tomlin et al. (2006) who used the same ASSR system, stimulus protocol and participant state of consciousness to determine ASSR thresholds that Yeung and Wong (2007) used. Yeung and Wong (2007) reported a mean difference score for the total participant group between ASSR thresholds and behavioural PT thresholds at 4 kHz of 4 dB. Tomlin et al. (2006) reported a mean difference score between ASSR threshold and behavioural PT threshold at 4 kHz for the group with normal hearing of 42 dB, while the difference score at 4 kHz for the participant group with hearing loss was 24 dB. The reason for the discrepancy may lie in the degree of hearing loss of the participants of the study used by Yeung and Wong (2007). A third of the participants included in the study by Yeung and Wong (2007) presented with a severe to profound hearing loss. This is in contrast to only 10 of the 66 participants in the study by Tomlin et al. (2006), that presented with a severe to profound hearing loss at 4 kHz. The small difference score between ASSR threshold and behavioural PT thresholds at 4 kHz reported by Yeung and Wong (2007) may, therefore, again be attributed to the effect of recruitment (Lins et al., 1996).

Both Tomlin et al. (2006) and Yeung and Wong (2007) made use of the GSI Audera single frequency ASSR system using a 40 Hz modulation rate. Participants were evaluated while alert. The comparative studies that made use of the GSI Audera ASSR system concluded that the SCAEP technique yielded more accurate estimations of behavioural PT thresholds. This is in contrast to the comparative studies that made use of the Biologic MASTER ASSR system versus the SCAEP technique which advocated the use of ASSR. Again, the longer recording duration offered by the Biologic MASTER ASSR system (viz. maximum of 15 min; John et al., 1998), in comparison to the maximum 89 s long recording duration of the GSI Audera ASSR system, is likely to be the reason for the lower ASSR sensation levels measured when using the Biologic MASTER ASSR system. The possibility that the high, rather than the low modulation rate, resulted in improved accuracy of the estimations of behavioural PT thresholds was discounted by Van Maanen and Stapells (2005) who found lower ASSR thresholds within subjects of the 40 Hz multiple ASSR technique, rather than the 80 Hz multiple ASSR technique. It is feasible that the multiple frequency ASSR technique improves the accuracy of estimations of behavioural PT thresholds when compared to a single frequency ASSR technique. Herdman and Stapells (2003) addressed this by comparing the ASSR thresholds, using a monotic multiple frequency ASSR protocol with those obtained with the same high modulation rate at a frequency of interest presented individually. Participants slept or relaxed during the ASSR assessment. The results of the study indicated that the difference between single frequency ASSR thresholds and those measured using a multiple frequency protocol were neither statistically nor clinically significant. The critical factor in determining the proximity of ASSR thresholds to behavioural PT thresholds, therefore appears to be the duration of a single ASSR recording. It is, therefore, evident that the longer recording duration offered by the Biologic MASTER ASSR system is a distinct advantage. The GSI Audera attempts to compensate for the short recording duration by incorporating the Rance et al. (1995) regression formulae when using ASSR thresholds to estimate behavioural PT thresholds (GSI, 2003).

The studies by Kaf, Durrant et al. (2006), Tomlin et al. (2006), Van Maanen and Stapells (2005) and Yeung and Wong (2007), therefore, all investigate the comparative accuracy of behavioural PT threshold estimation using SCAEP and various ASSR protocols. The researcher is, however, not aware of any comparative studies on the use of SCAEP and single frequency ASSR for adults exposed to occupational noise. In light of the lack of comparative research on SCAEP and single stimulus ASSR, the following question was formulated: How effective and how efficient is the clinical use of a single stimulus ASSR technique as compared to SCAEP, for behavioural PT threshold estimation in adults exposed to occupational noise?

2.5 CONCLUSION

Although not widely used in South Africa, SCAEP have been well established as the method of choice for behavioural PT threshold estimation for adults exposed to occupational noise and in compensation cases due to occupational noise induced hearing loss (Alberti et al., 1987; Coles & Mason, 1984; Hone et al., 2003; Hyde et al., 1986, 1997; Prasher et al., 1993; Stapells, 2002; Tsui et al., 2002). Reliable and valid methods of objective behavioural PT threshold estimation are crucial in determining hearing disability compensation. This is especially relevant in the context of South Africa, a developing country with more than 8.2 million workers in formal employment in factories, mines, on farms and other places of work (South African Department of Health, 1997).

Over the past decade, auditory ASSR have been proposed as an alternative AEP for behavioural PT threshold estimation (e.g. Dobie & Wilson, 1998; Lins et al., 1996; Rance et al., 1995; Vander Werff et al., 2002). Several characteristics of the ASSR suggest that this AEP may also be applicable for clinical use for behavioural PT threshold estimation in individuals exposed to occupational noise and at risk for noise induced hearing loss. The accuracy of threshold estimation, potentially better frequency specificity of continuous, rather than transient, tonal stimuli, independence of participant attention or state of arousal, and ability to obtain higher output levels, and the objective nature of response detection (Vander Werff et al., 2002).

Despite the possible suitability of the ASSR for threshold estimation in adults exposed to occupational noise, few studies were found that address this clinical application of ASSR for this population (Herdman & Stapells, 2003; Hyde et al., 1986; Hsu et al., 2003; Van Maanen & Stapells, 2005). Given the amount of individuals exposed to occupational noise in not only South Africa but internationally, the amount of research on ASSR for this population is insufficient.

A review of the literature revealed four comparative studies on the use of SCAEP and ASSR for the purpose of behavioural PT threshold estimation in a population of adults exposed to occupational noise (Kaf, Durrant et al., 2006; Tomlin et al., 2006; Van Maanen & Stapells, 2005; Yeung & Wong, 2007). There are, as yet, no comparative studies on the use of SCAEP and single frequency ASSR for the population in question. This then leads to the formulation of the research question and the current research project.

2.6 SUMMARY

This chapter presented a literature review with regard to the SCAEP and ASSR techniques being compared for the purpose of behavioural PT threshold estimation in a population of adults exposed to occupational noise. First the literature on SCAEP, then on ASSR was reviewed. This was achieved with reference to a historical overview, the neural generators, properties and components of the AEP, stimulus and participant effects. The method of response detection was then critically evaluated, followed by a list of the clinical use of each technique. The chapter concluded with a review of the use of the SCAEP and ASSR for the population in question.

CHAPTER THREE

RESEARCH DESIGN AND METHOD

3.1 INTRODUCTION

Noise induced hearing loss has been recognised as a major occupational health risk by the South African health care system. Identification of occupational noise induced hearing loss in adults exposed to occupational noise can be problematic, as this is a population where the incidence of nonorganic hearing loss is high. An accurate and objective method of quantification of hearing loss is therefore a priority.

The current study has provided quantitative data to support recommendation of the use of either the slow cortical auditory evoked potential (SCAEP), or the auditory steady-state evoked response (ASSR) technique in a population of adults exposed to occupational noise. The efficiency of use of SCAEP versus ASSR was determined by measuring the comparative accuracy and time efficiency of estimation of behavioural pure tone (PT) thresholds using each technique. The findings challenged the existing perception in South Africa that ASSR is the method of choice for a variety of purposes across a variety of populations.

3.2 AIMS OF THE STUDY

The main aim of this research project was to compare the clinical effectiveness and time-efficiency of SCAEP and ASSR for estimating behavioural PT thresholds in adults with normal hearing and in adults exposed to occupational noise. For the purpose of this research endeavour, clinical effectiveness was defined as the accuracy of behavioural PT threshold estimation, while clinical efficiency was determined by the amount of time necessary to acquire Auditory Evoked Potential (AEP) threshold responses.

In order to achieve the main aim of the study, three sub-aims were formulated.

- To compare behavioural tone burst thresholds and AM/FM (amplitude and frequency modulated) tone thresholds to behavioural PT thresholds at 0.5, 1, 2 and 4 kHz in a group of adult participants with normal hearing.

- To compare the SCAEP and ASSR thresholds to behavioural PT thresholds at 0.5, 1, 2 and 4 kHz in adult participants with normal hearing, and in a sample of adults with hearing loss who are exposed to occupational noise.

- To compare the time required to acquire SCAEP and ASSR thresholds in a group of adults with normal hearing, and in a group of adults with hearing loss who are exposed to occupational noise.

The aim and three sub-aims of the study are graphically displayed in Figure 3.1.

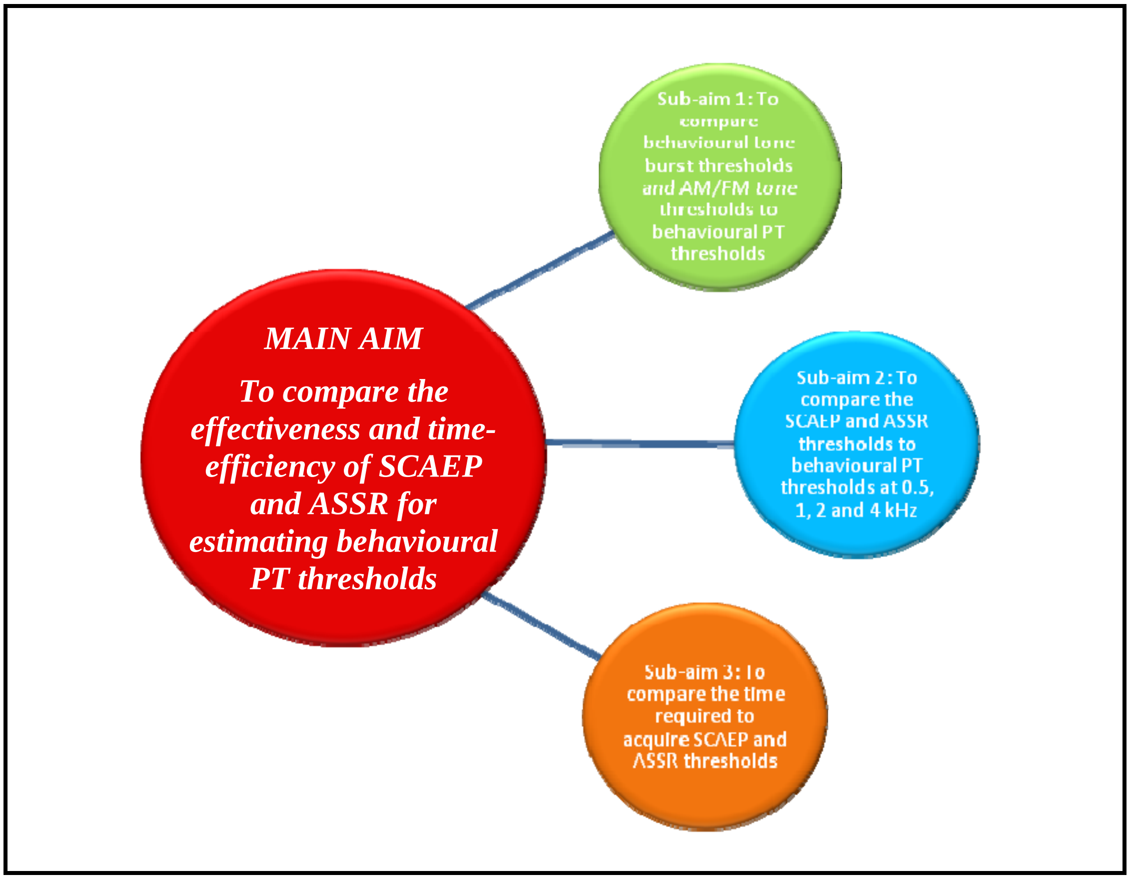

FIGURE 3.1 Diagrammatic representation of aim and sub-aims of the study

The first two sub-aims displayed in Figure 3.1 pertained to the effectiveness (accuracy) of the SCAEP and ASSR for behavioural PT threshold estimation, while the third sub-aim related to the time-efficiency of the SCAEP and ASSR techniques. Together, by acquiring data regarding the three sub-aims, the main aim of the study was realized and the research question answered.

3.3 RESEARCH DESIGN

The development of a research design follows logically from the research problem. Mouton (1996) defined research design as "a set of guidelines and instructions to be followed in addressing the research problem" (p. 107). The main function of the research design is to maximise the validity of the results through either minimising or eliminating potential error (Mouton, 1996).

A comparative quasi-experimental research design (Leedy & Ormrod, 2001; Trochim, 2006) was selected for this study. The research is classified as quasi-experimental research due to the use of two nonrandomized groups (Trochim, 2006). The researcher obtained evidence of comparative clinical efficiency of the AEP measures in adult participants with normal hearing and in adults with hearing loss who had a history of occupational noise exposure. The study therefore took the format of a within-participant repeated measures design (Dallal, 1998), as all the participants were evaluated using both the SCAEP and ASSR method. The data obtained was also compared between the two participant groups, providing a between-participant comparison. Figure 3.2 depicts the research design.

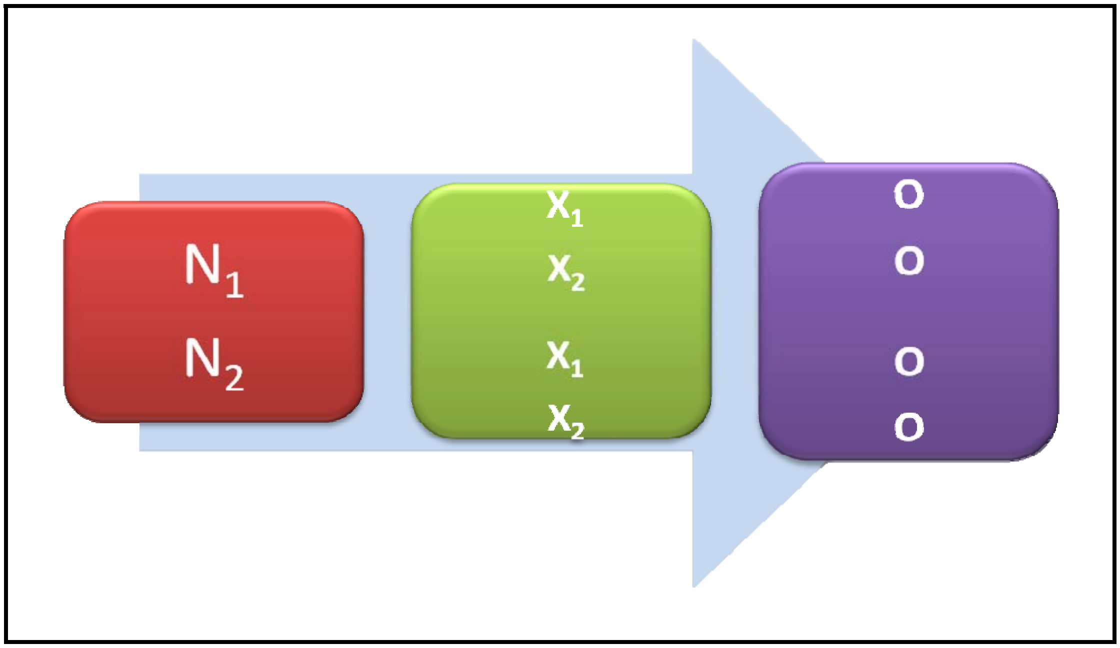

FIGURE 3.2 Quasi-experimental research design depicting two non-equivalent participant groups (N_1 and N_2), each evaluated using two measures (X_1 and X_2), yielding four groups of data (O)

Figure 3.2 depicts the two participant groups represented by the N_1 and N_2. The participant groups were non-equivalent with respect to hearing sensitivity and exposure to noise. Both participant groups were evaluated using two measures (X_1 and X_2) namely the SCAEP and ASSR techniques. The evaluations yielded four sets of data (O) which were compared within participants and between participant groups.

A quantitative research approach was chosen, due to the nature of the data collected. During quantitative research, controlled and standardized procedures are used to study independent variables and to collect numerical data (Leedy & Ormrod, 2001). The resulting numerical data allowed for the analysis of the data, using both descriptive and inferential statistical methods, facilitating conclusion formulation. The present study investigated the comparative ability of two clinical procedures to effectively function in practice. The research was, therefore, applied rather than basic, as the aim of acquisition of new knowledge is directed primarily towards a specific practical objective (Trochim, 2006).

Kaplan (1987) states that the use of research designs requires knowledge of not only research methodology, but also consideration of independent, dependent and confounding variables. The independent variables of this study are the two AEP techniques being compared, namely the SCAEP and ASSR techniques. The dependent or measured variables were the SCAEP thresholds and ASSR thresholds which provide estimates of behavioural PT thresholds, as well as the time required for completion of each technique used to acquire the SCAEP and ASSR thresholds.

3.4 ETHICAL ISSUES

The South African National Health Act (2007) states that medical and health care research is subject to ethical standards that promote respect for all human beings and protect their health and rights. In keeping with this statement, the current study was initiated and conducted within the framework of the ethical guidelines set out in the Guidelines of Practice in the Conduct of Clinical Trials in Human Subjects in South Africa (South African Department of Health, 2000) and in the South African National Health Act (2007). The individual principles presented in these documents are listed and discussed below in Table 3.1 as they were applied to the current study.

TABLE 3.1 Ethical principles applied to formulation of research design, participant selection and recruitment procedures, and data collection and analysis procedures (South African Department of Health, 2000; South African National Health Act, 2007)

Principle	Application to study
The right, safety and wellbeing of the study participants are the most important considerations and should prevail over interest of science and society. Foreseeable risks and inconveniences should be weighed against the anticipated benefit for individual participants and society. A study should only be initiated and continued if the anticipated benefits justify the risks.	There were no risks involved for the participants of this study with the only inconvenience being possible fatigue during auditory assessment using the SCAEP and ASSR due to the length thereof. The benefit for the population in question is future use of the most accurate AEP technique for estimation of behavioural PT thresholds. This will result in accurate determination of percentage loss of hearing and appropriate compensation for occupational noise induced hearing loss. Inaccurate behavioural PT threshold estimation leads to under or over compensation for occupational injury. Cost effectiveness is one of the cornerstones of the South African National Health Act (2007).
Research or experimentation on an individual may only be conducted after the participant has been informed of the objectives of the research or experimentation and any possible positive or negative consequences on his or her health.	There was no direct benefit to the participants but also no risks involved. Due to the length of the assessment session, fatigue may have resulted. This was taken into account by ordering the assessment session so that participants were asked to remain alert initially (during SCAEP) and are encouraged to relax or sleep later in the session, during ASSR recording. An information form (Appendix A) was presented to all individuals who were potential participants in the study. The information form concerned the broad purpose and rationale of the study, what participation would involve and participant rights. Individuals were encouraged to ask any questions they may have had regarding the study or their rights as participants in the study.
The health care provider must also, where possible, inform the individual in a language that the individual understands, and in a manner which takes into account the individual's level of literacy.	A criterion for selection of participants was that each participant had to be able to comprehend conversational English or Afrikaans in order to ensure comprehension of verbal instructions and consequently appropriate co-operation throughout the assessment. This also ensured understanding of the information and consent forms. If the participants were unable to read English or Afrikaans or were unable to fully comprehend any portion of the consent and information form, the researcher was contacted telephonically or in person in order to obtain verbal clarification. The consent form was also read aloud to the participant by the researcher or any other English or Afrikaans literate person. The participant was encouraged to ask any questions they may have had regarding the aims and objectives of the study, or their rights as participants in the study.
Freely given informed consent should be obtained from every participant prior to clinical trial participation.	Freely given informed consent was obtained from every participant through use of the informed consent form as presented in Appendix B. This enabled the researcher to acquire written consent from each participant prior to the assessment.
The participant should be informed of the right to abstain from participation in the study or to withdraw consent to participate at any time without reprisal.	This principle was stated in the informed consent form (Appendix B) and was reiterated verbally prior to commencement of the assessment session.
The confidentiality of records that could identify participants should be protected, respecting the privacy and confidentiality rules in accordance with the applicable regulatory requirement(s).	Participant confidentiality was ensured as SCAEP, ASSR and behavioural PT threshold information for each individual was reported using an alphabetical code. The identity of the participant represented by this code was known only to the researcher.
A preliminary study should be conducted in compliance with the protocol that has received prior institutional review board / independent ethics committee approval.	Prior to commencement of the study, a research proposal was compiled, detailing the motivation, aims, participant selection criteria, assessment procedure, equipment, as well as the anticipated results and contribution of the study. The proposal was submitted to and approved by the Research Ethics Committee of the Faculty of Humanities of the University of Pretoria (Appendix C).

3.5 ESTABLISHING RELIABILITY AND VALIDITY OF DATA

Mouton (1996) states that one of the purposes of the research design is to minimise contamination of results by extraneous variables. A research project must be designed so that these confounding variables are either controlled for, or eliminated (Kaplan, 1987). In doing so, the researcher ensures that the data collected by the study is both reliable and valid. Leedy and Ormrod (2001) defines validity as the extent to which the instrument measures what it is supposed to measure. Reliability is a measure of the consistency of the aforementioned relationship (Trochim, 2006). Validity and reliability of the data was ensured in a variety of ways:

- A thorough literature review and clear, logical concept definitions promoted theoretical validity (Mouton, 1996).
- Multiple indicators of variables were used in the study (Neuman, 1994). In terms of audiological assessment measures, behavioural PT audiometry is considered the gold standard. From a research point of view, it is considered both reliable, being capable of providing a consistent measure of a patient's behavioural PT hearing thresholds, and valid, as it is an accurate measure of hearing (Cope, 1995; Goldstein & Aldrich, 1999; Martin, 2002). As behavioural PT thresholds are used to determine the reliability and accuracy of the SCAEP and ASSR techniques, the reliability and validity of behavioural PT thresholds were paramount. To ensure this was the case, behavioural PT audiometry was repeated on three occasions for each participant with hearing loss and on two occasions for participants with normal hearing. With regard to participants with hearing loss, hearing screening was initially performed at two separate sittings as part of the hearing screening program. In order to verify that there had been no deterioration in hearing sensitivity in the period between hearing screening and the AEP assessment session, behavioural PT thresholds were again determined immediately following AEP assessment. Any participant who demonstrated variability of behavioural PT thresholds of more than 10 dBHL (decibel hearing loss) at one or more frequencies at 0.5, 1, 2 and 4 kHz, was excluded from the study. Further, when considering an individual for participation in the study, their behavioural PT average was compared to their speech reception threshold (as discussed in the participant selection criteria) to ensure accuracy of the screening

behavioural PT thresholds. With respect to participants with normal hearing, behavioural PT thresholds were measured on the day of assessment after SCAEP and ASSR threshold determination. At this time, speech reception thresholds were also measured for participants with normal hearing and compared to the behavioural PT average to ensure reliability of behavioural PT thresholds. The aforementioned measures aimed at eliminating, or at least reducing measurement variability and improving the validity and reliability of behavioural PT thresholds.

- Participant selection criteria were vital in minimizing or eliminating confounding variables. Participants with middle or external ear pathology, a neurological disorder or who were taking certain medications, were excluded from participation in the study as these criteria can affect (cause elevation of) SCAEP or ASSR thresholds. Any participant who could potentially negatively affect resulting data by failure to understand written or verbal case history questions or the instructions during behavioural toneburst, AM/FM stimuli, and PT threshold measurement, and during SCAEP or ASSR threshold determination, was excluded from the study.
- By matching the target population (i.e. adults exposed to occupational noise) with that of the participants in terms of age, sex and working environment, representative reliability of study participants was increased (Neuman, 1994).
- The use of convenience sampling, although not ideal, did limit researcher bias, as the first 16 participants with normal hearing and with hearing loss who were appropriate and willing candidates for participation in the study were recruited.
- Use of a single AEP system to measure both SCAEP and ASSR thresholds eliminates extraneous variables (e.g. calibration differences) that may potentially have contaminated the data, had two separate AEP systems been used.
- Regular calibration of audiometric equipment further controlled for error of measurement during behavioural toneburst, AM/FM tone, and PT threshold determination, and during SCAEP or ASSR threshold measurement. The GSI (Grason-Stadler Incorporated) Audera AEP system was calibrated both prior to the commencement of data collection and midway through the process, once 20 participants had been assessed. Both the screening audiometer used during participant selection and the diagnostic audiometer used to repeat behavioural PT audiometry on the day of assessment was calibrated prior to data collection. Electroacoustic

calibration was performed with reference to three parameters, namely intensity, frequency and time (phase and signal duration; Wilber, 2002). In addition, daily biologic checks were completed for both audiometers with reference to the clinician's behavioural PT hearing thresholds. Sub-aim one was formulated with the aim of executing a biologic calibration on the group of participants with normal hearing to determine not only accuracy of stimulus intensity, but also whether tone burst and AM/FM stimuli were comparable.

- The test environment was controlled by measuring behavioural PT thresholds, SCAEP and ASSR thresholds in a uniform setting, namely in a double walled soundproof booth.
- A uniform method of stimuli presentation and the order of assessment were utilized for all participants.
- A preliminary study explored the suitability of the chosen test protocol for the target population in a clinical setting. Any limitations of the protocol were identified in this manner and adjustments to the protocol were made. The construct validity of the research project was therefore evaluated during the preliminary study (Mouton, 1996).
- Researcher/clinician bias was reduced for the participants with hearing loss by performing behavioural PT audiometry on the day of AEP assessment after SCAEP and ASSR threshold determination. However, the group to which the participant belonged (group of participants with normal hearing or with hearing loss) was known. The researcher was, therefore, blinded to the behavioural PT hearing thresholds of the participants with hearing loss during SCAEP and ASSR measurement to a certain extent. It is, however, possible that the typical hearing loss of the target population, namely high frequency hearing loss, may have introduced bias during SCAEP and ASSR threshold determination.
- Mouton (1996) maintains that the statistical measures used to analyse and interpret data must be appropriate and conclusions must flow logically from empirical evidence. Both the threshold data and the relationship between the data were described using descriptive and inferential statistics. The types of statistics used, were comparable to the existing literature evaluating the use of different AEP techniques for the purpose of threshold estimation. This then facilitated comparisons between the current study and previous studies, and enabled valid conclusions to be drawn.

- Objectivity is vital in ensuring research validity (Mouton 1996). For this reason, two experienced clinicians were asked to identify thresholds SCAEP responses. Only when agreement on threshold response was reached, was the SCAEP threshold reported. The objective nature of response detection used in ASSR software, eliminated subjectivity and effect of clinician experience. The comparative advantage of the specific statistical technique used in the GSI Audera software, namely phase coherence, versus another statistic, was beyond the scope of the current study. Clinician experience did, however, affect choice of stimulus intensity during SCAEP threshold determination as this was based on subjective response detection.
- It was acknowledged that test-retest reliability of the SCAEP and ASSR techniques may potentially have affected reliability of the data reported in the study. The test-retest reliability of the SCAEP and ASSR techniques have been evaluated and confirmed by various studies (Jacobson et al., 1999; Kaf, Sobo et al., 2006; Pekkonen et al., 1995). Evaluation hereof was, however, beyond the scope of the current research project.
- External validity is the extent to which results apply to situations beyond the study (Neuman, 1994). This was addressed in two ways. Firstly, through selection of participants which were representative of the typical adult population for which behavioural PT threshold estimation using AEP would be necessary. Clinically, the highest percentage of adults seen for behavioural PT threshold estimation using AEP, is those exposed to occupational noise that could potentially claim for compensation for noise induced hearing loss. Secondly, use was made of the standard AEP manufacturer recommended stimulus and acquisition parameters for SCAEP and ASSR threshold determination, as would typically be used in a clinical environment. The aforementioned aspects of the study promote the generalization of the findings of the study to the total population and to clinical practice. The relatively small number of participants of the study does limit generalization to an extent, however.

3.6 PARTICIPANTS

The group of participants with normal hearing was composed of 15 adults. The data of two ears were excluded from the study, as a conductive hearing loss was present in these ears. The data from 28 ears was therefore used for the group with normal hearing.

Participants in this group were recruited from colleagues and friends of the researcher. The group of participants with hearing loss was composed of 16 individuals with sensorineural hearing loss. The data of two ears were excluded from the study, as a conductive hearing loss was present in one ear of one participant, while another participant had one ear with normal hearing. The data from 30 ears was therefore used for the group with hearing loss. The group of participants with hearing loss was recruited from individuals referred for audiometric screening, as part of hearing conservation programs, and as such, were exposed to occupational noise and at risk for developing occupational noise induced hearing loss. Individuals exposed to occupational noise were defined as individuals in the employment of an industry where individuals were exposed to continuous or impulse noise at or above an eight hour time weighted average noise level of 85 dBA (Occupational Health and Safety Act, 1993). The participants with hearing loss were recruited through use of convenience sampling of individuals that matched the participant selection criteria referred for hearing screening over a period of three months.

3.6.1 Participant selection criteria

Individuals were deemed potential participants if they matched certain criteria. The selection criteria of the participant groups with normal hearing and with hearing loss differed. The criteria for the two groups were controlled with respect to the participants' age, gender, language, middle ear and neurological status, medication, reliability and co-operation, and exposure to noise prior to assessment. The criteria for the two groups differed in terms of participant hearing sensitivity and noise exposure. The participant selection criteria are detailed below in Table 3.2.

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Table 3.2 Participant selection criteria for groups of participants with normal hearing and with hearing loss

	Selection criteria	Motivation
PARTICIPANTS WITH NORMAL HEARING & HEARING LOSS	***Age***	Participants ranged between the ages of 18 and 65 years as this was the typical age of employment for individuals exposed to occupational noise. Early latency AEP (including ASSR) do mature at an earlier age than slow latency responses (including SCAEP) but no significant maturational changes occur during the aforementioned age range that would affect behavioural PT threshold estimation using ASSR or SCAEP have been documented (Hall, 1992).
	Gender	Participants in the groups with normal hearing and with hearing loss were male as this is typical of the work force employed in local industries and is typical of clinical referrals from this population. Furthermore, larger SCAEP amplitudes are generally noted in female individuals than in male individuals (Hall, 1992). Inclusion of both male and female participants may therefore have potentially resulted in lower mean intensity of threshold responses than in a male only group. This is of relevance if participants are members of a largely male predominant population as was the case in this study.
	Language	Participants had to be competent in conversational English or Afrikaans as they were required to follow verbal instructions given in one of these languages in order to obtain the appropriate passive co-operation necessary to comply with the assessment battery.
	Middle ear status	Participants were required to present with normal middle ear function. For the purpose of this study, absence of middle ear pathology was confirmed by Type A tympanograms (compliance = 0.27 to 2.8 cc^3; peak pressure = +50 to -150 daPa; Jerger, 1970). Individuals with Type B (compliance = < 0.27 cc^3; peak pressure = no peak) or Type C (compliance = 0.27 to 2.8 $cc^{3;}$ peak pressure = $\geq$-200 daPa) tympanograms (Jerger, 1970) were excluded from the study. In addition, an acoustic reflex was required to be present at 100 dBHL at 1 kHz for participants with normal hearing.
	Neurological status	The neurological status of participants was ascertained by the participant questionnaire presented in Appendix D. Participants were required to indicate whether they had any chronic or neurological illnesses, and whether they had suffered any head injuries. In so doing, participants with previous or ongoing history of neurological pathology were identified and excluded from the study. Participants with neurological pathology were excluded due to the possible effect of neurological pathology on the accuracy of electrophysiological threshold estimation as a result of the neurophysiological basis of AEP (Hall, 1992).
	Medication	Individuals taking central nervous system drugs, including anticonvulsants, sedatives, depressants, tranquillisers and psychotherapeutic agents, were excluded from participation. This was necessary as a large number of drugs affect central nervous system activity and may therefore, in turn, influence AEP (Hall, 1992). The alteration brought about by drugs on AEP is specific to each drug. Participants taking these medications were identified by the participant questionnaire (Appendix D).
	Co-operation, reliability and accuracy of behavioural PT thresholds	Participants' responses during behavioural PT thresholds must have been considered reliable and repeatable as judged by an experienced audiologist (tester) and as evidenced by a correlation between speech reception thresholds and behavioural PT average for 0.5, 1 and 2 kHz of less than or equal to 7 dBHL (Hall & Mueller, 1997). This was a key participant selection criterion as accurate behavioural PT thresholds are the gold standard and reference against which the accuracy of the SCAEP and the ASSR was judged. Inaccurate reference behavioural PT thresholds would invalidate the results and the conclusions drawn from the study. The validity of the study was therefore underpinned by accurate behavioural PT thresholds, the result of participant co-operation and reliability of participant responses.
	Noise exposure prior to assessment	Participants in the group with a hearing loss should be removed from noise at least 24 hours prior to assessment (COIDA, 2001; SANS 10083, 2004). This was in keeping with legislation on audiological assessment within a hearing conservation program and was motivated by the noise induced temporary threshold shift resulting from a $\geq$ 75 dBA time weighted average exposure to noise (Feuerstein, 2002). The temporary deterioration in behavioural PT threshold is caused by physiological fatigue due to swelling of the cochlear hair cells (Schmiedt, 1984). Recovery, although correlated with intensity of noise and length of exposure, typically occurs within 16 hours of removal from the noisy environment (Feuerstein, 2002). Although participants in the group with hearing were not exposed to occupational noise, they were also required to avoid excessive exposure to noise for 24 hours prior to assessment.
PARTICIPANTS WITH HEARING LOSS	***Hearing sensitivity***	Participants had either normal hearing or a sensorineural hearing loss of any degree. Individuals presenting with either a conductive or mixed hearing loss were excluded from the study. The participants were divided into two groups on the basis of hearing sensitivity. Participants who presented with hearing within normal limits (i.e. behavioural PT thresholds of 20 dBHL or less, in accordance with Jerger & Jerger classification of degree of hearing loss, 1980) fell in group with normal hearing, while participants with a degree of sensorineural hearing loss (i.e. behavioural PT thresholds of > 20 dBHL; Jerger & Jerger, 1980) comprised the group with hearing loss.
	Occupational noise exposure	Participants with a hearing loss and in the group with hearing loss must have had a history of occupational noise exposure. Occupational noise exposure was defined as noise at or above the 85 dBA eight hour noise rating level on a daily basis, requiring a hearing conservation program, as stipulated by the South African Occupational Health and Safety Act,no. 208 of 1993 (1994) and SANS 10083 (2004). The group of participants with normal hearing sensitivity did not have any history of occupational noise exposure.

3.6.2 Participant selection material and apparatus

For the purpose of obtaining the information required for participant selection in accordance with the participant selection criteria, certain materials and apparatus were utilized. These are presented in Table 3.3.

TABLE 3.3 Material and apparatus for participant selection

Material	**Description and purpose**	**Appendix**
Information form	The form informed the individual of the nature of and motivation for the study, and the implications of voluntary participation therein.	Appendix A
Informed consent form	Individuals willing to participate in the study were given an informed consent form to complete and return to the researcher.	Appendix B
Case history questionnaire	The questionnaire requested the individual's personal and contact details, English and Afrikaans language competence, medical history, medication, history of noise exposure, otologic history, and perceived hearing ability.	Appendix D
Equipment	**Description and purpose**	**Calibration date**
Heine 2000 mini otoscope	Otoscopy was performed prior to audiometry to ensure that no signs of middle ear pathology were visible and that nothing was obstructing the ear canal.	N/a
GSI 33 middle ear analyser	A GSI 33 with a 226 Hz probe tone was used to perform tympanometry. Various sizes probe tips (sufficiently large to create a seal in the external meatus) were used during tympanometry assessment.	January 2004
Interacoustics AD229 audiometer	Behavioural PT air and bone conduction audiometry, and speech reception threshold determination was performed with the diagnostic audiometer using TDH-39 supra-aural headphones and B-70 bone conductor calibrated in dBHL.	January 2004
Soundproof booth	Used for on-site screening audiometry and speech reception threshold determination. Booth was single walled and measured 1 m by 1 m. The booth was necessary to reduce ambient noise levels during audiometric testing in accordance with SANS 10182 (2006).	January 2004 (ambient noise levels measured)

3.6.3 Procedure for participant selection

The procedures for participant selection for the participant groups with normal hearing and with hearing loss differed. Each procedure is set out below.

3.6.3.1 Participant group with normal hearing

The participants with normal hearing were recruited from colleagues and friends of the researcher. The participants with normal hearing were supplied with an information form (Appendix A) and were given information about the study verbally. If individuals were willing to participate in the study, they were asked to complete the informed consent form (Appendix B) and the case history questionnaire (Appendix D). On receipt and review of the case history questionnaire, individuals with previous or ongoing history of neurological pathology or individuals taking central nervous system drugs were excluded from the study.

Normal middle ear function was confirmed by otoscopy, tympanometry and acoustic reflex measurement at 1 kHz performed immediately prior to SCAEP and ASSR threshold determination. Otoscopy was performed using a hand held otoscope. During otoscopic examination, the ear canal had to be unoccluded, free of discharge or redness. The tympanic membrane had to appear translucent and pearly grey. The landmarks, including the cone of light, the pars tensa, pars flaccida and the handle of the malleus should be visualized (Castillo & Roland, 2007). Abnormalities would include change in colour, retraction, bulging or perforation of the tympanic membrane and absent or indistinct landmarks. Participants in the study were required to present with a Type A tympanogram (compliance = 0.27 to 2.8 cc^3; peak pressure = +50 to -150 daPa; Jerger, 1970) and an acoustic reflex elicited by a 1 kHz stimuli at an intensity of 100 dBHL. Individuals with Type B (compliance = $<$ 0.27 cc^3; peak pressure = no peak) or Type C (compliance = 0.27 to 2.8 cc^3; peak pressure = $\geq$ -200 daPa) tympanograms (Jerger, 1970) were excluded from the study.

Behavioural PT, air conduction thresholds were determined on the day of assessment after SCAEP and ASSR threshold determination by an audiologist. PT stimuli were presented via TDH-39 supra-aural headphones. Behavioural PT threshold testing began at 1 kHz in the ear perceived by the individual to be the better ear (if any). Behavioural PT thresholds were determined using the Carhart-Jerger modified Hughson-Westlake method (Hall & Mueller, 1997) with 5 dBHL increments. The initial stimulus intensity at each frequency was 60 dBHL. A response led to the intensity being decreased by 10 dBHL. If there was no response to the initial stimulus, the stimulus intensity was increased by 10 dBHL until a response was obtained. Hereafter, a 5 dBHL increase ensued when a no response was obtained. Threshold was defined as the lowest intensity at each frequency where 50% of stimuli were responded to. The order of behavioural PT threshold determination in each ear was as follows: 1, 0.5, 0.25, 2, 3, 4, 6, 8 kHz. After behavioural PT thresholds were determined for the better ear, the procedure was repeated at each frequency in the opposite ear. In order to be consistent with the criteria for participation in study for the group with normal hearing, individuals were required to present with behavioural PT thresholds at 0.125 to 8 kHz of 20 dBHL or less in accordance with the Jerger and Jerger (1980) classification method of hearing sensitivity.

Speech reception threshold was also measured and compared to the behavioural PT average to ensure reliability and validity of thresholds. The speech reception threshold was determined while the individual was seated within a soundproof booth compliant with the standards required by SANS 10182 (2006). The Young, Dudley and Gunter (1982) spondee word list was presented using monitored live voice. The spondaic words were presented in the individual's preference of English or Afrikaans. The initial stimulus level was established by calculating the behavioural PT average for 0.5, 1, and 2 kHz and adding 30 dBHL (Thibodeau, 2007). If the initial response was incorrect, the stimulus level was increased to 50 dBHL above the behavioural PT average. The stimulus intensity was decreased by 10 dBHL when the individual was able to correctly repeat the spondee and increased by 5 dBHL when the individual was unable to correctly repeat the spondee. The speech reception threshold was defined as the intensity where 50% of the spondees were correctly identified. The aforementioned procedure of speech reception threshold determination was advocated by Martin and Dowdy (1986). A discrepancy of more than 7 dBHL between speech reception threshold and behavioural PT average (Hall & Mueller, 1997) resulted in exclusion of the individual from participation in the study.

3.6.3.2 Participant group with hearing loss

The procedure followed for selection of participants with hearing loss is displayed diagrammatically in Figure 3.3.

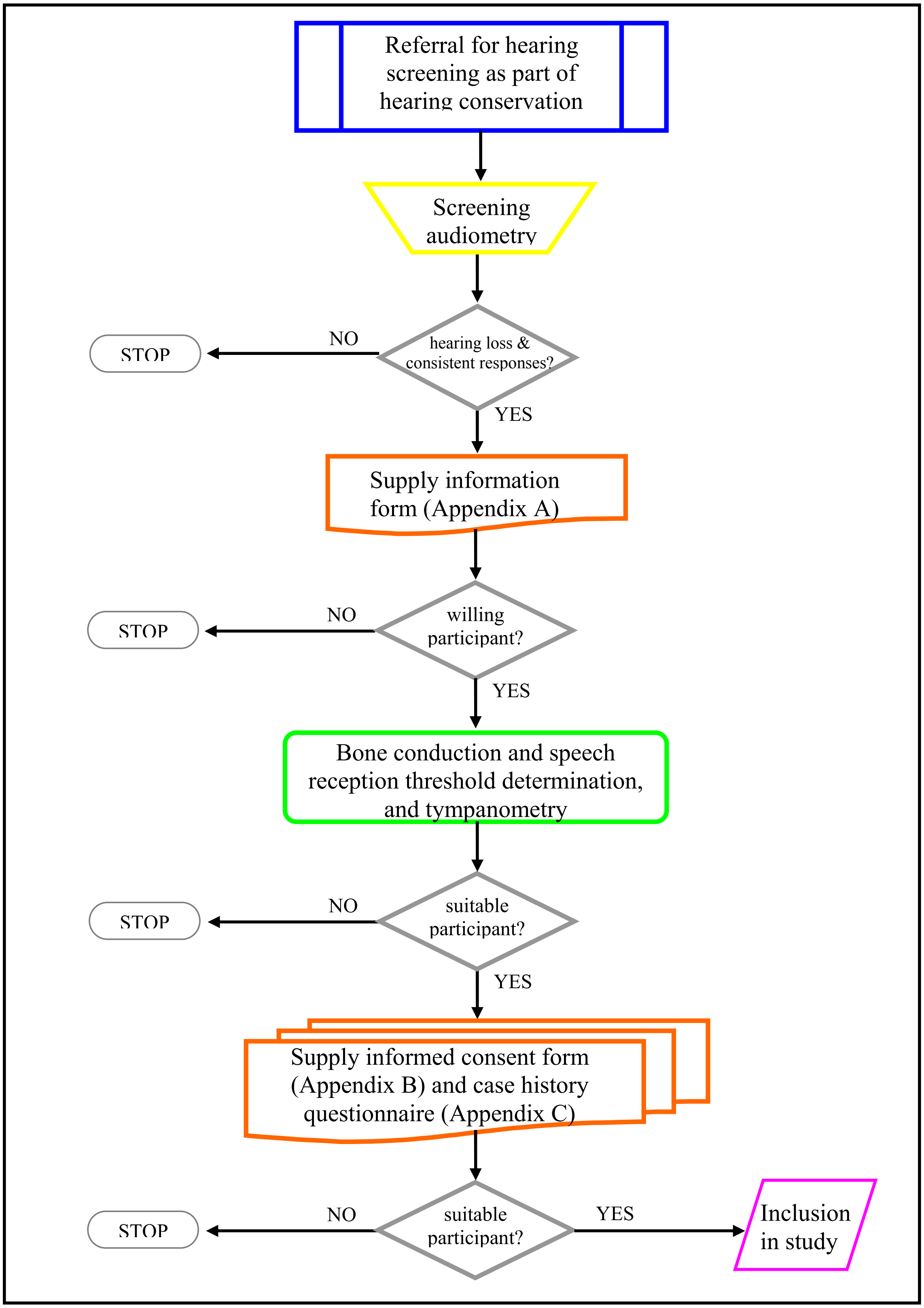


FIGURE 3.3 Procedure for participant selection for participant group with hearing loss

The participants with hearing loss were recruited from adults exposed to occupational noise, who were referred for audiometric screening as part of a hearing conservation program in accordance with SANS 10083 (2004). Behavioural PT screening audiometry took place in an on-site soundproof booth at Pretoria Porcelain and Cement in Olifantsfontein in Midrand, Gauteng. The booth complied with the limits for ambient noise as stipulated in SANS 10182 (2006) for screening audiometry. Ambient noise was therefore measured within the booth as less than 45 dBA, with a sound insulation index of at least 35 dB. An Interacoustics AD229 audiometer was used to perform the diagnostic behavioural PT audiometry. The audiometer underwent electroacoustic calibration prior to commencement of employee testing at the PPC factory in accordance with the procedures stipulated in SANS 10154-1 (2004) and SANS 10154-2 (2004). Calibration of the instrument was completed by a SABS certified professional as required by the South African Measuring Units and National Measuring Standards Act, 18 of 2006 (2007) and described in SANS 17025 (2005). Daily biologic calibrations were also performed with reference to the audiologist's behavioural PT thresholds.

Prior to behavioural PT audiometry of each employee, otoscopic examination was carried out by an audiologist. During otoscopic examination, the ear canal had to be unoccluded, free of discharge or redness. The tympanic membrane had to appear translucent and pearly grey. The landmarks, including the cone of light, the pars tensa, pars flaccida and the handle of the malleus should be visualized (Castillo & Roland, 2007). Abnormalities would include change in colour, retraction, bulging or perforation of the tympanic membrane and absent or indistinct landmarks. Screening behavioural PT audiometry was then performed by an audiologist. PT stimuli were presented via TDH-39 supra-aural headphones. The same procedure for behavioural PT audiometry followed for the selection of participants for the group with normal hearing was used for the selection of participants with hearing loss. Behavioural PT thresholds were determined for the better ear then repeated at each frequency in the opposite ear.

Individuals were offered information on the study if they presented with a hearing loss, responded reliably during determination of behavioural PT thresholds as judged by an experienced audiologist, and if there were no abnormalities visible during otoscopic examination. These individuals were supplied with the participant information form (see

Appendix A). If the individual was unable to read or completely comprehend the contents of the form, this was explained to them by an interpreter or audiologist who could speak the individual's home language. Any additional questions regarding participation in the study was answered by the researcher and interpreter.

Individuals willing to participate in the study then underwent behavioural PT bone conduction threshold determination, speech reception testing and tympanometry directly thereafter, prior to their return to their workstations. If any individual displayed a difference between air conducted behavioural PT thresholds in the right and left ears of greater than or equal to 40 dB (Katz & Lezynski, 2002), the aforementioned tests were proceeded by determination of masked air conducted behavioural PT thresholds. Masked air conduction, bone conduction, speech reception testing and tympanometry were completed by an audiologist.

For the determination of masked air conduction behavioural PT thresholds, the masking technique advocated by Katz and Lezynski (2002) was adhered to. The initial masking level was 20 dB above the individual's air conducted behavioural PT thresholds of the non-test ear, at each frequency. If the individual responded to the air conducted PT stimulus in the test ear with masking present in the non-test ear, no further masking was required. The intensity was marked as the threshold air conducted behavioural PT threshold. If the individual did not respond to the air conducted PT stimulus in the test ear, the stimulus intensity was increased and decreased using the Carhart-Jerger modified Hughson-Westlake method (Hall & Mueller, 1997). If the new behavioural PT threshold response fell within 10 dB of the original air conduction behavioural PT thresholds, no further masking was required. The original threshold intensity was marked as the threshold air conducted behavioural PT threshold. A shift in behavioural PT threshold of 15 dB or more resulted in a 20 dBHL increase in the intensity of the narrow band masking in the non-test ear. The aforementioned process was repeated until the air conduction behavioural PT threshold response was determined.

Bone conduction audiometry was performed using a B-70 bone conductor as the transducer for 0.25 to 4 kHz PT stimuli. Behavioural PT bone conduction threshold testing began at 1 kHz in the ear with the poorer behavioural PT air conducted thresholds with the non-test ear unoccluded. Behavioural PT, bone conduction, thresholds were determined using the Carhart-Jerger modified Hughson-Westlake method (Hall & Mueller, 1997) with 5 dBHL increments. The initial stimulus intensity at each frequency was 20 dBHL above the behavioural PT air conduction thresholds. A response led to the intensity being decreased by 10 dBHL. If there was no response to the initial stimulus, the stimulus intensity was increased by 10 dBHL until a response was obtained. Hereafter, a 5 dBHL increase ensued when a no response was obtained. Threshold was defined as the lowest intensity at each frequency where 50% of stimuli were responded to. The order of behavioural PT threshold determination in each ear was as follows: 1, 0.5, 0.25, 2, 3, 4 kHz. Masking using narrow band noise was introduced in the better ear when behavioural PT air conduction and bone conduction thresholds differed by more than 5 dBHL (Katz & Lezynski, 2002). The masking technique advocated by Katz and Lezynski (2002) was adhered to. The initial masking level was 20 dB above the individual's air conducted behavioural PT thresholds of the non-test ear, at each frequency. Initial masking level was increased by 15 dB when testing 0.25 and 0.5 kHz, and by 10 dB when testing 1 kHz to compensate for occlusion effect when the individual presented with normal hearing or with a sensorineural hearing loss in the non-test ear. The same procedure described for determination of masked air conduction behavioural PT thresholds was followed for masked bone conduction behavioural PT thresholds. After masking was completed for behavioural PT bone conduction thresholds in the poorer ear, the bone conductor was placed on the opposite mastoid and the masking procedure was repeated for any frequencies which demonstrated a 5 dBHL difference between behavioural PT air and bone conduction thresholds. Individuals were considered potential candidates for participation in the study in the group with hearing loss if behavioural PT audiometry indicated a sensorineural hearing loss. A sensorineural hearing loss is defined as individuals with behavioural PT thresholds greater than 20 dBHL at any frequency from 0.25 to 8 kHz with a difference between air and bone conduction behavioural PT thresholds of less than or equal to 5 dBHL (Stach, 1998).

The speech reception threshold was determined, while the individual was seated within a soundproof booth compliant with the standards required by SANS 10182 (2006). The Young et al. (1982) spondee word list was presented using monitored live voice. The spondaic words were presented in the individual's preference of English or Afrikaans. The procedure used during speech reception testing for selection of participants with normal hearing was followed for the selection of participants with hearing loss. Individuals who demonstrated correlation of less than or equal to 7 dBHL between speech reception thresholds and the behavioural PT average for 0.5, 1 and 2 kHz (Hall & Mueller, 1997), and who presented with Type A tympanograms (compliance = 0.27 to 2.8 cc^3; peak pressure = +50 to -100 daPa; Jerger, 1970) were deemed potential participants. The presence of an acoustic reflex at 1 kHz was not required for individuals with a hearing loss, as this would vary depending on the individual's behavioural PT threshold (and severity of the hearing loss) at 1 kHz. Individuals with Type B (compliance = $<$ 0.27 cc^3; peak pressure = no peak) or Type C (compliance = 0.27 to 2.8 cc^3; peak pressure = $\geq$-100 daPa) tympanograms (Jerger, 1970) were excluded from the study. Individuals who met the criteria for participation in the study in the group with hearing loss, were asked to complete and return an informed consent form (see Appendix B) and a case history questionnaire (see Appendix D) to the researcher in person or by post. This procedure was in keeping with research best practice guidelines which require freely given informed consent to be obtained from every participant prior to participation in the study (South African Department of Health, 2000; South African National Health Act, 2007). On receipt and review of the case history questionnaire, individuals with previous or ongoing history of neurological pathology, or individuals taking central nervous system drugs were excluded from the study.

3.6.4 Description of participants

Participants were divided into two participant groups. The groups were referred to as the group of participants with normal hearing (i.e. behavioural PT thresholds of 20 dBHL or less; Jerger & Jerger, 1980) and the group with hearing loss (i.e. behavioural PT thresholds of $>$ 20 dBHL; Jerger & Jerger, 1980). In addition to the difference in hearing sensitivity, the participants in only the group with hearing loss were all exposed to occupational noise.

3.6.4.1 Participant group with normal hearing

Fifteen participants (28 ears) were included in the group with normal hearing. The data of two ears were excluded from the study, as a conductive hearing loss was present in these ears. For the purpose of categorization of degree of hearing loss, use was made of the Jerger and Jerger (1980) classification method, which defines normal hearing as behavioural PT thresholds at 0.125 to 8 kHz of 20 dBHL or less. The mean age of the participants was 32 years, and ranged from 19 to 61 years. A Wilcoxon signed rank test (Welkowitz, Cohen, & Ewen, 2006) indicated no significant difference between the behavioural PT thresholds of the right and left ears. As a result, the data set for each ear was combined to form one single, larger sample. The motivation for doing so was to include a larger number of data points and subsequently minimizing the effect that one single data point may have.

Table 3.4 offers the mean behavioural PT threshold with standard deviations and range of behavioural PT thresholds for this group of participants.

TABLE 3.4 Group with normal hearing (n = 28): Mean behavioural PT thresholds (dBHL)

	500 Hz	1000 Hz	2000 Hz	4000 Hz	Mean threshold of 0.5, 1, 2 & 4 kHz
Mean behavioural PT threshold	3.8	1.1	0.0	2.0	1.7
Standard deviation	3.2	3.9	4.5	5.3	4.5
Range	0 to 10	-5 to 10	-10 to 5	-5 to 15	-10 to 15

The mean behavioural PT thresholds all fall below 5 dBHL with a mean threshold across 0.5, 1, 2 and 4 kHz of 1.7 dBHL.

3.6.4.2 Participant group with hearing loss

Sixteen participants with hearing loss were included in the participant group with hearing loss. The data of two ears were excluded from the study, as a conductive hearing loss was present in one ear of one participant, while another participant had one ear with normal hearing. Data was therefore collected from 30 ears in the participant group with hearing loss. The mean age of the participants was 52 years, and ranged from 42 to 62 years. The mean age between the groups of participants with normal hearing and with hearing loss is clearly very different and should ideally have been more similar. The higher mean age for the participants with hearing loss is, however, inevitable when evaluating individuals exposed to occupational noise, as older participants are likely to be exposed to occupational noise for a greater period of time, resulting in increased risk of occupational noise induced hearing loss and elevated behavioural PT thresholds, than for younger participants. A mean age of greater than 50 years for the participants with hearing loss is also often reported in the literature in studies comparing or evaluating estimated behavioural PT thresholds (Hyde et al., 1986; Tomlin et al., 2006; Tsui et al., 2002; Van Maanen & Stapells, 2005) and is typical of the target population. In addition, the key comparisons performed in the study were made within participants, between the estimated behavioural PT thresholds obtained by two separate techniques. For the purpose of this study, therefore, the age difference between the two groups was considered to have little impact.

A Wilcoxon signed rank test (Welkowitz et al., 2006) indicated no significant difference between the behavioural PT thresholds of the right and left ears, enabling the data sets for each ear to be combined to form one single, larger sample. Table 3.5 displays the mean behavioural PT thresholds with standard deviations and range of behavioural PT thresholds.

TABLE 3.5 Group with hearing loss (n = 30): Mean behavioural PT thresholds (dBHL)

	500 Hz	1000 Hz	2000 Hz	4000 Hz	Mean threshold of 0.5, 1, 2 & 4 kHz
Mean behavioural PT threshold	10.5	10.8	21.0	47.3	22.4
Standard deviation	9.7	10.3	16.1	16.2	20.1
Range	-5 to 35	-5 to 30	-10 to 50	15 to 85	-10 to 85

As is typical of the population targeted in this study, namely individuals exposed to occupational noise, the group with hearing loss typically presented with a high frequency sloping hearing loss. For the purpose of categorization of degree of hearing loss, use was made of the Jerger and Jerger (1980) classification method. The average hearing loss was mild to moderate in degree in the high frequencies (2 to 4 kHz), while the low and mid frequency behavioural PT thresholds fell within normal limits (Jerger & Jerger, 1980). The mean behavioural PT thresholds at 0.5 and 1 kHz are ≤ 20 dBHL, behavioural PT thresholds were on average 7 to 9.7 dBHL higher than the mean thresholds at 0.5 and 1 kHz for the group with hearing loss. The mean behavioural PT threshold across all four frequencies was 22.4 dBHL. The standard deviation for the mean behavioural PT thresholds was greater at all frequencies than that for the group with normal hearing, with the greatest standard deviation at 4 kHz, which was also the frequency with the highest mean behavioural PT threshold. The highest frequency, 4 kHz, was also the frequency with the greatest hearing threshold of the four listed in Table 3.5 for all but one ear of the group with hearing loss. With respect to degree of hearing loss at 4 kHz only, seven ears (23.3% of the participant group with hearing loss) presented with a mild hearing loss of less than 40 dBHL at 4 kHz, 15 ears presented with a moderate hearing loss of 40 to 59 dBHL (50%), six ears had a severe hearing loss of 60 to 79 dBHL (23.3%), and only two ears participants displayed a profound hearing loss of greater than 80 dBHL (6.7%) at 4 kHz.

3.7 RESEARCH MATERIAL AND APPARATUS

The apparatus used in order to achieve the main aim and sub-aims of the study is described below, in Table 3.6.

TABLE 3.6 Apparatus used to acquire data

Equipment	Description and purpose	Transducer	Disposables
Heine 2000 mini otoscope	Otoscopy was performed prior to audiometry and AEP assessment to ensure there was no signs of middle ear pathology visible and nothing obstructing the external auditory meatus that would preclude the use of insert earphones.		
Soundproof booth	Behavioural PT threshold measurement took place with each participant seated in a 2 m by 2 m double-walled soundproof booth. The booth is necessary to reduce ambient noise levels during audiometric testing in accordance with SANS 10182 (2006).		
GSI 61 diagnostic audiometer	Behavioural PT audiometry was performed on the day of the AEP assessment using the GSI 61 audiometer to ensure accuracy of behavioural PT thresholds and (in the case of participants with hearing loss) to ensure there was no deterioration in behavioural PT thresholds since screening audiometry.	TDH-39 supra-aural headphones calibrated in dBHL were used during behavioural PT audiometry.	
GSI Audera eletrophysiological system	Both SCAEP and ASSR were completed using the GSI Audera electrophysiological system with 32-bit application software (GSI, 2003). The GSI Audera is a Grason-Stadler device that was first manufactured by ERA Systems Inc. and based on ASSR research at the University of Melbourne. Use of one electrophysiological system to determine both SCAEP and ASSR thresholds eliminated potential variables that could be introduced had two systems been used.	GSI TIP 50 insert HA-2 tubephones were used with for AEP measures. Stimuli were calibrated in dBHL for ASSR testing and in dBnHL (decibel normal hearing level) for SCAEP testing in the GSI Audera system (GSI, 2003).	10 or 13 mm 3A foam eartips were used with the TIP 50 insert tubephones (size chosen depending on ear canal size). Four 6 mm silver chloride cup electrodes filled with electrolytic paste were used during AEP measurement. The contact surfaces were abraded using Omniprep abrasive electrode paste and a gauze pad. The electrodes were secured using micropore tape.

3.7.1 Audiometer

The Grason Stadler GSI 61 clinical audiometer was used for behavioural PT threshold measurement. PT stimuli were presented through TDH-39 earphones. The audiometer was calibrated in January 2004 in accordance with SANS 10154-1 (2004) specifications, prior to commencement of participant assessment sessions. Calibration of the instrument was completed by a SABS certified professional as required by SANS 17025 (2005). Daily biological calibrations were also performed with the audiologist's behavioural PT thresholds as reference.

3.7.2 AEP system

The GSI Audera electrophysiological system (GSI, 2003) was used for both SCAEP and ASSR threshold measurement. The GSI Audera software version 1.0.3.4 was used. The GSI Audera underwent calibration, prior to commencement of participant assessment in January 2004, and again in June 2004 (after 20 participants had undergone SCAEP and ASSR threshold determination). The second calibration was included in order to confirm calibration accuracy and to ensure that consistent measures were obtained throughout the data collection period. Calibration of the GSI TIP 50 insert HA-2 tubephones was done using a Larson Davis 824 type 1 sound level meter, artificial ear and a 711 coupler. The insert earphones were calibrated in dBHL at 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 6 and 8 kHz, at intensities of 0 to 130 dBHL, in accordance with SANS 10154-1 (2004). Calibration of the AM (amplitude modulation) frequency ranged from 20 to 200 Hz, while a 1 to 100% AM depth was calibrated in 1% steps. FM (frequency modulation) was calibrated 1 to 15% of the tonal frequency. Calibration of the instrument was completed by a SABS certified professional as required by the South African Measuring Units and National Measuring Standards Act, 18 of 2006 (2007) and described in SANS 17025 (2005). In addition, sub-aim one compared behavioural thresholds for tone burst stimuli (used for SCAEP) and for AM/FM tones (used for ASSR) for the participants with normal hearing in order to determine if the stimuli were directly comparable, or if calibration differences and differences between stimuli characteristics (i.e. transient versus continuous stimulus) needed to be accounted for prior to comparison of the SCAEP and ASSR thresholds obtained.

3.7.3 Stimulus and recording parameters

The preliminary study was performed prior to the data collection to enable the researcher to determine whether the proposed stimulus parameters were appropriate for use in the current study. The stimuli parameters used for the tone burst stimuli employed during SCAEP testing and the parameters used for the AM/FM stimuli employed during ASSR testing were retained for the purpose of behavioural threshold determination using the tone burst stimuli and the AM/FM stimuli.

Due to the importance of an alert state of attention for SCAEP threshold determination, the ASSR threshold determination was completed after SCAEP threshold determination. The GSI Audera's recommended protocol for ASSR stimulus and acquisition parameters was used. The GSI Audera offers the choice of two test protocols for ASSR assessment with adults, each of which incorporates a specific noise threshold limit for each frequency tested (GSI, 2003). The '> 10 years asleep' protocol makes use of a high modulation rate (74 to 95 Hz) and a low noise threshold. The '> 10 years awake' protocol makes use of a low, 46 Hz modulation rate and a high noise threshold. The '> 10 years awake' protocol with the lower, 46 Hz modulation rate was chosen for use during ASSR recording while participants slept, because this led to lower noise levels and because the long assessment session promoted sleep in all of the participants during the preliminary study.

On conclusion of the preliminary study, the stimulus and recording parameters used throughout the study were resolved as presented in Tables 3.7 and 3.8. The stimulus parameters presented in Table 3.7 were used for both behavioural threshold determination using tone burst stimuli and AM/FM stimuli, as well as for threshold estimation using SCAEP and ASSR.

TABLE 3.7 Stimulus recording parameters for behavioural PT threshold estimation using SCAEP and ASSR (GSI, 2003)

Parameter	SCAEP	ASSR
Type	Tone burst	100% AM; 15% FM tones
Duration	Transient 10 ms rise-fall 80 ms plateau	Continuous
Frequency	0.5, 1, 2, 4 kHz	0.5, 1, 2, 4 kHz
Rate	0.7/s	46 Hz
Polarity	Alternating	N/A
Sweeps	20	16 to 64
Replications	2 to 3	1 to 2
Presentation ***Ear(s)*** ***Mode***	 Monaural Air conduction	 Monaural Air conduction
Calibration	dBnHL	dBHL
Transducer	Insert earphones (ER-3A)	Insert earphones (ER-3A)

(AM = amplitude modulated tones; FM = frequency modulated tones; ms = milliseconds; Hz = Hertz; kHz = kilo Hertz; / s = per second; N/A = not applicable)

The acquisition parameters presented in Table 3.8 were used for the threshold estimation using SCAEP and ASSR techniques.

TABLE 3.8 Parameters for data acquisition for behavioural PT threshold estimation using SCAEP and ASSR (GSI, 2003)

Parameter	SCAEP	ASSR
Analysis time ***Overall*** ***Prestimulus***	 -10 to +500 ms -10 ms	 N/A N/A
Sample points	512	8 192
Gain	50 000	100 000
Sensitivity	50 $\pm$ µV	50 $\pm$ µV
Bandpass filters	1 to 15 Hz @ 6 to 12 dB / octave (Lightfoot et al., 2002; Stapells, 2002); Blackman filter + SCAEP low pass filter	3 to 5 kHz
Response detection	Subjective, by experienced evaluators	Objective, using phase coherence ($p<0.01$)
Electrodes ***Channel 1*** ***Ground***	 Cz-Ai Fz	 Cz-Ai Fz

(ms = milliseconds; N/A = not applicable; µV microvolts; Hz = Hertz; kHz = kilo Hertz; Cz = midline vertex; Ai = ipsilateral earlobe; Fz = midline high forehead)

Acquisition and stimulus parameters for both SCAEP and ASSR are as per the GSI Audera recommended protocol, unless otherwise stated (GSI, 2003).

The electrode montage selected for use was the same for both ASSR and SCAEP. The inverting (negative) electrode was placed on the ipsilateral earlobe (Ai) with the non-inverting (positive) electrode on the midline vertex (Cz). The ground electrode was placed on the midline high forehead (Fz). This configuration was shown to be effective for ASSR and SCAEP recording (GSI, 2003; Hall, 1992; Stürzbecher, Cebella, & Pschirrer, 2001). These authors claim that, compared with other electrode montages, the signal to noise ratio is largest. A high signal to noise ratio is desirable, because it leads to a higher response amplitude (Hood, 1998) and reduces testing time (Van der Reijden et al., 2001). Stürzbecher et al. (2001) state that the larger stimulus artefact caused by ipsilateral ear lobe electrode placement is not critical, since there is sufficient distance between the response and artefact in the frequency spectrum for middle and later latency AEP. The Ai-Cz electrode montage is therefore suitable for use with ASSR and SCAEP. There are, however, studies that contradict the findings of Stürzbecher et al. (2001), suggesting novel ASSR electrode placement rather than the conventional, more widely utilized montage as was selected for use during this study (Van der Reijden et al., 2001). Due to the convenience of using the same electrode configuration for the two AEP within the same assessment which are considered appropriate for both SCAEP and ASSR (Stürzbecher et al., 2001; Hall, 1992), the Ai-Cz with ground at Fz was, however, used in the current study. The electrode impedances were monitored periodically throughout each assessment to ensure impedances did not exceed 5 kΩ and that the difference between any two electrodes was less than or equal to 2 kΩ (Arnold, 2007).

3.7.4 Data collection material

The data collection form presented in Appendix E was used to document the following information during the assessment session of each participant:

- Behavioural tone burst threshold for 0.5, 1, 2 and 4 kHz for each ear
- Behavioural AM/FM tone threshold for 0.5, 1, 2 and 4 kHz for each ear
- Start and finish time for SCAEP threshold acquisition

- Start and finish time for ASSR threshold acquisition
- Clinician's subjective observation of participant's state of consciousness during SCAEP
- Clinician's subjective observation of participant's state of consciousness during ASSR

3.8 DATA COLLECTION PROCEDURES

The sequencing of the assessment procedure was selected in order to maximise participant state of alertness during the SCAEP. Drowsiness results in reduction in the amplitude of wave N1 and therefore elevates the level of SCAEP threshold responses (Davis, 1976; Hyde, 1997; Picton & Hillyard, 1974; Stapells, 2002). AEP stimulus and recording parameters were selected in order to facilitate SCAEP and ASSR threshold response detection. Personal biases were minimized by requiring agreement on the SCAEP threshold response between two clinicians familiar with interpretation of SCAEP. Validity and accuracy was also improved hereby. Finally, the inclusion of the preliminary study was necessary to ensure that the data collection procedure, the stimulus acquisition parameters and stimulus recording parameters facilitated the acquisition of the data as set out in each sub-aim.

3.8.1 Preliminary study

The preliminary study was performed prior to data collection with the group of participants with normal hearing. The preliminary study included participation of three young adult males with normal middle ear function and normal hearing sensitivity. Normal hearing sensitivity was defined as behavioural PT hearing thresholds of less than or equal to 20 dBHL at 0.125 to 8 kHz (Jerger & Jerger, 1980). A preliminary study enabled the researcher to determine whether the proposed data acquisition procedure was practically executable and whether the AEP stimulus parameters were appropriate for use in the study.

It was initially proposed that SCAEP and ASSR thresholds would be determined at 0.5, 1, 2, 3 and 4 kHz. These frequencies were selected for behavioural PT threshold estimation, as behavioural PT threshold data is required at these five frequencies for determination of percentage loss of hearing, in accordance with current South African legislation on occupational noise induced hearing loss (COIDA, 2001; SANS 10083, 2004). Inclusion of 3 kHz, however, further extended the already lengthy assessment session. The length of the assessment session had a detrimental effect on the participant attention and state of consciousness during the recording of the SCAEP, and participants often had to be prompted to remain alert. It was therefore decided that thresholds would only be determined at 0.5, 1, 2 and 4 kHz. The exclusion of 3 kHz had no negative effect on achievement of the aim or sub-aims of the study.

A review of the SCAEP literature on the recommended analysis time suggested a 50 to 500 ms prestimulus period (Hall, 1992; Hyde, 1997; Lightfoot et al., 2002; Stapells, 2002). The GSI Audera software, version 1.0.3.4, however, only allowed a maximum prestimulus period of 10 ms. The analysis time of 1000 ms post stimulus onset was recommended by Hyde (1997), Lightfoot et al. (2002) and Stapells (2002). The broad time base was recommended to facilitate identification of the P1-N1-P2 slow cortical waveform. The resulting display was, however, difficult to analyse in the opinion of the researcher, with the relevant waveforms compressed at the beginning of the display. An analysis time of 500 ms post stimulus onset displayed all the relevant waveforms, as well as some of the waveforms after the slow cortical waveform. An analysis time of –10 to 500 ms was therefore utilized for the study.

The GSI Audera software also did not allow for the adjustment of the rise-fall times and plateau of the tone burst for SCAEP. The default stimulus envelope was therefore used, namely 10 ms rise-fall time and 80 ms plateau (GSI, 2003). In addition, a comparison of the 1 to 15 Hz and the 1 to 30 Hz bandpass filter during the preliminary study revealed a noisier recording with the 1 to 30 Hz filter, making identification of the SCAEP waveforms more difficult. The researcher preferred and used the clearer display offered through application of the 1 to 15 Hz bandpass filter for the study.

During the preliminary study, an intraparticipant comparison of the two manufacturer recommended ASSR test protocols was carried out. The '> 10 years asleep' protocol makes use of a high modulation rate (74 to 95 Hz) and a low noise threshold (GSI, 2003). The '> 10 years awake' protocol makes use of a low, 46 Hz modulation rate and a high noise threshold (GSI, 2003). With the '> 10 years asleep' protocol, a threshold response could not be obtained at an intensity of 80 dBHL or less for the majority of the frequencies tested in two of the three participants with normal hearing. Excessive artefacts and noise responses were noted at the frequencies where thresholds could not be obtained, regardless of the fact that all participants slept peacefully throughout ASSR recording and that the testing took place within a double walled soundproof booth. This same observation was reported by Luts and Wouters (2005) and Van Maanen and Stapells (2005). Luts and Wouters (2005) reported that seven out of 10 of the participants with hearing loss could not be tested using the 80 Hz modulation rate protocol of the GSI Audera software, as noise levels exceeded the default noise criterion. Van Maanen and Stapells (2005) rejected 23 participants from the study (data was collected from 43 participants) due to excessive noise levels during ASSR measurement. Of these, three were from the 40 Hz multiple ASSR group and 20 were from the 80 Hz ASSR group. The GSI Audera software does not allow for an extension of recording time in order to overcome high EEG noise (GSI, 2003). In contrast, when using the '> 10 years awake' protocol, noise responses were significantly reduced and phase locked responses could be obtained at all frequencies for all three participants. No marked improvement in thresholds was obtained across all frequencies with this protocol when recorded with the participant awake or asleep, but noise levels were lower when the participants were asleep. The study by Dobie and Wilson (1998) on the effect of state and rate on the detectability of an ASSR at low stimulus intensity levels concluded that ASSR at low intensities in adults are best recorded in either the awake or sleeping state using a modulation rate of 40 to 50 Hz. Further, as a consequence of the lengthy assessment session, all participants fell asleep during ASSR recording. Therefore, despite literature indicating that the 40 Hz ASSR responses amplitudes (suprathreshold) are attenuated by sleep (Cohen et al., 1991), the '> 10 years awake' protocol with the lower, 46 Hz modulation rate was chosen for use during ASSR recording with sleeping participants, as this led to lower noise levels, detectability of threshold responses was not negatively influenced (Dobie & Wilson, 1998) and because the long assessment session promoted sleep in all of the participants assessed during the preliminary study.

3.8.2 Procedure for data acquisition

Behavioural PT audiometry, behavioural tone burst threshold determination, behavioural AM/FM threshold determination, SCAEP, and ASSR assessment were performed in a two by two meter double walled sound proof booth on the same day for each participant. The procedure for data acquisition is displayed in Figure 3.4 on the next page.

The procedure depicted in Figure 3.4 is described in steps I to VII below.

I. The assessment session began with otoscopic inspection of the ears of each participant, for any obstruction in the external meatus, discharge or redness that would prevent insertion of insert earphones (Castillo & Roland, 2007). The tympanic membrane had to appear translucent and pearly grey. The landmarks of the tympanic membrane including the cone of light, the pars tensa, pars flaccida and the handle of the malleus had to be visualized (Castillo & Roland, 2007). Abnormalities would include change in colour, retraction, bulging or perforation of the tympanic membrane and absent or indistinct landmarks. Any visible abnormalities would result in the individual or the ear in question being excluded from the study, as specified in the participant selection criteria.

II. A two channel electrode montage, namely vertex and ipsilateral ear lobe (Cz-Ai) with ground on the high forehead (Fz). This montage was chosen for AEP measurement as it was appropriate for use with both SCAEP and ASSR measurement, and is the manufacturer recommended protocol for the GSI Audera system (GSI, 2003). Four silver chloride cup electrodes filled with electrolytic paste were used. The contact surfaces were abraded, prior to securing of the electrodes with tape. Electrode contact impedances were measured prior to AEP measurement to ensure they were 5 kΩ or less, and that the difference between any two electrode impedances was no greater than 2 kΩ (Arnold, 2007).

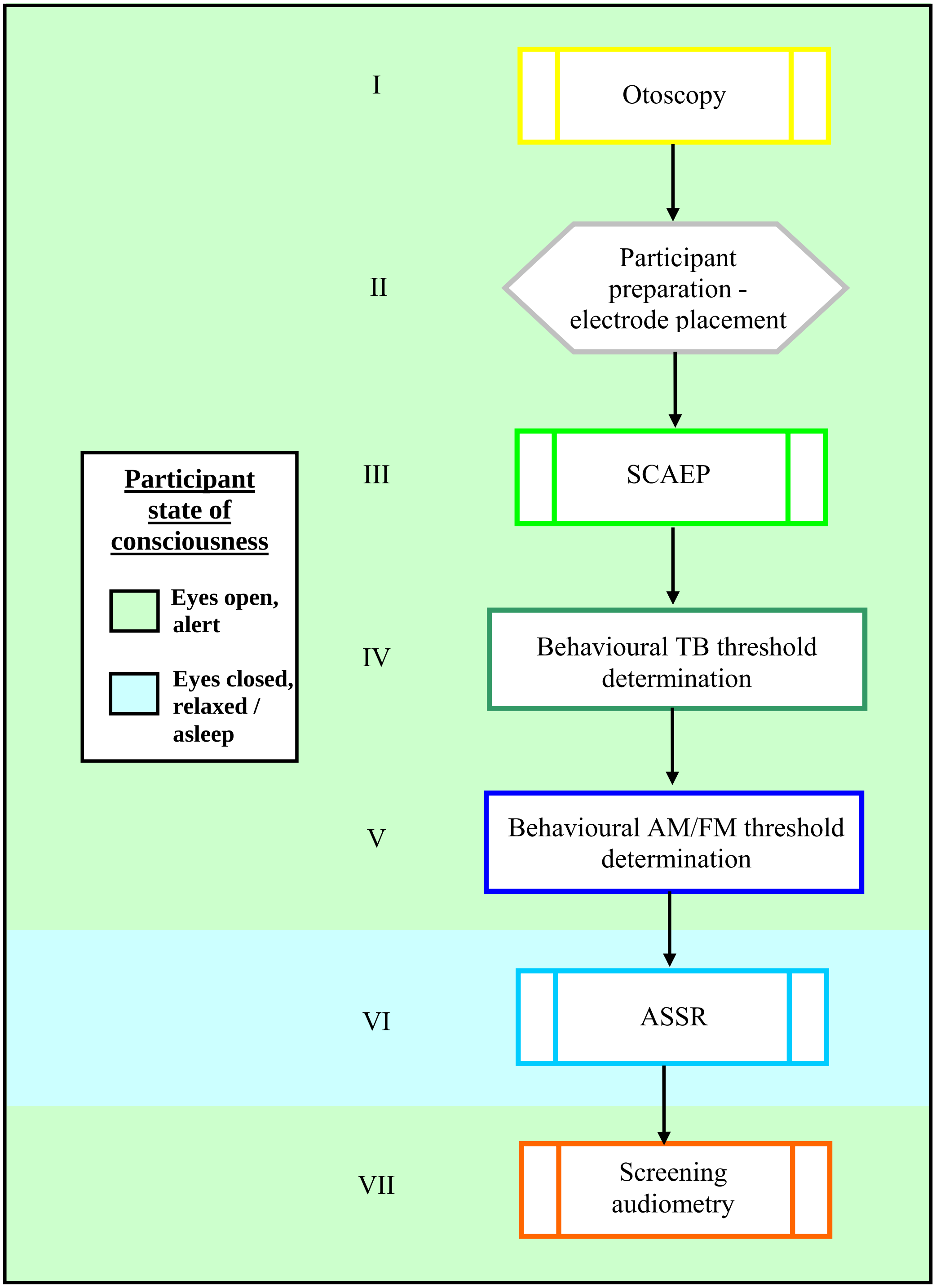


FIGURE 3.4 Procedure for data acquisition for each participant

III. Following electrode placement objective threshold determination using SCAEP took place. The participant was instructed to sit still with eyes open and alert, or to read. SCAEP thresholds were determined for what the participant perceived to be the better ear first, followed by the opposite ear at 0.5, 1, 2 and 4 kHz. An adaptive bracketing technique was used to determine the SCAEP thresholds with 10 dBnHL minimum increments or decrements. For participants in the group with normal hearing, the initial stimulus intensity at each frequency was 40 dBnHL with a maximum stimulus intensity of 80 dBnHL, while a 60 dBnHL initial stimulus was used for the participants with hearing loss and a maximum stimulus intensity of 100 dBnHL. When a response was judged to be present by the researcher, the stimulus intensity was decreased by 20 dBnHL. If there was no response to the stimulus, the stimulus intensity was increased by 10 dBnHL until a response was obtained. A SCAEP response was defined as the presence of the P1-N1 complex between 80 and 150 ms (Hyde, 1997; Prasher et al., 1993).

The acquisition of SCAEP thresholds was timed from initial stimulus presentation, after patient preparation and electrode positioning. The timing was halted at the end of data acquisition. The start and finish time was recorded on the data collection form (see Appendix E).

IV. After SCAEP threshold determination at the aforementioned frequencies, the participant's behavioural threshold at each frequency, using the same tone burst stimuli used during SCAEP, was determined. The participant was required to indicate when the stimulus was heard by raising a finger. The Carhart-Jerger modified Hughson-Westlake method (Hall & Mueller, 1997) of threshold measurement with a minimum of 5 dBnHL increments was used. The initial stimulus intensity at each frequency was 60 dBnHL. A response led to the intensity being decreased by 10 dBnHL. If there was no response to the initial stimulus, the stimulus intensity was increased by 10 dBnHL until a response was obtained. A 10 dBnHL decrease followed a response and a 5 dBnHL increase followed no response. Threshold was defined as the lowest intensity at each frequency where 50% of stimuli were responded to. The maximum stimulus intensity was 80 dBnHL for participants with normal hearing and 120 dBnHL for participants with hearing loss. The behavioural tone burst threshold was recorded on the data collection form (see Appendix E)

V. Determination of behavioural AM/FM tone thresholds took place after behavioural toneburst threshold determination. This was done using the same format as that used during behavioural threshold determination for tone bursts described in step IV. The maximum stimulus intensity for participants with normal hearing was 80 dBHL and for participants with hearing loss was 120 dBHL. The behavioural AM/FM threshold was recorded on the data collection form (see Appendix E)

VI. ASSR measurement followed after SCAEP measurement, as ASSR at low intensities in adults can be recorded in either the awake or sleeping state using a modulation rate of 40 Hz (Dobie & Wilson, 1998), in contrast to the detrimental effect of sleep on SCAEP (Picton & Hillyard, 1974). Attention and state of arousal may have deteriorated and the participant may have fatigued as the assessment continued, due to the length of the assessment session. The order of assessment also avoided the effect of awakening after a short sleep, believed to diminish the SCAEP (Ferrara et al., 2001). The SCAEP testing was therefore performed first, followed by ASSR testing. The preliminary study indicated that sleep led to reduced noise levels during ASSR testing. Furthermore, the sequence and length of the assessment session naturally promoted sleeping during recording of the ASSR.

The procedure for ASSR data acquisition followed the same format as that of SCAEP explained in step III. The continuous nature of the ASSR stimuli meant, however, that a greater maximum stimulus intensity with the participant with hearing loss could be used, namely 120 dBHL. Participants were asked to close their eyes and relax or even sleep. ASSR threshold was defined as the minimum level at which the response was present.

The measurement of ASSR thresholds was timed from initial stimulus presentation, after patient preparation and electrode positioning. The timing was halted at termination of ASSR acquisition and automated threshold response detection. The start and finish time was recorded on the data collection form (see Appendix E).

VII. Behavioural PT audiometry took place after threshold determination using ASSR and SCAEP. Behavioural PT thresholds were again determined using the Carhart-Jerger modified Hughson-Westlake method (Hall & Mueller, 1997) with 5 dBHL increments. The initial stimulus intensity at each frequency was 60 dBnHL. A response led to the intensity being decreased by 10 dBHL. If there was no response to the initial stimulus, the stimulus intensity was increased by 10 dBHL until a response was obtained. Hereafter, a 5 dBHL increase ensued when a no response was obtained. The behavioural PT threshold was defined as the lowest intensity at each frequency where 50% of stimuli were responded to. Behavioural PT threshold determination began with the ear perceived, by the participant, to be the better ear, followed by the opposite ear. For the participants with hearing loss, the repetition of behavioural PT threshold determination on the day of AEP assessment was necessary, in order to confirm accuracy of PT thresholds and to ensure there was no deterioration in hearing sensitivity, since occupational hearing screening which was performed anything from one to six months prior to assessment for the purpose of the study. Accuracy of behavioural PT thresholds was key to validity of the study as the SCAEP and ASSR thresholds are referenced to behavioural PT thresholds. By performing behavioural PT audiometry for both participant groups on the day of assessment, variables that may have contaminated the validity of the data had SCAEP, ASSR and behavioural PT threshold determination be performed on different days, were eliminated.

3.8.3 Response detection procedure

SCAEP data collection is considered to be objective, as it is not dependent on subjective judgements or behavioural responses of the participant, but interpretation of SCAEP data is highly subjective. Despite this, Hall (1992) states that visual detection of a response is confirmed by research as adequate. Reliability, however, is highly dependent on the skills and experience of the clinician. Visual response detection by the clinician is necessary for SCAEP in the GSI Audera (GSI, 2003). Analysis of SCAEP was performed after the participant assessment, although judgements regarding whether an increase and decrease of stimulus intensity was required by the researcher during SCAEP testing.

In order to improve reliability of analysis, two clinicians familiar with interpretation of SCAEP were therefore asked to determine threshold SCAEP responses. A SCAEP response was defined as the presence of the P1-N1 complex between 80 and 150 ms (Hyde, 1997; Prasher et al., 1993). Threshold SCAEP response was defined as the lowest intensity at each frequency where the response was deemed to be present by two independent clinicians. The researcher was responsible for the administration of the data collection protocol. For the purpose of analysis, off-line scoring was carried out by the author and by a second experienced clinician who was blinded to the behavioural PT thresholds of the participants. Two clinicians were used to analyse the waveforms in order to improve reliability and validity of SCAEP thresholds. SCAEP waveforms were presented for analysis in the original form and as averaged traces across the two or three sweeps recorded at each intensity. Agreement on threshold intensity between both clinicians was accepted as the threshold response. An example of SCAEP threshold judgements was included in Appendix F. The time taken to analyse SCAEP waveforms was not added to the data acquisition time.

Whereas visual response detection was relied upon for SCAEP threshold determination, ASSR technique makes use of objective response detection. In the GSI Audera software the raw electroencephalogram (EEG) is passed through a preamplifier, bandpass filtered (10 to 500 Hz), and then Fourier analysed at each stimulus modulation rate to extract response phase and amplitude information of up to 64 samples of 1486 ms each (Cohen et al., 1991; Rance et al., 2005). The presence or absence of a response (coherence) is determined automatically with a statistical detection criterion based on non random phase behaviour, namely the phase coherence (PC^2) algorithm (Dobie & Wilson, 1993). Three types of results can occur. A 'noise' result occurs when no response is found after 64 samples were collected and when the EEG exceeds the noise threshold limit. The 'no response' result is depicted in Figure 3.5.

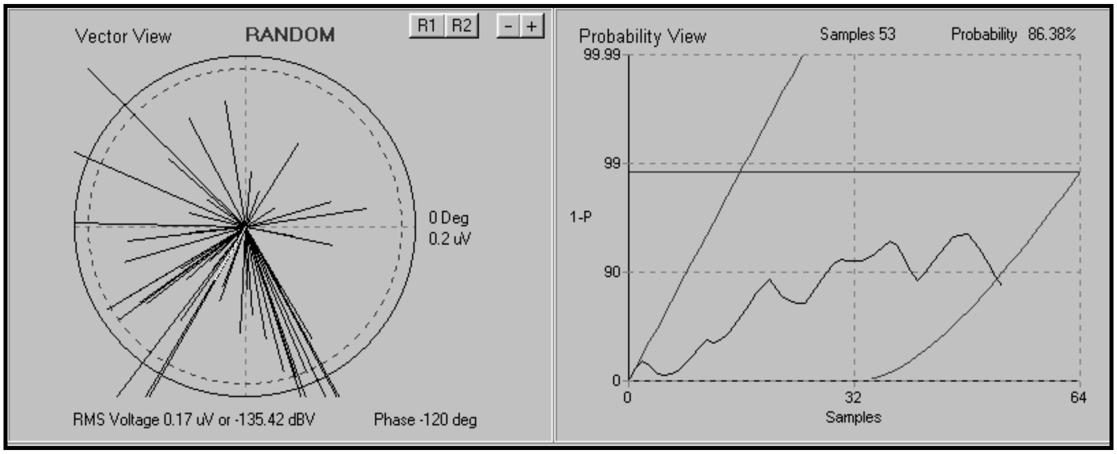


FIGURE 3.5 GSI Audera ASSR 'no response' result (GSI, 2003)

A 'no response' result occurs when no response is found after the collection of 64 samples and the EEG did not exceed the noise threshold limit. Figure 3.5 therefore displays no coherence of response phase. A maximum recording duration of 89 s is allowed by the GSI Audera ASSR software (GSI, 2003). Figure 3.6 displays a 'phased locked' response.

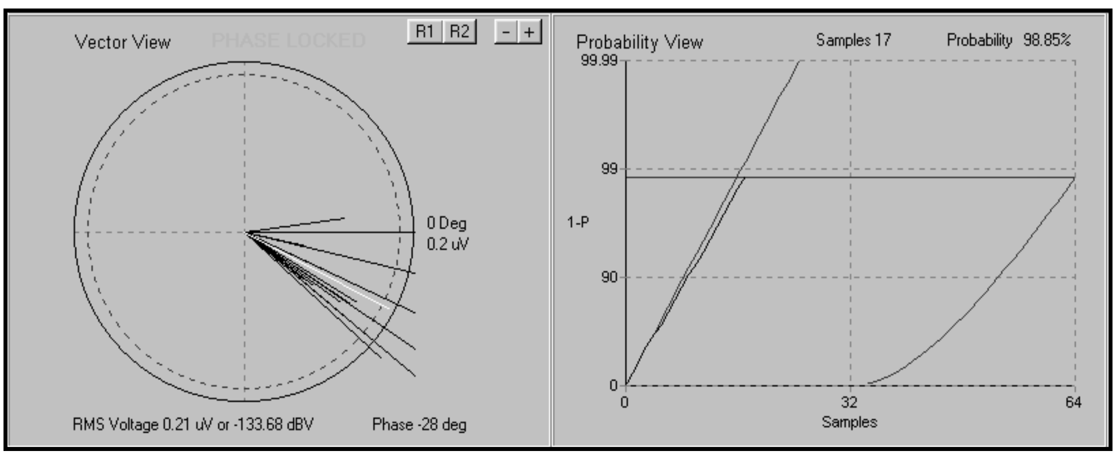


FIGURE 3.6 GSI Audera ASSR 'phase locked' response (GSI, 2003)

A 'phase locked' response occurs when a response is deemed present at a level when phase-lock to the modulation envelope of the stimulus is statistically significant at the $p < 0.01$ level regardless of the noise levels (Cone-Wesson, Dowell et al., 2002; Luts & Wouters, 2005; Rance et al., 2005).

3.9 DATA ANALYSIS

Neuman (1994) describes data analysis as a search for patterns within data. Quantitative data analysis methods were chosen for the purpose of data analysis of this comparative quasi-experimental research design (Trochim, 2006). This was appropriate as controlled procedures (viz. behavioural PT audiometry, SCAEP and ASSR techniques) were used to obtain numerical threshold data. The quantitative data was collated using a Microsoft Office Excel 97-2003 spreadsheet. The same software package was used for the statistical calculations and for the generation of graphical presentations of the statistical data. In order to compare the numerical data, both descriptive and inferential statistics were made use of. Table 3.9 presents the quantitative statistical method used in order to achieve the three sub-aims of the study.

TABLE 3.9 Statistical analysis methods implemented for each sub-aim

Sub-aim	Quantitative method	Statistical procedure
#1 To compare behavioural thresholds of PT, tone burst and AM/FM stimuli	a) Descriptive statistics b) Inferential statistics	a) Mean PT, tone burst and AM/FM stimuli; standard deviation (Trochim, 2006) b) Non parametric paired T-test (Kaplan, 1987)
#2 To compare accuracy of SCAEP and ASSR thresholds with reference to behavioural PT thresholds	a) Descriptive statistics b) Inferential statistics	a) Mean difference scores between SCAEP / ASSR thresholds and behavioural PT thresholds; standard deviation of difference score; range of difference scores (Trochim, 2006); frequency distribution of difference scores (bar graph; Trochim, 2006); scatter plots (Massoud et al., 2001) b) Pearson product correlation co-efficients (r; Kaplan, 1987); linear regression lines; linear regression formula; R-squared correlations (R^2; Welkowitz et al., 2006)
#3 To compare time taken to acquire SCAEP and ASSR thresholds	a) Descriptive statitics	a) Mean time; range; standard deviation; range (Trochim, 2006)

Table 3.9 is discussed with reference to each of the sub-aims of the study.

- **Sub-aim one:** AEP data (calibrated in either dBnHL, with reference to the group of individuals with normal hearing sensitivity, or in dBHL) and behavioural PT threshold data (measured in dBHL) can be compared directly to each other. This is possible because PT stimuli in dBHL are referenced to the average threshold for individuals with normal hearing (Stach, 1998). The same is not necessarily true of SCAEP thresholds and ASSR thresholds employing different stimuli, each with its own stimulus duration and presentation rate. The transient tone burst stimuli of the SCAEP are measured in dBnHL, while the continuous AM/FM tones utilized for ASSR are measured in dBHL. Sub-aim one investigated whether the stimuli used for SCAEP and ASSR techniques were directly comparable.

  In accordance with sub-aim one, the significance of the relationship between the behavioural thresholds using tone burst stimuli, AM/FM tones and PT stimuli for the group of individuals with normal hearing was assessed. A paired T-test analysis (Kaplan, 1987) was performed to determine the significance of the relationship between behavioural tone burst thresholds and behavioural PT thresholds, between behavioural AM/FM thresholds and PT thresholds, and between behavioural tone burst and AM/FM thresholds. The T-test indicates exceedence probability (p) values, which is indicative of significant statistical differences when comparing variables (Kaplan, 1987). An exceedence probability (p) of less than 0.01 is considered highly significant, and a p-value of less than 0.05 is considered significant (Neuman, 1994). A significant difference would imply significant calibration differences between the three stimuli. If this was found to be the case, direct comparison between SCAEP, ASSR and behavioural PT thresholds would not be valid. Inversely, no significant difference between the behavioural thresholds would validate a direct comparison of thresholds of behavioural PT audiometry, SCAEP and ASSR. Correction of the SCAEP and ASSR thresholds would be required if a significant difference was found between each stimulus.

- **Sub-aim two:** In realization of sub-aim two, the comparative accuracy of estimation of behavioural PT thresholds, using SCAEP and ASSR, was determined with reference to behavioural PT thresholds, the gold standard audiometric measure (Martin, 2002; Melnick & Morgan, 1991). The data was presented firstly using descriptive statistics so as to order and summarize the data, then compared using inferential statistics, which enabled conclusions to be made regarding the population from which the sample was drawn (Leedy & Ormrod, 2001; Trochim, 2006). The primary statistic used was the difference values which were determined between SCAEP thresholds and the behavioural PT thresholds, and between ASSR thresholds and behavioural PT thresholds. The difference values illustrated the proximity of the SCAEP and ASSR thresholds to the behavioural PT threshold. The standard deviation of the difference between SCAEP or ASSR thresholds and behavioural PT thresholds provided an indication of the variability of the relationship. Scatter plots represented the linear regression analysis performed on the data and were used to illustrate the strength of the correlation between the variables (Massoud et al., 2001). The variables compared, using the visual display provided by the scatter plots, were behavioural PT thresholds and SCAEP thresholds, and behavioural PT thresholds and ASSR thresholds. The scatter plots were fitted with trendlines with the R-squared values (Welkowitz et al., 2006), describing the amount of variance of the dependent variable (behavioural PT threshold) that is accounted for by the independent variable (SCAEP or ASSR threshold). Put differently, the R-squared value demonstrates how closely the trendline was able to predict the correlation between the data points illustrated on the scatter plots. The linear relationship between behavioural PT threshold data, and the SCAEP and ASSR thresholds were further compared using the following statistical measures of correlation: Pearson product-moment correlation co-efficients (at each frequency and for all frequencies combined) and linear regression formulae (Kaplan, 1987). Frequency specific linear regression formulae (Kaplan, 1987) were utilized in order to determine the formula that calculates the behavioural PT thresholds from the SCAEP and ASSR thresholds measured.

- **Sub-aim three** concerns the last dependent variable that was compared, namely the time taken to acquire SCAEP and ASSR thresholds, excluding preparation time and SCAEP threshold response determination. The data was measured in minutes for each participant (both ears), and was converted to a mean time for the group of participants with normal hearing, the group of participants with hearing loss and the data from both participant groups for each of the two AEP before being compared. In addition, the range of times taken to measure SCAEP and ASSR thresholds were added to the list of descriptive statistics used for the sub-aim.

3.10 SUMMARY

Chapter three has detailed the research methodology adhered to in this study. The procedures implemented in the research method were dictated by the main and sub-aims that were formulated in order to answer the research question posed. The choice of a comparative quasi-experimental research design provided the study with structure. The part[i]cipant groups with normal and impaired hearing were described, as were the criteria used to select the participants. The material and apparatus, as well as the stimulus and recording parameters to be utilized were specified. This was followed by a record of the procedure adhered to during data collection and for statistical analysis of the data. The study was initiated and conducted within the framework of the ethical considerations examined.

CHAPTER FOUR

RESULTS

4.1 INTRODUCTION

Noise induced hearing loss has been recognised as a major occupational health risk by the South African health care system (South African Occupational Health and Safety Act, 2003). Identification of occupational noise induced hearing loss in adults exposed to occupational noise can be problematic, as this is a population where the incidence of nonorganic hearing loss is high. An accurate and objective method of quantification of hearing loss is therefore a priority.

The current study has provided quantitative data to support recommendation of the use of either the slow cortical auditory evoked potential (SCAEP) or the auditory steady-state evoked response (ASSR) technique in a population of adults exposed to occupational noise. The clinical effectiveness and efficiency of SCAEP versus ASSR was determined by measuring the comparative accuracy and time efficiency of estimation of behavioural pure tone (PT) thresholds using each technique. The data collected in order to affect this comparison was presented with respect to each of the three sub-aims.

4.2 RESULTS FROM SUB-AIM ONE: BEHAVIOURAL THRESHOLDS FOR PT STIMULI, TONE BURSTS AND AMPLITUDE AND FREQUENCY MODULATED TONES (AM/FM TONES)

The comparison of behavioural thresholds of PT stimuli, tone bursts and AM/FM tones was vital for the validity of the study. Before a comparison between the thresholds obtained using SCAEP and ASSR techniques can be conducted, the stimuli used for each technique needs to be compared in terms of biologic thresholds with these stimuli which vary in temporal and frequency constituents. A short duration stimulus, such as a tone burst, produces less energy per second than a continuous tone, and therefore a greater sound pressure level is required in order to achieve the equivalent intensity (Lightfoot et al., 2002). This phenomenon is known as temporal integration (Lightfoot et al., 2002;

Martin, 1981). A system that allows for modification of stimulus parameters, such as the stimulus duration, is therefore prone to inherent variability. The SCAEP and ASSR techniques that are being compared in the current study, differ in both nature and calibration scale. The SCAEP technique makes use of transient tone burst stimuli calibrated in dBnHL, with reference to the manufacturer's biological calibration data. Additionally, it is recommended that clinicians recalibrate their clinical SCAEP equipment in the environment the equipment will be used, using the stimulus parameters chosen for use during clinical SCAEP threshold determination (Hall, 1994; Stapells et al., 1994). For the purpose of this local biological calibration, behavioural thresholds are determined with reference to a group of young adults with normal hearing using the SCAEP toneburst stimuli. The ASSR technique makes use of continuous AM/FM stimuli calibrated in dBHL. Therefore, direct comparison between thresholds obtained using SCAEP and ASSR techniques, albeit within the GSI (Grason-Stadler Incorporated) Audera AEP (auditory evoked potential) system, is not necessarily valid. Comparison of the behavioural thresholds obtained using tone burst and AM/FM stimuli with a common stimulus, namely the gold standard behavioural PT stimulus, was therefore required before SCAEP and ASSR thresholds could be compared.

Table 4.1 presents the average behavioural thresholds obtained using PT, tone bursts and AM/FM stimuli, for the participant group with normal hearing.

TABLE 4.1 Group with normal hearing: Mean behavioural thresholds for PT, tone bursts and AM/FM tones (n = 28)

	PT ± std dev (dBHL)	Tone bursts ± std dev (dBnHL)	AM/FM ± std dev (dBHL)
500 Hz	3.8 ± 3.2	12.7 ± 8.0	9.3 ± 6.8
1000 Hz	1.1 ± 3.9	11.3 ± 4.6	8.9 ± 5.8
2000 Hz	0.0 ± 4.5	10.0 ± 5.8	7.0 ± 6.3
4000 Hz	2.0 ± 5.3	12.0 ± 7.7	10.0 ± 7.3
MEAN	**1.7 ± 4.5**	**11.5 ± 6.7**	**9.0 ± 6.6**

Behavioural tone burst thresholds were on average 9.8 dB larger than behavioural PT thresholds, while behavioural AM/FM stimuli were on average 7.3 dB larger than behavioural PT thresholds. A diagrammatic representation of the mean data offered in

Figure 4.1 below, highlights that the AM/FM stimuli were detected at a lower intensity than tone bursts were.

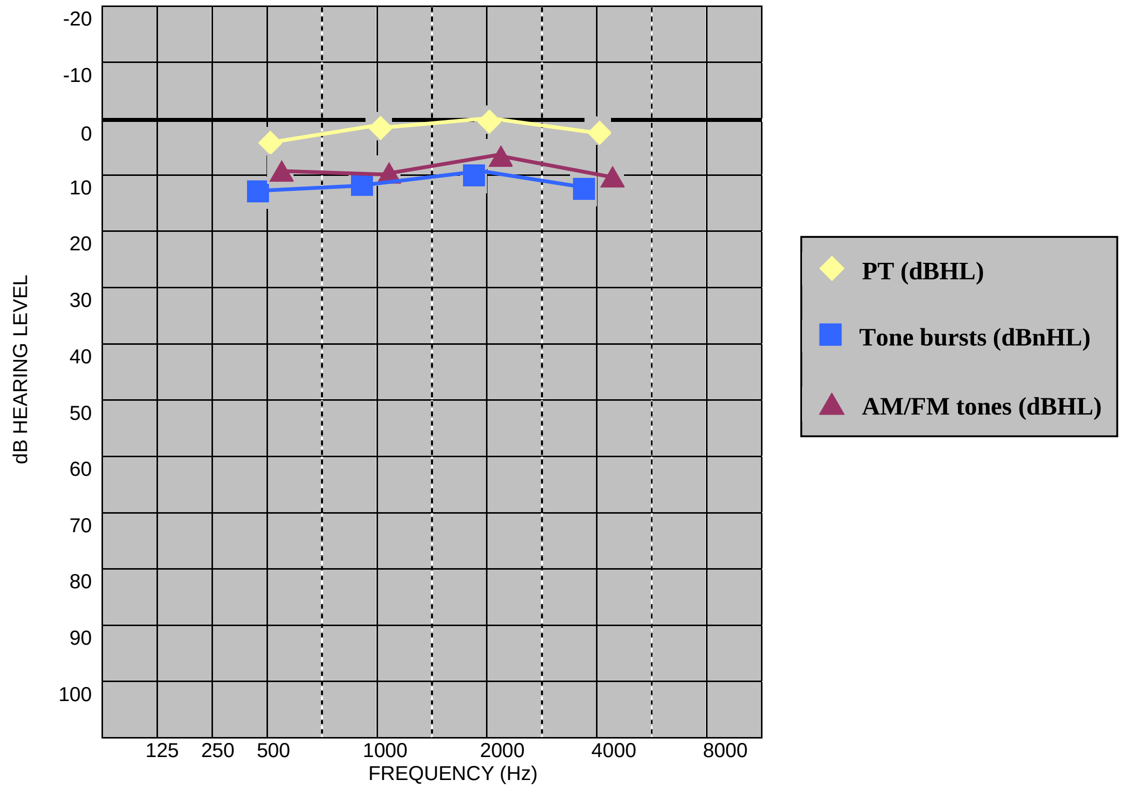


FIGURE 4.1 Group with normal hearing: Mean behavioural thresholds for PT, tone burst and AM/FM tones

A paired T-test (Kaplan, 1987) was employed in order to determine whether there was a significant difference between the thresholds of the three different stimuli. The T-test was performed between the mean behavioural PT and tone bursts thresholds, between the behavioural PT and AM/FM tone thresholds, and between behavioural tone bursts and AM/FM tone thresholds. P values of less than 0.05 were found at all frequencies for both tone burst compared to behavioural PT, and between AM/FM stimuli compared to behavioural PT. The P values are indicative of a highly significant difference between the thresholds using these stimuli. The paired T-test also indicated a significant difference between mean tone burst and AM/FM stimuli at 0.5, 1 and 2 kHz, but no significant difference between thresholds at 4 kHz ($p = 0.59$). These statistics imply that, with the exception of the difference between mean tone burst and AM/FM stimuli at 4 kHz, AEP using the stimuli compared here cannot be compared directly to each other, or to behavioural PT thresholds.

As SCAEP and ASSR make use of tone burst and AM/FM stimuli respectively, the threshold data obtained by these two techniques had to be corrected, using the data from the group of participants with normal hearing (as listed in Table 4.1) prior to statistical comparison between SCAEP and ASSR thresholds for both the group of participants with normal hearing and with hearing loss. Correction of SCAEP and ASSR thresholds was therefore deemed necessary for all frequencies, due to the significant difference between behavioural tone burst and AM/FM stimuli at eleven out of the twelve conditions evaluated.

The mean behavioural thresholds for tone burst and AM/FM tones at each frequency for the group with normal hearing were used as the normal hearing level (nHL) for the SCAEP and ASSR techniques respectively. In other words, the mean behavioural tone burst threshold values at each frequency were subtracted from SCAEP thresholds and the mean behavioural AM/FM tone thresholds were subtracted from ASSR thresholds at each frequency. This resulted in the SCAEP and ASSR thresholds being comparable to both each other and to behavioural PT thresholds. The resulting corrected SCAEP and ASSR threshold values were therefore measured in dB normal hearing level (dBnHL).

Sub-aim one was formulated in order to determine the validity of a direct comparison between the objective thresholds obtained, using SCAEP and ASSR techniques, with reference to behavioural PT thresholds of hearing. The preceding comparison between behavioural PT, tone burst and AM/FM tone thresholds concluded that these three stimuli are not directly comparable. A valid comparison of the thresholds obtained using the AEP techniques utilizing tone burst and AM/FM tone stimuli, could therefore only be achieved through use of corrected SCAEP and ASSR thresholds using the behavioural thresholds for the stimuli used to evoke each of the AEP techniques obtained from a group of participants with normal hearing. Once this was completed, sub-aim two could ensue with the comparison of the corrected thresholds of the two AEP techniques with the behavioural PT thresholds.

4.3 RESULTS FROM SUB-AIM TWO: COMPARING SCAEP, ASSR AND BEHAVIOURAL PT THRESHOLDS

Clinical efficiency was defined for the purpose of this study as, firstly, the accuracy of threshold estimation and, secondly, the amount of time necessary for acquisition and analysis of the AEP. Therefore, in adherence to the former part of the definition and in order to determine the comparative accuracy of threshold estimation using SCAEP and ASSR techniques, thresholds obtained using the SCAEP and ASSR were compared to each other and to behavioural PT thresholds. The direct comparison of the thresholds of the two AEP techniques was possible following correction of the SCAEP and ASSR thresholds, using the behavioural thresholds of the respective stimuli in participants with normal hearing, as was completed in sub-aim one.

4.3.1 Mean corrected SCAEP and ASSR thresholds

It was necessary to exclude five SCAEP thresholds from the study, when a threshold response could not be determined as judged by two experienced audiologists. This was often due to tester inexperience, as either more replications or an increase in stimulus intensity was required in order to judge a response to be present or absent. Averaging of recordings had to be performed rather laboriously after completion of the assessment session, as an ‘online’ averaging function was not offered by the GSI Audera software. (This function has, however, been added in the most recent version of the software.) The use of averaged waveforms was found to be most valuable during response detection. Access to averaged waveforms during the evaluation session would have facilitated the tester’s decision making in a clinical session of limited duration. In addition to threshold responses that could not be determined, the SCAEP data from three ears (i.e. 12 SCAEP thresholds) and four 0.5 kHz SCAEP thresholds was irretrievable, due to software error. Five ASSR thresholds were excluded from the study as threshold response could not be determined at the maximum stimulus intensity for participants with normal hearing, namely 80 dBHL. All five ASSR thresholds were measured from the same participant. Excessive internal noise levels were consistently measured for this participant, despite the fact that the participant slept throughout the ASSR recording. The mean corrected thresholds for the SCAEP and the ASSR*, with the standard deviation for each (Trochim, 2006), are displayed in Table 4.2 for the group with normal hearing.

TABLE 4.2 Group with normal hearing: Mean SCAEP thresholds and mean ASSR thresholds (dBnHL)

	SCAEP threshold ± std dev	ASSR threshold ± std dev
500 Hz	0.3 ± 7.3 (n = 20)	29.6 ± 14.2 (n = 27)
1000 Hz	6.6 ± 7.4 (n = 23)	22.5 ± 13.0 (n = 28)
2000 Hz	6.0 ± 7.1 (n = 25)	31.9 ± 11.4 (n = 26)
4000 Hz	3.7 ± 9.0 (n = 23)	34.5 ± 10.7 (n = 26)
MEAN	**4.3 ± 8.0 (n = 91)**	**29.5 ± 13.1 (n = 107)**

The differences in mean SCAEP and ASSR thresholds are apparent from Table 4.2. The mean SCAEP thresholds range from 0.3 to 6.6 dB with a standard deviation of 7.1 to 9 dB. The mean ASSR thresholds are larger at each threshold, ranging from 22.5 dB to 34.5 dB, with larger standard deviations (range = 10.7 to 14.2 dB). Table 4.3 presents the mean SCAEP and ASSR thresholds for the group of participants with hearing loss.

TABLE 4.3 Group with hearing loss: Mean SCAEP thresholds and mean ASSR thresholds (dBnHL)

	SCAEP threshold ± std dev	ASSR threshold ± std dev
500 Hz	12.8 ± 11.5 (n = 29)	35.0 ± 12.8 (n = 30)
1000 Hz	11.5 ± 11.3 (n = 29)	32.7 ± 9.9 (n = 30)
2000 Hz	24.6 ± 15.0 (n = 28)	53.7 ± 13.1 (n = 30)
4000 Hz	45.7 ± 17.6 (n = 30)	69.8 ± 13.6 (n = 30)
MEAN	**23.9 ± 19.7 (n = 116)**	**47.8 ± 19.5 (n = 120)**

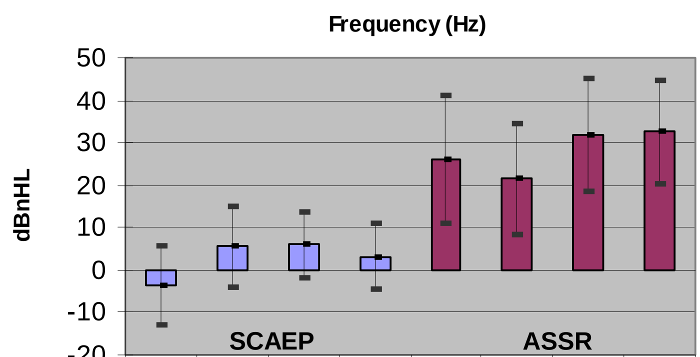
The group with hearing loss demonstrates a similar difference between mean SCAEP and ASSR thresholds as was seen in the group with normal hearing. Mean ASSR thresholds across all frequencies were again approximately 25 dB larger than the mean SCAEP

* The SCAEP and ASSR thresholds, difference scores and standard deviations measured for the current study and referred to from this point forward were therefore calibrated in dBnHL, but denoted in text by dB for simplicity.

thresholds for all frequencies. The mean standard deviation scores across all frequencies were, however, similar for the SCAEP and ASSR thresholds.

4.3.2 Difference values between SCAEP or ASSR thresholds and behavioural PT thresholds

The difference values between SCAEP or ASSR thresholds and behavioural PT thresholds were calculated by subtracting the SCAEP and ASSR thresholds in dBnHL from the behavioural PT thresholds in dBHL. The difference scores, standard deviation (Trochim, 2006) and participant numbers are depicted graphically in Figure 4.2 for participants with normal hearing.

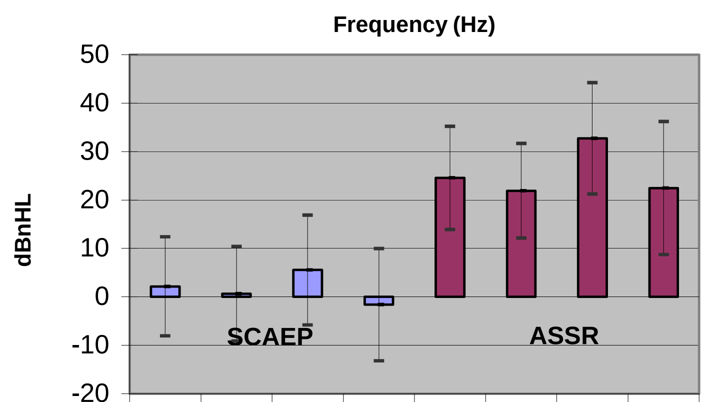


	500	1000	2000	4000	500	1000	2000	4000
Mean diff	-3.7	5.5	6.0	3.3	26.1	21.4	31.9	32.6
Std dev	9.3	9.7	7.8	7.9	14.9	13.0	13.2	12.1
Mean diff – std dev	-12.9	-4.2	-1.8	-4.6	11.1	8.5	18.7	20.5
Mean diff + std dev	5.6	15.2	13.8	11.2	41.0	34.4	45.1	44.6
n	20	23	25	23	27	28	26	26

FIGURE 4.2 Group with normal hearing: Difference between SCAEP and behavioural PT thresholds compared to difference between ASSR and behavioural PT thresholds (mean, standard deviation and number of participants)

(diff = difference between SCAEP or ASSR and behavioural PT thresholds; std dev = standard deviation; n = number of ears)

Figure 4.2 illustrates that mean differences between AEP thresholds and behavioural PT thresholds for the SCAEP were markedly smaller than those for ASSR for participants with normal hearing, across all frequencies. The mean difference scores between behavioural PT and SCAEP thresholds ranged from 3.3 to 6 dB for the group with normal hearing. The standard deviations for the SCAEP difference scores are also smaller than for the ASSR difference scores. Figure 4.3 displays the mean SCAEP and ASSR difference scores, standard deviation and the number of participants with hearing loss.

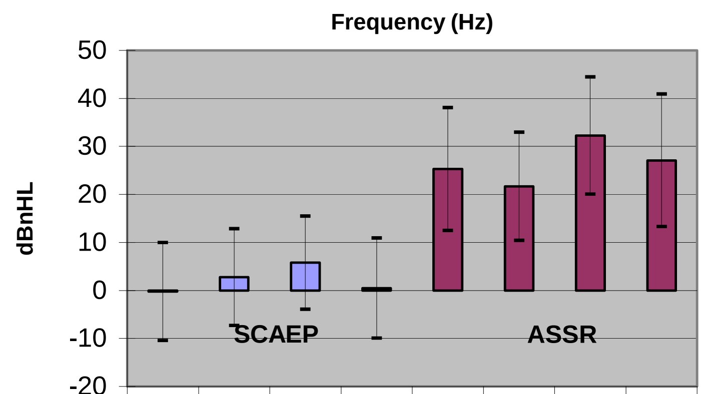


	500	1000	2000	4000	500	1000	2000	4000
Mean diff	2.2	0.6	5.5	-1.6	24.5	21.9	32.7	22.4
Std dev	10.2	9.8	11.3	11.6	10.6	9.7	11.5	13.7
Mean diff – std dev	-8.1	-9.1	-5.8	-13.2	13.9	12.2	21.2	8.7
Mean diff + std dev	12.4	10.4	16.9	10.0	35.2	31.6	44.2	36.2
n	29	29	28	30	30	30	30	30

FIGURE 4.3 Group with hearing loss: Difference between SCAEP and behavioural PT thresholds compared to difference between ASSR and behavioural PT thresholds (mean, standard deviation and number of participants)

(diff = difference between SCAEP or ASSR and behavioural PT thresholds; std dev = standard deviation; n = number of ears)

It is clear from Figure 4.3 that, for the participants with hearing loss, the mean differences between SCAEP threshold and behavioural PT thresholds was again smaller than those for ASSR. The mean difference scores between behavioural PT and SCAEP thresholds ranged from 0.6 to 5.5 dB in contrast to mean ASSR mean difference scores, which ranged from 21.4 to 32.6 dB. The standard deviations for the SCAEP and ASSR difference scores were, however, similar. When comparing Figures 4.2 and 4.3, a closer relationship between the AEP and behavioural PT thresholds in participants with hearing loss is evident, compared to AEP and behavioural PT thresholds in participants with normal hearing. In order to facilitate comparison with existing literature, where reference was frequently made to statistics for pooled data, the data for participant groups with normal hearing and with hearing loss were combined in Figure 4.4. Figure 4.4 presents the mean difference scores and standard deviations for the participant groups combined.



	500	1000	2000	4000	500	1000	2000	4000
Mean diff	-0.2	2.8	5.8	0.5	25.3	21.7	32.3	27.1
Std dev	10.2	10.1	9.7	10.4	12.8	11.3	12.2	13.8
Mean diff – std dev	-10.4	-7.3	-3.9	-9.9	12.5	10.4	20.1	13.3
Mean diff + std dev	10.0	12.9	15.5	10.9	38.1	33.0	44.5	40.9
n	49	52	53	53	57	56	56	56

FIGURE 4.4 Combined participant groups: Difference between SCAEP and behavioural PT thresholds compared to difference between ASSR and behavioural PT thresholds (mean, standard deviation and number of participants)

(diff = difference between SCAEP or ASSR and behavioural PT thresholds; std dev = standard deviation; n = number of ears)

The mean difference score for SCAEP for the participant groups with normal hearing and with hearing loss collectively, is 2.2 dB, in comparison to 26.6 dB for ASSR. The preceding graphs facilitate observations regarding disparities of mean difference scores, not only between AEP techniques, but also between each frequency. The largest difference scores were measured for 2 kHz for both SCAEP and ASSR. At the frequency where the greatest degree of hearing loss is likely to be present for individuals exposed to occupational noise, namely 4 kHz, a mean difference between SCAEP threshold and behavioural PT threshold of 0.5 dB was measured, in comparison to a mean ASSR difference score of 27.1 dB. With regard to standard deviations, SCAEP again demonstrated an advantage over ASSR. The standard deviation of the mean difference scores for both participant groups for SCAEP was 10.2 dB, while that of ASSR was measured as 13.1 dB.

The comparative distribution of difference scores (Trochim, 2006) for the group with normal hearing and the group of participants with hearing loss combined is illustrated in Figure 4.5.

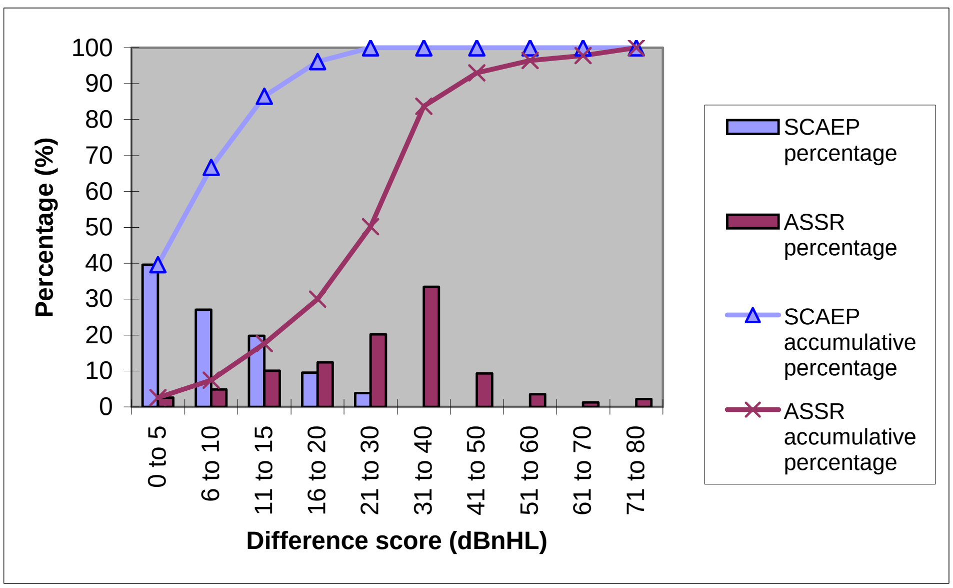


FIGURE 4.5 Combined participant groups: Distribution of difference scores between SCAEP and behavioural PT thresholds, compared to the distribution of difference scores between ASSR and behavioural PT thresholds

(difference score = difference between SCAEP or ASSR and behavioural PT thresholds)

The majority of SCAEP thresholds (66.7%) fell within 10 dB of behavioural PT thresholds, with 100% of thresholds within 30 dB. In contrast, half of ASSR thresholds

(50.2%) fell within 30 dB while 93% of thresholds were identified within 50 dB of behavioural PT thresholds.

4.3.3 Relationship between SCAEP, ASSR and behavioural PT thresholds

The bivariate distributions of the behavioural PT thresholds and either SCAEP or ASSR thresholds are displayed by way of scatter plots (Massoud et al., 2001). The relationship between the behavioural PT thresholds and SCAEP thresholds is depicted in Figure 4.6 for the group with normal hearing.

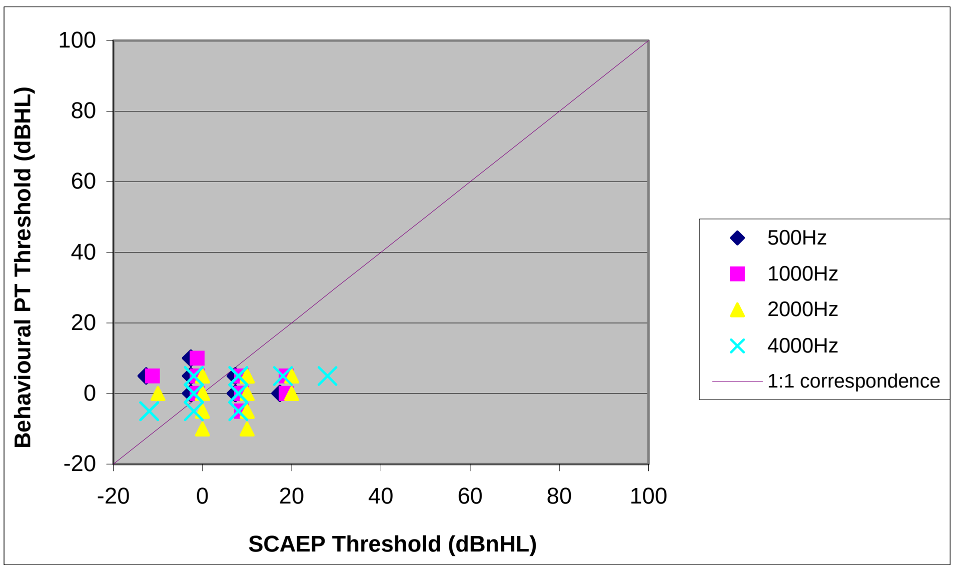


FIGURE 4.6 Group with normal hearing: Behavioural PT threshold correlates of SCAEP thresholds

Figure 4.6 indicates that all the correlation points fall within 20 dB of the line of equivalence for the group with normal hearing. SCAEP thresholds were therefore measured within 20 dB of the behavioural PT thresholds. The low and mid frequencies (0.5 and 1 kHz) appear to demonstrate a closer relationship between SCAEP threshold and behavioural PT threshold than 2 and 4 kHz. The relationship between the behavioural PT thresholds and SCAEP thresholds is depicted in Figure 4.7 for the group with hearing loss.

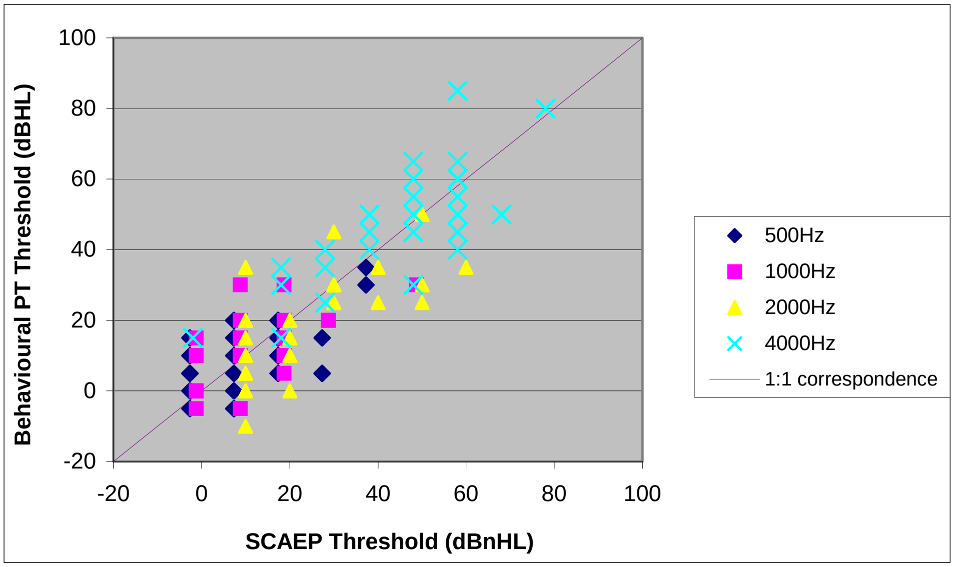


FIGURE 4.7 Group with hearing loss: Behavioural PT threshold correlates of SCAEP thresholds

Figure 4.7 shows a relatively even distribution for each frequency of behavioural PT threshold correlates with SCAEP thresholds around the line representing perfect correspondence for the group of participants with hearing loss. The bulk of the data points are again present within 20 dB of perfect correspondence, irrespective of behavioural PT threshold or frequency. A different picture emerges with respect to the results for the ASSR thresholds. The behavioural PT threshold correlates for the ASSR thresholds, are illustrated in Figure 4.8 for the group with normal hearing.

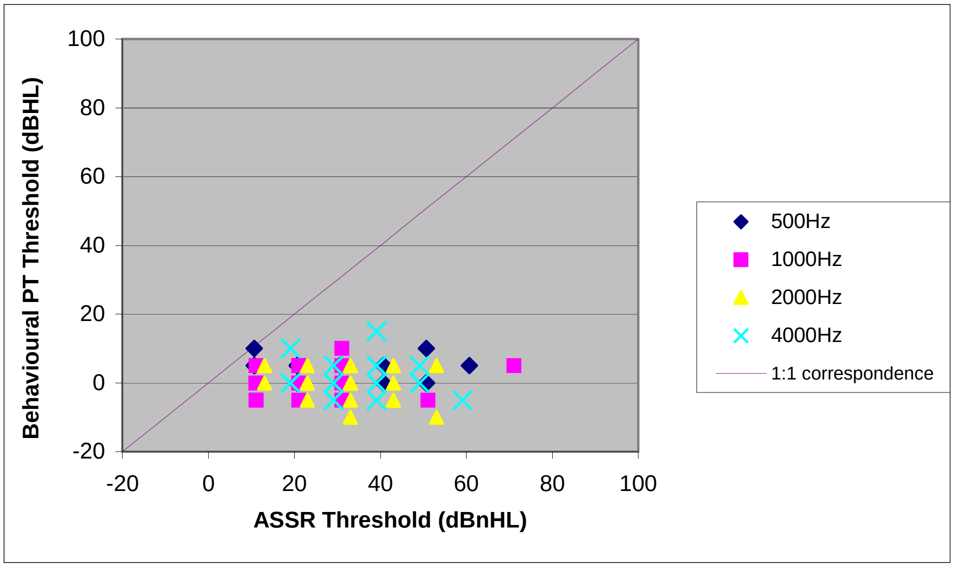


FIGURE 4.8 Group with normal hearing: Behavioural PT threshold correlates of ASSR thresholds

The ASSR thresholds are all elevated with reference to the corresponding behavioural PT thresholds. The data for the group with normal hearing depicted in Figure 4.8, varies considerably, with ASSR thresholds typically elevated by anything from 5 to 65 dB. Figure 4.9 depicts the behavioural PT threshold correlates for the ASSR thresholds for the participant group with hearing loss.

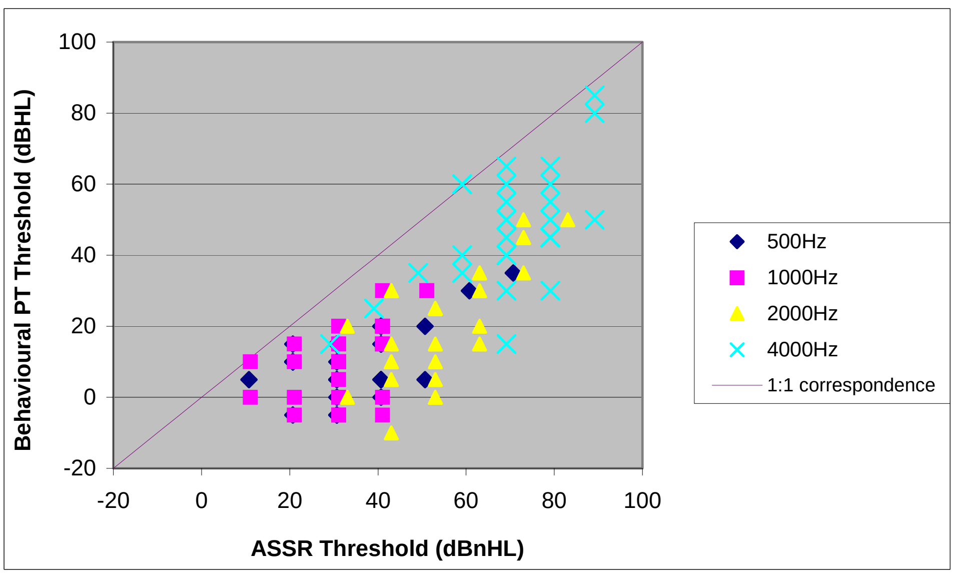


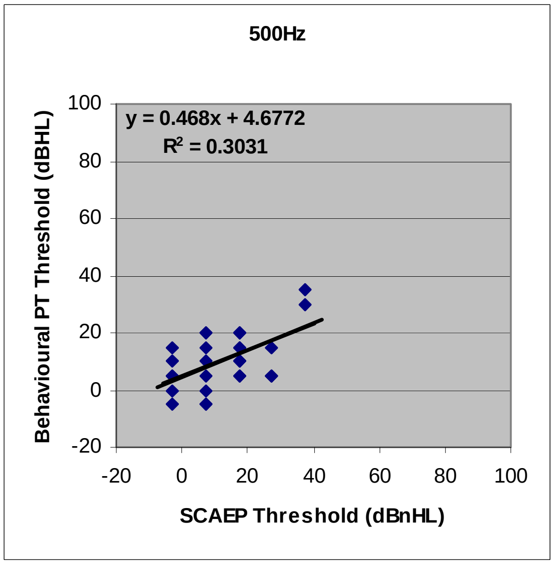
FIGURE 4.9 Group with hearing loss: Behavioural PT threshold correlates of ASSR thresholds

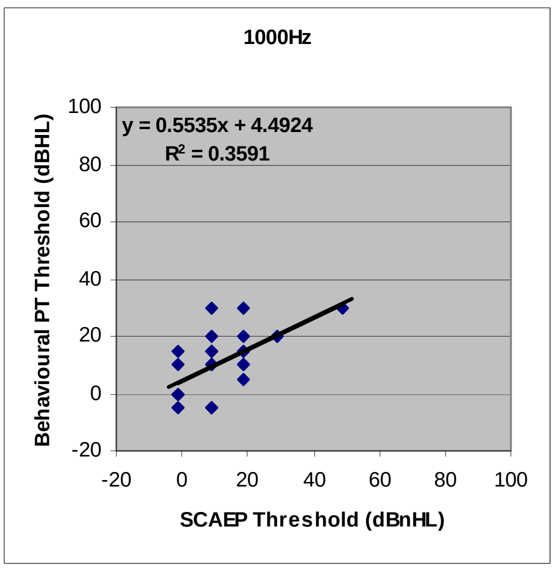
Bearing in mind that the average hearing loss for the group with hearing loss is a high frequency hearing loss, as is typical of individuals exposed to occupational noise, Figure 4.9 again demonstrates marked variability for participants with hearing loss. Normal behavioural PT thresholds were often measured for the participants with hearing loss at 0.5, 1 kHz and for certain data points at 2 kHz. ASSR thresholds are less elevated with increasing behavioural PT threshold and increasing frequency.

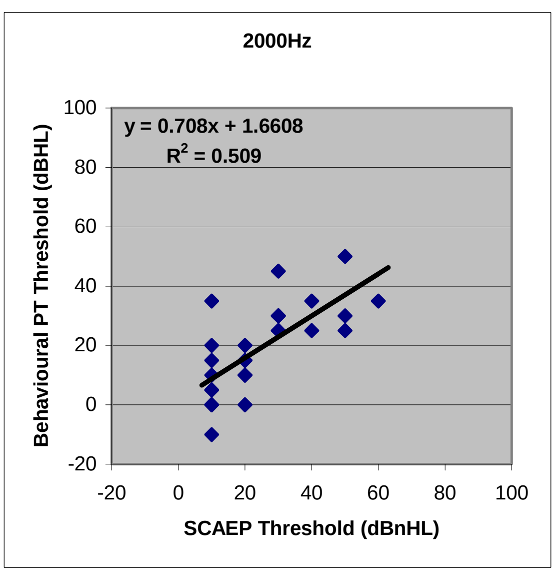
The R-squared values (Welkowitz et al., 2006) were calculated for the participants with normal hearing for both SCAEP and ASSR. The R-squared value is a number from 0 to 1 that reveals how closely the trendline corresponded to the actual data. A trendline is most reliable when its R-squared value is at or near 1. R-squared values indicated poor correlation between the trendline and the data points ($R^2 \leq 0.005$). This is an indication of significant variability between behavioural PT thresholds and SCAEP or ASSR thresholds for the group with normal hearing. The correlation between the behavioural PT thresholds and the ASSR thresholds was particularly variable, with R-squared value calculated at 0.0011.

To further compare correspondence for the two techniques at each frequency for the participants with hearing loss, scatter plots with linear trendlines and regression formulae (Welkowitz et al., 2006) were created at individual frequencies. The R-squared value was calculated on the basis of the trendline. Figure 4.10 provides frequency specific scatter plots with trendlines, R-squared values and regression equations for the group with hearing loss for both SCAEP and ASSR thresholds.

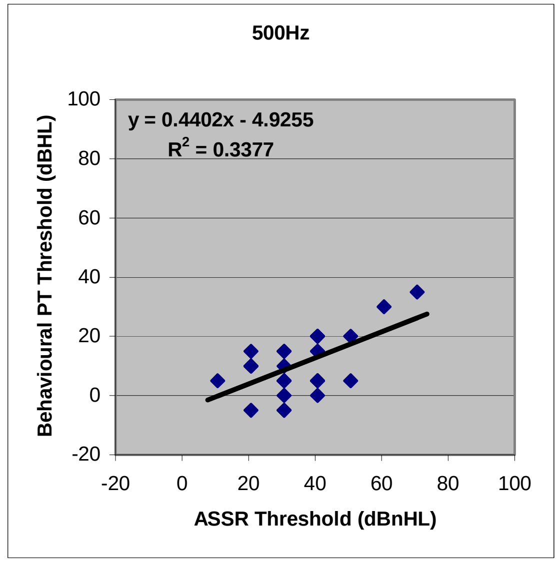
SCAEP results

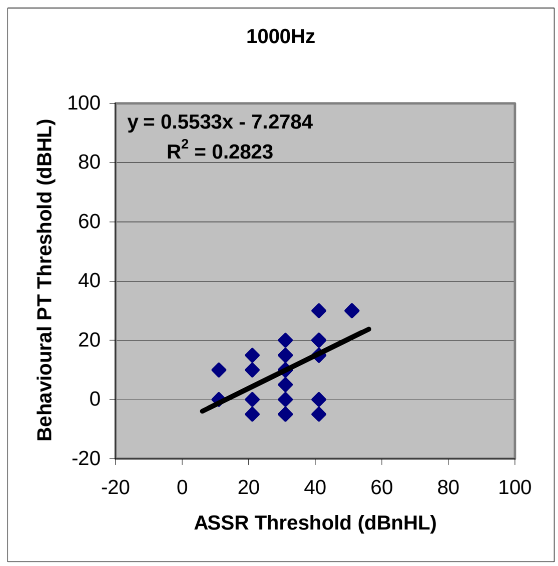


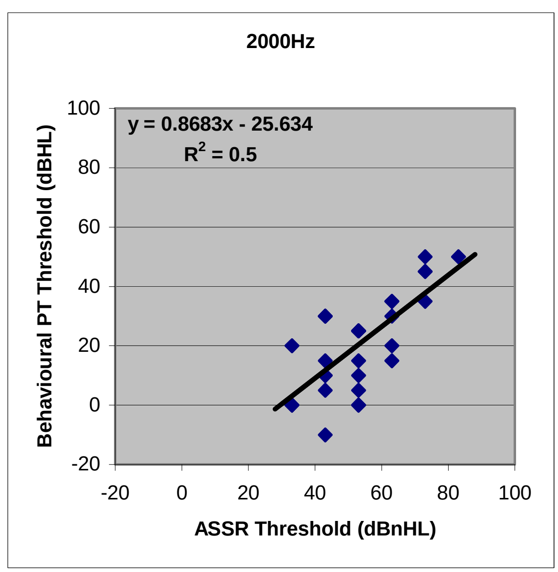




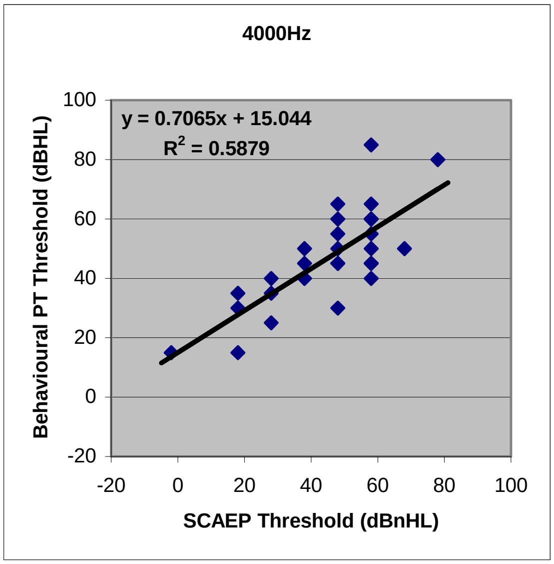
ASSR results







SCAEP results



ASSR results

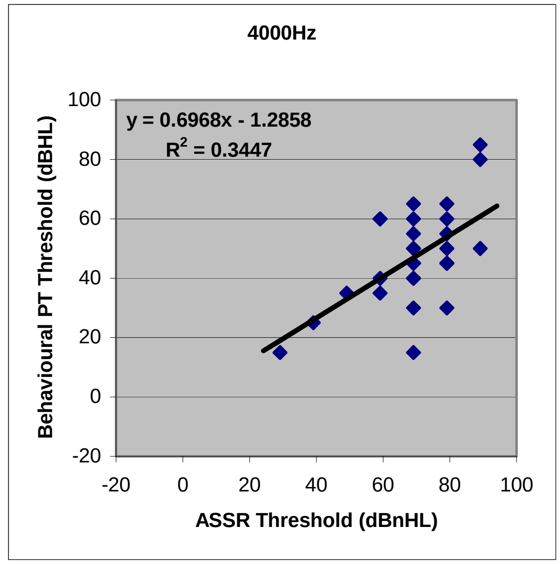


FIGURE 4.10 Group with hearing loss: Correlation points between SCAEP or ASSR thresholds and behavioural PT thresholds with trendlines, R-squared values and regression formulae

The SCAEP correlation points in Figure 4.10 demonstrated higher R-squared values than those for ASSR at all frequencies but 0.5 kHz. When all frequencies were grouped together, the R-squared value was again greater for SCAEP (r^2 = 0.72) than for that of ASSR (r^2 = 0.66). This is indicative of less variability and a closer correspondence with the trendline for SCAEP thresholds. The behavioural PT thresholds, estimated from the SCAEP thresholds, were therefore more predictable and displayed less variability than the behavioural PT thresholds estimated using ASSR thresholds.

The R-squared value for the correlation between the behavioural PT thresholds and ASSR threshold at 0.5 kHz was, however, only slightly better, with a 34% common variance in comparison with the 30% common variance measured between the behavioural PT and SCAEP thresholds. The only ASSR frequency which exhibited a common variance of 50% or more, is 2 kHz. In contrast, both 2 and 4 kHz for SCAEP thresholds displayed a common variance of greater than 50%. As is typical of a noise induced hearing loss, 2 and 4 kHz were the frequencies where hearing loss was measured. The greatest variability was measured at 0.5 and 1 kHz for SCAEP and ASSR, where one would typically measure behavioural PT thresholds within normal limits for the population in question.

The correlation points between the SCAEP and ASSR thresholds, and behavioural PT thresholds in the group with hearing loss, demonstrate higher R-squared values (R^2 = 0.282 to 0.5879) than those of the group with normal hearing (R^2 = 0.2261 to 0.0002). The regression formulae were therefore better able to predict the behavioural PT threshold from the SCAEP and ASSR thresholds in the group of participants with hearing loss, than for the participants with normal hearing.

The scatter plots allowed for graphical representation of the raw data. In order to obtain a further statistical measurement of correlation of SCAEP and ASSR thresholds with behavioural PT thresholds, Pearson product-moment correlation co-efficients (Kaplan, 1987) were determined at each frequency. This not only facilitated further conclusion regarding correlation, but also enabled comparison with existing literature, where correlations are frequently reported by means of Pearson correlations. The Pearson product-moment correlations were displayed in Table 4.4 for the group with normal hearing.

TABLE 4.4 Group with normal hearing: Pearson product correlation co-efficients

	SCAEP	ASSR
500 Hz	-0.39	-0.13
1000 Hz	-0.36	0.15
2000 Hz	0.18	-0.23
4000 Hz	0.48	-0.01
All frequencies	**-0.07**	**-0.03**

The Pearson product correlation co-efficient for the participant group with normal hearing across all frequencies, demonstrated values that were close to statistical independence. If you examine the correlations between SCAEP thresholds and behavioural PT thresholds at each frequency, a medium correlation[#] is apparent at 0.5, 1 and 4 kHz (negative

[#] Use was made of the classification of correlation scores advocated by Cohen (1988), viz. small or weak = ± 0.1 to ± 0.29; moderate = ± 0.3 to ± 0.49; strong = ± 0.5 to ± 1.0.

correlations at 0.5 and 1 kHz), with the strongest correlation at 4 kHz (r = 0.48). Weak ASSR correlations were measured at each frequency for the group with normal hearing, with the weakest correlation at 4 kHz (r = -0.01). Table 4.5 lists correlations for the group of participants with hearing loss.

TABLE 4.5 Group with hearing loss: Pearson product correlation co-efficients

	SCAEP	ASSR
500 Hz	0.55	0.58
1000 Hz	0.60	0.53
2000 Hz	0.71	0.71
4000 Hz	0.77	0.59
All frequencies	**0.85**	**0.81**

Table 4.5 displays a strong correlation between both techniques and the behavioural PT threshold (r = 0.85 for SCAEP; r = 0.81 for ASSR). Strong correlations of greater than 0.5 (Cohen, 1988) were also measured at each frequency in the hearing impaired group. Correlations for SCAEP and behavioural PT thresholds increased with increasing frequency. The strongest correlation was measured at 2 kHz between ASSR and behavioural PT thresholds. The Pearson correlation data for both the participants with normal hearing and with hearing loss were pooled and presented in Table 4.6.

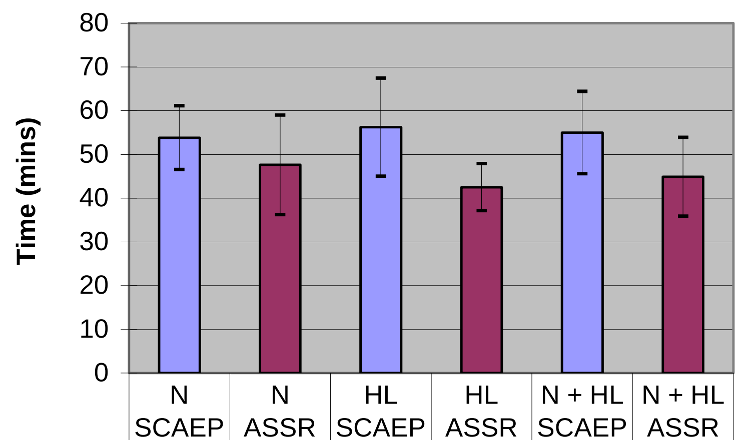
TABLE 4.6 Combined participant groups: Pearson product correlation co-efficients

	SCAEP	ASSR
500 Hz	0.53	0.40
1000 Hz	0.48	0.49
2000 Hz	0.79	0.72
4000 Hz	0.92	0.85
All frequencies	**0.85**	**0.75**

Strong mean Pearson product correlation co-efficients were measured between the SCAEP and ASSR thresholds, and behavioural PT thresholds for both the normal and hearing impaired groups together. The SCAEP correlation across frequencies (r = 0.85) was stronger than ASSR correlations (r = 0.75). Both SCAEP and ASSR displayed stronger correlations at high frequencies (2 to 4 kHz) than at mid and low frequencies.

4.4 RESULTS FROM SUB-AIM THREE: SCAEP AND ASSR THRESHOLD ACQUISITION TIMES

In adherence to this study's definition of clinical efficiency, once accuracy of threshold estimation was evaluated in sub-aim two, the amount of time necessary for acquisition of SCAEP and ASSR thresholds was then examined in sub-aim three. The time required for SCAEP and ASSR threshold acquisition was noted for each participant for both ears together. The results were calculated separately for each participant group and for the two groups together. The mean acquisition time (Trochim, 2006) for groups of participants with normal hearing, hearing loss and for both participant groups is presented in Figure 4.11.



	N SCAEP	N ASSR	HL SCAEP	HL ASSR	N + HL SCAEP	N + HL ASSR
Mean time	53.8	47.6	56.2	42.5	55.0	44.9
std dev	7.3	11.4	11.2	5.2	9.4	9.0
mean time + std dev	61.1	59.0	67.4	47.9	64.4	53.9
mean time - std dev	46.5	36.2	45.0	37.1	45.6	35.9
n	15	15	16	16	31	31

FIGURE 4.11 Mean time required for acquisition of SCAEP and ASSR thresholds (in minutes)

(N = group with normal hearing; HL = group with hearing loss; std dev = standard deviation; n = number of participants)

The mean time reported in Figure 4.11 represents the time taken, in minutes, to acquire all thresholds in each ear for each participant, using either the SCAEP or ASSR technique, in other words, the thresholds at eight frequencies. The additional waveform analysis time required for the SCAEP technique was not included. For the two participants with normal hearing and the two participants with hearing loss for whom only one ear was evaluated using SCAEP and ASSR techniques, the acquisition time was doubled.

For each participant group and for the combined participant groups, the mean time taken to acquire the SCAEP thresholds was greater than for that required to acquire ASSR thresholds. The longest mean threshold acquisition time of 56.2 min was measured for SCAEP threshold acquisition for the group of participants with hearing loss, while the shortest acquisition time (42.5 min), was reported for acquisition of ASSR thresholds for the group with hearing loss. For the combined participant groups, the SCAEP thresholds took on average 10.1 min longer to acquire than the ASSR thresholds. The times for SCAEP threshold acquisition ranged from 31 to 72 min, while that for ASSR threshold acquisition ranged from 35 to 75 min.

4.5 CONCLUSION

The study compared the proximity of the SCAEP and ASSR thresholds to behavioural PT thresholds and compared the variability of this relationship. These two factors determined the accuracy of each of the two AEP techniques. The results of sub-aim one determined that behavioural PT thresholds, SCAEP thresholds and ASSR thresholds were statistically different and could therefore not be compared directly to each other. In order to compensate for this, the mean behavioural tone burst threshold and mean behavioural AM/FM tone threshold at each frequency for the group with normal hearing, was subtracted from the SCAEP and ASSR thresholds respectively. Comparison of the accuracy of the SCAEP and ASSR techniques, using the corrected SCAEP and ASSR thresholds, was then possible.

Difference scores between SCAEP or ASSR thresholds and behavioural PT thresholds were smaller for SCAEP than for ASSR for the group with normal hearing, with hearing loss and for the participant groups combined. The standard deviations for SCAEP difference scores were also smaller for each participant group. All SCAEP thresholds could be measured within 30 dB of the behavioural PT thresholds but only 50.2% of the ASSR thresholds could be measured within 30 dB of behavioural PT thresholds. Scatter plots, regression analyses, R-squared value and Pearson product-moment correlation co-efficient described the relationship between SCAEP or ASSR thresholds and behavioural PT thresholds. A closer relationship and stronger correlation was measured between SCAEP and behavioural PT thresholds ($r = 0.85$ across frequencies for the combined participant groups) than between ASSR and behavioural PT thresholds ($r = 0.75$).

The time efficiency of the two techniques was appraised by comparing the time required in order to acquire SCAEP and ASSR thresholds. The mean time taken to measure SCAEP thresholds was 10.1 min greater than for ASSR thresholds. The comparative accuracy and time efficiency of the SCAEP and ASSR techniques together, allowed for assessment of the clinical effectiveness and efficiency of the two methods.

4.6 SUMMARY

This chapter presented the results of the comparative experimental study, with the intention of addressing the main aim of the study. Each of the three sequential sub-aims presented the quantitative results in the form of descriptive and inferential statistics. The results of sub-aim one prompted the correction of the SCAEP and ASSR thresholds, in order to compensate for the loss in sensitivity, due to the effect of temporal integration in tone bursts and AM/FM tones. This then allowed for the comparison of SCAEP and ASSR thresholds with behavioural PT thresholds, as was done in sub-aim two. The time taken to acquire SCAEP and ASSR thresholds was then compared in sub-aim three. The presentation of the results of sub-aim two and sub-aim three allows for conclusions to be drawn regarding the accuracy and time efficiency of SCAEP and ASSR. Chapter five, which follows, will discuss these results with reference to the three sub-aims of the study within the context of exiting literature.

CHAPTER FIVE

DISCUSSION

5.1 INTRODUCTION

The current study aimed to compare the clinical efficiency of the slow cortical auditory evoked potential (SCAEP) and auditory steady-state evoked response (ASSR) thresholds for a population of adults with normal hearing and adults with hearing loss who were exposed to occupational noise. In individuals claiming compensation for occupational noise induced hearing loss, a population with a high incidence of nonorganic hearing loss, a reliable and valid behavioural pure tone (PT) threshold is not always achievable. In such cases an audiologist is reliant on objective AEP (auditory evoked potential) techniques which enable behavioural PT thresholds to be estimated.

Although not widely used in South Africa, SCAEP is well established as the AEP of choice for adults claiming workmen's compensation for occupational noise induced hearing loss (Alberti et al., 1987; Hone et al., 2003; Rickards & De Vidi, 1995; Stapells, 2002; Tsui et al., 2002). The ASSR, as the comparatively more recent clinical tool, is potentially appropriate for use in estimating behavioural PT thresholds in this population. Yet, despite this, literature on the use of ASSR for this purpose is limited (Herdman & Stapells, 2003; Hyde et al., 1986; Hsu et al., 2003; Van Maanen & Stapells, 2005). The South African Department of Health states that even the best, proven diagnostic procedure must continuously be challenged through research for its effectiveness, efficiency, accessibility and quality (South African Department of Health, 2000). As such, a comparison between the SCAEP technique, as the established AEP for adults for whom an objective measure of behavioural PT threshold estimation was required, and the newer clinical technique, the ASSR, was deemed necessary.

Recent studies have compared the accuracy of behavioural PT threshold estimation using SCAEP and ASSR (Kaf, Durrant et al., 2006; Tomlin et al., 2006; Van Maanen & Stapells, 2005; Yeung & Wong, 2007). There is, however, only one comparative study on the use of SCAEP and the ASSR for the purpose of behavioural PT threshold estimation in a population of adults exposed to occupational noise (Van Maanen & Stapells, 2005). The study by researchers Van Maanen and Stapells (2005) compared the use of the multiple ASSR technique, using both 40 Hz and 80 Hz modulation frequencies and SCAEP to estimate behavioural PT thresholds in adults claiming workmen's compensation. There are, as yet, no comparative studies on the use of SCAEP and single frequency ASSR for the population in question that the researcher is aware of. This led to a research endeavour with the purpose of addressing the lack of research on the comparative efficiency of SCAEP and monotic single frequency ASSR techniques for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise. The results of this comparison will be discussed within the context of existing literature in accordance with each of the three sub-aims formulated.

5.2 DISCUSSION OF SUB-AIM ONE RESULTS: BEHAVIOURAL THRESHOLDS FOR PT STIMULI, TONE BURSTS AND AMPLITUDE AND FREQUENCY MODULATED TONES (AM/FM TONES)

Sub-aim one was formulated in order to determine the validity of a direct comparison between the objective thresholds obtained, using SCAEP (measured in dBnHL, decibel normal hearing) and ASSR (measured in dBHL, decibel hearing loss) techniques with reference to behavioural PT thresholds of hearing. This was achieved using a paired T-test, which was employed in order to determine whether there was a significant difference between the behavioural thresholds of the PT, tone burst, and amplitude and frequency modulated (AM/FM) stimuli for the participant group with normal hearing. P values of < 0.05 were found at all frequencies for all conditions, with the exception of the comparison between mean tone burst and AM/FM stimuli at 4 kHz, where no significant difference was measured ($p = 0.59$). These statistics imply that, due to the significant difference in 11 out of the 12 stimuli comparisons, SCAEP and ASSR thresholds obtained using the stimuli compared here cannot be related directly to each other or to behavioural PT thresholds.

The statistically significant difference in thresholds between the behavioural tone burst and AM/FM stimuli can be explained by temporal integration. Behavioural PT thresholds and comfort levels tend to decrease with increased stimulation rate, due to effects of temporal integration, a phenomenon related to neural adaptation (Brown, Lopez, Hughes, & Abbas, 1999; Skinner, Holden, Holden, & Demorest, 2000). The behavioural threshold for the transient tone burst is therefore affected by temporal integration for a brief (< 10 msec) stimulus duration so that the threshold for a train of tone bursts is elevated with respect to the continuous AM/FM tone (Cone-Wesson, Dowell et al., 2002). This statement finds support in the mean behavioural tone burst and AM/FM tone thresholds of the participants with normal hearing. The mean behavioural tone burst threshold was 11.5 dB, while the mean behavioural AM/FM tone threshold was 9 dB. Martin (1981) describes temporal integration as a time-intensity trading relationship in which the intensity of a stimulus must be increased when stimulus duration decreases below approximately 200 ms.

Cone-Wesson, Dowell et al. (2002) found a higher mean behavioural threshold for 2-1-2 tone burst stimuli (representing the duration of the rise – plateau – fall of the stimulus) than for AM/FM stimuli (100% amplitude modulation [AM] and 10% frequency modulation [FM]). The study reported a difference between mean behavioural tone burst thresholds and behavioural AM/FM stimulus thresholds with a 41 Hz modulation rate of 6.5 dB for 0.5 kHz and 5.5 dB at 4 kHz for female adults with normal hearing. The current study revealed less of a difference between mean behavioural tone burst and AM/FM stimuli thresholds, namely 3.4 and 2 dB respective mean difference at 0.5 and 4 kHz. In keeping with the theory of temporal integration, the longer duration of the SCAEP tone burst used in the current study (viz. 10 cycles or ms; 1-8-1) than that of the typical ABR tone burst (five cycles or ms) may account for the lower tone burst detection threshold found in this study. Lins et al. (1996) found a comparable mean difference of 12.5 dBSPL (decibel sound pressure level) across frequencies between behavioural PT and AM/FM tone stimuli modulated at a higher rate, namely at 85 Hz.

The preceding comparison between behavioural PT, tone burst and AM/FM tone thresholds concluded that the thresholds of these three stimuli were not directly comparable. A valid comparison of the thresholds obtained using either the SCAEP or ASSR techniques utilizing tone burst and AM/FM tone stimuli respectively, can therefore only be achieved through use of a correction factor applied to SCAEP and ASSR thresholds. This was accomplished by using the mean behavioural thresholds for tone burst and AM/FM tones at each frequency for the group with normal hearing (presented in Table 4.1) as the normal hearing level (nHL) for the SCAEP and ASSR techniques respectively. In other words, the mean behavioural tone burst threshold values at each frequency were subtracted from SCAEP thresholds and the mean behavioural AM/FM tone thresholds were subtracted from ASSR thresholds at each frequency. The resulting corrected SCAEP and ASSR threshold values were therefore measured in dB normal hearing level (dBnHL). The mean corrected SCAEP and ASSR thresholds were presented in Table 4.2 and 4.3 for the group of participants with normal hearing and for the group of participants with hearing loss. Once this was completed, sub-aim two ensued with the comparison of the corrected thresholds of the SCAEP and ASSR techniques (measured in dBnHL) with the behavioural PT thresholds.

5.3 DISCUSSION OF SUB-AIM TWO RESULTS: COMPARING SCAEP, ASSR AND BEHAVIOURAL PT THRESHOLDS

The aim of the second sub-aim was to compare the accuracy of threshold estimation by SCAEP and ASSR techniques at 0.5, 1, 2 and 4 kHz in adult participants with normal hearing and in a sample of adults exposed to occupational noise who present with a hearing loss. The quantitative results presented in the preceding chapter were discussed for the SCAEP and ASSR techniques individually, before comparing the threshold data of the two techniques. The SCAEP and ASSR threshold intensity, or the difference between behavioural PT threshold intensity and SCAEP or ASSR threshold intensity, was measured in dBnHL as discussed in sub-aim one. For simplicity, use is made of the abbreviation dB only with reference to the aforementioned data from this point onwards.

5.3.1 SCAEP thresholds compared to behavioural PT thresholds

For the participant group with normal hearing, mean differences between SCAEP thresholds and behavioural PT thresholds at each frequency ranged from 3.1 to 6 dB, while a mean difference of 3.1 dB across all frequencies was measured. This mean difference score was slightly greater than that for the group with hearing loss (viz. range = 0.6 to 5.5 dB; mean across frequencies = 1.6 dB). The mean difference score between SCAEP and behavioural PT thresholds for the participant groups with normal hearing and with hearing loss collectively, was 2.2 dB. These smaller difference scores for individuals with hearing loss than for individuals with normal hearing have consistently been reported (Kaf, Durrant et al., 2006; Tomlin et al., 2006; Yeung & Wong, 2007). Hyde (1997) states that for a cochlear hearing loss, the magnitude of the SCAEP amplitude and latency input-output function slope usually increases, with rapid convergence to normal values at raised sensation levels. This is comparable to loudness recruitment. The group of participants with sensorineural hearing loss in the current study were all exposed to occupational noise. Although diagnosis with a noise induced hearing loss was not a criterion for participation in the study, it is likely that the majority of participants presented with a noise induced hearing loss and, consequently, with cochlear pathology (Rosen, Vrabec, & Quinn, 2001; Sataloff & Sataloff, 1987). This assumption is supported by the mean behavioural PT hearing thresholds measured in the participants with hearing loss, namely a mild to moderate, sloping, high frequency hearing loss. This audiometric configuration is typical of a noise induced hearing loss (Kowalska & Sulkowski, 1997; Rosen et al., 2001; Sataloff & Sataloff, 1987).

In order to facilitate comparison with existing literature, the summary, in chronological order, of the differences between SCAEP thresholds and behavioural PT thresholds, the correlation scores and participant numbers of previous studies initially presented in Chapter 2 was repeated in Table 5.1, with the addition of the findings of the current study.

TABLE 5.1 SCAEP studies, including present study, reporting differences between SCAEP thresholds and behavioural PT thresholds (difference score in dBnHL = SCAEP threshold minus behavioural PT threshold), correlation scores and participant numbers

Study	**500 Hz**			**1000 Hz**			**2000 Hz**			**4000 Hz**		
	diff	**r**	**n**	**diff**	**r**	**n**	**diff**	**r**	**n**	**diff**	**r**	**n**
Coles & Mason (1984)	0 ± 10	-	14 N+HL	0 ± 6	-	129 N+HL	0 ± 11	-	95 N+HL	0 ± 7	-	18 N+HL
Prasher et al. (1993)	-	-	-	-0.3 ± 11 2 ± 8	0.79 0.9	62 HL NIHL 27 N+HL Ménière's	-	-	-	0.6 ± 10 1 ± 8	0.89 0.89	62 HL NIHL 27 N+HL Ménière's
Tsui et al. (2002)	-	-	-	-2 ± 11	-	204 N+HL	-1 ± 9	-	204 N+HL	-	-	-
Van Maanen & Stapells (2005)	20 ± 6	0.81	46 N+HL	20 ± 9	0.82	46 N+HL	20 ± 12	0.80	46 N+HL	-	-	-
Kaf, Durrant et al. (2006)	-	-	-	-	-	-	10 ± 6 8 ± 6	0.89	16 N 16 SH	-	-	-
Lightfoot & Kennedy (2006)	-	-	-	10.7 ± 6	-	48 N+HL	9.7 ± 10 *(3 kHz)*	-	48 N+HL	-	-	-
Tomlin et al. (2006)	13 ± 6 8 ± 7	0.95	36 N 27 HL	-	-	-	-	-	-	12 ± 4 13 ± 12	0.96	36 N 20 HL
Yeung & Wong (2007)	6 ± 9	0.96 (r^2)	34 N+HL	8 ± 7	0.98 (r^2)	34 N+HL	8 ± 8	0.97 (r^2)	34 N+HL	-2 ± 15	0.97 (r^2)	34 N+HL
Current study	**-3.7 ± 9.3** **2.2 ± 10.2** **-0.2 ± 10.2**	**0.55** **0.53**	**16 N** **16 HL** **32 N+HL**	**5.5 ± 9.7** **0.6 ± 9.8** **2.8 ± 10.1**	**0.60** **0.48**	**16 N** **16 HL** **32 N+HL**	**6.0 ± 7.8** **5.5 ± 11.3** **5.8 ± 9.7**	**0.71** **0.79**	**16 N** **16 HL** **32 N+HL**	**3.3 ± 7.9** **-1.6 ± 11.6** **0.5 ± 10.4**	**0.77** **0.92**	**16 N** **16 HL** **32 N+HL**

(diff = difference score; r = correlation; n = number of participants; N = participants with normal hearing; HL = participants with hearing loss; NIHL = participants with noise induced hearing loss; Ménière's = participants with Ménière's disease; SH = participants with simulated hearing loss)

The data presented in Table 5.1 is discussed with reference to firstly, the difference between SCAEP threshold and behavioural PT threshold and secondly, the relationship and correlation between SCAEP threshold and behavioural PT threshold.

5.3.1.1 Difference values between SCAEP thresholds and behavioural PT thresholds

To simplify comparison of the mean difference values between SCAEP thresholds and behavioural PT thresholds measured at each frequency in the current study with that of earlier studies, the information in Table 5.2 lists the studies with difference scores (SCAEP threshold minus behavioural PT threshold) which were smaller (by > 10 dB), within 6 to 10 dB, within 5 dB, and which were greater (by > 10 dB) than those of the combined participant groups of the current study. Therefore, the studies listed higher up in the table reported SCAEP thresholds closer to the behavioural PT threshold (the best being 0 dB difference between SCAEP and behavioural PT threshold) than those listed lower down.

TABLE 5.2 Comparison of differences between SCAEP thresholds and behavioural PT thresholds for the combined participant groups with previous SCAEP studies (difference score in dBnHL = SCAEP threshold minus behavioural PT threshold)

	500 Hz	1000 Hz	2000 Hz	4000 Hz	Mean: All frequencies
Smallest difference score	0 dB Coles & Mason (1984)	0 dB Coles & Mason (1984)	0 dB Coles & Mason (1984)	0 dB Coles & Mason (1984)	0 dB Coles & Mason (1984)
↓	**0 dB Current study**	0 dB Prasher et al. (1993)	-1 dB Tsui et al. (2002)	**1 dB Current study**	1 dB Prasher et al. (1993)
	6 dB Yeung & Wong (2007)	-2 dB Tsui et al. (2002)	**6 dB Current study**	1 dB Prasher et al. (1993)	-2 dB Tsui et al. (2002)
	11 dB Tomlin et al. (2006)	**3 dB Current study**	8 dB Yeung & Wong (2007)	-2 dB Yeung & Wong (2007)	**2 dB Current study**
	20 dB Van Maanen & Stapells (2005)	8 dB Yeung & Wong (2007)	9 dB Kaf, Durrant et al. (2006)	12 dB Tomlin et al. (2006)	5 dB Yeung & Wong (2007)
		11 dB Lightfoot & Kennedy (2006)	10 dB Lightfoot & Kennedy (2006)		9 dB Kaf, Durrant et al. (2006)
		20 dB Van Maanen & Stapells (2005)	20 dB Van Maanen & Stapells (2005)		11 dB Lightfoot & Kennedy (2006)
					12 dB Tomlin et al. (2006)
Largest difference score					20 dB Van Maanen & Stapells (2005)

(■ = difference scores within 5 dB of those reported in current study; □ = difference scores within 6 to 10 dB of those reported in current study)

Table 5.2 displayed the proximity of SCAEP thresholds to behavioural PT thresholds for the combined participant groups for the various studies. For studies that reported separate difference scores for participant groups with normal hearing and with hearing loss, the mean differences for the total number of ears tested were reported.

As can be seen from Tables 5.1 and 5.2, the studies of Coles and Mason (1984), Prasher et al. (1993), Tsui et al. (2002) and Yeung and Wong (2007) reported comparable[1] mean difference scores (between SCAEP threshold and behavioural PT thresholds) and standard deviations with those of the present study. Kaf, Durrant et al. (2006) only measured SCAEP thresholds at 2 kHz. The mean difference between the behavioural PT thresholds and SCAEP thresholds at 2 kHz, namely 9 dB, was comparable to that of the current study at this frequency (viz. 6 dB). Although the study by Lightfoot and Kennedy (2006) did include participants with some degree of hearing loss, the participants predominantly presented with normal hearing. The difference scores reported by Lightfoot and Kennedy (2006) were comparable to those in the group with normal hearing of the current study. The difference between SCAEP and behavioural PT thresholds in the study by Tomlin et al. (2006) found slightly larger mean difference scores at 0.5 and 4 kHz, which ranged from 8 to 13 dB.

In contrast to the present study, Van Maanen and Stapells (2005) displayed a mean difference between SCAEP threshold and behavioural PT threshold of approximately 20 dB. In fact, the difference scores were not only markedly higher than in the present study, but were also higher than is reported elsewhere. Van Maanen and Stapells (2005) also used a male only population, with 40 out of 46 participants claiming compensation and, consequently, frequently presenting with a noise induced high frequency hearing loss. With the many similarities between this study and the current study, difference scores would be expected to be more similar. The authors chose to use a shorter plateau for the tone burst stimuli, namely a 40 ms plateau in contrast to the 80 ms plateau used in the present study. This plateau duration is also shorter than the 60 ms duration advocated by Hall (1992) and significantly shorter than the 200 to 300 ms plateau recommended by Onishi and Davis (1968). Hyde (1997) cautions against the use of abrupt stimulus onsets

[1] Difference scores, as measured between AEP thresholds and behavioural PT thresholds, were considered comparable when they fell within 5 dB of each other.

with short stimulus duration as these result in energy spread (spectral splatter) and consequently to reduced frequency specificity. This would lead to underestimation of behavioural PT high frequency thresholds especially for sloping audiometric configurations. Spectral splatter results which may activate lower frequency regions of the cochlea, generating a response. Stimulus duration is therefore an important factor for estimation of behavioural PT thresholds in a population exposed to occupational noise and at risk of developing a sloping high frequency hearing loss. The shortened stimulus plateau used by Van Maanen and Stapells (2005) may have played a role in the disparity in results between the Van Maanen and Stapells (2005) study and the current one. One would, however, expect that use of a stimulus with reduced frequency specificity would have a minimal effect on SCAEP threshold intensity of the low frequencies and that underestimation of mid and high frequency behavioural PT thresholds of a sloping high frequency hearing loss would result, rather than overestimation of the mid frequencies as was reported by Van Maanen and Stapells (2005). The use of a 5 dB stimulus intensity increments, as compared to the 10 dB increments utilized in the present study, may have resulted in a decrease of no more than 1 dB in difference scores, and a 1 to 2 dB decrease in standard deviation scores (Luts & Wouters, 2004; Van Maanen & Stapells, 2005). Van Maanen and Stapells (2005) ascribed the reason for the elevated SCAEP thresholds to the calibration method utilized. SCAEP stimuli were calibrated in dBeHL (dB estimated hearing level), so that a 20 dBeHL SCAEP threshold was equivalent to a 20 dB behavioural PT threshold. Van Maanen and Stapells (2005) suggest that the SCAEP thresholds reported would have been approximately 9 dB smaller, had the typical nHL been used instead of the dBeHL scale selected. A 9 dB decrease in SCAEP thresholds, although substantial, would, however, still mean that the SCAEP threshold data of Van Maanen and Stapells (2005) remains elevated, with reference to the majority of existing literature, albeit considerably less so.

In instances where there is no clear reason for variations in difference between SCAEP threshold and behavioural PT threshold data between studies, such as in the case of studies by Van Maanen and Stapells (2005), it is possible that fluctuations in participant attention state may have played a role. Attention significantly affects SCAEP response amplitude and waveform both between and within individuals (Hyde, 1997). The amplitude of the N1 and P2 is larger when an individual pays attention to the stimuli (Stapells, 2002), although each of these waves may not be equally affected by attention (Hyde, 1997). An increase in N1 and / or P2 amplitude results in a lower SCAEP threshold and a smaller difference between SCAEP threshold and behavioural PT threshold. Amplitude changes due to attention are most marked near threshold (Hyde, 1997). Dependence on participant attention and state of consciousness is largely due to the neural generators of the SCAEP, namely the primary auditory cortex and its associated cortical areas (Pantev et al., 1990; Vaughan & Ritter, 1970). Therefore the participants' attention and state of consciousness may have affected not only the proximity of the SCAEP threshold to the behavioural PT threshold, but also the variability (or standard deviation) of difference scores.

When comparing differences between SCAEP thresholds and behavioural PT thresholds at individual frequencies for the participants with hearing loss in the current study, the largest mean difference score was measured for 2 kHz (viz. 5.8 dB). Despite this being comparatively the largest difference score, this still indicates a close proximity of the SCAEP threshold to behavioural PT thresholds at this frequency. The smallest mean difference scores were measured at 0.5 and 4 kHz for the group of participants with hearing loss (0.5 kHz = -0.2 dB; 4 kHz = 0.5 dB). The SCAEP threshold at 0.5 kHz consistently appeared within 12.4 dB of the behavioural PT threshold for participants with hearing loss. This is noteworthy, as 0.5 kHz is heavily weighted in the percentage loss of hearing or PLH calculations (COIDA, 2001), which then determines percentage handicap and the amount of compensation awarded. As is typical of a noise induced hearing loss, 4 kHz is likely to display the greatest behavioural PT threshold (Kowalska & Sulkowski, 1997; Rosen et al., 2001; Sataloff & Sataloff, 1987). The closer the SCAEP threshold to the behavioural PT threshold, the more accurate the estimation of behavioural PT threshold. Large discrepancies between SCAEP and behavioural PT thresholds result in overestimation of behavioural PT thresholds, a larger percentage loss of hearing (COIDA, 2001) and excessive compensation. The small mean difference between SCAEP threshold and behavioural PT threshold at 4 kHz for participants with hearing loss in the current study (viz. -1.6 dB) is not only indicative of the accuracy of the SCAEP technique, but will also reduce the amount of monetary compensation owed. This can be considered the ideal outcome for the South African healthcare system, where both quality and cost-efficacy are prioritised (South African Department of Health, 1997). In addition, the small difference between SCAEP threshold and behavioural PT threshold at 4 kHz for the participants with hearing loss, is evidence of good frequency specificity yielded by the SCAEP stimuli. The participants with hearing loss in this study were exposed to occupational noise and typically presented with a sloping high frequency hearing loss. The SCAEP did, therefore, not underestimate the degree of the hearing loss at 4 kHz, despite a difference of 26 dB between the mean behavioural PT threshold at this frequency and that of 2 kHz.

The distribution of SCAEP thresholds with respect to the behavioural PT thresholds, as displayed in Figure 4.5 in the previous chapter, the present study measured 67% of SCAEP thresholds within 10 dB and 87% of SCAEP thresholds within 15 dB of behavioural PT thresholds. This is similar to the results of recent literature, as Tsui et al. (2002) found 83% of SCAEP thresholds within 10 dB of the behavioural PT threshold, while Lightfoot and Kennedy (2006) reported 80% of SCAEP thresholds within 10 dB of behavioural PT thresholds and 94% of threshold within 15 dB of the behavioural PT thresholds. The earlier study by Alberti et al. (1987) stated that 96.4% of SCAEP thresholds could be identified within 10 dB of the behavioural PT thresholds. The better distribution score is likely to be related to the considerably larger number of participants included in the study (n = 1168) than were included in the present study (n = 32).

Accuracy of an AEP technique is often judged not by the proximity of the AEP threshold to behavioural PT threshold alone, but by both proximity and the variability of this relationship (Picton et al., 2005; Rance et al., 1995; Tomlin et al., 2006). The standard deviations of the difference scores between SCAEP thresholds and behavioural PT thresholds measured in the current study, ranged from 7.9 to 11.6 dB and are comparable to those reported in existing literature (range = 6 to 15 dB; Coles & Mason, 1984; Kaf, Durrant et al., 2006; Lightfoot & Kennedy, 2006; Tsui et al., 2002; Van Maanen & Stapells, 2005; Yeung & Wong, 2007). The measure of variability offered by the standard deviation of the SCAEP threshold is therefore consistently low for this and for previous studies. Consistency of the relationship between SCAEP and behavioural PT thresholds facilitates estimations of behavioural PT thresholds from SCAEP thresholds. The regression formulae generated for this purpose (as displayed in Figure 4.9), can therefore be considered reliable.

5.3.1.2 Relationship between SCAEP thresholds and behavioural PT thresholds

The statistical correlation between the SCAEP thresholds and behavioural PT thresholds in the group with hearing loss, was strong (mean $R^2 = 0.72$; $r = 0.85$). The SCAEP thresholds for the group of participants with normal hearing, though, demonstrated a weak correlation with behavioural PT thresholds (mean $R^2 = 0.0046$; mean $r = -0.07$). When examining the correlation scores in the group of participants with normal hearing at each frequency individually, however, moderate correlations were apparent at 0.5 and 1 kHz (both negative correlations), and at 4 kHz (positive correlation). Significantly stronger correlation co-efficients were measured for the participants with hearing loss than for the participants with normal hearing ($p < 0.01$). This has been reported previously by Hyde (1997), and is thought to be related to recruitment. The physiological response increases in amplitude more steeply with increasing intensity when there is a hearing loss. This results in the SCAEP responses for individuals with a sensory hearing loss being recognized closer to the behavioural PT threshold intensity. Strong correlations of greater than 0.5 (Cohen, 1988) between SCAEP thresholds and behavioural PT thresholds were also measured at each individual frequency in the participant group with hearing loss.

The correlations for the combined participant groups of the current study ($r = 0.85$ across all frequencies) were comparable to that of Kaf, Durrant et al. (2006). Similar correlation data to that of the current study were also reported by Tomlin et al. (2006) for 4 kHz ($r = 0.96$) and for Van Maanen and Stapells (2005) for 2 kHz ($r = 0.80$). These two studies, however, demonstrated stronger correlations for all participants at 0.5 kHz ($r = 0.81$ to 0.95) and 1 kHz ($r = 0.82$) than for the current study ($r = 0.53$ and 0.48 for 0.5 and 1 kHz respectively). Two factors may explain the stronger correlations measured by Van Maanen and Stapells (2005). The smaller standard deviations of the mean difference scores between SCAEP thresholds and behavioural PT thresholds (std dev = 6 to 9 dB), as compared to the current study (std dev = 10 dB), in addition to the larger number of participants ($n = 46$ in the study by Van Maanen & Stapells, 2005, versus $n = 32$ in the current study), may have contributed to the stronger correlation co-efficients measured by Van Maanen and Stapells (2005) at 0.5 and 1 kHz. Tomlin et al. (2006) chose participants for the group with hearing loss with elevated behavioural PT hearing thresholds at 0.5 kHz (mean behavioural PT threshold = 39.8 dB). This is in contrast to the mean behavioural PT threshold at 0.5 kHz in the current study of 10.5 dB. A raised behavioural PT threshold typically yields SCAEP thresholds closer to behavioural PT threshold and better correlation co-efficients (Hyde, 1997; Johnson & Brown, 2005). The elevated behavioural PT thresholds at 0.5 kHz is therefore the likely cause of the stronger correlation co-efficients reported by Tomlin et al. (2006) at this frequency, than in the current study.

On average the SCAEP thresholds were therefore highly correlated with behavioural PT thresholds (r measured across all frequencies = 0.85) and can be used to obtain accurate estimates of behavioural PT thresholds, due to their proximity to the behavioural PT thresholds (mean difference score across all frequencies = 2.8 dB) and low mean measures of variability (mean std dev across all frequencies = 10.2 dB). These findings correspond well with existing literature, which states that the SCAEP is appropriate for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise. Even with this challenging population of individuals who may not be willing participants to assessment, and who typically present with a sloping sensory hearing loss, the SCAEP is sufficiently robust when testing alert individuals, is accurate and displays good frequency specificity.

5.3.2 ASSR thresholds compared to behavioural PT thresholds

A low modulation rate was chosen when testing the sleeping participants of this study. In order to facilitate comparison with existing literature, the summary (in chronological order) of differences between ASSR thresholds and behavioural PT thresholds, correlation scores and participant numbers of previous 40Hz ASSR studies, is again presented in Table 5.3, with the addition of the findings of the current study using the 40 Hz ASSR technique.

TABLE 5.3 40 Hz ASSR studies, including present study, reporting differences between ASSR thresholds and behavioural PT thresholds(difference score in dBnHL = ASSR threshold minus behavioural PT threshold), correlation scores (dBnHL) and participant numbers

Study	ASSR stimulus technique	500 Hz			1000 Hz			2000 Hz			4000 Hz		
		diff	r	n	diff	r	n	diff	r	n	diff	r	n
Aoyagi et al. (1993)	SF	11 ± 10 8 ± 7	-	15 N 18 HL	11 ± 11 9 ± 6	-	15 N 18 HL	13 ± 10 13 ± 8	-	15 N 18 HL	18 ± 12 12 ± 6		15 N 18 HL
De Koker (2004) * *40 + 80 Hz single frequency*	SF	8	-	41 HL	6	-	41 HL	-	-	-	-	-	-
Van Maanen & Stapells (2005)	MF	14 ± 7	0.70	23 N+HL	11 ± 6	0.92	23 N+HL	12 ± 14	0.73	23 N+HL	0 ± 9	0.93	23 N+HL
Scherf et al. (2006)	SF	-	0.86	63 N+HL	-	0.91	62 N+HL	-	0.83	60 N+HL	-	0.82	59 N+HL
Tomlin et al. (2006)	SF	17 ± 10 11 ± 9	0.84	36 N 30 HL	-	-	-	-	-	-	42 ± 14 24 ± 8	0.85	36 N 30 HL
Van der Reijden et al. (2006)	MF	10 ± 0	-	11 N	-	-	-	10 ± 0	-	11 N	-	-	-
Yeung & Wong (2007)	SF	11 ± 10	0.96 (r^2)	34 N+HL	14 ± 10	0.97 (r^2)	34 N+HL	12 ± 10	0.97 (r^2)	34 N+HL	4 ± 12	0.95 (r^2)	34 N+HL
Current study		**26.1 ± 14.9** **24.5 ± 10.6** **25.3 ± 12.8**	**0.40**	**16 N** **16 HL** **32 N+HL**	**21.4 ± 13.0** **21.9 ± 9.7** **21.7 ± 11.3**	**0.49**	**16 N** **16 HL** **32 N+HL**	**31.9 ± 13.2** **32.7 ± 11.5** **32.3 ± 12.2**	**0.72**	**16 N** **16 HL** **32 N+HL**	**32.6 ± 12.1** **22.4 ± 13.7** **27.1 ± 13.8**	**0.85**	**16 N** **16 HL** **32 N+HL**

*(diff = difference score; r = correlation; n = number of participants; N = participants with normal hearing; HL= participants with hearing loss; SF = single frequency ASSR technique; MF = multiple frequency ASSR technique; * = 29 of 41 participants tested with 40 Hz ASSR)*

After the presentation of previous research regarding the 40 Hz ASSR technique, Table 5.4 follows which offers a summary (in chronological order) of differences between ASSR thresholds and behavioural PT thresholds, correlation scores and participant numbers for research, using a high modulation rate ASSR technique.

TABLE 5.4 80 Hz ASSR studies reporting differences between ASSR thresholds and behavioural PT thresholds (difference score in dBnHL = ASSR threshold minus behavioural PT threshold), correlation scores (dBnHL) and participant numbers

Study	ASSR stimulus technique	500 Hz			1000 Hz			2000 Hz			4000 Hz		
		diff	r	n	diff	r	n	diff	r	n	diff	r	n
Aoyagi et al. (1994)	SF	34 ± 15	-	20 N	29 ± 14	-	20 N	30 ± 15	-	20 N	9 ± 14	-	20 N
Lins et al. (1995)	MF	-	-	-	16 ± 8	-	8 N	-	-	-	-	-	-
*Rance et al. (1995)**	SF	20 ± 7	0.97	60 N+HL	13 ± 6	0.98	60 N+HL	16 ± 5	0.99	60 N+HL	10 ± 4	0.99	60 N+HL
Lins et al. (1996)	MF	14 ± 11	-	56 N	12 ± 11	-	56 N	11 ± 8	-	56 N	13 ± 11	-	56 N
Picton et al. (1998)	MF	21 ± 9	-	10 N	26 ± 13	-	10 N	18 ± 13	-	10 N	20 ± 10	-	10 N
Herdman & Stapells (2001)	MF	14 ± 10	-	10 N	8 ± 7	-	10 N	8 ± 9	-	10 N	15 ± 9	-	10 N
Perez-Abalo et al. (2001)	MF	12 ± 11	-	40 N	13 ± 9	-	40 N	10 ± 10	-	40 N	13 ± 10	-	40 N
Dimitrijevic et al. (2002)	MF	14 ± 11	0.85	45 N+HL	5 ± 9	0.94	45 N+HL	5 ± 9	0.95	45 N+HL	9 ± 10	0.95	45 N+HL
Herdman & Stapells (2003)	MF	14 ± 13	0.75	26 HL	8 ± 9	0.89	29 HL	10 ± 10	0.88	27 HL	3 ± 10	0.85	28 HL
Hsu et al. (2003)	SF	18 ± 4	0.86	11 HL	19 ± 3	0.92	11 HL	17 ± 3	0.94	11 HL	12 ± 5	0.95	11 HL
De Koker (2004)	MF	14	-	40 HL	9	-	40 HL	-	-	-	-	-	-
*Johnson & Brown (2005)**	MF	-	0.87	10 N+HL	-	-	-	-	0.98	10 N+HL	-	0.95	10 N+HL

*(diff = difference score; r = correlation; n = number of participants; N = participants with normal hearing; HL = participants with hearing loss; SH = simulated hearing loss; SF = single frequency ASSR technique; MF = multiple frequency ASSR technique; * = includes data from both adults and children)*

Study	ASSR stimulus technique	500 Hz			1000 Hz			2000 Hz			4000 Hz		
		diff	r	n	diff	r	n	diff	r	n	diff	r	n
Luts & Wouters (2005) *40 + 80 Hz single frequency*	SF	48 ± 21 20 ± 8	0.54	10 N 10 HL	40 ± 21 14 ± 7	0.72	10 N 10 HL	33 ± 10 13 ± 7	0.92	10 N 10 HL	30 ± 20 14 ± 13	0.85	10 N 10 HL
Luts & Wouters (2005) *Dichotic multiple frequency*	MF	24 ± 11 17 ± 12	0.83	10 N 10 HL	17 ± 9 12 ± 8	0.95	10 N 10 HL	14 ± 7 17 ± 8	0.97	10 N 10 HL	21 ± 11 19 ± 12	0.93	10 N 10 HL
Picton et al. (2005)	MF	21 ± 8 11 ± 18	-	10 N 10 HL	7 ± 8 -4 ± 9	-	10 N 10 HL	10 ± 6 3 ± 11	-	10 N 10 HL	13 ± 7 5 ± 12	-	10 N 10 HL
Schmulian et al. (2005)*	MF	14 ± 16	0.88	25 HL	18 ± 18	0.84	25 HL	15 ± 13	0.91	25 HL	14 ± 15	0.86	25 HL
Van Maanen & Stapells (2005)	MF	17 ± 11	0.65	23 N+HL	15 ± 7	0.91	23 N+HL	19 ± 9	0.90	23 N+HL	4 ± 10	0.87	23 N+HL
Attias et al. (2006)*	MF	13 ± 13 2 ± 12	0.86	18 N 29 HL	10 ± 8 0 ± 7	0.93	18 N 29 HL	3 ± 7 0 ± 10	0.94	18 N 29 HL	3 ± 7 -2 ± 8	0.93	18 N 29 HL
Kaf, Durrant et al. (2006)	MF	17 ± 12 17 ± 10	0.53	16 N 16 SH	13 ± 8 9 ± 8	0.75	16 N 16 SH	10 ± 5 3 ± 5	0.93	16 N 16 SH	12 ± 8 6 ± 10	0.75	16 N 16 SH
Van der Reijden et al. (2006)	MF	18 ± 10	-	11 N	-	-	-	12 ± 4	-	11 N	-	-	-
Ahn et al. (2007)	MF	-	0.94	111 N+HL	-	0.95	111 N+HL	-	0.94	111 N+HL	-	0.92	111 N+HL
Swanepoel & Erasmus (2007)	MF	8 ± 10	-	7 HL	2 ± 7	-	7 HL	5 ± 8	-	7 HL	5 ± 8	-	7 HL
D'haenens et al. (2008)	MF	19 ± 11	-	29 N	13 ± 10	-	29 N	10 ± 9	-	29 N	13 ± 10	-	29 N
Average	MF	17.9 ± 9.3	-	-	14.3 ± 9.1	-	-	12.8 ± 8.2	-	-	11.5 ± 7.5	-	-

*(diff = difference score; r = correlation; n = number of participants; N = participants with normal hearing; HL = participants with hearing loss; SH = simulated hearing loss; SF = single frequency ASSR technique; MF = multiple frequency ASSR technique; * = includes data from both adults and children)*

The relevance of the quantitative results of the current study will be reviewed with reference to existing data, as was presented in the preceding tables.

5.3.2.1 Difference values between ASSR and behavioural PT thresholds

In the group of participants with normal hearing, the present study found a mean difference score across all frequencies between ASSR thresholds and behavioural PT thresholds of 27.9 dB. The difference score across all frequencies for the group of participants with hearing loss was 25.4 dB. Several authors have found that individuals with a hearing loss demonstrate less of a difference between ASSR thresholds and behavioural PT thresholds than in individuals with normal hearing (Aoyagi et al., 1993; Attias et al., 2006; Hsu et al., 2003; Kaf, Durrant et al., 2006; Lins et al., 1996; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Picton et al., 2005; Rance & Rickards, 2002; Rance et al., 1995, 2005; Swanepoel & Erasmus, 2007; Tomlin et al., 2006). This phenomenon is attributed to recruitment (Lins et al., 1996). The effect of recruitment was also recorded in the current study, although mean difference scores were smaller for the group with hearing loss than in the group with normal hearing by only 2.5 dB.

The data on the differences between 40 Hz ASSR thresholds and behavioural PT thresholds presented in Table 5.3 was recorded in Table 5.5 to display the studies with difference scores which were smaller (by > 10 dB), within 6 to 10 dB, within 5 dB and greater (by > 10 dB) than those of the current study. Studies which reported ASSR thresholds closest to behavioural PT thresholds are therefore listed first.

TABLE 5.5 Comparison of differences between 40 Hz ASSR thresholds and behavioural PT thresholds for the combined participant groups with previous 40 Hz ASSR studies (difference score in dBnHL = ASSR threshold minus behavioural PT threshold)

	500 Hz		1000 Hz		2000 Hz		4000 Hz		Mean: All frequencies
Smallest difference score	8 dB De Koker (2004)[#]		6 dB De Koker (2004)[#]		10 dB Van der Reijden et al. (2006)		0 dB Van Maanen & Stapells (2005)		7 dB De Koker (2004)[#]
	9 dB Aoyagi et al. (1993)		10 dB Aoyagi et al. (1993)		12 dB Van Maanen & Stapells (2005)		4 dB Yeung & Wong (2007)		9 dB Van Maanen & Stapells (2005)
	10 dB Van der Reijden et al. (2006)		11 dB Van Maanen & Stapells (2005)		12 dB Yeung & Wong (2007)		15 dB Aoyagi et al. (1993)		10 dB Van der Reijden et al. (2006)
	11 dB Yeung & Wong (2007)		14 dB Yeung & Wong (2007)		13 dB Aoyagi et al. (1993)		**27 dB** **Current study**		10 dB Yeung & Wong (2007)
	14 dB Van Maanen & Stapells (2005)		**22 dB** **Current study**		**32 dB** **Current study**		30 dB Tomlin et al. (2006)		12 dB Aoyagi et al. (1993)
	14 dB Tomlin et al. (2006)								22 dB Tomlin et al. (2006)
Largest difference score	**25 dB** **Current study**								**27 dB** **Current study**

(= difference scores within 5 dB of those reported in current study; = difference scores within 6 to 10 dB of those reported in current study; [#] = 40 + 80 Hz single frequency ASSR, 29 of 41 participants tested with 40 Hz modulation rate)

When comparing the current research with previous studies that made use of a 40 Hz ASSR technique, as was done in Tables 5.3 and 5.5, the difference scores between ASSR threshold and behavioural PT thresholds measured were larger in the current study than in the studies by Aoyagi et al. (1993), De Koker (2004), Van der Reijden et al. (2006), Van Maanen and Stapells (2005), Yeung and Wong (2007). The only exception was the mean difference scores across all frequencies reported by Tomlin et al. (2006), which was comparable to the mean difference scores across all frequencies in the present study. Difference scores were typically 15 dB smaller (calculated across frequencies) in the study by Aoyagi et al. (1993), 20 dB smaller in the study by De Koker (2004), 17 dB smaller in the Van Maanen and Stapells (2005) study, 19 dB smaller in the Van der Reijden et al. (2006) study and 16 dB smaller than the current study in the study of Yeung and Wong (2007) than in the current research project.

Yeung and Wong (2007) reported on 40 Hz ASSR thresholds measured, using the GSI (Grason-Stadler Incorporated) Audera and the manufacturer recommended protocol, as was done in the present study. Of the 34 participants (63 ears) included in the study, 20 ears presented with a severe to profound hearing loss. A mean difference of 10.3 dB was measured between ASSR threshold and behavioural PT threshold across the four frequencies evaluated, considerably less than the mean difference of 26.6 dB of the current study. Several authors have found that individuals with a hearing loss demonstrate a closer proximity of ASSR threshold to behavioural PT thresholds, than in individuals with normal hearing (Attias et al., 2006; Hsu et al., 2003; Kaf, Durrant et al., 2006; Rance et al., 1995, 2005; Swanepoel & Erasmus, 2007; Tomlin et al., 2006) and closer proximity of ASSR thresholds to behavioural PT thresholds for a severe to profound hearing loss, than to the behavioural PT thresholds for a moderate hearing loss (e.g. Picton et al., 2005; Rance et al., 1995; Yeung & Wong, 2007). The current study included only two behavioural PT thresholds of over 70 dB. The smaller mean differences between ASSR thresholds and behavioural PT thresholds in the Yeung and Wong (2007) study, than in the current study, are likely to be due to the fact that a third of the participants presented with behavioural PT thresholds of greater than 70 dB in contrast to less than 0.001% in the current study.

The studies by Aoyagi et al. (1993), De Koker (2004), Tomlin et al. (2006) and Yeung and Wong (2007) also utilized a monotic single frequency 40 Hz ASSR technique, as was the case in the present study. The participants in all of the studies listed in Tables 5.3 and 5.5 were assessed in an alert state of attention, in contrast to the restful or sleeping state of the participants of the current study. It is therefore possible that the participant state of attention improved proximity to behavioural PT thresholds with the 40 Hz modulation rate ASSR technique. This observation is consistent with early research that suggested that 40 Hz ASSR amplitudes are smaller in sleeping or sedated adults than in the awake state (Aoyagi et al., 1993; Galambos et al., 1981; Linden et al., 1985), resulting in elevation of ASSR threshold intensity. It would, however, also contradict reports that, despite this reduction in ASSR amplitude during sleep, response detectability at threshold is improved due to the decreased background noise levels in sleeping participants (Dobie & Wilson, 1998).

Although the mean difference between ASSR threshold and behavioural PT thresholds across frequencies reported by Tomlin et al. (2006) was comparable to that of the current study, Tomlin et al. (2006) reported differences between the ASSR threshold and behavioural PT thresholds at 0.5 kHz that were 9 and 14 dB smaller for participants with normal hearing and with hearing loss respectively, than in the current study. In addition, Tomlin et al. (2006) measured a mean difference between ASSR thresholds and behavioural PT thresholds for participants with normal hearing, which was 9 dB larger at 4 kHz (difference score = 42 dB) than that of the present study (difference score = 33 dB). The contrasting difference scores between the current study and that of Tomlin et al. (2006), are especially noteworthy as Tomlin et al. (2006) made use of the GSI Audera ASSR system, using the 40 Hz modulation rate with the manufacturer recommended stimulus and acquisition parameters, as was done in the present study. It was decided in the present study to evaluate participants with 40 Hz ASSR while participants were restful or asleep, to reduce the amount of responses with excessive amounts of artefacts or noise. The participants in the Tomlin et al. (2006) study were evaluated while relaxed, but awake. It is therefore feasible that the elevated ASSR thresholds measured at the low and mid frequencies in the current study, is a result of the restful or sleeping state of the participants during assessment. Conversely, it may be concluded that the 40 Hz ASSR threshold at 4 kHz (at least for participants with normal hearing), is negatively affected by an alert state of attention. This is contrary to the findings of Linden et al. (1985), who found no difference in the 40 Hz ASSR threshold values in awake versus sleeping participants. Interestingly, the aforementioned conclusions suggest that detectability of 40 Hz ASSR in the alert or sleeping state may be different for 4 kHz, than it is for lower frequencies. This pattern is, however, not echoed by other studies that made use of 40 Hz ASSR and an alert participant state of attention. Both Van Maanen and Stapells (2005) and Yeung and Wong (2007) report smaller difference scores (between ASSR thresholds and behavioural PT thresholds) at 4 kHz than at lower frequencies.

The effect of state of consciousness on 4 kHz when performing 40 Hz ASSR, is an important consideration when targeting individuals who are likely to present with a high frequency hearing loss, as is the case in a population exposed to occupational noise. Even small deviations from true thresholds can translate into a significant difference in financial outcome (Coles et al., 1991; Alberti et al., 1987). The current study typically measured 4 kHz ASSR thresholds for participants with hearing loss at a 22 dB sensation level. Similarly, Tomlin et al. (2006) measured mean ASSR thresholds for 4 kHz for participants with hearing loss at a level of 24 dB above behavioural PT thresholds. These elevated ASSR thresholds are likely to lead to overestimation of behavioural PT thresholds at 4 kHz. This frequency is heavily weighted in the calculation of percentage loss of hearing (COIDA, 2001). The resulting larger percentage loss of hearing leads to a larger percentage of permanent disability and excessive compensation for noise induced hearing loss claims (Rickards & De Vidi, 1995).

Van Maanen and Stapells (2005) offered a novel alternative for improved accuracy of behavioural PT threshold estimation using ASSR thresholds. The study is the first of only two studies the researcher is aware of that used a 40 Hz dichotic multiple frequency ASSR technique for the purpose of behavioural PT threshold estimation in adults. Van Maanen and Stapells (2005) compared the ability of SCAEP, 40 Hz dichotic multiple frequency ASSR and the 80 Hz dichotic multiple frequency ASSR to estimate behavioural PT thresholds. The population included male participants claiming compensation for occupational hearing loss. This was similar to the target population of the current study, as the majority of the participants presented with an occupational noise induced hearing loss. Van Maanen and Stapells (2005) concluded that the 40 Hz dichotic multiple frequency

ASSR technique was the AEP of choice for the purpose of estimation of behavioural PT thresholds due to the proximity of the ASSR thresholds to the behavioural PT thresholds and the time taken to complete the assessment. The mean difference between the behavioural PT thresholds and the 40 Hz ASSR thresholds at 4 kHz was 0.4 dB.

The second study that examined the use of the 40 Hz dichotic multiple frequency ASSR technique for the purpose of behavioural PT threshold estimation, that of Van der Reijden et al. (2006), reported ASSR thresholds at 10 dB sensation level at 0.5 and 2 kHz. Van der Reijden et al. (2006) used only 11 participants for the study who presented with normal hearing sensitivity. It is expected that had the participants presented with a hearing loss, that the ASSR thresholds would have been closer to behavioural PT thresholds, as is often reported (Attias et al., 2006; Hsu et al., 2003; Kaf, Durrant et al., 2006; Rance et al., 1995, 2005; Swanepoel & Erasmus, 2007; Tomlin et al., 2006). Therefore, threshold estimation, using the 40 Hz multiple frequency ASSR technique by both Van Maanen and Stapells (2005) and Van der Reijden et al. (2006), yielded promising results, due to the proximity of the resulting ASSR threshold to behavioural PT threshold. The reason for the lack of research on the 40 Hz multiple frequency ASSR is possibly the findings of early research on dichotic multiple ASSR by John et al. (1998), who recommended using modulation frequencies between 70 and 110 Hz rather than lower modulation frequencies, due to the large amount of interaction between simultaneously presented stimuli when employing lower modulation frequencies of 30 to 50 Hz.

When the results of the current research are compared to those using a high modulation rate, as was done in Table 5.4, it is evident that the large majority of the difference scores between 80 Hz ASSR threshold and behavioural PT threshold at each frequency (for both participants with normal hearing and with hearing loss), were smaller than the difference between the 40 Hz ASSR thresholds and behavioural PT thresholds of the present study (Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Hsu et al., 2003; Kaf, Durrant et al., 2006; Lins et al., 1996; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Picton et al., 1998; Rance et al., 1995; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van der Reijden et al., 2006; Van Maanen & Stapells, 2005). Table 5.6, which follows, presents the 80 Hz ASSR studies in order of the proximity of ASSR threshold to behavioural PT thresholds measured. The table displays the differences between ASSR thresholds and behavioural PT thresholds which were smaller (by > 10 dB), within 6 to 10 dB, within 5 dB and greater (by > 10 dB) than the difference between the 40 Hz ASSR thresholds and behavioural PT thresholds reported by the current study.

TABLE 5.6 Comparison of differences between 40 Hz ASSR thresholds and behavioural PT thresholds for the combined participant groups with previous 80 Hz ASSR studies (difference score in dBnHL = ASSR threshold minus behavioural PT threshold)

	500 Hz	1000 Hz	2000 Hz	4000 Hz	Mean: All frequencies
Smallest difference score	6 dB Attias et al. (2006)	2 dB Swanepoel & Erasmus (2007)	1 dB Attias et al. (2006)	0 dB Attias et al. (2006)	3 dB Attias et al. (2006)
	8 dB Swanepoel & Erasmus (2007)	4 dB Attias et al. (2006)	5 dB Dimitrijevic et al. (2002)	3 dB Herdman & Stapells (2003)	5 dB Swanepoel & Erasmus (2007)
	12 dB Perez-Abalo et al. (2001)	5 dB Dimitrijevic et al. (2002)	5 dB Swanepoel & Erasmus (2007)	4 dB Van Maanen & Stapells (2005)	8 dB Dimitrijevic et al. (2002)
	14 dB De Koker (2004)	8 dB Herdman & Stapells (2001)	7 dB Kaf, Durrant et al. (2006)	5 dB Swanepoel & Erasmus (2007)	9 dB Herdman & Stapells (2003)
	14 dB Dimitrijevic et al. (2002)	8 dB Herdman & Stapells (2003)	8 dB Herdman & Stapells (2001)	9 dB Aoyagi et al. (1994)	11 dB Herdman & Stapells (2001)
	14 dB Herdman & Stapells (2001)	9 dB De Koker (2004)	10 dB Herdman & Stapells (2003)	9 dB Dimitrijevic et al. (2002)	11 dB Kaf, Durrant et al. (2006)
	14 dB Herdman & Stapells (2003)	11 dB Kaf, Durrant et al. (2006)	10 dB Perez-Abalo et al. (2001)	9 dB Kaf, Durrant et al. (2006)	12 dB De Koker (2004)
	14 dB Lins et al. (1996)	12 dB Lins et al. (1996)	11 dB Lins et al. (1996)	10 dB Rance et al. (1995)	12 dB Perez-Abalo et al. (2001)
	14 dB Schmulian et al. (2005)	13 dB Perez-Abalo et al. (2001)	12 dB Van der Reijden et al. (2006)	12 dB Hsu et al. (2003)	13 dB Lins et al. (1996)
	17 dB Kaf, Durrant et al. (2006)	13 dB Rance et al. (1995)	15 dB Schmulian et al. (2005)	13 dB Lins et al. (1996)	14 dB Van Maanen & Stapells (2005)
	17 dB Van Maanen & Stapells (2005)	15 dB Luts & Wouters (2005) *	16 dB Luts & Wouters (2005) *	13 dB Perez-Abalo et al. (2001)	15 dB Rance et al. (1995)
	18 dB Hsu et al. (2003)	15 dB Van Maanen & Stapells (2005)	16 dB Rance et al. (1995)	14 dB Schmulian et al. (2005)	15 dB Schmulian et al. (2005)
	18 dB Van der Reijden et al. (2006)	16 dB Lins et al. (1995)	17 dB Hsu et al. (2003)	15 dB Herdman & Stapells (2001)	15 dB Van der Reijden et al. (2006)
	20 dB Rance et al. (1995)	18 dB Schmulian et al. (2005)	18 dB Picton et al. (1998)	20 dB Luts & Wouters (2005) *	16 dB Lins et al. (1995)
	21 dB Luts & Wouters (2005) *	19 dB Hsu et al. (2003)	19 dB Van Maanen & Stapells (2005)	20 dB Picton et al. (1998)	17 dB Hsu et al. (2003)
	21 dB Picton et al. (1998)	**22 dB Current study**	23 dB Luts & Wouters (2005) #	22dB Luts & Wouters (2005) #	18 dB Luts & Wouters (2005) *
	25 dB Current study	26 dB Picton et al. (1998)	30 dB Aoyagi et al. (1994)	**27 dB Current study**	21 dB Picton et al. (1998)
	34 dB Aoyagi et al. (1994)	27 dB Luts & Wouters (2005) #	**32 dB Current study**		26 dB Aoyagi et al. (1994)
	34 dB Luts & Wouters (2005) #	29 dB Aoyagi et al. (1994)			**27 dB Current study**
Largest difference score					27 dB Luts & Wouters (2005) #

(*= difference scores within 5 dB of those reported in current study;* *= difference scores within 6 to 10 dB of those reported in current study;* * = dichotic multiple frequency ASSR; # *= 40 + 80 Hz single frequency ASSR)*

Typically, as evidenced by the data presented in Table 5.6, differences between 80 Hz ASSR thresholds and behavioural PT thresholds were 9 to 17 dB smaller (averaged across frequencies) than those measured in the current study.

Not only did the aforementioned studies use a high modulation rate ASSR technique but the majority, with the exception of Aoyagi et al. (1994), Hsu et al. (2003) and Rance et al. (1995), used a specific dichotic multiple frequency ASSR system, namely the Biologic MASTER ASSR system (John et al., 1998). The Biologic MASTER system allows for ASSR response to be recorded for up to 15 min or 900 s in order to improve the signal to noise ratio of recordings (John et al., 1998). This is in comparison with the single frequency GSI Audera ASSR system used in the present study, which allows a maximum recording duration of 89 s (GSI, 2003). Recording duration is a key factor in determination of accuracy of an ASSR technique (Picton et al., 2005). ASSR responses need to be distinguished from noise, as threshold estimation is made with reference to the noise level at which a response is judged to be absent. The accuracy hereof will vary with the size of the response, the amount of electrical noise in the recording, and, importantly, the time taken to reduce this noise by averaging or increasing the sweep of the fast Fourier transform analysis (Picton et al., 2003). The long recording duration offered by the Biologic MASTER system is therefore an advantage. The opinion of Picton et al. (2005) that the duration of a single response recording is a major factor in ASSR threshold determination, was supported by Luts and Wouters (2004, 2005). They found that increasing the stimulus duration resulted in a decrease in difference between ASSR threshold and behavioural PT threshold and a decrease in standard deviations. These statements obtain further verification from the research done by Attias et al. (2006) on sleeping adults with normal hearing and with hearing loss, using the Biologic MASTER system. Attias et al. (2006) report using a response recording time of up to 17 min, longer than is typically reported. This would explain why the difference scores were on average 21 and 26 dB smaller for the participants with normal hearing and hearing loss respectively than were measured in the current study. The study by Attias et al. (2006) also represents the study with the closest proximity of ASSR thresholds to behavioural PT thresholds (mean difference score for both participants with normal hearing and with hearing loss = 3.6 dB). In studies where shorter recording durations were used, such as in the study by Aoyagi et al. (1994), who reported response recordings of 51 to 300 s each, mean differences between ASSR thresholds and behavioural PT thresholds were comparable to that of the present study (mean difference scores across frequencies were within 2.5 dB of the current study). Kaf, Durrant et al. (2006) provide another example of the effect of shorter recording duration. Kaf, Durrant et al. (2006) employed a maximum recording duration of eight min rather than the maximum 15 min permitted by the Biologic MASTER system. This remains considerably longer than the maximum 89 s allowed by the GSI Audera ASSR system used in the current study (GSI, 2003). Kaf, Durrant et al. (2006) reported a correlation at 0.5 kHz (viz. $r = 0.53$), which was closer to that of the present study at this frequency ($r = 0.40$) and weaker than the correlation at 0.5 kHz of the other studies using the Biologic MASTER system and the typical maximum 15 minute recording duration (Ahn et al., 2007; Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2003; Luts & Wouters, 2005; Schmulian et al., 2005). The 0.5 kHz frequency is most likely to be affected by a shorter recording duration as EEG (electroencephalographic) noise levels are greatest at lower frequencies (Picton et al., 2005) and the participants with hearing loss in the current study presented with a mean 0.5 kHz behavioural PT threshold of 10.5 dB. A longer recording time would be required to reduce noise levels and detect the small response associated with behavioural PT threshold that fall within normal limits (Picton et al., 2003). Therefore the smaller difference scores reported by the majority of studies using a high modulation rate may be the result of the higher modulation rate or the dichotic multiple frequency ASSR technique, but it is more likely due to longer averaging periods.

The high modulation rate ASSR studies that made use of a monotic single stimulus technique in adults, namely those of Aoyagi et al. (1994), Rance et al. (1995) and Hsu et al. (2003), report differences between ASSR thresholds and behavioural PT thresholds that were closer to those reported in the current study than to the studies using a high modulation dichotic multiple stimulus technique. Aoyagi et al. (1994) reports mean difference scores that were comparable to the present difference scores (viz. 2.8 mean differences between ASSR threshold and behavioural PT thresholds across frequencies). ASSR thresholds in the study by Hsu et al. (2003) were on average (across all frequencies) 9 dB closer to behavioural PT thresholds than those reported in the present study with a comparable difference score at 1 kHz. Rance et al. (1995) found difference scores (for both normal and hearing impaired participants together), that were comparable at the low frequency but were on average 17 dB smaller across the higher frequencies than in the current study. The closer proximity of the high frequency ASSR thresholds reported by Rance et al. (1995) is likely to be related to the inclusion of a greater number of severe and profoundly elevated behavioural PT hearing thresholds at the higher frequencies than at the low frequencies (Picton et al., 2003, 2005; Yeung & Wong, 2007).

The difference scores between ASSR threshold and behavioural PT threshold for 80 Hz single frequency ASSR studies (viz. for Aoyagi et al., 1994; Rance et al., 1995; Hsu et al., 2003), being closer to those of the present study than for 80 Hz dichotic multiple frequency ASSR, were larger than was reported for the majority of research using 80 Hz dichotic multiple frequency ASSR (Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Kaf, Durrant et al., 2006; Lins et al., 1996; Perez-Abalo et al., 2001; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van der Reijden et al., 2006; Van Maanen & Stapells, 2005). One may, therefore, conclude that the application of the multiple stimulus technique resulted in improved proximity of ASSR thresholds to behavioural PT thresholds, when compared to a single stimulus ASSR technique. The dichotic multiple stimulus ASSR technique used in these studies, namely the Biologic MASTER, does however, make use of a significantly longer recording duration (maximum of 15 min; John et al., 1998) in comparison to that of the various monotic single stimulus ASSR methods, the recording durations of the latter varying between 51 and 300 s. The longer recording duration is likely to be the cause of the closer proximity of the ASSR threshold to behavioural PT thresholds, therefore, rather than the stimulus presentation condition. By the same token, the similarities between proximity of 40 and 80 Hz monotic single frequency ASSR thresholds to behavioural PT thresholds are liable to be due to similar recording durations rather than due to the method of presentation of stimuli.

Luts and Wouters (2005) further examined the use of a single versus a multiple stimuli ASSR system. Luts and Wouters (2005) compared the ability of a commercially available monotic single stimulus ASSR technique (viz. GSI Audera) with that of a commercially available dichotic multiple frequency ASSR technique (viz. Biologic MASTER) to estimate behavioural PT thresholds in adults. In contrast to the long response recording duration offered by the Biologic MASTER system (viz. 900 s; John et al., 1998), the GSI

Audera's maximum duration of a single response recording is only 89 s, which can be repeated in the event of a recording with high levels of noise (GSI, 2003). The GSI Audera ASSR system does not allow lengthening of data collection time irrespective of noise levels. Previous studies indicate that both the single (Aoyagi et al., 1994, 1999; Hsu et al., 2003; Rance et al., 1995, 1998; Rance & Briggs, 2002) and multiple frequency ASSR thresholds (Dimitrijevic et al., 2002; Herdman & Stapells, 2001; Lins et al., 1995, 1996; Luts & Wouters, 2004; Perez-Abalo et al., 2001) were highly correlated with behavioural PT thresholds. The effect of the longer response recording duration offered by the Biologic MASTER ASSR system, was evident when comparing the difference between behavioural PT thresholds and ASSR thresholds obtained using the GSI Audera ASSR and Biologic MASTER ASSR systems. For the total participant group, the Biologic MASTER ASSR system displayed smaller difference scores and standard deviations than the GSI Audera ASSR system. In addition, by performing statistical comparisons within each ASSR system, Luts and Wouters (2005) found (in support of the authors' earlier research, viz. Luts & Wouters, 2004) that prolongation of the recording duration improved the correlation between ASSR threshold and behavioural PT thresholds. Luts and Wouters (2005) concluded, however, that both the Biologic MASTER and GSI Audera ASSR systems performed equally well with participants with hearing loss when comparable recording durations were used. This again highlights the advantage of a longer response recording duration.

Luts and Wouters (2005) began ASSR assessment of sleeping adults using a high modulation rate for both the dichotic, multiple frequency ASSR technique, and for the monotic, single frequency ASSR technique. Luts and Wouters (2005), however, found (as was the case in the present study), that many participants with hearing loss could not be assessed using the 80 Hz protocol of the GSI Audera ASSR system, due to excessive noise levels, despite the fact that participants were asleep. This, then, necessitated a change to the 40 Hz modulation rate for a total of nine out of 20 sleeping participants. Thus the use of the two different modulation rates used during GSI Audera ASSR testing, although only for the minority of participants, introduces another variable to the comparison between the GSI Audera and Biologic MASTER ASSR thresholds. Not only were single and multiple ASSR techniques being compared, but the two ASSR systems made use of different modulation rates and different recording durations. This consequently limited the conclusions that could be drawn on the comparative accuracy of the two systems.

When examining the threshold data reported by Luts and Wouters (2005) using the GSI Audera, differences between ASSR thresholds and behavioural PT thresholds were on average (across all frequencies) 10 dB larger than those of the present study for the group with normal hearing, and 10 dB smaller for the group with hearing loss. This was true, despite the fact that both the Luts and Wouters (2005) and the current study used the same ASSR system for threshold determination. The differences between ASSR thresholds and behavioural PT thresholds reported by Luts and Wouters (2005) in the group with normal hearing were largest for 0.5 and 1 kHz (ASSR thresholds were 22 and 19 dB greater than in the current study at 0.5 and 1 kHz respectively), while those at the high frequencies were comparable. The larger difference scores between ASSR thresholds and behavioural PT thresholds at 0.5 and 1 kHz recounted by Luts and Wouters (2005) may be explained by reports that the 40 Hz ASSR amplitude is greater for low frequency stimuli than for high frequency stimuli (Galambos et al., 1981; Picton et al., 1987; Rodrigués et al., 1986). Picton et al. (2005) also report that EEG noise levels decreased with increasing stimulus frequency. The majority of sleeping participants that underwent ASSR testing using the GSI Audera in the Luts and Wouters (2005) study, were evaluated using the 80 Hz modulation rate protocol. It is well established that 80 Hz ASSR response amplitudes are two to three times smaller than those for the 40 Hz ASSR technique (Cohen et al., 1991; Levi et al., 1993; Lins et al., 1995). Although the sleeping state of the participants in the current study is likely to have reduced the amplitude of the 40 Hz response, the amplitude remains larger than that of the high modulation ASSR response (Linden et al., 1985). Therefore, the use of the 80 Hz modulation rate for the majority of participants in the study by Luts and Wouters (2005) may account for the divergent differences between ASSR thresholds and behavioural PT thresholds at low and mid frequencies between the current study and that by Luts and Wouters (2005).

The difference score reported by Luts and Wouters (2005) between the ASSR threshold and behavioural PT threshold at 2 kHz for the group with hearing loss was 20 dB closer to the behavioural PT threshold than was reported in the present study. It is postulated that the disparity between the difference scores between the two studies at 2 kHz may be related to the higher degree of hearing loss at this frequency in the Luts and Wouters (2005) study than in the present study. The mean behavioural PT threshold at 2 kHz for the participants with hearing loss in the Luts and Wouters (2005) study was 63 dBSPL, while that of the current study was 21 dB. It is known that the difference between ASSR threshold and behavioural PT threshold decreases with increasing behavioural PT threshold (Attias et al., 2006; Hsu et al., 2003; Kaf, Durrant et al., 2006; Rance et al., 1995, 2005; Swanepoel & Erasmus, 2007; Tomlin et al., 2006). Therefore, the greater degree of hearing loss at 2 kHz of participants of the Luts and Wouters (2005) study than in the current study, resulted in the ASSR response being recognizably closer to behavioural PT threshold. In addition, Swanepoel and Erasmus (2007) established poor correlation of ASSR threshold to behavioural PT thresholds for mildly elevated behavioural PT thresholds, as was the case for 2 kHz in the current study. The mild degree of hearing loss for the average participant with hearing loss at 2 kHz in the present study is, therefore, likely to have resulted in a larger difference between ASSR threshold and behavioural PT threshold.

Two studies did complete a comparison of ASSR thresholds using low and high modulation rates within a single ASSR system. Both Van der Reijden et al. (2006) and Van Maanen and Stapells (2005) compared the ASSR thresholds obtained, using different modulation rates within a dichotic multiple frequency ASSR system, namely the Biologic MASTER. Van der Reijden et al. (2006) compared ASSR thresholds for 11 (awake) adults with normal hearing. Van Maanen and Stapells (2005) compared ASSR thresholds for two groups of 23 adults with only three of each group presenting with normal hearing. In contrast to the alert state of participants in the study by Van der Reijden et al. (2006), Van Maanen and Stapells (2005) evaluated participants using the 80 Hz ASSR technique while asleep, while participants were asked to relax, but remain awake during the 40 Hz ASSR testing. Both studies reported that the low modulation ASSR technique demonstrated significantly closer proximity of ASSR thresholds to behavioural PT thresholds and smaller standard deviations (of the difference score between ASSR and behavioural PT threshold), than for the high modulation rate ASSR. Therefore, within a dichotic multiple frequency ASSR system, a low modulation rate appears to yield more accurate estimations of behavioural PT thresholds. This finding is supported by the earlier research of Dobie and Wilson (1998), who found that a 40 Hz modulation rate afforded better ASSR detectability for low intensity levels than 80 Hz modulation rate in adults, whether alert or sedated albeit it with a single frequency ASSR system rather than the multiple frequency system compared by Van der Reijden et al. (2006) and Van Maanen and Stapells (2005). The author is not aware of studies on the comparative proximity of ASSR thresholds to behavioural PT thresholds, using a low versus a high modulation rate within a commercially available monotic, single stimulus ASSR system since the study by Dobie and Wilson (1998).

A comparison of the difference scores that denote the proximity of ASSR thresholds to behavioural PT thresholds, indicates that 2 kHz yielded the largest mean difference score for the combined participant group in the present study (viz. 32 dB), as compared to the other frequencies (viz. 25, 22 and 27 dB at 0.5, 1 and 4 kHz respectively). Galambos et al. (1981) and Picton et al. (1987) reported a decrease in response amplitude with increasing stimulus frequency, possibly due to the broader activation pattern in the cochlea at lower frequencies, resulting in larger difference scores with increasing stimulus frequency. The frequently reported improved proximity of ASSR threshold to elevated behavioural PT thresholds (Attias et al., 2006; Hsu et al., 2003; Kaf, Durrant et al., 2006; Rance et al., 1995, 2005; Swanepoel & Erasmus, 2007; Tomlin et al., 2006), explains why the difference score for the combined participant group at 4 kHz for the current study is slightly smaller (viz. 27 dB) than at 2 kHz (viz. 32dB). The large difference score at 2 kHz may also be related to the mild degree of hearing loss at this frequency. The mean behavioural PT threshold at 2 kHz of the participants with hearing loss in the current study was 21 dB. The recent study by Swanepoel and Erasmus (2007) reported a poor correlation ($r = 0.21$) of ASSR thresholds (at 0.5 to 4 kHz) with behavioural PT thresholds of less than 55 dB. Similarly, Scherf et al. (2006) stated that when the average ASSR threshold across 0.5, 1, 2 and 4 kHz was equal to or less than 40 dB, then the standard deviations of the difference between ASSR threshold and behavioural PT threshold at each frequency were too great to provide accurate estimates of behavioural PT thresholds. The large mean difference between ASSR threshold and behavioural PT threshold measured at 2 kHz in the current study, is of concern in a population of adults exposed to occupational noise that would typically present with a sloping sensorineural hearing loss and a mildly elevated behavioural PT threshold at 2 kHz. The large difference score implies that the behavioural PT threshold at 2 kHz would often be overestimated, leading to a larger percentage loss of hearing (COIDA, 2001) and over compensation for permanent disability. The reduced accuracy afforded by the 40 Hz ASSR at 2 kHz for the purpose of behavioural PT threshold estimation in sleeping adults, therefore impacts on its utility for occupational health purposes.

Standard deviation affords a measure of variability of the difference between ASSR thresholds and behavioural PT thresholds. Those of this study ranged from 12.1 to 14.9 dB for the participants with normal hearing and ranged from 9.7 to 13.7 dB for the participants with hearing loss. This is comparable to the standard deviations for the 40 Hz ASSR body of research (range 6 to 18 dB; Aoyagi et al., 1993; Tomlin et al., 2006; Yeung & Wong, 2007). The exception, as can be viewed in Table 5.3, are the 0 dB standard deviation scores reported by Van der Reijden et al. (2006) for each frequency tested. The reason for this lies in the structure of the research methodology applied. The study used a small sample of only 11 adults, all with normal hearing and fixed stimulus levels of 10, 20 and 30 dB sensation level. The 0 dB standard deviation is reported as ASSR thresholds could be measured at 10 dB sensation level for all participants at the two stimulus frequencies tested, namely 0.5 and 2 kHz. Van der Reijden et al. (2006) also made use of a longer recording duration of 4.4 min in contrast to the 89 s recording duration in the present study. The longer recording duration reduces the noise levels resulting in lower ASSR threshold intensities.

The standard deviations listed in Table 5.4 for high modulation ASSR studies indicate a broader range of standard deviations than reported in the current study, namely from 3 to 21 dB (Aoyagi et al., 1994; Attias et al., 2006; Herdman & Stapells, 2003; Hsu et al., 2003; Kaf, Durrant et al., 2006; Lins et al., 1995, 1996; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Picton et al., 1998; Rance et al., 1995; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van der Reijden et al., 2006; Van Maanen & Stapells, 2005). The largest standard deviations were recounted by Luts and Wouters (2005), when assessing participants with normal hearing, using the GSI Audera single stimulus ASSR system (standard deviations = 7 to 21 dB). The differences between ASSR thresholds and behavioural PT thresholds at each frequency and the standard deviations of these difference scores reported by Luts and Wouters (2005) for participants with normal hearing, is also larger than those for the group of participants with normal hearing in the present study. The current study, however, which also made use of the GSI Audera ASSR system and therefore the same recording duration, reported standard deviation scores (in the group with normal hearing) which were 6 to 8 dB smaller than that reported in the Luts and Wouters (2005) study. The current study used a slightly larger participant group (n = 28 versus n = 20), which may have contributed to the reduced variability of the standard deviation values. The difference in participant numbers is, however, not sufficient to explain the discrepancy in standard deviation scores between the two studies. The standard deviation scores for the difference between ASSR thresholds and behavioural PT thresholds of Luts and Wouters (2005) for individuals with normal hearing, were also larger than reported elsewhere (Aoyagi et al., 1994; Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Hsu et al., 2003; Kaf, Durrant et al., 2006; Lins et al., 1995, 1996; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Picton et al., 1998; Rance et al., 1995; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van Maanen & Stapells, 2005; Van der Reijden et al., 2006). The reason for the larger standard deviation scores reported by Luts and Wouters (2005) is not clear.

Hsu et al. (2003) report the smallest standard deviation scores for studies using the 80 Hz ASSR technique (std dev = 3 to 5 dB). Hsu et al. (2003) used the GSI Audera ASSR system and a high modulation rate, and reported differences between ASSR thresholds and behavioural PT thresholds of 12 to 19 dB with standard deviations of 3 to 5 dB. These standard deviations were considerably smaller than those reported in the current study. Hsu et al. (2003) did not include participants with normal hearing in their study. Even so, the standard deviations are also smaller than those for the participants with hearing loss in the present study. This is true, despite the equivalent recording durations, as both the present study and that by Hsu et al. (2003) made use of the GSI Audera ASSR system. The modulation rate did differ, suggesting that the use of a high ASSR modulation rate results in smaller standard deviations than the use of a low ASSR modulation rate. This is not, however, supported by the majority of 80 Hz ASSR studies listed in Table 5.4 which reported comparable standard deviations to the current study. Hsu et al. (2003) did include only 11 participants in the study. It is possible that the small number of participants may have contributed to the smaller standard deviation scores. More probable is the possible effect of sleep on the 40 Hz ASSR thresholds. The current study made use of a low modulation rate to measure ASSR in sleeping adult participants, in order to reduce the measured noise levels. There are different opinions on the use of the 40 Hz ASSR protocol with sleeping participants. Early research learned that the 40 Hz ASSR amplitudes are smaller in sleeping or sedated adults than in the alert state (Aoyagi et al., 1993; Galambos et al., 1981; Linden et al., 1985). Although Jerger et al. (1986) and Picton et al. (2003) suggest that the sleeping state results in elevation of ASSR threshold intensity, Dobie and Wilson (1998) found that a 40 Hz modulation rate afforded better ASSR detectability for low intensity levels than the 80 Hz modulation rate in adults, whether alert or sedated. It is possible that the 80 Hz modulation rate and consequent lower neurological source of the ASSR reduces the variability of the relationship between the behavioural PT thresholds and ASSR thresholds. One would, however, then expect more supporting evidence from the standard deviations of the difference scores reported by the 80 Hz ASSR body of research.

5.3.2.2 Relationship between ASSR thresholds and behavioural PT thresholds

As was the case with the SCAEP thresholds, ASSR thresholds for the participants with normal hearing correlated poorly with normal behavioural PT thresholds (mean R^2 = 0.0011; mean r = -0.03). This was true of individual frequencies, in addition to the mean correlation score across all frequencies. The researcher is not aware of any correlation statistics reported in the literature for individuals with normal hearing alone. Correlation scores are always reported for both participants with normal hearing and with hearing loss together. This finding is, however, in line with the report by Swanepoel and Erasmus (2007) regarding poor correlation between ASSR thresholds and behavioural PT thresholds for behavioural PT thresholds of less than 60 dBHL (r = 0.21). This is especially true when assessing individuals with normal hearing with the GSI Audera ASSR, as was observed by Scherf et al. (2006). Scherf et al. (2006) reported considerable variation of estimations of behavioural PT thresholds for individual frequencies when the average ASSR thresholds across 0.5, 1, 2 and 4 kHz were equal to or less than 40 dB. The short recording duration of 89 s allowed by the GSI Audera ASSR system (GSI, 2003) means that the small threshold ASSR responses associated with normal behavioural PT thresholds are only recognised at elevated intensities due to the amount of noise in the recording (Picton et al., 2003, 2005). The study by Luts and Wouters (2005) supported this observation by the large differences between ASSR thresholds and behavioural PT thresholds and the large standard deviations when using the GSI Audera to estimate behavioural PT thresholds in individuals with normal hearing.

The closer proximity of ASSR thresholds to behavioural PT thresholds for the group of participants with hearing loss, produced stronger statistical correlations between ASSR thresholds and behavioural PT thresholds. There was a strong mean correlation across frequencies between the elevated behavioural PT thresholds and ASSR thresholds ($r = 0.81$). There are two studies that drew participants exclusively from the same population as the present study did, with which comparisons can be made, namely Hsu et al. (2003) and Van Maanen and Stapells (2005). Hsu et al. (2003) used a high modulation rate (in contrast to the low modulation rate of the current study), to measure ASSR thresholds in 11 adults with noise induced hearing loss during natural sleep. The audiometric configuration of the participants of that study and of the group with hearing loss of the current study were therefore similar, both typically displaying high frequency sensorineural hearing losses. Pearson correlation co-efficients reported by Hsu et al. (2003) increased with increasing frequency and therefore also with increasing degree of hearing loss. This was also true of the correlation co-efficients for the participant group with hearing loss in the current study, which were stronger in the high frequencies (2 kHz: $r = 0.71$; 4 kHz: $r = 0.59$) than at 0.5 and 1 kHz ($r = 0.58$ and 0.53 respectively). In addition to behavioural PT hearing threshold, ASSR amplitudes are also affected by stimulus frequency. The 40 Hz ASSR amplitude is greater for low frequency stimuli and decreases with increasing stimulus frequency (Galambos et al., 1981; Picton et al., 1987; Rodrigués et al., 1986). Therefore, the finding of a closer correspondence between ASSR thresholds and behavioural PT thresholds with increasing behavioural PT thresholds, may also be due to the larger amplitude at lower frequencies in combination with the effect of recruitment. The correlation co-efficients were, however, stronger in the Hsu et al. (2003) study than in the current study (range = 0.86 to 0.95). Hsu et al. (2003) also utilised the GSI Audera ASSR system, as was done in this study, therefore response recording duration was also the same. Participant state of consciousness was another common factor between the two studies. The modulation rate used by Hsu et al. (2003) and in the current study did differ though. It is possible that the use of the higher modulation rate (i.e. 90 Hz) for evaluation of sleeping participants, in contrast to the low modulation rate used in the current research, may have contributed to the stronger correlation co-efficients reported by Hsu et al. (2003).

The bulk of studies report correlations for both individuals with normal hearing and hearing loss grouped together. In this study, moderately robust correlations were found at 0.5 and 1 kHz (r = 0.40 and 0.49 respectively), while strong correlations were found at 2 and 4 kHz (r = 0.72 and 0.85 respectively) for the participants with normal hearing and with hearing loss grouped together. The mean Pearson correlation co-efficient across all frequencies was 0.75. Correlation co-efficients between ASSR thresholds, and behavioural PT thresholds for both participant groups were weaker in the present study than reported previously (Ahn et al., 2007; Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2003; Hsu et al., 2003; Johnson & Brown, 2005; Kaf, Durrant et al., 2006; Lins et al., 1996; Luts & Wouters, 2005; Rance & Rickards, 2002; Rance et al., 1995, 2005; Scherf et al., 2006; Schmulian et al., 2005; Tomlin et al., 2006; Van Maanen & Stapells, 2005; Yeung & Wong, 2007).

In the majority of cases, the weaker (smaller) correlation scores reported in the present study were probably related to the longer response recording duration available for the commercial dichotic multiple frequency ASSR system (Biologic MASTER), than for the monotic single stimulus ASSR system (GSI Audera) used in the present study (Picton et al., 2003). The correlation scores of previous studies that made use of the GSI Audera ASSR system were also, however, stronger (Hsu et al., 2003; Luts & Wouters, 2005; Rance et al., 1995; Scherf et al., 2006; Tomlin et al., 2006; Yeung & Wong, 2007). Of these, Hsu et al. (2003), Luts and Wouters (2005) and Rance et al. (1995) made use of a high rather than a low modulation rate. Again, as previously concluded, the high modulation rate appears to have reduced the proximity of ASSR thresholds to behavioural PT thresholds and, consequently increased the correlation scores.

Scherf et al. (2006), Tomlin et al. (2006) and Yeung and Wong (2007) made use of the GSI Audera ASSR system with the same modulation rate, namely 40 Hz, as was the case in the present study. The only methodological difference between these studies and the present study, other than target population, is the participant state of consciousness. The aforementioned studies reported similar Pearson correlation co-efficients at 4 kHz, as was reported in the current study with data of participants with normal hearing and with hearing loss grouped together. The correlations at 0.5 kHz were, however, much stronger (r = 0.84 to 0.86 for Tomlin et al., 2006, and Scherf et al., 2006, respectively; r^2 = 0.95 for Yeung & Wong, 2007) than in the present study (r = 0.40). However, in contrast to the typically normal behavioural PT thresholds at 0.5 kHz for participants with hearing loss (mean behavioural PT threshold for group with hearing loss at 0.5 kHz = 10.5 dBHL) in the current study, 0.5 kHz was, however, elevated to mild to profound levels in 30 of the 66 participants in the Tomlin et al. (2006) study. As generally found in this and previous studies, correlation values increase with increasing behavioural PT threshold intensity (Aoyagi et al., 1993; Attias et al., 2006; Hsu et al., 2003; Kaf, Durrant et al., 2006; Lins et al., 1996; Perez-Abalo et al., 2001; Rance & Rickards, 2002; Rance et al., 1995, 2005; Tomlin et al., 2006). The stronger correlation scores at 0.5 kHz reported by Tomlin et al. (2006), may therefore be related to the number of behavioural PT thresholds that represent a degree of sensorineural hearing loss at this frequency. It is suspected that the strong low frequency correlation scores described by Scherf et al. (2006) and Yeung and Wong (2007), are also related to degree of hearing loss as participants with profound hearing losses were included, although the mean behavioural PT thresholds at this frequency were not divulged in either study. Therefore, it is possible that the degree of hearing loss rather than participant state of attention when using 40 Hz ASSR protocol strengthened correlation co-efficients.

Use of a 80 Hz ASSR protocol, rather than the 40 Hz modulation rate, was not, however, feasible in the current study, as ASSR thresholds could not be obtained in two of the three sleeping participants in the preliminary study when using the 80 Hz modulation rate, due to excessively high noise levels. When using the GSI Audera ASSR system, noise cannot be reduced by extending the recording duration. A single recording can only be repeated in the event of high noise levels (GSI, 2003). The high noise levels observed in the preliminary study when using a high modulation rate ASSR, parallel those of Luts and Wouters (2005) and Van Maanen and Stapells (2005). Luts and Wouters reported that seven out of ten of their sleeping participants with hearing loss could not be tested using the 80 Hz modulation rate protocol of the GSI Audera ASSR software, as noise levels exceeded the default noise criterion. Van Maanen and Stapells (2005) made use of a dichotic multiple frequency ASSR system, but reported the same difficulty with use of the high modulation rate. A total of 23 participants were rejected from the study (data was collected from 43 participants), due to excessive noise levels during ASSR measurement. Of the 23 participants that could not be assessed, three participants were evaluated with the 40 Hz multiple ASSR technique and 20 were from the 80 Hz multiple ASSR group. This was true, despite the fact that participants slept during 80 Hz ASSR threshold acquisition. Sleep typically reduces noise levels during ASSR threshold acquisition, in comparison with an alert state of attention (Picton et al., 2005). The same pattern of excessive noise levels for 80 Hz ASSR was therefore reported by studies using a monotic single ASSR system and a dichotic multiple frequency ASSR system. De Koker (2004) reported requiring the use of a sedative for sleeping adult participants, in order to reduce noise levels when using the GSI Audera ASSR system with a high modulation rate. This is not always a clinically feasible option. The adaptive procedure for acquisition of ASSR thresholds using the GSI Audera system recommended by Luts and Wouters (2005), is perhaps a better option.

Luts and Wouters (2005) compared ASSR thresholds acquired using a single frequency ASSR system (the GSI Audera) with a multiple frequency ASSR system (the Biologic MASTER). The participants were instructed to keep their eyes closed and to relax or sleep. Therefore the precise state of consciousness of each participant was not specified. During assessment with the GSI Audera, testing began with the high modulation rate protocol and researchers switched to the low modulation protocol when high EEG levels resulted in ‘noise’ results. Luts and Wouters (2005) therefore made use of both high and low modulation frequencies (nine out of 20 participants were tested using a low modulation rate, while the remaining 11 participants were evaluated with a high modulation rate). Therefore nine participants were tested with the 40 Hz modulation rate while asleep, as was the case in the present study. The resulting mean correlation score across frequencies (for participants with normal hearing and with hearing loss grouped together), was similar to that of the current study when using the GSI Audera ASSR system (mean r = 0.77 reported by Luts & Wouters, 2005, compared to mean r = 0.75 for current study). The comparable correlations between Luts and Wouters (2005) when using the GSI Audera and the current study are seemingly the result of similar ASSR protocol and participant state. This suggests that use of either an adaptive choice of modulation rate based on participant noise levels or a fixed 40 Hz modulation rate, results in comparable correlation scores when using the GSI Audera ASSR system.

It is interesting to note that previous studies that made use of the Biologic MASTER dichotic multiple ASSR system, did not report excessively high noise levels when employing a high modulation rate as was done by Van Maanen and Stapells (2005). Van Maanen and Stapells (2005) did, however, employ a shorter recording duration than the majority of Biologic MASTER studies (maximum 8 min recording duration). The studies by Ahn et al. (2007), Attias et al. (2006), Dimitrijevic et al. (2002), Herdman and Stapells (2003), Luts and Wouters (2005) and Schmulian et al. (2005) report continuing response recording until a statistically significant response was reached and mean noise levels were below 10 nV. Dimitrijevic et al. (2002) state that the 10 nV noise levels are typically reached after approximately 15 min. In contrast to these recording parameters, Van Maanen and Stapells (2005) describe continuing the response recording until noise levels were below 20 nV. If a threshold estimation procedure considers that a response is absent at a noise level of 20 nV, then the ASSR thresholds will be higher than if one uses a criterion level of 10 nV (Dimitrijevic et al., 2002). This explains why noise levels were often higher for several participants in the study by Van Maanen and Stapells (2005) when using the 80 Hz ASSR modulation rate. Prolonging the recording duration would also therefore have reduced the noise levels measured of the participants that could not be assessed with the shorter response duration and less strict noise criterion used by Van Maanen and Stapells (2005). The Biologic MASTER system allows for a lower noise criterion and longer recording duration than for the GSI Audera, which reduces the high noise levels often reported with use of the 80 Hz modulation rate. It must be emphasised that this is a feature of the Biologic MASTER software, rather than a feature of a dichotic multiple ASSR system. Therefore comparisons between the GSI Audera and the Biologic MASTER ASSR systems need to take this point into consideration when drawing conclusions. The GSI Audera ASSR system uses a maximum response recording duration of only 89 s (GSI, 2003). A shorter recording duration leads to greater noise levels in an ASSR response and elevated ASSR thresholds above behavioural PT thresholds, especially for individuals with normal hearing (Picton et al., 2003). Further evidence hereof is provided by difference scores between ASSR thresholds and behavioural PT thresholds for individuals with normal hearing reported by Tomlin et al. (2006), Luts and

Wouters (2005) and the current study. The GSI Audera compensates for the short recording duration and resulting larger differences between ASSR thresholds and behavioural PT thresholds, by using regression formulae suggested by Rance et al. (1995). The Rance et al. (1995) formulae result in larger corrections for normal and mildly elevated behavioural PT thresholds compared to more severe degrees of hearing loss. After examining the effect of different research methodologies on ASSR thresholds in the current research and previous literature, certain conclusions can be drawn and recommendations made.

5.3.2.3 Effect of participant, stimulus and recording variables on the clinical effectiveness of ASSR

The discussion of the findings of the current study regarding difference values and the relationship between ASSR and behavioural PT thresholds within the context of existing literature has highlighted a number of participant variables, and ASSR stimulus and recording variables that have a significant effect on the accuracy of the ASSR technique. Table 5.7 summarizes the effect of the most important variables that play a role in determining the clinical effectiveness of the ASSR, for the purpose of behavioural PT threshold estimation in adults with normal hearing and in adults with hearing loss who were exposed to occupational noise.

TABLE 5.7 Effect of different participant, stimulus and recording variables on clinical effectiveness of ASSR

		Modulation rate		Stimulus presentation method		Recording duration		Comments
		Low 40 Hz	High 90 Hz	Single frequency	Multiple frequency	Short (eg. ≤ 89 s)	Long (eg. 8 to 15 min)	
Degree of hearing loss	Normal hearing (< 25 dB)	-	-	-	-	-	-	Research suggests a poor correlation between ASSR thresholds and behavioural PT thresholds in individuals with normal hearing sensitivity or with a hearing loss of ≤ 40 to 55 dB (Scherf et al., 2006; Swanepoel & Erasmus, 2007). This is true with use of either a low (Scherf et al., 2006) or high modulation rate (Swanepoel & Erasmus, 2007), or different recording durations (Scherf et al., 2006, used a short recording duration while Swanepoel & Erasmus, 2007, used a long recording duration). When comparing ASSR thresholds using different recording durations, as was done by Luts and Wouters (2005), a longer recording duration does reduce ASSR thresholds compared to a short recording duration.
	Mild to moderate hearing loss (26 to 55 dB)	-	-	-	-	-	-	
	Moderately-severe to profound hearing loss (> 55 dB)	+	+	+	+	Neither + nor -	+	The ASSR response increases in amplitude more steeply with increasing intensity when there is a hearing loss. As a result ASSR in adults with a sensory hearing loss are recognizable closer to behavioural PT threshold than for adults with normal hearing. Short response duration is therefore sufficient to identify ASSR thresholds in close proximity to behavioural PT thresholds for adults with behavioural PT thresholds of > 55 dB (Rance et al., 1995; Scherf et al., 2006).
Stimulus presentation method	Single frequency	+/-	+/-			-	+	Research indicates a closer proximity of multiple frequency ASSR thresholds to behavioural PT thresholds than for single frequency ASSR but the majority of studies used the Biologic MASTER ASSR system with a long maximum recording duration of 15 min. It is difficult to draw conclusions regarding stimulus presentation method due to different variables used by the two most researched commercial ASSR systems. Van Maanen and Stapells (2005) and Van der Reijden et al. (2006) found multiple frequency ASSR thresholds closer to behavioural PT thresholds with a low than a high modulation rate. The author is not aware of research that compared high and low modulation rate within a single frequency ASSR system in the last decade. A comparison of findings between studies using a single frequency ASSR technique reveals variable results (Hsu et al., 2003; Rance et al., 1995; Tomlin et al., 2006; Yeung & Wong, 2007).
	Multiple frequency	+	-			+/-	+	
Recording duration	Short (eg. ≤ 89 s)	-	-	-	+/-			Longer recording duration is advantageous regardless of the subject variables, modulation rate or stimulus presentation method with the exception of participants with severe to profound hearing losses where a short recording duration is not disadvantageous. The author is not aware of research using a multiple frequency ASSR system and a short recording duration similar to that of the GSI Audera ASSR.
	Long (eg. 8 to 15 min)	+	+	+	+			
State of consciousness	Awake	+	- Due to high noise levels	+/- Determined by recording duration and noise levels	+/- Determined by recording duration and noise levels	-	+	Sleep reduces noise levels (Dimitrijevic et al., 2002). The 80 Hz ASSR is more sensitive to myogenic noise than the 40 Hz ASSR (Pethe et al., 2004). Luts and Wouters (2005; using GSI Audera) and Van Maanen and Stapells (2005; using Biologic MASTER) report high noise levels with several participants when using a high modulation rate despite the participant's restful or sleeping state. Luts and Wouters (2005) resolved this by selecting a low modulation rate. Dobie and Wilson (1998) reported that ASSR at low intensities are best recorded in either the awake or sleeping state using a low rather than a high modulation rate. Despite this, previous research with the exception of the study by Luts and Wouters (2005), recorded 40 Hz ASSR with participants awake and 80 Hz ASSR while participants slept. This is likely to be due to the reduction in 40 Hz ASSR amplitude when participants fell asleep, which was noted by Aoyagi et al. (1993), Galambos et al. (1981) and Linden et al. (1985). Dobie and Wilson (1998) state that the aforementioned studies did not, however, take the reduced noise levels with sleep into consideration which may improve ASSR detectability at low sensation levels. The effect of state of consciousness has not been re-examined in commercially available ASSR systems in recent literature. Recording duration appears to have a greater effect on ASSR threshold intensity than state of consciousness (Luts & Wouters, 2005).
	Restful / asleep	+/-	+/- Determined by recording duration and noise levels	+/- Determined by recording duration and noise levels	+/- Determined by recording duration and noise levels	-	+	

(+ = advantageous; - = disadvantageous; +/- = variable results, further research required)

Table 5.7 demonstrates both the consistent (consistently advantageous or disadvantageous) and the conflicting findings regarding the effect of participant, stimulus and recording variables on the accuracy of the ASSR technique (proximity of ASSR thresholds to behavioural PT thresholds and the variability of this relationship) in literature. The preceding comparison between the results of the current research and existing literature did not demonstrate a clear recommendation regarding the optimal stimulus presentation method (i.e. single or multiple frequency), modulation rate or the optimal state of consciousness. The most widely researched commercial ASSR systems, namely the GSI Audera and Biologic MASTER, differ with respect to not only stimulus presentation method, but also recording duration and statistical response detection method. It is then difficult to ascertain the relative importance (with respect to accuracy) of each factor of ASSR testing, due to the number of variables present when comparing findings using the two ASSR systems. In addition, the studies that have compared single versus multiple frequency techniques, such as those by De Koker (2004) and Luts and Wouters (2005), used 40 and 80 Hz modulation rates during single frequency ASSR testing and compared this to a multiple frequency ASSR technique with an 80 Hz modulation rate. The use of a combination of modulation rates during single frequency ASSR testing adds a further variable to the already complex comparison.

The choice of modulation rate is often determined by the recording duration of the ASSR system used and the noise levels measured with each individual. The 80 Hz modulation rate is more influenced by myogenic activity than the 40 Hz response is (Pethe et al., 2004). It is often necessary to change the modulation rate from 80 to 40 Hz due to excessive noise levels, as was the case during the preliminary study of the current research and in the studies by Luts and Wouters (2005) and Van Maanen and Stapells (2005). The optimal state of consciousness appears to be a sleeping state, as sleeping reduces noise levels (Dimitrijevic et al., 2002). Although sleep is known to reduce the amplitude of 40 Hz ASSR responses, Dobie and Wilson (1998) found that 40 Hz ASSR responses are easier to detect at threshold intensity due to the associated reduction in noise levels. Despite the research of Dobie and Wilson (1998), authors such as Jerger et al. (1986) and Picton et al. (2003) suggest, however, that the use of 40 Hz modulation rate on sleeping adults causes an elevation in ASSR threshold intensities. Research that made use of the 40 Hz ASSR protocol of the GSI Audera while participants were alert, did report mean ASSR thresholds which were 5 and 17 dB closer to behavioural PT thresholds than those of the current study which were measured while participants slept (Tomlin et al., 2006, and Yeung & Wong, 2007, respectively). As far as the author is aware, a comparison of the effect of different states of consciousness on 40 Hz ASSR thresholds within a single commercially available ASSR system has not been completed in over a decade. Further research is required to resolve the conflicting reports in literature and to confirm that a sleeping state of consciousness is indeed the optimal state of consciousness with a 40 Hz ASSR modulation rate.

Two consistent, defining factors have emerged during the discussion of the results when considering the utilisation of ASSR for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise, namely response recording duration and typical degree of hearing loss.

- **Influence of the response recording duration on the ASSR threshold**

The noise level at which a response is judged to be absent, depends on both the participant state (which determines the amount of noise to be reduced) and also on the extent of noise reduction by the analysis procedure (Dimitrijevic et al., 2002). Noise reduction by averaging varies with the time over which the recording is continued. When responses are recorded over a shorter period of time, there is more residual noise in the recording and the response will not be recognised until the intensity and response amplitude increase (Picton et al., 2003). The studies by Luts and Wouters (2004) examined the effect of ASSR recording duration in terms of accuracy of estimation of behavioural PT thresholds. Luts and Wouters (2004) found that increasing the length of recordings of individual frequencies from five min to 15 min, increased the accuracy of estimation of behavioural PT thresholds (with respect to difference and correlation scores between ASSR threshold to behavioural PT threshold, as well as standard deviation of the difference score), independently of the test frequency. Picton et al. (2005) found it necessary to lengthen recording times to ten min or more in order to recognize the small responses in participants with mild or no hearing loss.

The Biologic MASTER ASSR system uses a lower noise criterion (viz. 10 nV) and longer recording duration (maximum of 15 min) which reduces noise levels (John et al., 1998), leading to closer proximity of ASSR threshold to behavioural PT thresholds. In contrast, the GSI Audera ASSR system allows a maximum recording duration of only 89 s (GSI, 2003). The GSI Audera ASSR system does not allow an extension of the recording duration in order to reduce noise levels. A single recording can only be repeated in the event of high noise levels (GSI, 2003). The advantage of the longer recording duration is evident, when comparing the difference between ASSR thresholds and behavioural PT thresholds of the current study, using the GSI Audera ASSR system to that of studies that used the Biologic MASTER ASSR system. The studies that used the Biologic MASTER ASSR (and therefore a longer recording duration), measured mean ASSR thresholds (across all frequencies) that were 7 to 26 dB smaller than in the current study (Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Kaf, Durrant et al., 2006; Lins et al., 1996; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Picton et al., 1998; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van der Reijden et al., 2006; Van Maanen & Stapells, 2005). It must be emphasised that this is a feature of the Biologic MASTER software, rather than a feature of a dichotic multiple ASSR system. As the majority of the aforementioned studies made use of a high ASSR modulation rate, one may argue that the effect of the different modulation rate to the current study may have contributed to the smaller difference scores. Two of the aforementioned studies, however, used the Biologic MASTER ASSR system with a low modulation rate. Van Maanen and Stapells (2005) and Van der Reijden et al. (2006) compared high and low modulation rate within a dichotic multiple frequency ASSR system. Both concluded that the 40 Hz modulation rate yielded ASSR thresholds closer to behavioural PT thresholds and smaller standard deviations of difference scores (value between ASSR threshold and behavioural PT threshold). Van Maanen and Stapells (2005) and Van der Reijden et al. (2006) reported mean differences between ASSR threshold and behavioural PT threshold scores of 0 to 14 dB compared to 22 to 32 dB in the current study. Van Maanen and Stapells (2005) made use of a similar population sample as was done in the current study, as the individuals were claiming compensation for occupational hearing loss and were therefore likely to have a history of noise exposure and to present with a noise induced hearing loss. The studies demonstrated that the improved proximity of ASSR thresholds to behavioural PT thresholds is unlikely to be attributed to the high modulation rate used by the majority of studies that utilized the Biologic MASTER ASSR system. The long recording duration offered by the Biologic MASTER ASSR system, appears to be a distinct advantage over the short recording duration offered by the GSI Audera ASSR system.

In addition to reducing the intensity of the ASSR threshold, prolonging the recording duration will also reduce the noise levels of the participants that could not be assessed with the shorter response duration and less strict noise criterion. Dimitrijevic et al. (2002) state that, during AEP assessment, the main noise source is the scalp and neck muscles, and since sleep relaxes these muscles, testing participants when asleep is an effective method of reducing noise. The 80 Hz ASSR is more influenced by myogenic activity than the 40 Hz response is (Pethe et al., 2004). Consequently, due to the decreased background noise levels when participants are asleep, the 40 Hz ASSR, although reduced in amplitude with sleep, may become more detectable (Dobie & Wilson, 1998). In a population of adults who are referred for objective assessment due to (typically) wilful exaggeration of behavioural PT thresholds, who are liable to be rather anxious about the outcome of the assessment, high noise levels are likely to be measured. As was the case in the current research, Luts and Wouters (2005) report frequently having to select a low rather than a high modulation rate when assessing adults, due to excessively high noise levels. This was true in the case of the present study and that by Luts and Wouters (2005) despite the fact that participants were relaxed or asleep during ASSR assessment. De Koker (2004) even reported requiring the use of a sedative for the assessment of sleeping adults in order to reduce noise levels when using the GSI Audera with a high modulation rate. This is not always a clinically feasible option. The choice of modulation rate may therefore be dependant on noise levels. The adaptive procedure for acquisition of ASSR thresholds using the GSI Audera system recommended by Luts and Wouters (2005), is perhaps a better option, provided that use of a 40 Hz modulation rate ASSR with sleeping adults doesn’t cause elevation in ASSR thresholds, as suggested by Jerger et al. (1986) and Picton et al. (2003). As far as the author is aware, the effect of state of consciousness has not been re-examined within a commercially available ASSR system in over a decade.

The advantage of a longer recording duration is also observed by the number of participants who displayed excessive noise levels with a high modulation rate. The studies by Luts and Wouters (2005) and Van Maanen and Stapells (2005) made use of ASSR systems with different stimulus presentation methods and different recording durations. Luts and Wouters (2005) compared ASSR systems using the GSI Audera ASSR system with a short (89 s) recording duration and the Biologic MASTER ASSR system (maximum 15 min recording duration). Van Maanen and Stapells (2005) used the Biologic MASTER ASSR system, but restricted recording duration to a maximum of 8 min. When using the GSI Audera and the short recording duration, Luts and Wouters (2005) reported that 80 Hz ASSR thresholds could not be determined for 70% of participants with hearing loss. This is similar to the finding of the preliminary study of the current research. ASSR thresholds could not be determined for two out of three (66.7%) of the participants assessed, using the 80 Hz ASSR protocol of the GSI Audera. Van Maanen and Stapells (2005) reported that 30% of participants, the large majority of which presented with a hearing loss, were excluded from the study due to excessively high noise levels. When using the Biologic MASTER ASSR system and a longer recording duration than used by Van Maanen and Stapells (2005), however, Luts and Wouters (2005) were able to complete 80 Hz ASSR thresholds determination for all participants. The use by Luts and Wouters (2005) of a lower noise criterion (viz. 10 nV) and longer recording duration was effective in reducing noise levels during 80 Hz ASSR threshold determination, without requiring a change in modulation rate, as was required when using the GSI Audera ASSR and the shorter recording duration. The use of a low rather than a high modulation rate ASSR may not be problematic in adults (in fact it has been shown to be advantageous when using a multiple frequency ASSR system, Van der Reijeden et al., 2006; Van Maanen & Stapells, 2005) but the use of a 40 Hz modulation rate during ASSR testing with children and infants may deliver inconsistent detection of responses and variable estimates of behavioural PT thresholds (Aoyagi et al., 1993; Stapells, 1988).

The opinion of Picton et al. (2005), that duration of a single recording is a major factor in ASSR threshold determination, obtains further verification from the research done by Attias et al. (2006) which represents the study with the closest proximity of ASSR thresholds to behavioural PT thresholds. Attias et al. (2006) report using a response recording time of up to 17 min with the Biologic MASTER ASSR system, longer than is typically reported. The difference scores were on average 21 and 26 dB smaller (across frequencies) for the participants with normal hearing and hearing loss respectively, than were measured in the current study. In studies where shorter recording durations were used, such as in the study by Aoyagi et al. (1994), who reported recordings of 51 to 300 s each, mean differences between ASSR thresholds and behavioural PT thresholds were comparable to that of the present study (mean difference score across frequencies were within 2.5 dB of the current study).

Having established that a longer recording duration reduces ASSR threshold intensity, one must also consider that lengthening response recording duration will lead to a longer evaluation time. When considering the use of the ASSR technique for estimating behavioural PT thresholds with reference to both clinical effectiveness and efficiency, as is the case in the present study (the latter of which is defined as the amount of time necessary for acquisition of the threshold AEP responses), prolonging evaluation time is disadvantageous. The debate of relative importance between effectiveness (accuracy) and efficiency, will be further considered when discussing the results of sub-aim three, during which the time that was required for SCEAP and ASSR threshold acquisition was compared.

The second defining factor that emerged when considering the utilisation of ASSR for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise, in addition to recording duration, was the typical degree of hearing loss.

- **Influence of degree of hearing loss on ASSR threshold**

A population of individuals exposed to occupational noise will include both individuals with normal hearing and with hearing loss, the latter of which will typically exhibit a high frequency hearing loss with normal low and mid frequency behavioural PT thresholds. In the current study, the participants with hearing loss, who were all exposed to occupational noise, presented with mean behavioural PT thresholds of 10.5, 10.8, 21 and 47.3 dB at 0.5, 1, 2 and 4 kHz respectively. Therefore, the average individual in this study presented with normal hearing at 0.5 and 1 kHz, with a mild hearing loss at 2 kHz and a moderate hearing loss at 4 kHz. A recent study by Swanepoel and Erasmus (2007) evaluated the ability of the ASSR to estimate moderate behavioural PT thresholds. Swanepoel and Erasmus (2007) found a poor correlation ($r = 0.21$) of ASSR threshold with behavioural PT thresholds of less than 55 dB. This finding was supported by the research of Scherf et al.

(2006), who reported considerable variation of estimations of behavioural PT thresholds for individual frequencies when the average ASSR thresholds across 0.5, 1, 2 and 4 kHz were equal to or less than 40 dB. This is of particular relevance then to the typical participant in this study, and if the sample chosen for the current study can be considered representative of the target population, of relevance to adults exposed to occupational noise, who characteristically present with behavioural PT thresholds of less than 55 dB.

5.3.3 Comparison of SCAEP and ASSR estimations of behavioural PT thresholds

The average SCAEP difference scores which indicate proximity between SCAEP thresholds and behavioural PT thresholds, were considerably smaller than ASSR difference scores. The mean difference score across frequencies for SCAEP for the groups of participants with normal hearing and with hearing loss collectively was 2.2 dB, in comparison with a mean difference score of 26.6 dB for ASSR. A mean SCAEP difference score of 3 dB was measured across frequencies for the group with normal hearing. This was slightly greater than that for the group with hearing loss (mean difference score across frequencies = 1.6 dB). These small difference scores were in stark contrast to the large difference scores between ASSR and behavioural PT thresholds. The present study reported a mean difference score across all frequencies of 27.9 dB for the group with normal hearing and 25.4 dB for the group with hearing loss.

Figure 4.5 in the results chapter, graphically depicts the contrasting proximity of SCAEP versus ASSR thresholds to behavioural PT thresholds. The majority of SCAEP thresholds (viz. 66.7%) fell within 10 dB of behavioural PT thresholds, with 100% of SCAEP thresholds within 30 dB of behavioural PT thresholds. In contrast, only half of the ASSR thresholds fell within 30 dB, while 93% of ASSR thresholds were identifiable within 50 dB of behavioural PT thresholds.

Although correlation between the behavioural PT thresholds and SCAEP thresholds in the group with normal hearing were on average weak ($r = -0.07$), they do display a marginally better mean correlation than between normal behavioural PT thresholds and ASSR ($r = -0.03$). Robust mean correlations were measured between elevated behavioural PT thresholds and both SCAEP ($r = 0.85$) and ASSR ($r = 0.81$) thresholds across frequencies in the group of participants with hearing loss. Therefore, with regard to the participants with hearing loss, a stronger mean correlation between behavioural PT thresholds and SCAEP thresholds than between behavioural PT thresholds and ASSR thresholds was evident. Based on these results with regard to proximity and correlation of AEP threshold to behavioural PT threshold, SCAEP, rather than ASSR, is the AEP of choice for adults with normal hearing, or with hearing loss and exposed to occupational noise. The previous studies by Tomlin et al. (2006) and Yeung and Wong (2007) comparing SCAEP and ASSR threshold estimation, came to the same conclusion. In contrast, the studies by Van Maanen and Stapells (2005) and Kaf, Durrant et al. (2006) advocated the use of ASSR, rather than SCAEP, for behavioural PT threshold estimation.

Van Maanen and Stapells (2005) reported a closer proximity of ASSR thresholds to behavioural PT thresholds (and smaller difference scores) for both the high and low modulation rate multiple ASSR techniques (thresholds obtained using the two rates were compared), than between SCAEP thresholds and behavioural PT thresholds. However, the mean difference between SCAEP thresholds and behavioural PT thresholds (i.e. difference scores) reported in the study, are 14 to 20 dB larger than the mean difference scores reported in the current study, and larger than has been reported elsewhere (eg. Alberti et al., 1987; Coles & Mason, 1984; Hone et al., 2003; Hyde et al., 1986; Kaf, Durrant et al., 2006; Tomlin et al., 2006; Tsui et al., 2002). This was true, despite similar research methodologies between their study and the current study, including a similar SCAEP stimulus protocol and a male only population, the majority of which presented with a high frequency noise induced hearing loss. Van Maanen and Stapells (2005) attribute the large difference between SCAEP thresholds and behavioural PT thresholds to the calibration method used. Van Maanen and Stapells (2005) suggest that the SCAEP thresholds reported would have been approximately 9 dB smaller, had the typical nHL been used instead of the dBeHL scale selected. A 9 dB decrease in SCAEP thresholds would however still mean that the intensity of the SCAEP thresholds of the Van Maanen and Stapells (2005) study remain elevated, with reference to the current study and in comparison to the majority of existing literature. In addition to the larger difference between SCAEP thresholds and behavioural PT thresholds, Van Maanen and Stapells (2005) measured ASSR thresholds at lower sensation levels than in the current study. ASSR thresholds were on average 17 and 13 dB closer to behavioural PT thresholds across frequencies for the 40 and 80 Hz ASSR techniques respectively, than was reported in the present study. This is likely to be due to the longer recording duration offered by the Biologic MASTER ASSR system (maximum of 8 min recording duration utilized in the study by Van Maanen & Stapells, 2005) at threshold intensity levels, as compared to the considerably shorter maximum 89 s recording duration (GSI, 2003) allowed by the GSI Audera ASSR system used in the current study. Therefore, the elevated SCAEP thresholds and low ASSR thresholds provide the basis for the conclusion reached by Van Maanen and Stapells (2005) that the 40 Hz multiple frequency ASSR technique, rather than the SCAEP technique, is advocated for the purpose of behavioural PT threshold estimation for adults claiming workmen's compensation. The study by Van der Reijden et al. (2006) also found, as did Van Maanen and Stapells (2005), a closer proximity of ASSR threshold to behavioural PT thresholds when using a 40Hz ASSR modulation rate, than with an 80 Hz ASSR modulation rate.

Kaf, Durrant et al. (2006) compared multiple frequency ASSR thresholds obtained using a high modulation rate, to SCAEP thresholds at 2 kHz only. The proximity of ASSR and SCAEP thresholds to behavioural PT thresholds was the same for the group with normal hearing, but ASSR thresholds were closer to behavioural PT thresholds than SCAEP thresholds at 2 kHz in participants with a simulated sensorineural hearing loss. Once again, it is postulated that the longer response recording time allowed by the Biologic MASTER ASSR system resulted in a reduction of noise levels and, consequently, in ASSR thresholds closer to behavioural PT thresholds.

As was true of the present study, the study by Tomlin et al. (2006) concluded that, with reference to both proximity to behavioural PT thresholds and variability of this relationship, the SCAEP technique demonstrated a clear advantage over the 40 Hz ASSR. Yeung and Wong (2007) also reported that the SCAEP technique estimated behavioural PT thresholds slightly more accurately than the ASSR did. However, ASSR thresholds in the study by Yeung and Wong (2007) were closer to the behavioural PT thresholds than those of the current study, most significantly at 4 kHz. Yeung and Wong (2007) reported differences between ASSR or SCAEP threshold and behavioural PT threshold grouped, depending on the intensity of the behavioural PT threshold. The mean behavioural PT threshold at 4 kHz for the current study was 47.3 dB. This is therefore comparable to the difference scores reported by Yeung and Wong (2007) for the participants with behavioural PT thresholds which fell within the range of 30 to 55 dB. Yeung and Wong (2007) reported a difference score between ASSR thresholds and behavioural PT thresholds at 4 kHz of 2.4 dB with a standard deviation of 10.6 dB. This is considerably smaller than the difference score between ASSR threshold and behavioural PT threshold at 4 kHz of 22.4 dB with a standard deviation of 13.7 dB found in the present study. One may postulate that the alert participant state of consciousness (in contrast to the restful or sleeping state of the participants evaluated using the ASSR technique in the current study), contributed to the smaller difference scores reported by Yeung and Wong (2007), than in the current study. The difference score between ASSR thresholds and behavioural PT thresholds at 4 kHz reported by Yeung and Wong (2007), however, is also considerably smaller than those reported by Tomlin et al. (2006), who used the same ASSR system, stimulus protocol and participant state of consciousness to determine ASSR thresholds that Yeung and Wong (2007) used. Tomlin et al. (2006) reported a mean difference score between ASSR threshold and behavioural PT threshold at 4 kHz for the group with normal hearing of 42 dB, while the difference score at 4 kHz for the participant group with hearing loss was 24 dB. A third of the participants in the study by Yeung and Wong (2007) presented with a severe to profound degree of hearing loss. The effect of recruitment on the ASSR amplitude is likely to be the reason for the close proximity of ASSR thresholds to behavioural PT thresholds at 4 kHz.

With reference to the better difference scores reported by Tomlin et al. (2006) and Yeung and Wong (2007) at 0.5 kHz than were measured in the current study, the methodological reason is less mysterious. Difference scores between ASSR threshold and behavioural PT threshold at 0.5 kHz for Yeung and Wong (2007) and for Tomlin et al. (2006) were comparable. Tomlin et al. (2006) reported a mean difference between ASSR threshold and behavioural PT threshold at 0.5 kHz of 14 dB (participants with normal hearing and with hearing loss group together), while the mean difference at 0.5 kHz was measured as 11 dB in the study by Yeung and Wong (2007). The difference scores of the two studies at 0.5 kHz were possibly smaller than those of the current study (viz. 25 dB), due to the inclusion of moderate to severely raised behavioural PT thresholds in the participant group with hearing loss in contrast to the typical behavioural PT threshold at 0.5 kHz for participants with hearing loss in the current study which fell within normal limits.

Many authors are of the opinion that the accuracy of estimations of behavioural PT thresholds using AEP, is not determined by proximity of the AEP threshold to the behavioural PT threshold alone, but by the consistency of this relationship (Picton et al., 2005; Rance et al., 1995; Tomlin et al., 2006). As established by the scatter plots in Figure 4.9 of Chapter 4, and the standard deviation of the difference scores between SCAEP thresholds and behavioural PT thresholds, an advantage was again demonstrated, albeit only barely, over the ASSR, especially with reference to participants with normal hearing. This is contrary to the early statement by Rance et al. (1995), speculating that the use of automated response detection offered by the ASSR technique may result in reduction of standard deviation values. The standard deviations were slightly larger for ASSR thresholds (mean std dev for combined participant group = 13.1 dB) than SCAEP thresholds (mean std dev for combined participant group = 10.2 dB). Naturally because the AEP techniques differ, there are other variables concerned than automated versus visual response detection.

The standard deviations of the difference scores between SCAEP thresholds and behavioural PT thresholds measured in the current study, ranged from 7.9 to 11.6 dB and are comparable to those reported in existing literature (range = 6 to 15 dB; Coles & Mason, 1984; Kaf, Durrant et al., 2006; Lightfoot & Kennedy, 2006; Tsui et al., 2002; Van Maanen & Stapells, 2005; Yeung & Wong, 2007). With reference to the standard deviation scores of the proximity of ASSR thresholds to behavioural PT thresholds, those of the current study were measured at 9.7 to 14.9 dB. This is comparable to the standard deviations for the majority of the 40 Hz ASSR body of research (range 6 to 18 dB; Aoyagi et al., 1993; Tomlin et al., 2006; Yeung & Wong, 2007). The standard deviations of the relationship between high modulation ASSR threshold and behavioural PT thresholds listed in Table 5.4 vary from 4 to 18 dB (Aoyagi et al., 1994; Attias et al., 2006; Herdman & Stapells, 2003; Kaf, Durrant et al., 2006; Lins et al., 1995, 1996; Luts & Wouters, 2005; Perez-Abalo et al., 2001; Picton et al., 1998; Rance et al., 1995; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van der Reijden et al., 2006; Van Maanen & Stapells, 2005). The standard deviations reported by Hsu et al. (2003; std dev = 3 to 5 dB) and Van der Reijden et al. (2006; std dev = 0 dB) are however noticeably smaller than those reported by any of the ASSR studies listed in Table 5.3 and 5.4. Hsu et al. (2003) made use of the 80 Hz modulation rate and a monotic single frequency ASSR system. It is possible that the use of the higher modulation rate (i.e. 90 Hz) for evaluation of sleeping participants by Hsu et al. (2003), in contrast to the low modulation rate used in the present study, may have contributed to the smaller correlation co-efficients. The reason why Van der Reijden et al. (2006) reported a 0 dB standard deviation lies in the structure of the methodology. The study used a small sample of only 11 adults, all with a hearing loss and a fixed stimulus level of 10, 20 and 30 dB sensation level. ASSR thresholds could be measured for all participants at 0.5 and 2 kHz at a 10 dB sensation level. Van der Reijden et al. (2006) also made use of a longer recording duration of 4.4 min, in contrast to the maximum 89 s recording duration in the present study. The longer recording duration reduces the noise levels resulting in lower ASSR threshold intensities.

In the current study, the largest standard deviation of the difference between AEP thresholds and behavioural TP thresholds were measured for ASSR thresholds in participants with normal behavioural PT thresholds (mean ASSR std dev for the participant group with normal hearing = 13.9 dB), while the smallest standard deviation score was measured for the difference between SCAEP thresholds and behavioural PT thresholds for participants with normal hearing (std dev of SCAEP difference scores of the group with normal hearing = 9.3 dB). The slightly higher variability indicated by the larger standard deviation scores of the ASSR difference scores, limits the predictive ability of the ASSR technique to some extent, to estimate behavioural PT thresholds in individuals with normal hearing in comparison to the SCAEP technique. This is relevant when considering the typical adult population that will require objective assessment in order to estimate behavioural PT thresholds due to exaggerated audiometric thresholds. A population of predominantly male individuals exposed to occupational noise, will include both individuals with normal hearing and with hearing loss, the latter of which will typically exhibit a high frequency hearing loss with normal low and mid frequency behavioural PT thresholds. Therefore, the ability of the chosen AEP to estimate normal behavioural PT thresholds is essential to obtain accurate percentage loss of hearing (COIDA, 2001) and appropriate compensation based on percentage disability. Consistency of the relationship between SCAEP and behavioural PT thresholds facilitates estimations of behavioural PT thresholds from SCAEP threshold. The smaller standard deviation scores render the regression formulae generated for the purpose of behavioural PT thresholds from SCAEP thresholds (as displayed in Figure 4.9) reliable.

In summary of what was considered the two defining factors when considering the reliability of the ASSR thresholds for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise, the short response recording duration offered by the GSI Audera ASSR system limits the potential accuracy of behavioural PT threshold estimation, while the typical mild to moderate high frequency hearing loss of the target population renders the SCAEP technique a better choice of AEP than ASSR, due to the closer proximity of SCAEP thresholds, than ASSR thresholds to behavioural PT thresholds. The SCAEP technique generated difference scores between SCAEP thresholds and behavioural PT thresholds that were on average 24 dB smaller across all frequencies, than between ASSR thresholds and behavioural PT thresholds, with slightly smaller standard deviation scores of this difference value than those for ASSR difference scores (by 2.9 dB). Therefore, the SCAEP provided a more accurate estimation of behavioural PT thresholds, in terms of proximity to behavioural PT thresholds and variability of this relationship, than the 40 Hz ASSR using the GSI Audera for adults exposed to occupational noise. The GSI Audera ASSR system compensates for the short recording duration, by using regression formulae suggested by Rance et al. (1995). The GSI Audera ASSR estimates of behavioural PT thresholds have not been considered to date when comparing SCAEP and ASSR thresholds in the current study. The effect of the Rance et al. (1995) regression formulae were therefore evaluated below.

5.3.4 Comparison of GSI Audera ASSR estimated behavioural PT thresholds with SCAEP thresholds

The GSI Audera ASSR formulae, proposed by Rance et al. (1995), result in larger corrections for normal and mildly elevated behavioural PT thresholds compared to more severely elevated behavioural PT thresholds. The difference in correction factor based on the ASSR threshold intensity is necessary, as the GSI Audera makes use of a short (in comparison to that of the Biologic MASTER ASSR system) maximum recording duration and the recording duration cannot be lengthened in the case of high noise levels in the response (GSI, 2003). The result is that, when measuring small ASSR responses, as is the case for normal and mildly elevated behavioural PT thresholds, the difference between ASSR thresholds and behavioural PT thresholds is greater and a greater correction is required to accurately estimate behavioural PT thresholds from the ASSR thresholds. In contrast, the effect of recruitment means that ASSR responses for participants with a sensory hearing loss are recognizably closer to behavioural PT threshold intensity (Lins et al., 1996). This occurs as the physiological response increases in amplitude more steeply with increasing intensity when there is a hearing loss. Therefore a smaller correction is required in order to estimate behavioural PT thresholds from ASSR thresholds in individuals with a moderate or more severe sensory hearing loss than for normal hearing or mild hearing loss. The GSI Audera ASSR estimates of behavioural PT thresholds for the combined participant group were used in Figure 5.1, to compare the percentage distribution of SCAEP and ASSR thresholds within categories of difference scores denoting the proximity of SCAEP and ASSR thresholds to behavioural PT thresholds.

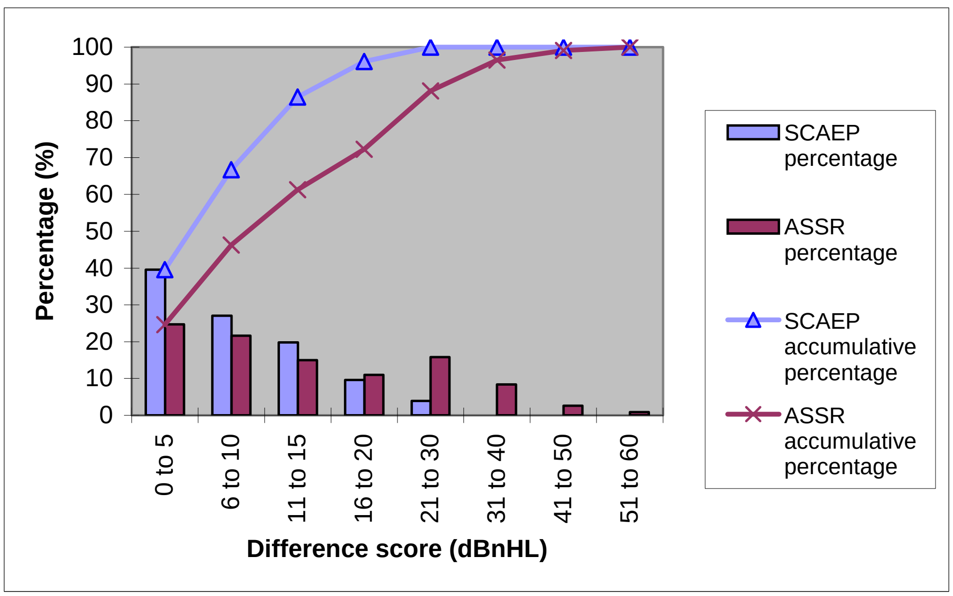
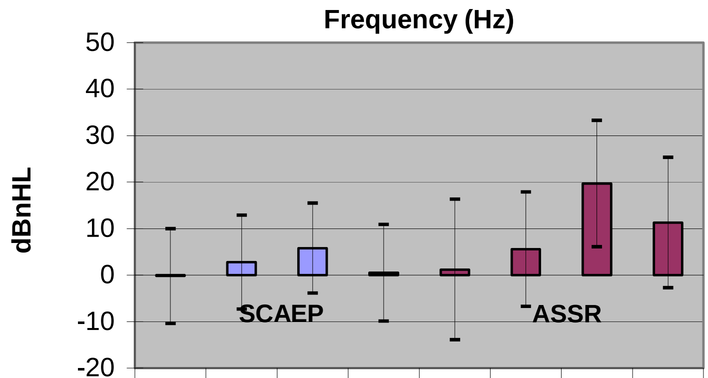


FIGURE 5.1 Combined participant groups: Distribution of difference scores between SCAEP and behavioural PT thresholds, compared to the distribution of difference score between GSI Audera ASSR estimates of behavioural PT thresholds and behavioural PT thresholds

(difference score = SCAEP or ASSR minus behavioural PT thresholds)

As can be seen from Figure 5.1 46% of the GSI Audera ASSR estimated behavioural PT thresholds were found within 10 dB of the behavioural PT thresholds, in comparison with 68% of SCAEP thresholds. This is a vast improvement over the uncorrected ASSR thresholds which fell within 10 dB of behavioural PT thresholds for only 9.5% of the

ASSR thresholds. One hundred percent of GSI Audera ASSR estimated behavioural PT thresholds were found within 60 dB of behavioural PT thresholds, while 100% of SCAEP were found to be within 30 dB. Figure 5.2 presents the mean difference scores (SCAEP or ASSR threshold minus behavioural PT thresholds) for the combined participant groups using the GSI Audera's ASSR estimated behavioural PT thresholds and SCAEP thresholds.



	500	1000	2000	4000	500	1000	2000	4000
Mean diff	-0.2	2.8	5.8	0.5	1.2	5.6	19.7	11.3
Std dev	10.2	10.1	9.7	10.4	15.1	12.3	13.6	14.0
Mean diff – std dev	-10.4	-7.3	-3.9	-9.9	-13.9	-6.7	6.1	-2.7
Mean diff + std dev	10.0	12.9	15.5	10.9	16.3	17.9	33.3	25.3
n	49	52	53	53	57	56	56	56

FIGURE 5.2 Combined participant groups: Difference between SCAEP and behavioural PT thresholds, compared to difference between GSI Audera ASSR estimates of behavioural PT thresholds and behavioural PT thresholds (mean, standard deviation and number of ears)

(diff = difference score between SCAEP or ASSR minus behavioural PT thresholds; std dev = standard deviation; n = number of ears)

The mean difference between the GSI Audera ASSR estimates of behavioural PT thresholds and the behavioural PT thresholds for the combined participant group across all frequencies was 9.4 dB with a standard deviation of 15.3 dB. As can be expected, the GSI Audera ASSR difference score was markedly smaller than the difference score between the uncorrected ASSR thresholds and the behavioural PT thresholds (average difference score across frequencies = 26.6 dB). GSI Audera ASSR estimates were within 1.2, 5.6 and 11.3 dB of the behavioural PT thresholds at 0.5, 1 and 4 kHz respectively. One can then conclude that the GSI Audera ASSR system was able to accurately estimate the behavioural PT thresholds by making use of the Rance et al. (1995) regression formulae. The mean GSI Audera ASSR estimate of behavioural PT threshold at 2 kHz was, however, 19.7 dB greater than the behavioural PT threshold. The elevated GSI Audera ASSR estimate of the behavioural PT threshold at 2 kHz may lead to overestimation of behavioural PT threshold and a greater percentage loss of hearing (COIDA, 2001). The concern regarding possible overestimation of behavioural PT thresholds by the GSI Audera ASSR system, was echoed by Ballay, Tonini, Waninger, Yoon and Manolidis (2005). Ballay et al. (2005) examined the ability of the GSI Audera ASSR, using the Rance et al. (1995) regression formulae, to estimate behavioural PT thresholds in a group of children with steeply sloping sensorineural hearing losses. The study concluded that the GSI Audera ASSR system may overestimate the degree of hearing loss above 0.5 kHz by 15 to 20 dB. Of bearing to the estimation of behavioural PT thresholds in individuals with occupational noise induced hearing loss, a 15 to 20 dB overestimation would result in inaccurate diagnosis of percentage loss of hearing (COIDA, 2001) and excessive compensation.

It was interesting to note that the standard deviation scores of the difference between ASSR thresholds and behavioural PT thresholds were slightly larger once the Rance et al. (1995) regression formulae were applied (std dev scores ranged from 12.3 to 15. 1 dB), than when the regression formulae were not taken into account (std dev ranged from 11.3 to 13.8 dB). In comparison with the SCAEP data (mean difference score = 2.2 $\pm$ 10.2), both the mean ASSR difference score (between GSI Audera ASSR estimates of behavioural PT thresholds and behavioural PT thresholds) and the standard deviation value were larger. Therefore, despite the closer proximity of GSI Audera ASSR estimates of behavioural PT thresholds to behavioural PT threshold and the improved accuracy of estimation of behavioural PT thresholds, SCAEP thresholds remained closer to the behavioural PT thresholds.

The reduction in size of difference scores that resulted when taking the GSI Audera ASSR estimates of behavioural PT thresholds into consideration, meant that the difference between ASSR threshold and behavioural PT threshold scores in the current study were smaller than those quoted by Tomlin et al. (2006), who reported on uncorrected GSI Audera ASSR thresholds using a 40 Hz modulation rate. The same is true for the low and mid frequencies in the studies by Kaf, Durrant et al. (2006), Yeung and Wong (2007) and Van Maanen and Stapells (2005) for the 40 Hz modulation rate, but the mean GSI Audera ASSR estimates of behavioural PT thresholds in the current study were measured at a higher sensation level at 2 and 4 kHz, than in the aforementioned studies. In addition, the ASSR standard deviation scores presented in Figure 5.2 were larger, indicating more variability than is reported elsewhere in literature (Kaf, Durrant et al., 2006; Tomlin et al., 2006 for the combined participant group; Van Maanen & Stapells, 2005; Yeung & Wong, 2007). If one accepts the opinion of Picton et al. (2005) and Rance et al. (1995), that the consistency of the relationship between AEP threshold and behavioural PT thresholds is a better determinant of accuracy than the proximity of these two values, then the SCAEP technique would remain the AEP of choice for estimation of behavioural PT thresholds in adults with normal hearing, and in adults with hearing loss and exposed to occupational noise.

Table 5.8 summarizes the results of the statistical comparison between SCAEP thresholds and ASSR thresholds for the purpose of behavioural PT threshold estimation in the target population, with the addition of the statistics generated using the GSI Audera corrected ASSR thresholds.

TABLE 5.8 Comparative statistics between SCAEP, ASSR and GSI Audera corrected ASSR thresholds denoting difference values, standard deviation and correlations scores between AEP threshold and behavioural PT threshold

		Difference score	Standard deviation	Correlation
SCAEP	N	3.1	9.3	-0.07
	HI	1.6	10.9	0.85
	N + HI	2.2	10.2	0.85
ASSR	N	27.9	13.9	-0.03
	HI	25.4	12.2	0.81
	N + HI	26.6	13.1	0.75
GSI Audera Corrected ASSR Thresholds	N + HI	9.4	13.3	

(N = participant group with normal hearing; HI = participant group with hearing loss; N + HI = combined participant group with participants with normal hearing and with hearing loss; difference score = SCAEP or ASSR threshold minus behavioural PT threshold)

With respect to each of the key statistics generated from the data collected in the current study, namely the difference score between AEP thresholds and behavioural PT thresholds, the standard deviation of the difference score and the correlation between AEP threshold and behavioural PT thresholds, the SCAEP technique was able to estimate behavioural PT thresholds in the target sample most accurately. The SCAEP technique was therefore deemed to provide the most accurate estimates of behavioural PT thresholds in a sample of adults with normal hearing and adults with hearing loss who were exposed to occupational noise.

5.4 DISCUSSION OF SUB-AIM THREE RESULTS: SCAEP AND ASSR THRESHOLD ACQUISITION TIMES

For each participant group and for the combined participant groups, the mean time required to acquire the SCAEP thresholds for a participant was greater than for the ASSR thresholds. SCAEP testing took on average 6.2 min longer for the group with normal hearing (SCAEP threshold acquisition time = 53.8 min; ASSR = 47.6 min) and 13.7 min longer for the group of participants with hearing loss (SCAEP threshold acquisition time =

56.2 min; ASSR = 42.5 min) than ASSR threshold acquisition did. With both participant groups with normal hearing and hearing loss combined, SCAEP threshold acquisition took 10.1 min longer than ASSR threshold acquisition took (SCAEP threshold acquisition time = 55 min; ASSR = 44.9 min). Despite this, the range of threshold acquisition times for the two techniques was similar. SCAEP threshold acquisition time ranged from 31 to 72 min while that for ASSR threshold acquisition ranged from 35 to 75 min. When considering, that the ASSR makes use of objective response detection, and that the SCAEP threshold acquisition time reported here does not include the time required in order to identify threshold SCAEP responses, the GSI Audera ASSR system demonstrates a clear advantage in terms of required time.

The mean time taken for behavioural PT threshold estimation in two ears using SCAEP in this study, namely 55 min, was markedly longer than the 29.8 min reported to complete SCAEP threshold acquisition in the study by Van Maanen and Stapells (2005). This can be explained on the basis of different stimulus parameters and timing method. Van Maanen and Stapells (2005) made use of a slightly faster stimulation rate and shorter (by 40 msec) stimulus duration. Van Maanen and Stapells (2005) estimated the typical time required for SCAEP threshold acquisition by multiplying the number of sweeps required by the time taken per sweep. This then eliminates the time required by the tester to change stimulus intensity, frequency and ear, and to resume each new sweep, all of which were taken into account in the current study, which reported actual time taken. Van Maanen and Stapells (2005) also found that four frequency threshold estimation in both ears was fastest with SCAEP, in comparison with both the 40 and 80 Hz multiple frequency ASSR techniques (mean acquisition time per participant for both ears was 41 and 72 min for the 40 and 80 Hz ASSR techniques respectively). ASSR threshold acquisition times were similar, with a difference of only 3.9 min between 40 Hz multiple frequency ASSR technique used by Van Maanen and Stapells (2005) and the 40 Hz single stimulus technique utilized in the current study. Similarly, Rance et al. (1995) estimated that it took 30 to 60 min to complete monotic single frequency ASSR testing for frequencies in two ears.

The ASSR threshold acquisition times for participants with normal hearing, hearing loss and for the combined participant groups quoted in this study, were within a minute of those measured by Luts and Wouters (2005) while using the GSI Audera ASSR system. Luts and Wouters (2005) state that data acquisition of ASSR thresholds took on average 5.1 min longer for the group with normal hearing (mean threshold acquisition time = 46 min), than for the group with hearing loss (mean = 42 min). Both the current study and Luts and Wouters (2005) recorded a shorter threshold acquisition time for participants with hearing loss, than for participants with normal hearing using the GSI Audera ASSR system. This may be ascribed to recruitment in individuals with a moderate or more severe hearing loss (Lins et al., 1996). The physiological response increases in amplitude more steeply with increasing intensity when there is a sensory hearing loss. This makes the ASSR responses for participants with a sensory hearing loss recognizably closer to behavioural PT threshold intensity. It was interesting to note that SCAEP thresholds for individuals with normal hearing and with hearing loss did not demonstrate this same pattern.

Recording responses to multiple stimuli simultaneously, can increase the speed of testing over recording responses to individual stimuli (Dimitrijevic et al., 2002; John et al., 1998). Ideally, however, the conditions that must be met in order to decrease recording time of ASSR responses to four stimuli to the recording time of a single ASSR response, as reported by John et al. (2002), are not always fulfilled (Picton et al., 2003). Herdman and Stapells (2003) reported a mean recording time of 47 min to acquire ASSR thresholds at four frequencies when using a multiple frequency ASSR system. This is comparable to the 45 min recording time reported in the current study to acquire four frequency ASSR thresholds in both ears. Again, this recording time was estimated from the amount of sweeps required to obtain threshold, rather than the actual recording time. The short mean recording time of only 21 min, reported by Perez-Abalo et al. (2001) using a dichotic multiple frequency ASSR technique is likely related to the flat audiogram configuration of the participants and the maximum 5 min recording duration utilized. Swanepoel, Schmulian and Hugo (2004) reported a mean test time for eight frequencies presented dichotically with a multiple frequency ASSR technique of 23 min with a standard deviation of 8 min for adults with normal hearing, considerably shorter than the mean 48 min required in order to obtain ASSR thresholds for individuals with normal hearing using the monotic, single frequency system used in the present study. Swanepoel, Schmulian et al. (2004), however, state that behavioural PT threshold estimation is likely to be significantly longer if a multiple frequency ASSR technique is used for a population who typically presents with a sloping hearing loss with normal low frequency behavioural PT thresholds, as was the case with the target population in the current study.

With regard to time efficiency of the SCAEP technique, an early report by Hyde et al. (1986) states that a four frequency SCAEP threshold acquisition in both ears typically takes 1.5 hours. This is considerably longer than the average of 55 min found in the current research project. More recently, a study by Lightfoot and Kennedy (2006) made use of a SCAEP system, with online averaging and random interstimulus intervals, in addition to the automation of various classically manual tasks during SCAEP assessment. They established that with this system, a six threshold estimate took on average 20.6 min to complete, with a mean error in behavioural PT threshold estimate of 6.5 dB. An eight threshold estimate would then have taken approximately 30 min with this optimized system. Therefore, despite the longer threshold acquisition time of SCAEP than ASSR reported for the current study, there are ways of decreasing SCAEP test time. This is especially necessary in light of the fact that the automated response detection algorithms are used to determine the presence of an ASSR response, which reduces the amount of time for the identification of ASSR thresholds.

A review of the literature therefore highlights the variables that determine the time required to acquire SCAEP and ASSR thresholds for the purpose of behavioural PT threshold estimation. The ASSR response recording duration, the noise criterion (if any) used by the ASSR system during objective response detection, the stimulus presentation method (i.e. monotic or dichotic and multiple or single frequency stimuli), the individual’s behavioural PT thresholds and the amount of automation of routine tasks offered by the AEP system used, all influence test time. The quandary between time efficiency and accuracy of ASSR thresholds for behavioural PT threshold estimation was highlighted by Luts and Wouters (2005). Luts and Wouters (2005) demonstrated that if the maximum response duration of 15 min offered by the Biologic MASTER ASSR system was utilized, this improved the accuracy of behavioural PT threshold estimation from ASSR thresholds, reducing mean difference scores by 6 dB for the group with normal hearing and by 5 dB for participants with hearing loss. The standard deviation values of these difference scores also decreased. This improvement in accuracy was at the expense of time efficiency though, as mean ASSR test time was calculated as 87 min. This is longer than either the ASSR or SCAEP threshold acquisition times reported in this study. The comparative importance of accuracy and time efficiency of an AEP technique must be deliberated in the context of use of an AEP technique for a population of adults exposed to occupational hearing loss in South Africa. This point is reflected on in the next chapter.

5.5 CONCLUSION

The South African Department of Health states that even the best, proven diagnostic procedure must continuously be challenged through research for its effectiveness, efficiency, accessibility and quality (South African Department of Health, 2000). Chapter four discussed the findings regarding the clinical effectiveness and efficiency of the SCAEP, which is the proven diagnostic (and objective) measure for the purpose of behavioural PT threshold estimation in adults with normal hearing and in adults with hearing loss who are exposed to occupational noise. The SCAEP was pitted against the newer clinically available AEP, the ASSR.

Sub-aim one concerned the comparison of behavioural PT, tone burst and AM/FM thresholds. The discussion of the results generated through the comparison of the three stimuli, concluded that the stimuli were statistically different and were therefore not directly comparable. Temporal summation provided justification for the statistical difference between the three stimuli requiring the correction of SCAEP and ASSR thresholds.

The focus of aim of sub-aim two was to compare the accuracy of threshold estimation of SCAEP and ASSR, with reference to the behavioural PT thresholds. The results clearly indicate that the SCAEP thresholds are closer to the behavioural PT thresholds than the ASSR threshold for the group of participants with normal hearing and with hearing loss. The smaller difference scores for SCAEP than for the ASSR technique, were supported by stronger correlation values between the SCAEP and behavioural PT thresholds for both participant groups. The studies comparing SCAEP and ASSR threshold estimation for the purpose of behavioural PT threshold estimation undertaken by Tomlin et al. (2006) and Yeung and Wong (2007), came to the same conclusion as the present research. In contrast, the studies by Kaf, Durrant et al. (2006) and Van Maanen and Stapells (2005) advocated the use of ASSR rather than SCAEP for behavioural PT threshold estimation. This conclusion was based, in part at least, on lower ASSR thresholds than were measured in the current study. The lower ASSR thresholds reported by Kaf, Durrant et al. (2006) and Van Maanen and Stapells (2005) may be attributed to their use of an ASSR system, which allows a considerably longer recording duration than that of the GSI Audera ASSR system utilized for the present study. One must recognize, however, that accuracy alone does not determine efficacy of a clinically viable AEP technique. The time taken to obtain these results, together with accuracy of estimation of behavioural PT thresholds, determines clinical efficacy (Oxford dictionary, 1967; Stapells, 2002).

Sub-aim three explored the clinical efficiency of the SCAEP and ASSR techniques. The SCAEP required 10.1 mins longer than the ASSR to measure eight thresholds responses from two ears. Van Maanen and Stapells (2005) also compared the time efficiency of the SCAEP and ASSR techniques, but found that the SCAEP was able to provide the quickest estimates of behavioural PT thresholds. Van Maanen and Stapells (2005) did not take the time required to change stimulus level, frequency and ear into account as the current research did. Research that made use of the GSI Audera ASSR system, reported similar threshold acquisition times to the current research (Luts & Wouters, 2005). Literature examining the Biologic MASTER ASSR system report either a similar threshold acquisition time (Herdman & Stapells, 2003; Van Maanen & Stapells, 2005, using a 40 Hz ASSR), or shorter threshold acquisition time (Perez-Abalo et al., 2001; Swanepoel, Schmulian et al., 2004; Van Maanen & Stapells). A sloping audiometric configuration was, however, reported to lengthen test time with the Biologic MASTER ASSR system (Swanepoel, Schmulian et al., 2004; Van Maanen & Stapells, 2005). The behavioural PT thresholds of the participants, the SCAEP or ASSR system used and the response recording duration, all play a role in determining time efficiency. The trade off between accuracy and time efficiency, when using the ASSR technique, was highlighted as an important consideration for use of the technique in a clinical setting.

5.6 SUMMARY

Chapter five presented a discussion of the results of the statistical analysis of the data with respect to the three sub-aims of the study and in the context of previous research findings. The review of the findings of sub-aim one pertained to the comparison of behavioural PT, tone burst and AM/FM thresholds. Literature provided the rational for the statistical difference between the three stimuli, which led to the correction of SCAEP and ASSR thresholds prior to comparison. The discussion of sub-aim two followed with the SCAEP, then ASSR results regarding the difference between AEP thresholds and behavioural PT thresholds, as well the relationship between the aforementioned variables. Results of the study were compared to previous literature, highlighting methodological differences. The comparison facilitated the identification of the variables that affected the accuracy of the ASSR thresholds. GSI Audera ASSR estimates of behavioural PT thresholds, calculated using the Rance et al. (1995) regression formulae, were then introduced into the comparison between SCAEP and ASSR thresholds. Finally, the results of sub-aim three were examined with reference to existing literature. In so doing, the effect of different recording and stimulus variables on the time required to obtain SCAEP and ASSR thresholds was considered.

CHAPTER SIX

CONCLUSIONS AND IMPLICATIONS

6.1 INTRODUCTION

Occupational injuries and diseases have an important role to play in health, particularly in developing and middle-income countries such as South Africa (South African Department of Health, 1997). South Africa has more than 8.2 million workers, who spend at least eight hours per day in formal employment in factories, mines, on farms and other places of work (South African Department of Health, 1997). By affecting the health of the working population, occupational injuries and diseases have profound effects on productivity and the economic and social well-being of workers, their families and dependants. The statutory obligations of the South African Department of Health as stated in the South African Occupational Diseases in Mines and Works Amendment Act (2003), include benefit (compensation) examinations of not only current, but also of former employees. With the emphasis on building the economy, expansion of service provision must also be achieved in a cost efficient manner (South African Department of Health, 1997).

In individuals claiming compensation for occupational noise induced hearing loss, a population with a high incidence of nonorganic hearing loss, a reliable and valid behavioural pure tone (PT) threshold is not always achievable. In such cases, several authors have named slow cortical auditory evoked potentials (SCAEP) as the objective measure of choice for behavioural PT threshold estimation for the aforementioned population (Alberti et al., 1987; Hone et al., 2003; Rickards & De Vidi, 1995; Stapells, 2002; Tsui et al., 2002). Over the past decade, a relatively new clinically available AEP (auditory evoked potential) technique, the auditory steady-state evoked response (ASSR) has been proposed as an alternative AEP for behavioural PT threshold estimation (Dobie & Wilson, 1998; Lins et al., 1996; Rance et al., 1995).

Subsequent to the identification of a lack of comparative research on SCAEP and ASSR for use in a population of adults exposed to occupational noise, the research project was initiated within a changing healthcare system. The transformation of the South African healthcare system is directed by the South African Department of Health, which demands continuous research into efficiency of diagnostic procedures, procedures that must be capable of accurately identifying both the new and the backlog of workers with noise induced hearing loss (South African Department of Health, 1997). The main aim of this research endeavour was to compare the clinical effectiveness and efficiency of the SCAEP and the ASSR for behavioural PT threshold determination in adults exposed to occupational noise. The results of the project were presented and discussed in the context of existing literature, with reference to each sub-aim and in realization of the main aim. In so doing the research question of the current project was answered, namely, how effective and how efficient is the clinical use of a single stimulus ASSR technique as compared to SCAEP for behavioural PT threshold estimation in adults exposed to occupational noise.

6.2 CONCLUSIONS

For the purpose of the study, clinical effectiveness was defined as the accuracy of behavioural PT threshold estimation while clinical efficiency was defined as the amount of time necessary for acquisition of the SCAEP or ASSR thresholds. Three sub-aims were then formulated to answer the research question. Following the preceding results presented in Chapter four and the discussion presented in Chapter five, the conclusions can be drawn. The conclusion drawn from each of the key statistics, were summarized in Table 6.1, in respect of the AEP of choice.

TABLE 6.1 Summary of AEP of choice with reference to clinical effectiveness and clinical efficiency

		Participant group with normal hearing	Participant group with hearing loss
Clinical effectiveness	Difference score	SCAEP	SCAEP
	Standard deviation	SCAEP	SCAEP
	Correlation	SCAEP	SCAEP
Clinical efficiency	Time taken to acquire AEP thresholds	ASSR	ASSR

The conclusions reached from analysis of the statistical data as summarized in Table 6.1, were discussed with reference to the definitions of clinical effectiveness and clinical efficiency.

6.2.1 Clinical effectiveness: Accuracy of SCAEP and ASSR estimation of behavioural PT thresholds

Investigation of comparative accuracy of the SCAEP and ASSR was done through the formulation of sub-aim one and sub-aim two.

The first sub-aim determined that the direct comparison between the objective thresholds obtained using SCAEP and ASSR techniques, with reference to behavioural PT thresholds of hearing, was not valid. A correction factor was therefore applied to SCAEP and ASSR thresholds before comparing and determining the accuracy of behavioural PT threshold estimation for each technique.

The second sub-aim compared the accuracy of SCAEP and ASSR techniques, with reference to the ability to estimate behavioural PT thresholds. In terms of both proximity of SCAEP and ASSR thresholds to behavioural PT thresholds, and the variability of the relationship (standard deviation), the SCAEP technique demonstrated an advantage over the 40 Hz ASSR in both the group of participants with normal hearing and with hearing loss. In the combined participant group, SCAEP thresholds were on average 24 dB closer to behavioural PT thresholds than ASSR thresholds. The mean standard deviation for the difference between SCAEP thresholds and behavioural PT thresholds, was marginally better than the mean standard deviation for ASSR difference scores. Robust correlations were measured for the participant group with hearing loss between behavioural PT thresholds and both SCAEP (r = 0.85) and ASSR (r = 0.81) thresholds. The same was true of the combined participant groups (SCAEP r = 0.85; ASSR r = 0.75). Comparatively, stronger mean correlations were evident between behavioural PT thresholds and SCAEP thresholds, than between behavioural PT thresholds and ASSR thresholds. The SCAEP, therefore, provides a more accurate and more predictable estimate of behavioural PT thresholds than the ASSR technique does. The more consistent relationship between SCAEP and behavioural PT thresholds provides greater confidence ofestimation of behavioural PT thresholds in adults exposed to occupational noise.

6.2.2 Clinical efficiency: Time required for SCAEP and ASSR threshold acquisition

For each participant group, the mean time taken to acquire the SCAEP thresholds was greater than was necessary for ASSR thresholds. With both participants with normal hearing and hearing loss combined, SCAEP threshold acquisition took on average 10.1 min longer per person. When considering that the ASSR makes use of objective response detection, and that the SCAEP threshold acquisition time reported here does not include the time required in order to identify SCAEP responses, the ASSR demonstrates a clear advantage in terms of speed.

6.3 CLINICAL IMPLICATIONS

More so now than ever before, the South African Department of Health demands efficacy in research by documenting the effectiveness of diagnostic procedures in controlled clinical experiments (South African Department of Health, 2007). The current study has provided quantitative data to support the recommendation of the use of either SCAEP or ASSR techniques. The findings challenge the existing perception in South Africa that

ASSR is the method of choice for all purposes across a variety of populations. The greater accuracy of the SCAEP for the purpose of behavioural PT threshold estimation in adults with either normal hearing or with a predominantly sloping high frequency hearing loss due to occupational noise exposure, is important for the generation of recommendations for the population in question.

ASSR threshold acquisition and detection is, however, quicker than SCAEP threshold acquisition alone. Therefore, the importance of accuracy versus speed of AEP threshold acquisition must be deliberated within the changing South African health care system, and must be consistent with the priorities highlighted in the Policy of Quality in Health Care for South Africa (South African Department of Health, 2007). Noise induced hearing loss is a major occupational health risk in South Africa (Zinsser, 2004). The prevalence of compensable noise induced hearing loss is higher in the mining industry than in most other industries (Franz & Phillips, 2001). While noise induced hearing loss constitutes 12 to 14% of all occupational injury claims in the mining industry, it accounts for 40% of the amount of compensation awarded (Franz & Phillips, 2001). Noise induced hearing loss is also the most common occupational disease outside the mining industry, with a prevalence of 56% (Franz & Phillips, 2001). Noise induced hearing loss therefore poses a risk to economic sustainability that South Africa, as a developing country, can ill afford. Reliable and valid audiometric results are vital in determining compensation for hearing disability. Without accurate identification of behavioural PT thresholds, there will be excessive or inadequate compensation for noise induced hearing loss claims (Rickards & De Vidi, 1995). Even small deviations from true thresholds can translate into a significant difference in financial outcome (Coles et al., 1991; Alberti et al., 1987). Identification of occupational noise induced hearing loss in a population of adults exposed to occupational noise, where the incidence of nonorganic hearing loss is high, is therefore a priority. Therefore, it is fair to place precedence on accuracy of the AEP tool choice for the purpose of behavioural PT threshold estimation, rather than on speed of threshold acquisition. The larger difference scores and greater variability in estimation of behavioural PT thresholds found for ASSR compared to SCAEP in the current study implies that the behavioural PT thresholds may be overestimated and exaggerators of behavioural PT thresholds may, therefore, not be identified. This would then result in a larger percentage loss of hearing (COIDA, 2001) and overcompensation for permanent disability. Given the high prevalence of occupational noise induced hearing loss, the amount of compensation paid is likely to have a greater financial impact on the developing South African economy than the ten minute longer test time required for SCAEP threshold acquisition.

It is important to note that the conclusion reached in the current study arose from the comparison of the SCAEP with a specific ASSR technique. A monotic, single frequency ASSR technique was used with a 40 Hz modulation rate to assess restful or sleeping adults, that presented with normal hearing, or that presented with a hearing loss and were exposed to occupational noise. The stimulus and recording variables, and the participant variables selected for the study played a significant role in determining the ability of the ASSR technique to estimate behavioural PT thresholds. The two defining factors that led to the conclusion drawn by the current study when considering the suitability of ASSR for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise, are the response recording duration and the typical degree of hearing loss of the target population.

The short response recording duration offered by the GSI (Grason-Stadler Incorporated) Audera ASSR system (maximum of 89 s; GSI, 2003) limits the potential accuracy of behavioural PT threshold estimation and increases amount of excessively noisy responses measured, especially when using a high modulation rate. The GSI Audera applies the Rance et al. (1995) regression formulae to the ASSR thresholds measured to compensate for the short response recording duration. When the GSI Audera corrected ASSR thresholds were taken into account, despite the improved proximity of GSI Audera ASSR estimates of behavioural PT thresholds to behavioural PT thresholds, SCAEP difference and standard deviation scores between SCAEP thresholds and behavioural PT thresholds remained smaller. The commercially available Biologic MASTER technique allows for continuation of response recording for up to 15 min or until a 10 nV noise level is reached (John et al., 1998), which is considerably longer than that allowed by the GSI Audera ASSR system. Studies that utilized ASSR systems with longer recording durations, reported mean ASSR thresholds (across all frequencies) that were 7 to 26 dB smaller than in the current study (Attias et al., 2006; Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Kaf, Durrant et al., 2006; Lins et al., 1996; Luts & Wouters, 2005; Perez-

Abalo et al., 2001; Picton et al., 1998; Schmulian et al., 2005; Swanepoel & Erasmus, 2007; Van der Reijden et al., 2006, using both 40 and 80 Hz modulation rate; Van Maanen & Stapells, 2005, using both 40 and 80 Hz modulation rate). The present study measured mean difference scores between SCAEP thresholds and behavioural PT thresholds, across frequencies, were 24 dB smaller that those between ASSR thresholds and behavioural PT thresholds. Therefore, had the SCAEP technique been compared to an ASSR system with a longer recording duration, as was done by Van Maanen and Stapells (2005), the proximity ASSR and SCAEP thresholds to behavioural PT thresholds may have been more comparable and a different conclusion may have been reached.

The manufacturer protocol of the GSI Audera ASSR system recommends making use of an 80 Hz ASSR protocol when testing sleeping adults (GSI, 2003). This was, however, found to be impractical in the current study, as ASSR thresholds could not be obtained in two of the three participants in the preliminary study, due to excessively high noise levels. When using the GSI Audera ASSR system, noise cannot be reduced by extension of response recording duration. A single recording can only be repeated in the event of high noise levels. The observation of frequent high noise levels with use of the 80 Hz ASSR modulation rate parallels those of Luts and Wouters (2005, using the GSI Audera ASSR system) and Van Maanen and Stapells (2005, using the Biologic MASTER ASSR system with a maximum of eight instead of 15 min recording duration as is typically reported). A longer recording duration facilitates the reduction of high noise levels often associated with the 80 Hz ASSR. The current research found that the short recording duration allowed by the GSI Audera ASSR system did not permit a sufficient reduction in noise levels when using the 80 Hz modulation rate in restful or sleeping adults. De Koker (2004) even reported requiring the use of a sedative for sleeping adult participants in order to reduce noise levels when using the GSI Audera with a high modulation rate. This is not always a clinically feasible option. The adaptive procedure for acquisition of ASSR thresholds using the GSI Audera system recommended by Luts and Wouters (2005) may be a better option. Luts and Wouters (2005) started by testing sleeping adults with an 80 Hz ASSR protocol and switched to a 40 Hz modulation rate in the event of excessive noise levels. Changing between modulation rate as these authors did may, however, not be warranted when considering that the difference scores between ASSR threshold and behavioural PT thresholds, and the standard deviations reported by Luts and Wouters

(2005) using an adaptive approach to determining modulation rate, were comparable to those calculated by the present study, which used a fixed 40 Hz modulation rate.

In addition to the excessive noise levels measured with the 80 Hz ASSR, the length of the assessment session in the current study naturally promoted sleep after completion of the SCAEP, during which participants were required to be awake (Hyde, 1997). Dobie and Wilson (1998) reported that ASSR at low intensities are best recorded in either the awake or sleeping state using a low rather than a high modulation rate. Despite this, previous research, with the exception of the study by Luts and Wouters (2005), recorded 40 Hz ASSR with participants awake and 80 Hz ASSR while participants slept. Research that made use of the 40 Hz protocol of the GSI Audera ASSR system while participants were alert reported mean ASSR thresholds which were closer to behavioural PT thresholds than those of the current study (Tomlin et al., 2006; Yeung & Wong, 2007). This suggests that the use of a 40 Hz modulation rate while recording ASSR for sleeping adults may have a negative effect on proximity of ASSR thresholds to behavioural PT thresholds. Notably, the effect of state of consciousness has not been re-examined in commercially available ASSR systems in recent literature. The author postulates that the recording duration may have a greater effect on ASSR threshold intensity than state of consciousness.

The second critical factor affecting accuracy of behavioural PT threshold estimation using the ASSR technique is degree of hearing loss. The typical adult population exposed to occupational noise will include both individuals with normal hearing and individuals with hearing loss, the latter of which will typically exhibit normal hearing at 0.5 and 1 kHz, with a mild hearing loss at 2 kHz and a moderate hearing loss at 4 kHz (mean behavioural PT threshold of 4 kHz in current study = 47 dB). A recent study by Swanepoel and Erasmus (2007) drew attention to the poor correlation between ASSR threshold and behavioural PT thresholds of less than 55 dB. The results by Swanepoel and Erasmus (2007) found support from Scherf et al. (2006), who reported considerable variation of estimations of behavioural PT thresholds for individual frequencies when the average ASSR thresholds across 0.5, 1, 2 and 4 kHz were equal to or less than 40 dB. Therefore, for the particular population targeted in the current study, and because of the degree of hearing loss the population often presents with, ASSR may be a poor choice of AEP. In contrast, the SCAEP difference scores were not negatively affected by normal or mildly elevated behavioural PT thresholds. SCAEP thresholds fell within 0.5 to 6 dB of behavioural PT thresholds at 0.5 to 2 kHz for the group with hearing loss, where the mean behavioural PT thresholds fell within normal limits, or represented a mild degree of hearing loss. The SCAEP is, therefore, a better choice of AEP than the GSI Audera 40 Hz ASSR with restful or sleeping participants for the purpose of estimating behavioural PT thresholds in adults with normal hearing, and in adults with hearing loss who were exposed to occupational noise.

The general trend in healthcare towards improved quality of service delivery and health technology is opposed by several forces (Massoud et al., 2001). Foremost, particularly in developed countries, has been what Deyo (2002) calls a '*technological imperative*' comprising a fascination with technology, the expectation that new is better, and the inclination to use a technology that has potential for some benefit, however marginal or even poorly substantiated. The same trend was evident over the past decade in South Africa. The ASSR technique was rapidly adopted into clinical practice, especially for the purpose of identification of hearing loss in neonates and children (Stapells, Herdman, Small, Dimitrijevic, & Hatton, 2005; Stroebel et al., 2007; Swanepoel & Steyn, 2005). At times, presumably due to the ease of use as a consequence of the objective response detection, the ASSR has found favour in South Africa at the expense of more established AEP methods, for example the auditory brainstem response (ABR). The rapid acceptance of the new technique into clinical use was in contrast to the lack hereof for the SCAEP technique. The current research challenged the existing perception in South Africa that the ASSR is the method of choice for unrestricted use, for a variety of purposes and across different populations.

The heightened focus on quality in heath care internationally is driven by the increasing complexity of health care delivery, the emerging need for efficient and cost-effective care, the increased expectation of customers, and the advances in knowledge of clinical practices (Massoud et al., 2001). The Policy on Quality in Health Care for South Africa (South African Department of Health, 2007) credits the same factors for its creation, and includes the expansion of research on evidence of effectiveness as one of the aims. The policy lists inadequate diagnosis and the underuse of services (and by extension, technology) as two of the shortcomings of the South African health care system (South

African Department of Health, 2007). The SCAEP technique has been extensively researched and used in clinical practice (especially in Australia, Canada and the United Kingdom), specifically with adults claiming compensation of occupational noise induced hearing loss (Hyde, 1997). Several authors named the SCAEP as the AEP of choice for use in behavioural PT threshold estimation for adults exposed to occupational noise, and in whom a nonorganic hearing loss is suspected (Alberti et al., 1987; Coles & Mason, 1984; Hone et al., 2003; Hyde, 1997; Hyde et al., 1986; Rickards & De Vidi, 1995; Stapells, 2002; Tsui et al., 2002). Despite this, the SCAEP is not used in South Africa.

One may speculate that the disinterest in the SCAEP is a consequence of the cost of the SCAEP system. Interest in cost analyses has accompanied concerns about rising health care costs, putting pressure on health care policymakers to allocate resources, and requiring health product manufacturers and health care professionals to demonstrate the economic benefits of their technologies (Goodman, 2004). Several references in the current research have been made to the GSI Audera ASSR and Biologic MASTER ASSR systems, as these ASSR systems are the most widely used systems in South Africa. GSI and Biologic offer equipment with AEP platforms which include both the ASSR and SCAEP techniques. Therefore, the SCAEP technique is not utilized regardless of the availability of the SCAEP equipment in South Africa, at a similar cost to that of the ASSR system. The lack of clinicians experienced in the interpretation of the SCAEP waveforms may therefore be the underlying reason for the underuse of the SCAEP technique in South Africa. The objective response detection offered by the ASSR may well have facilitated the proliferation of the clinical use of the ASSR technique in South Africa. The subjective response detection of the SCAEP (although not necessarily disadvantageous in terms of accuracy of threshold response detection according to Kaf, Durrant et al., 2006, and Yeung & Wong, 2007) and the need for clinicians experienced in the detection of threshold SCAEP responses, appear to be factors that have limited the clinical use of the SCAEP in South Africa. The recommendation of the current research that SCAEP be used for the purpose of objective behavioural PT threshold estimation in adults that are exposed to occupational noise (either with normal hearing or with hearing loss), may provide an incentive for clinicians in South Africa to (re)consider routine clinical use of the technique.

6.4 CRITICAL EVALUATION OF THE STRENGTHS OF THE STUDY

- The SCAEP and ASSR were compared to the gold standard in terms of audiological assessment measures, namely behavioural PT audiometry. From a research point of view, behavioural PT thresholds are considered both reliable, being capable of providing a consistent measure of a patient's behavioural PT hearing thresholds, and valid, as it is an accurate measure of hearing (Cope, 1995; Goldstein & Aldrich, 1999; Martin, 2002).
- The accuracy of behavioural PT thresholds was ensured by applying the cross-check principle (Jerger & Hayes, 1976). Accuracy of behavioural PT thresholds was confirmed by determining the speech reception threshold, and comparing this to the average behavioural PT threshold at 0.5, 1 and 2 kHz. In addition, behavioural PT audiometry was performed on the day of SCAEP and ASSR assessment to eliminate any variables that may have contaminated the data had behavioural PT audiometry and AEP assessment been performed on different days.
- Use of a single AEP system, namely the GSI Audera, to measure both SCAEP and ASSR thresholds eliminates extraneous variables (e.g. calibration differences) that may potentially have contaminated the data had two separate AEP systems be used.
- The comparison of behavioural PT, toneburst and AM/FM (amplitude and frequency modulated) stimuli, and the subsequent correction of the SCAEP and ASSR thresholds obtained using the toneburst and AM/FM stimuli respectively, ensured that calibration methods did not provide continuous stimuli with an advantage over transient stimuli based purely on the nature of the stimulus, due to the effects of temporal integration (Lightfoot et al., 2002; Martin, 1981). In so doing, a valid comparison of SCAEP thresholds and ASSR thresholds could be realized, in addition to the comparison with behavioural PT thresholds.
- A similar choice of research approach and key statistical calculations was made in the present study to that of the majority of previous research projects that evaluated the ability of SCAEP and ASSR to estimate behavioural PT thresholds. This facilitated comparisons between the quantitative data of the current study with the data of existing literature.

6.5 CRITICAL EVALUATION OF THE LIMITATIONS OF THE STUDY

- It is acknowledged that test-retest reliability of the SCAEP and ASSR techniques may potentially have affected reliability of the data reported in the study. Exploration hereof was, however, beyond the scope of the current research project.
- Generalization of the findings of the study to the target population were facilitated by choosing participants who were representative of the typical adult population for which threshold estimation using AEP would be necessary, and by making use of the standard manufacturer recommended stimulus and recording parameters for SCAEP and ASSR threshold determination, as would typically be used in a clinical environment. Despite this, the relatively small number of participants selected for the study (viz. 31) does limit generalization to an extent.
- Researcher / clinician bias may have affected the judgements made during SCAEP testing, as the group to which the participant belonged (group of participants with either normal hearing or hearing loss) was known.
- Accuracy of ASSR estimation of behavioural PT thresholds is strongly influenced by stimulus, recording and participant variables. Although the same may be argued for the SCAEP technique, this is true to a less extent. Certain variables at play, such as the reliability and validity of the statistical method used by the GSI Audera to detect threshold ASSR responses, were beyond the scope of the study. The conclusions reached in the current study are valid, and limited to, the comparison of the SCAEP technique with the specific ASSR protocol selected in the current study, namely a monotic, single frequency ASSR technique, with a 40 Hz modulation rate, which was used to assess restful or sleeping adults that presented with normal hearing, and that presented with a hearing loss who were exposed to occupational noise.

6.6 RESEARCH IMPLICATIONS

The current research endeavour has brought to light the need for further research in certain areas.

- Van Maanen and Stapells (2005) and Van der Reijden et al. (2006) found multiple frequency ASSR thresholds closer to behavioural PT thresholds with a low than with a high modulation rate within the Biologic MASTER ASSR system. The author is not aware of research that compared high and low modulation rate using a single frequency ASSR technique since that of Dobie and Wilson (1998) over a decade ago. A comparison of findings between studies using a single frequency ASSR technique, reveals variable results (Hsu et al., 2003; Rance et al., 1995; Tomlin et al., 2006; Yeung & Wong, 2007). Further research on this topic is, therefore, warranted.
- In a population of adults who are referred for objective assessment due to (typically) wilful exaggeration of behavioural PT thresholds, who are liable to be rather anxious about the outcome of the assessment, high noise levels are likely to measured. As was the case in the preliminary study of the current research endeavour, Luts and Wouters (2005) and Van Maanen and Stapells (2005) reported frequently measuring excessively high noise levels during 80 Hz ASSR recording. By prolonging the response duration and making use of a lower noise criterion, these noise levels can be reduced, albeit at the expense of time efficiency. This is a feature offered by the Biologic MASTER ASSR software (John et al., 1998), although it is not specific to the dichotic multiple ASSR technique. The application of this feature in commercially available single frequency ASSR systems (such as the GSI Audera ASSR system) would be a significant addition. The GSI Audera ASSR system does apply the Rance et al. (1995) regression formulae to improve estimations of behavioural PT thresholds from the ASSR thresholds generated (GSI, 2003). Despite the decrease in the ASSR threshold intensity when these regression formulae are used, however, SCAEP thresholds in the current study remained closer to the behavioural PT thresholds. The Rance et al. (1995) regression formulae also increased the variability (standard deviations) of the estimates of behavioural PT thresholds. A longer recording duration would also reduce the number of participants that can not be assessed using a high modulation ASSR protocol. This feature would then enable more controlled comparisons between monotic single and dichotic multiple frequency ASSR techniques, without the considerable advantage of the prolonged response duration in only one of the two methods being compared.
- The current study noted, as did Dimitrijevic et al. (2002), that sleep reduces noise levels frequently associated with 80 Hz ASSR recordings (Luts & Wouters, 2005;

Pethe et al., 2004). Dobie and Wilson (1998) reported that ASSR at low intensities were best recorded in either the awake or sleeping state, using a low rather than a high modulation rate. This statement is refuted by Jerger et al. (1986). As far as the author is aware a comparison of the effect of different states of consciousness on 40 Hz ASSR thresholds within a single commercially available ASSR system has not been completed in over a decade, since the research by Cohen et al. (1991), Dobie and Wilson (1998), Levi et al. (1993), Linden et al. (1985). Further research is required to resolve the conflicting reports in literature, and to confirm whether a sleeping state of consciousness results in the elevation of ASSR threshold intensities.

6.7 FINAL COMMENTS

The SCAEP technique is clinically more effective (accurate) than the single stimulus 40 Hz ASSR technique for the purpose of behavioural PT threshold estimation in adults exposed to occupational noise. The improved accuracy is at the expense of clinical efficiency as the ASSR technique is able to provide estimates of behavioural PT thresholds in less time. In addition, an experienced clinician is required to identify threshold SCAEP responses. This is an element not required by the ASSR due to the objective response detection offered by the technique. Clinical effectiveness was given comparably more weight than the clinical efficiency of the AEP technique to estimate behavioural PT thresholds. As such, the study acknowledged the SCAEP as the AEP of choice for the purpose of behavioural PT thresholds in adults exposed to occupational noise.

The conclusion reached in the current study arose from the comparison of the SCAEP with a specific ASSR technique. Accuracy of ASSR estimation of behavioural PT thresholds is strongly influenced by stimulus, recording and participant variables. A monotic, single frequency ASSR technique was used with a 40 Hz modulation rate to assess restful or sleeping adults that presented with normal hearing, or that presented with a hearing loss who were exposed to occupational noise. The stimulus and recording variables, and the participant variables selected for the study played a significant role in determining the ability of the ASSR technique to estimate behavioural PT thresholds. The current research and existing literature did not demonstrate a clear recommendation regarding the optimal stimulus presentation method (i.e. single or multiple frequency), modulation rate or the optimal state of consciousness. The two defining factors that led to the conclusion drawn by the current study are the response recording duration and the typical degree of hearing loss of the target population. The conclusions reached in the current study are valid within a comparison of the SCAEP technique with the specific ASSR protocol selected in the current study.

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APPENDIX A

PARTICIPANT INFORMATION FORM

[university of Pretoria letterhead and address]
Leigh Biagio, Researcher
P.O. Box 1588, Faerie Glen, Pretoria, 0043
Tel. & Fa.x.: (012) 996 0418

Dear Sir,

Re. *Information Form Regarding Participation in the Research Project*

Thank you for considering participating in this research project. The project is entitled 'Slow Cortical Auditory Evoked Potentials and Auditory Steady-State Evoked Responses in Adults Exposed to Occupational Noise'. The study is being completed in fulfilment of the requirements of the Masters in Communication Pathology.

Background Information

The main aim of this study is to compare the accuracy of, and time taken to perform two objective tests of hearing. These tests of hearing are referred to as 'objective tests' as they require no co-operation from the participant, other than to remain alert through one and relaxed for the duration of the other. Objective tests of hearing are required when a client cannot or will not co-operate for the normal behavioural hearing assessment. An objective test of hearing is useful in order to determine the client's true thresholds of hearing.

Rationale for the research project

The reason it has become necessary to compare the performance of these two tests is because there is now a newer objective test of hearing, called auditory steady-state evoked responses or ASSR, which is potentially more accurate and faster than the objective test that has been used in the past for persons with a hearing loss caused by noise exposure. The objective test normally used for this population is called slow cortical auditory evoked potentials or SCAEP.

Who would participate in this study?

Participation in this study is completely voluntary, and participation can be withdrawn at any point. Certain of the participants in this study must be individuals exposed to noise in their place of work. In order to determine the accuracy of the objective tests, the participants must be people who co-operate well and respond consistently during behavioural assessment. Participants must also be able to understand English or Afrikaans so that they can follow the instructions given during the assessment.

What would participation involve?

Participation in this study involves a single assessment session lasting approximately two and a half hours. The session will involve a quick test to ensure the middle ear is healthy, an assessment of hearing using the two objective tests as well as the traditional behavioural hearing assessment. The behavioural assessment involves placing earphones on the participant, who will be asked to respond by pressing a button to indicate whenever a pure tone or beep is heard. The objective tests will be performed by putting four electrodes on the participant's forehead and ear lobes. Soft sponge earphones will be put in each ear canal, through which sounds of different volumes will be presented. The participant will be asked to remain still but alert during the SCAEP, and will be encouraged to relax, or even sleep, during the ASSR. It will also be necessary to ask each participant their age, length of exposure to occupational noise, whether or not they have a history of neurological problems, and what medication they make use of.

Confidentiality and anonymity

The assessment will take place at a private audiology practice in Pretoria. Only the participant and the researcher will be present during the assessment. Once the assessment is completed, the results of the SCAEP will be shown to another audiologist who will assist in interpretation thereof. The results of the assessment will be completely confidential and will not be given to the employer or any other party. Anonymity of the participant is ensured by referring to each participant using letters participants, namely participant A, B, C, etc. The participant's name will not be used in any form. The results of the assessment will be presented verbally to each participant directly after completion of the assessment. The health and safety department of Pretoria Porcelain and Cement will also receive a written report of the findings for each of their employees that take part in the research project.

Why should I participate in the research project?

There is no direct benefit to the participant in the research project, but the results will give audiologists information on the comparative accuracy and time taken to complete the two objective tests of hearing. This is one of the first studies that compare these two objective tests in a clinical setting. The results will guide audiologists in choosing the most accurate and quickest objective method of hearing assessment to be used at clinics.

There is no risk involved in the assessment and no discomfort on the part of the participant. Due to the length of the assessment session, fatigue may result. However, as mentioned previously, during part of the assessment, the participant is encouraged to relax or sleep.

The participant is entitled to contact me at any point in the event of any further queries regarding the research project. The participant will also have access to the results of the study on request from the researcher. An article summarizing the study will also be published in an audiological journal.

Please feel free to contact me on (021) 552 4943 if you need to clarify any of the above information. I would be most grateful if you would agree to participate in this research project.

With thanks and kind regards

Leigh Biagio: Researcher / Audiologist

APPENDIX B

PARTICIPANT CONSENT FORM

[university of Pretoria letterhead and address]
Leigh Biagio, Researcher
P.O. Box 1588, Faerie Glen, Pretoria, 0043
Tel. & Fa.x.: (012) 996 0418

Date: ____________________

Consent Form Regarding Participation in the Research Project

I, ____, hereby consent to participate in the research project entitled 'Slow Cortical Auditory Evoked Potentials and Auditory Steady-State Evoked Responses in Adults Exposed to Occupational Noise', undertaken by Leigh Biagio in fulfilment of the requirements of the Masters in Communication Pathology. I have read and understood the information form detailing the aims and assessment procedure of the research project. I have been given the opportunity to ask the researcher questions in order to obtain clarification of any aspect of the study. I understand that involvement in the research project is voluntary and that I may withdraw from participation in the study at any point without any negative consequences.

____________________________	____________________________
Participant	Date
____________________________	
Researcher	
____________________________	____________________________
Supervisor	Place of signing

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APPENDIX C

LETTER OF ETHICAL CLEARANCE FROM RESEARCH ETHICS COMMITTEE

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UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Our Ref: Ms P Woest / 9425683
Tel: 012420 2736
Fax: 012420 2698
E-mail: petru.woest@up.ac.za

18 November 2003

Ms L Biagio
2 Mika Street
Welgelegen
CAPE TOWN
7530

Dear Ms Biagio

TITLE: MASTERS' DISSERTATION: M COMMUNICATION PATHOLOGY

I have pleasure in informing you that the following has been approved:

Title of dissertation/essay: Threshold prediction using Slow Cortical Evoked Potentials and Auditory Steady State Evoked Potentials in individuals at risk of noise induced hearing loss

Director of studies: Dr D Schmulian

Co-director of studies: Dr M Soer

I would like to draw your attention to the following:

1. **ENROLMENT**
   (i) You must be enrolled as a student for at least one academic year before submission of your dissertation/essay.
   (ii) Your enrolment as a student must be renewed annually before 31 March, until you have complied with all the requirements for the degree.

2. **APPROVAL FOR SUBMISSION AND ENROLMENT FOR THE EXAMINATION**

On completion of your dissertation/essay enough copies for each examiner as well as the prescribed examination enrolment form which includes a statement by your director of studies that he/she approves of the submission of your dissertation/essay, as well as a statement, signed by you in the presence of a Commissioner of Oaths, must be submitted to the Faculty Administration.

3. **NUMBER OF COPIES OF DISSERTATION/ESSAY REQUIRED**

Apart from the examination copies, two additional copies are required. One of the additional copies must be an A4-unbound copy and suitable for microfilming. The two additional copies must be submitted at least one month before the graduation ceremony, failing which the degree cannot be conferred at the ceremony concerned. These copies may also be submitted together with the examination copies. An amount of R50 is payable on submission of the dissertation/essay for microfilming purposes.

4. **INSTRUCTIONS REGARDING THE PREPARATION OF THE DISSERTATION/ESSAY AND THE SUMMARY APPEARS ON THE REVERSE SIDE OF THIS LETTER.**

Yours sincerely

for **DEAN: FACULTY OF HUMANITIES**

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

APPENDIX D

PARTICIPANT QUESTIONNAIRE

1. Name:____

2. Date of birth: ____

3. Address: ____

____

4. Contact telephone number: (H)____________________(W)_____________________

5. Home language: ____

6.1 Which language would you prefer the audiologist to use during the assessment? Please circle the appropriate answer:

English / Afrikaans

6.2 How would you describe your command of the language chosen above (i.e. either English or Afrikaans)? Please circle to appropriate answer.

Poor / Fair / Good

7. How long have you worked in a noisy environment? _________years _______months

8. Have you been exposed to occupational noise in the past 24 hours? Please circle the appropriate answer:

Yes / No

9.1 Do you suffer from any serious or chronic illness(es)? Please circle the appropriate answer:

Yes / No

9.2 If you answered yes, please name the illness. ______________________________

____

10.1 Do you suffer from any neurological illness(es)? Please circle the appropriate answer:

Yes / No

10.2 If you answered yes, please name the illness.______________________________

____

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11.1 Are you taking any medication at present? Please circle the appropriate answer:

Yes / No

11.2 If you answered yes, please list the medications. ______________________________

____

12. Have you ever had any head injuries? Please circle the appropriate answer:

Yes / No

13.1 Are you concerned that you may have a hearing loss? Please circle the appropriate answer:

Yes / No

13.2 If you answered yes, how long have you been aware of the deterioration in your hearing?

____

14.1 Is there a family history of hearing loss? Please circle the appropriate answer:

Yes / No

14.2 If you answered yes, describe your relationship to this person. __________________

____

15.1 Have you ever suffered from ear infections? Please circle the appropriate answer:

Yes / No

15.2 If you answered yes, when did you last have an ear infection? ___________________

____

16.1 Have you ever had any operations on your ears? Please circle the appropriate answer:

Yes / No

16.2 If you answered yes, when was the operation and on which ear? ________________

____

17.1 Do you experience any dizziness or balance problems? Please circle the appropriate answer:

Yes / No

17.2 If you answered yes, how often do you experience the dizziness or unbalance? ____

____

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APPENDIX E

DATA COLLECTION SHEET

Name: ________________________________ Date: _____________________________

	500Hz	1000Hz	2000Hz	4000Hz	Start time	Finish	State of Consciousness
Behavioural tone burst threshold (dBnHL)	R	R	R	R			
	L	L	L	L			
Behavioural AM/FM threshold (dBHL)	R	R	R	R			
	L	L	L	L			

Name: ________________________________ Date: _____________________________

	500Hz	1000Hz	2000Hz	4000Hz	Start time	Finish	State of Consciousness
Behavioural tone burst threshold (dBnHL)	R	R	R	R			
	L	L	L	L			
Behavioural AM/FM threshold (dBHL)	R	R	R	R			
	L	L	L	L			

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APPENDIX F

EXAMPLE OF IDENTIFICATION OF THRESHOLD SCAEP WAVEFORMS

Examiner: [redacted] Cortical AEP Report [redacted]
Site: [redacted] Inc. Pretoria Examined: 23/06/2004 14:00

Chart 3: 500Hz Averaged L -- Waveform details

T19 Add [5] [4]	Left	0.0 dB nHL	Not used		

Trace	Rep Rate	Sweeps	Rejected	HP filter	LP filter
T16 Add [1] [2]					
T17 Add [6] [3]					
T18 Add [3] [7]					
T19 Add [5] [4]					

Trace	Test set
T16 Add [1] [2]	
T17 Add [6] [3]	
T18 Add [3] [7]	
T19 Add [5] [4]	

Chart 2: 500Hz R -- Waveforms

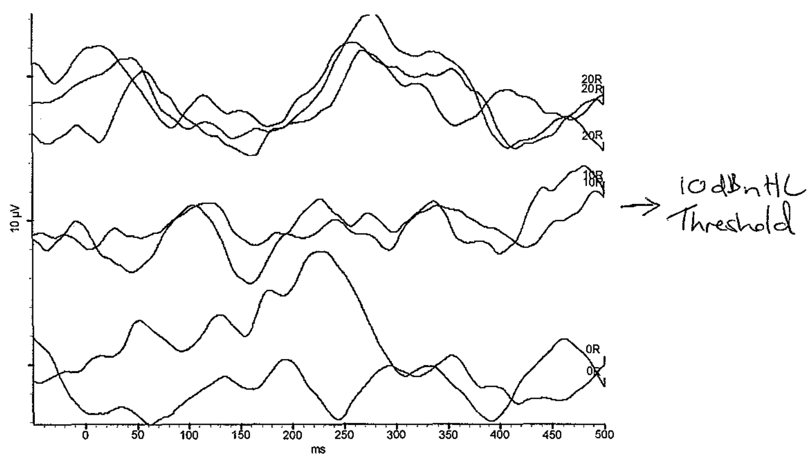

Chart 2: 500Hz R -- Measurements

This measurement table has not been printed because it is blank.

Chart 2: 500Hz R -- Waveform details

Trace	Ear	Stim Level	Mask Level	Stim Type	Stim Pol.
T10 20.0 dB nHL R 0.70 Hz [10]	Right	20.0 dB nHL	Not used	500 Hz Blackman TB 5-40-5 cycles	Alternating
T15 20.0 dB nHL R 0.70 Hz [15]	Right	20.0 dB nHL	Not used	500 Hz Blackman TB 5-40-5 cycles	Alternating
T9 20.0 dB nHL R 0.70 Hz [9]	Right	20.0 dB nHL	Not used	500 Hz Blackman TB 5-40-5 cycles	Alternating
T11 10.0 dB nHL R 0.70 Hz [11]	Right	10.0 dB nHL	Not used	500 Hz Blackman TB 5-40-5 cycles	Alternating
T12 10.0 dB nHL R 0.70 Hz [12]	Right	10.0 dB nHL	Not used	500 Hz Blackman TB 5-40-5 cycles	Alternating

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