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THE AUDITORY STEADY-STATE RESPONSE: A WEB BASED TUTORIAL

by
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THESIS APPROVAL PAGE

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ABSTRACT

The Auditory Steady-State Response: A Web Based Tutorial

Trisha A. Bents

A comprehensive literature review of the Auditory Steady-State Response (ASSR) was performed and an informational website designed for doctor of Audiology (Au.D.) students, recent Au.D. graduates, and audiologists unfamiliar with the current recommended evidence-based ASSR testing protocol was also developed. The ASSR is a unique auditory evoked potential (AEP) that encompasses unique terminology. Topics reported in this literature review include the history of the ASSR and its initial limitations, its neural generators, terminology specific to the ASSR, unique stimuli (sinusoidally amplitude modulated (AM), frequency modulated (FM), mixed modulated (MM), and repeating sequence tones (RSG)), single frequency (SF) and multiple frequency (MF) stimulation techniques, methods for analyzing the ASSR (Phase Coherence and Fast Fourier Transform with F-ratio), recommended recording parameters, the accuracy of behavioral threshold prediction, calibration considerations, and the clinical application of the ASSR. The website is an easily accessible central resource for current evidence-based practices in ASSR testing.

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CHAPTER 1

INTRODUCTION

The Auditory Steady-State Response (ASSR) is an auditory evoked potential that is becoming a more accepted method to assess hearing sensitivity in difficult to test populations. While behavioral testing remains the gold standard in clinical practice, it requires a subjective response from test subject that is not always possible in populations that are difficult to test. Provided that the ASSR eliminates the need for test subjects to subjectively respond, there is immense potential for the clinical application of the ASSR for those populations that cannot reliably respond during behavioral testing.

The "40 Hz Response" was initially coined by Galambos, Makeig, and Talmachoff (1981) as this Event Related Potential (ERP) repeated itself at a stimulus repetition rate of 40 cycles per second. Numerous research studies have followed Galambos et al.'s (1981) initial research (i.e. Aoyagi et al., 1993; Cohen, Rickards, & Clark, 1991; Rickards et al., 1994; Stapells, Galambos, Costello, & Makeig, 1988; Stapells, Liden, Suffield, Hamel, & Picton, 1984; Suzuki & Kobaysi, 1984) which has identified and discussed the initial limitations of the 40 Hz response. Through this research, recommended testing parameters have been developed in order to adequately manage the initial limitations. The remainder of this paper contains a thorough literature review on the following ASSR topics: the history of the Auditory Evoked Potential (AEP), its underlying neural generators, specific terminology associated with the ASSR, stimuli utilized, stimulation techniques, response analysis techniques, technical recording parameters, subject variables, frequency and place specificity, threshold estimation including the accuracy of air conduction ASSR testing in predicting behavioral thresholds for adults with normal hearing sensitivity and sensorineural hearing loss, the accuracy of bone conduction ASSR testing for predicting behavioral thresholds in both adults and children, various clinical applications including its utilization for cochlear implant and hearing aid technologies, stimuli calibration, and areas of future research. A comprehensive literature review of the ASSR was performed and an informational website designed for Doctor of Audiology (Au.D.) students, recent Au.D. graduates, and audiologists unfamiliar with the current recommended evidence-based ASSR testing protocol was also developed. This website includes detailed information on the various topics listed above, animated figures, stimuli sound clips, printer friendly clinical reference sheets, and a self-test to assess understanding of the ASSR.

CHAPTER 2

LITERATURE REVIEW

Auditory Evoked Potentials (AEPs)

Auditory evoked potentials (AEPs) are brain responses elicited by the presentation of some type of auditory stimulus, such as a click, a tone burst, or a speech stimulus (Stapells, 2009). However, AEPs often reflect more than just activity related to the auditory stimuli thus, the term Auditory Event-Related Potentials (AERPs). AERPs can be recorded to the presentation of a single sensory stimulus, such as a 1000 Hz tone burst. Or can be elicited in an oddball paradigm, where one stimulus (e.g., a 1000 Hz tone burst) acts as the frequent or standard stimulus and the second stimulus (e.g., a 2000 Hz tone burst) acts as the deviant or infrequent stimulus. The listener's task is to identify the odd or deviant stimuli in the sequence of sounds. All types of AEPs are time locked to the presentation of the auditory stimulus. Auditory evoked potentials are recorded from humans using surface electrodes located at various regions on the scalp.

Picton (1990) proposed four different ways to classify AEPs. These four classification schemes are related to: (a) the latency or timing of the evoked potential, (b) the temporal relationship of the evoked potential to the stimulus, (c) the underlying neural generator sites for the various potentials, and (d) whether the potential is classified as a sensory potential or a processing-contingent potential (Picton, 1990; Stapells, 2009). These classification schemes will be briefly described in the next section of the literature review.

Classification System

The most commonly observed classification scheme is based upon the latency of the AEP (Picton, 1990). The latency of the response is related to when in time, usually measured in milliseconds (ms), the response occurs following the presentation of the stimulus. This classification scheme divides AEPs into the following broad classifications: first, fast, middle, slow, or late responses (Picton, 1990). First responses occur between 0 to 5 ms following the onset of the auditory stimulus. First responses include the eighth nerve compound action potential (CAP), the cochlear microphonic (CM), waves I and II of the auditory brainstem response (ABR) and the summating potential (SP). Fast responses are slightly later in time; they occur between 2 to 20 ms post-stimulus onset. Fast responses include waves III, IV, and V of the ABR. Middle latency responses (MLRs) follow the fast responses and occur between 10 to 100 ms following the onset of the stimulus. The primary components of the MLR include waves Na, Pa, and Nb. Next in the hierarchy are the slow cortical responses which are elicited between 50 and 300 ms post stimulus onset. Slow responses include waves P1, N1, P2, and N2. The final AEPs are classified as late cortical potentials and these occur between 150 and 1000 ms post-stimulus onset. These responses include the mismatch negativity (MMN), the later cortical potentials (waves N2b and P3b), and the potential contingent negative variation (CNV) (Picton, 1990).

The second classification scheme for AEPs is based upon the AEP’s temporal relationship to its stimulus. This scheme divides AEPs into 3 general categories: transient, sustained, and steady-state potentials. Transient evoked potentials are evoked at a stimulus rate slow enough so that the response to one stimulus has been completed prior to the presentation of the following stimulus (Picton, 1990). Thus, there is no overlap of the responses within the post-stimulus analysis window (Linden, Campbell, Hamel, & Picton, 1985). In contrast, sustained potentials are elicited throughout the duration of a continuous stimulus (Picton, 1990). Lastly, Auditory Steady-State Responses (ASSR) occur when stimuli are presented at a sufficiently high repetition rate, such that the response to one stimulus overlaps with the responses to the successive stimuli within the same post stimulus analysis window (Linden et al., 1985; Picton, 1990). ASSRs are the focus of the literature review and will be discussed in detail in the subsequent sections.

A third classification scheme describes AEPs as either sensory or processing-contingent potentials (Picton, 1990). Sensory potentials are dependent on the presentation of the stimulus. Sensory responses, also known as exogenous responses, are obligatory responses, meaning that they are dependent upon the physical characteristics of the stimulus. If the physical characteristics of the stimuli change (e.g., the stimuli intensity increases or the stimulus frequency decreases), than the response properties of the AEP will change accordingly. In contrast, processing-contingent potentials (PCPs), or endogenous potentials, are associated with the processing of the auditory stimuli beyond what is automatically driven by the physical properties of the auditory stimulus. Processing-contingent potentials require active, attention driven, perceptual or cognitive processes that occurs when there is a change in stimulus presentation (Picton, 1990).

Lastly, AEPs can further be classified according to their underlying neural site of generation (Picton, 1990). The neural generation sites are the anatomic regions in either the peripheral and/or central auditory nervous system (CANS) that are the primary contributors to the response. For example, first AEPs originate in the cochlea while fast responses come from the auditory brainstem region. The longer the latency of the response, the higher in the auditory system the generation site is located. That is why later evoked potentials, such as MLRs, slow AEPs, and late AEPs are primarily cortical responses (Picton, 1990).

The remainder of this literature review will now focus on the Auditory Steady-State Response (ASSR).

History of the ASSR

Galambos, Makeig, and Talmachoff (1981) first described the existence of auditory steady-state potentials in the AEP literature. In their experiment, Galambos and colleagues (1981) simultaneously recorded the ABR and MLR to a 500 Hz tonal stimulus in 20 adults with normal hearing sensitivity. This tonal stimulus was presented at stimulus rates ranging from 3.3 to 50 cycles per second (Hz) and stimulus intensities ranging from 5 to 50 dB SL re: behavioral thresholds. Galambos and colleagues (1981) discovered that when the stimulus repetition rate was increased to 40 Hz, there was an overlap of the ABR and MLR responses that occurred within the same post stimulus analysis window (see Figure 1A). This overlap pattern occurred every 25 ms and it resembled four sinusoids that repeated at intervals of 1-25 ms, 26-50 ms, 51-75 ms, and 76-100 ms, as depicted on the lower right side of Figure 1B. The response at 40-Hz consisted of wave V of the auditory brainstem response (ABR) and the successive components of the middle latency response (Na, Pa, and Nb) as depicted in Figure 1C. This repeating pattern was not seen at any of the lower stimulus rates as clearly identified in the left portion of Figure 1A. These investigators then plotted the amplitudes of the responses as a function of the various stimulus rates used in the study. This graph clearly demonstrated that the largest response amplitude for the adults' responses occurred at 40 Hz, as shown in the adult response labeled in Figure 2. Galambos and colleagues then coined the term "40 Hz response" to describe the unique characteristics of this response (Galambos et al., 1981).

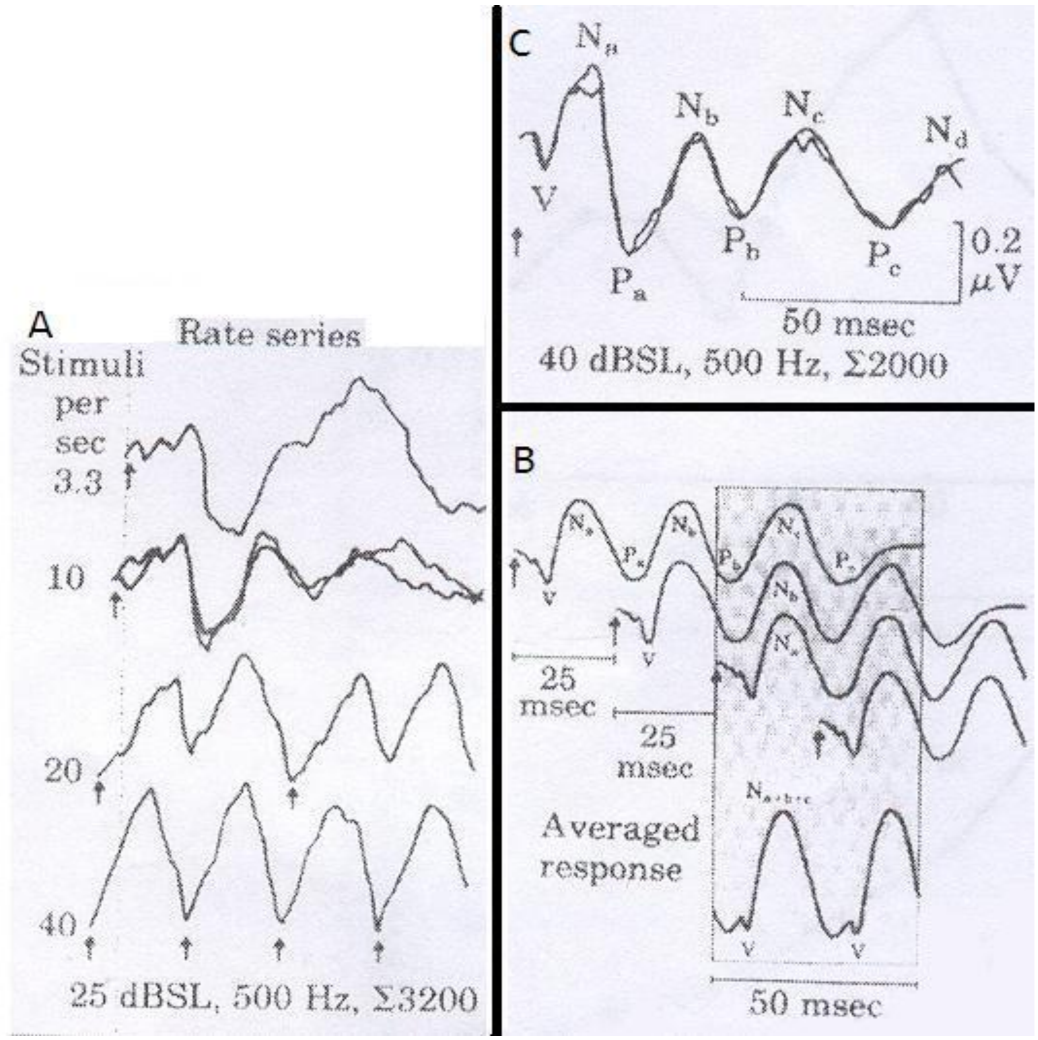


Figure 1. Panel A demonstrates the temporal waveforms of a series of stimulus rate trials. Stimulus repetition rates from 3.3 to 40 Hz are illustrated. The 40 Hz stimulus repetition rate is the only rate that shows a repeating pattern. Panel C shows the repeating pattern seen with a 40 Hz stimulus repetition rate is actually the components of wave V of the ABR followed by the successive components of the MLR. Each of these components repeats every 25 msec as depicted in panel B. Figure adapted from Galambos et al. (1981).

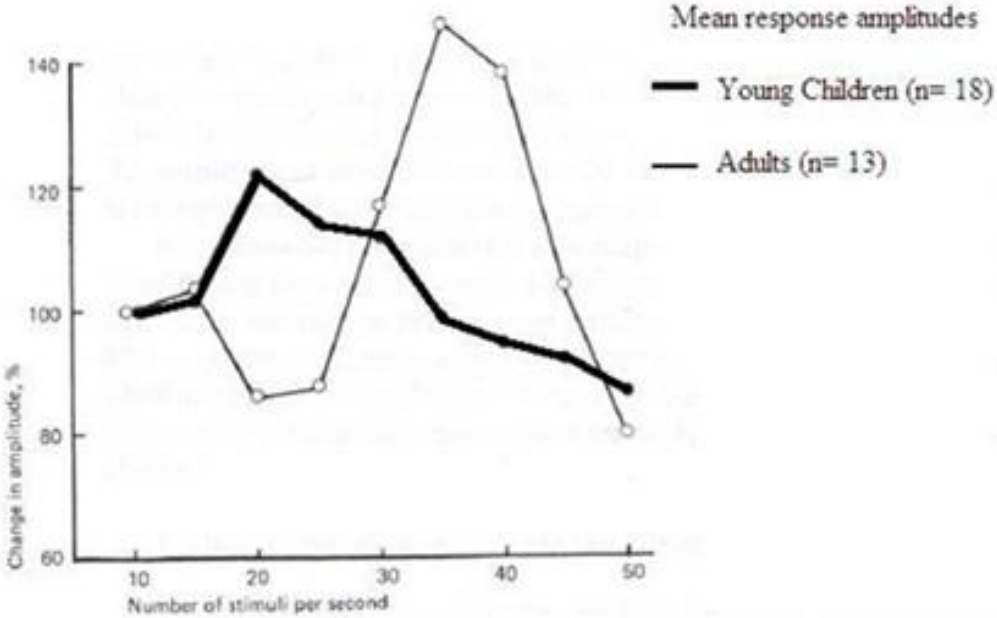


Figure 2. Mean response amplitudes for both adults (n=13) and young children (n=18) plotted as a function of stimulus repetition rate (Suzuki & Kobayashi, 1984).

Galambos and colleagues (1981) successfully recorded the 40-Hz response Event Related Potential (ERP) to both low and high frequency stimuli ranging from 250- 5000 Hz. These investigators reported that relatively large response amplitudes were recorded close to the adults' behavioral thresholds for all 20 subjects. Therefore, these investigators concluded that the 40-Hz Event Related Potential (ERP) was easily recordable in normal hearing adults and it could be used to accurately estimate their behavioral pure tone thresholds at 250-4000 Hz. Subsequent studies, however, identified two major limitations with the 40-Hz ERP which limited its clinical application for estimating behavioral thresholds. These limitations were: (1) that the 40-Hz response could not be reliably recorded in infants and young children (Suzuki and Kobayashi, 1984; Stapells, Galambos, Costello and Makeig, 1988) and (2) the 40- Hz response is strongly influenced by subject state (Linden, Campbell, Hamel, & Picton, 1985). Amplitudes of the response vary greatly from a waking to sleeping state in both adults (Cohen, Rickards, & Clark, 1991) and in infants and young children (Rickard, Tan, Cohen, Wilson, Drew, & Clark, 1994; Aoyagi, Kiren, Kim, Suzuki, Fuse, & Koike, 1993). The data that support these two limitations is discussed below.

Suzuki and Kobayashi (1984) examined the effects of stimulus rate on the amplitude of ASSRs in adults and children. The stimuli employed in this study were clicks presented at stimulus rates ranging from 10 to 50 Hz in 5 Hz steps. These investigators compared the ASSRs of seven audiologically normal adults to those of 10 infants and young children all tested while the subjects were asleep. Suzuki and Kobayashi (1984) demonstrated that the response amplitudes for the adults' responses were the largest at 40 Hz, which is in agreement with Galambos et al.'s (1981) findings.

In contrast, the results for the younger children demonstrated a peak in their response amplitudes at stimulus repetition rates of approximately 20 Hz (see Figure 2). Stapells et al. (1988) replicated the findings of Suzuki and Kobayashi and also reported that infants and young children (age 3 weeks to 28 months) do not have a 40 Hz response, but rather their peak response amplitude occurs at ~ 20 Hz (Stapells, Galambos, Costello, & Makeig, 1988). Stapells and colleagues (1988) explained that ASSRs cannot be reliably recorded in young children at high stimulus rates because the superimposition of wave V of the ABR and the MLR components is not the same in children as they are in adults (Stapells et al., 1988). At these higher stimulus rates, infants and children lack wave Pa of the MLR and the components that follow and thus infants' responses are much more susceptible to effects of increasing stimulus repetition rates in comparison to adults' responses (Stapells et al., 1988).

The following section of the literature review will discuss the second limitation of the 40-Hz ERP: Subject state. The influence of subject state in adults will initially be discussed and will be followed by the results found in infants and young children.

Cohen, Rickards, and Clark (1991) were interested in determining the optimal stimulus repetition rate for recording the ASSR in 10 audiologically normal sleeping adults (mean age = 22 years) (Cohen, Rickards, & Clark, 1991). These investigators examined the effects that varying the stimulus click rates between 30 to 190-Hz would had on the ability to successfully record ASSRs during natural sleep stages. In this study, the ASSRs were recorded over a 13 hour period for each subject. At the beginning of the test session, the subjects were awake and were then allowed to fall into a natural sleep. No formal study of sleep stages was conducted. Cohen and colleagues (1991) reported that the amplitudes of the ASSRs and the level of background EEG noise were reduced during natural sleep in comparison to the awaken stage. These investigators also reported that the use of stimulus repetition rates greater than 70- Hz had less of an impact on the response amplitude of the ASSR than if the 40- Hz stimulus repetition rate was utilized. Cohen et al. (1991) plotted the amplitude of these ASSRs as a function of stimulus rate and reported a robust secondary peak in the response amplitude at stimulus repetition rates between 80-100 Hz. This peak was in addition to the original peak obtained at 40 Hz. Based on these findings, Cohen et al. (1991) hypothesized that if ASSRs were recorded at high stimulus repetition rates (i.e., greater than 70 Hz), it would likely produce ASSRs in young children, which were otherwise absent or inconsistent at best when evoked at a 40- Hz repetition rate.

Aoyagi and colleagues (1993) sought to identify if there was an optimal stimulus repetition rate for recording ASSRs in sleeping children (Aoyagi , Kiren, Kim, Suzuki, Fuse, & Koike, 1993). The investigators compared ASSRs recorded in 10 normal hearing adults, both awake and asleep, to the responses obtained in 10 normal hearing children who were asleep. The researchers recorded ASSRs to MFs between 20 and 200 Hz. They obtained responses to MFs in 20 Hz steps. Aoyagi and colleagues (1993) identified increased neural synchrony at high stimulus repetition rates (80 – 100 Hz) while the 40 Hz repetition rate was less synchronous making it harder to detect. They also suggested that although auditory steady-state responses can be clearly evoked to stimuli presented at 40-Hz in wakeful adults, the use of higher stimulus presentation rates (80-100 Hz) allows for robust responses to be recorded while these same adults were sleeping. Overall these researchers concluded that stimulus repetition rates ranging from 80 to 100 Hz are optimal for recording ASSRs in young sleeping children (Aoyagi et al., 1993).

Rickards and colleagues (1994) were interested in determining the optimal stimulus repetition rate for eliciting robust ASSRs in sleeping newborns (Rickards, Tan, Cohen, Wilson, Drew, & Clark, 1994). These investigators tested sixty-three full-term newborns, ranging in age from 1-7 days, who were tested during natural sleep. These investigators recorded ASSRs to amplitude and frequency modulated tones presented at stimulus repetition rates ranging from 60 to 100 Hz. Rickards et al. (1994) reported a significant increase in the detectability of the response at stimulus rates between 55 and 110-Hz (4.20-15.85 mean detection efficiency) as compared to the lower detection rate at 40-Hz (<2.6 detection efficiency).

Collectively, the findings from these three studies (Cohen et al., 1991; Aoyagi et al., 1993; and Rickards et al., 1994) suggest that the use of high stimulus repetition rates (greater than 70- Hz) results in robust ASSR amplitudes which are less affected by subject state in comparison to the use of lower stimulus repetition rates. This finding is true for both adults and children.

Given the findings that emerged from these studies, reference to the 40 Hz response was largely abandoned and a new term was coined: The Auditory Steady State Response (ASSR). The ASSR has also been referred to in the literature synonymously as the amplitude-modulation-following response (AMFR) (Pethe, von Specht, Muhler, & Hocke, 2001), the frequency-modulation following response (Boettcher, Madhotra, Poth, & Mills, 2002), the envelope-following response (EFR) (Supin & Popov, 1995), the steady-state evoked potential (SSEP) (Cohen et al., 1991), and the steady- state response (Lins, Picton, & Boucher, 1996 as cited in Stach, 2002).

Researchers began probing into the question of why the ASSR behaves differently at lower stimulus rates (40- Hz or less) versus higher stimulus rates (70- Hz or greater). One leading hypothesis for this rate sensitive effect was that the underlying neural generators of the ASSR are different for lower versus higher stimulus repetition rates. This issue will be addressed in the following section of the literature review.

Underlying Neural Generators

Multiple brain imaging techniques as well as animal studies have been used to investigate the underlying neural generator sources of the ASSR. These brain imaging techniques include: Brain Electrical Source Analysis (BESA), Magnetoencephalographic (MEG) Techniques, and Functional Magnetic Resonance Imaging (fMRI). While the various techniques used to investigate the neural generators of the ASSR are vastly different, collectively their findings suggest that ASSRs receive contributions from multiple underlying neural generators. These generators appear to be contingent on the properties of the stimulus, in particular the stimulus repetition rate or modulation frequency. Below is a brief description of the findings from these neural generator studies as a function of technique used to study this issue.

Brain Electrical Source Analysis (BESA)

Herdman and colleagues (2002) used the BESA technique to identify the neural anatomical structures responsible for ASSRs recorded at slow (12-Hz), medium (39-Hz), and fast (88-Hz) stimulus repetition rates in 10 adults with normal hearing (Herdman, Lins, Van Roon, Stapells, Scherg, & Picton, 2002). Brain Electrical Source Analysis is a brain imaging technique used to identify cortically stimulated areas. The results of this study suggested that the ASSR contains contributions from both brainstem and bilateral cortical generators. These cortical generators were focused near the supratemporal plane. While the brainstem was active during all rates of stimulation, cortical involvement varied. The responses collected utilizing a slow 12-Hz stimulus rate indicated that both cortical and sub cortical involvement occurred. At an increased repetition rate of 39- Hz, both cortical and brainstem structures were also active. Lastly, at a high 88-Hz repetition rate, the response was primarily generated from the auditory pathways of the brainstem. Therefore, Herdman and colleagues (2002) concluded that as the stimulus repetition rate increases, the level of cortical involvement decreases.

Magnetoencephalographic (MEG) Technique

Hari and colleagues (1989) investigated ASSR neural generator sites through the use of MEG techniques (Hari, Hamalainen, & Joutsiniemi, 1989). The MEG technique involves measuring magnetic fields produced by electrical activity within the brain. Hari and colleagues (1989) investigated what effect varying the stimulus repetition rate from 10 to 70-Hz had on MEG activity in 10 healthy adults. Their results suggested that ASSRs recorded to stimuli presented at a repetition rate of 40-Hz are primarily generated in the cortical structures located deep within the Sylvian fissure. There was also sufficient evidence to conclude that some degree of cortical involvement is associated with all repetition rates tested (10-70 Hz).

Gutschalk and colleagues (1999) performed MEG studies on 15 subjects (8 males; 7 females) ranging in age from 21 to 36 years. ASSR testing was performed on each subject binaurally using click stimuli presented at varying repetition rates ranging from

32.3 to 52.6 Hz. Gutschalk et al.'s (1999) research clearly identified two main source generators for the ASSR response in both the left and right primary auditory cortex at Heschl's gyrus. Similarly to Hari et al.'s (1989) research, Gutschalk and colleagues (1999) reported that the majority of the underlying neural source generators are located in the auditory cortex for stimulus repetition rates up to 52.6 Hz, which was the maximum repetition rate tested (Gutschalk et al., 1999).

Roβ, Borgmann, Draganova, Roberts, and Pantev (2000) recorded the cerebral magnetic field of the ASSR via MEG activity in four males and four females who were audiologically normal and were between the ages of 22 and 32 years old. These investigators recorded ASSRs to 250, 500, 1000, 2000, and 4000 Hz tones presented at 70 dB SL using stimulus repetition rates ranging from 10 to 100 Hz. Their results demonstrated that the auditory cortex responds to changes in stimulus repetition rate between 10 to 98 Hz, which suggests that cortical involvement is occurring at these stimulus repetition rates. These investigators also reported that as the modulation frequency increased to rates ≥ 70Hz, the time delay decreased, which suggested that brainstem activity was predominant at these higher rates. The overall findings reported by Roβ et al. (2000) are in good agreement with those of Hari and colleagues (1998) and Gutschalk et al. (1999).

Functional Magnetic Resonance Imaging (fMRI)

A third technique used to investigate the neural generators of the ASSR is Functional Magnetic Resonance Imaging (fMRI). Functional Magnetic Resonance Imaging measures changes in blood flow related to the neural activity in the brain. Giraud et al. (2000) investigated how the temporal envelope of sounds is processed in the human brain in 5 normal hearing subjects via fMRI techniques. The investigators studied white noise stimuli presented at repetition rates varying between 4 and 256-Hz. Their results suggested that the auditory system is organized as a hierarchical filter system, meaning that anatomical structures located higher in the central auditory nervous system prefer signals presented at lower stimulus repetition rates while structures located in the lower portion of the CANS prefer higher repetition rates. For example, the lower brainstem responds optimally at the highest repetition rates while the primary auditory cortex prefers to respond at lower stimulus rates between 4 to 8-Hz.

Animal Studies

Lastly, some investigators have examined the neural generators of the ASSR in animals. For example, Kuwada and colleagues (2002) studied ASSRs recorded to tone burst stimuli presented at stimulus repetition rates ranging from 0 to 800-Hz on the surface of the brain of unanaesthetized rabbits (n= 6). These investigators recorded ASSRs from the surface of the brain at various locations both before and after the injection of pharmacological agents that were likely to either augment or repress the ASSRs' neural generators. Similar to the results of previously mentioned studies, Kuwada and colleagues (2002) results suggested that ASSRs are the result of multiple neural generators. All stimulus repetition rates, from 0-800-Hz, resulted in ASSRs with more than one neural generator site. ASSRs recorded using low stimulus rates (≤ 80 Hz) corresponded to primarily cortical generator sites while ASSRs recorded using higher frequency stimulus repetition rates (>150 Hz) correspond to generator sites along brainstem pathway of the rabbits. Specifically, the cortical neurons in rabbits respond best to stimulus rates below approximately 15-Hz, while midbrain responses show peaks at approximately 100 Hz.

The overall consensus in the ASSR literature supports the notion that the underlying neural generators responsible for the ASSR vary depending on the stimulus repetition rate/modulation frequency. It is generally accepted that repetition rates lower than 20-Hz primarily reflect cortical activity. ASSRs elicited by moderate repetition rates, between 20 and 60-Hz, primarily reflect both cortical and sub cortical involvement in the midbrain, thalamus, and primary auditory cortices. Lastly, ASSRs recorded using high repetition rates (≥ 60-Hz) are primarily generated by the brainstem: Specifically the cochlear nucleus, the superior olivary complex, and the inferior colliculus (Cone-Wesson, Dowell, Tomlin, Rance, & Ming, 2002a).

The evidence discussed above regarding differences in the neural generators as a function of stimulation rate helps to somewhat explain the initial limitations demonstrated in the 40-Hz response. A robust 40 Hz response could be successfully recorded in normal waking hearing adults as their auditory cortex and its association areas are fully developed. In contrast, the 40 Hz response, which relies on contributions from both cortical and sub cortical neural generators, was absent in the pediatric population. In this clinical pediatric population, the primary auditory cortex as well as the midbrain and thalamus are still maturing and do not reach full development until early adulthood. A robust ASSR, however, could be successfully elicited at higher stimulation rates (80-100 Hz) in infants and young children both awake and asleep. At these higher stimulus rates, the ASSR is primarily receiving contributions from the auditory brainstem region, similar to the ABR.

There is specific terminology that is unique to the ASSR and these terms will be discussed in the following section of the literature review.

Terminology

There is certain terminology that is associated solely with the ASSR. Comprehension of the associated terminology is vital to understanding the components of the ASSR in order to apply it clinically. The following section will briefly outline the terminology that is unique to the ASSR.

The term **carrier frequency (CF)** is used to describe the pure tone that stimulates hair cells located at a specific region along the basilar membrane which is best tuned to that frequency (Stach, 2002). Typical CF tones used during clinical ASSR testing include 500, 1000, 2000, and 4000 Hz. Figure 3 illustrates a 1000 Hz CF tone entering the ear canal, which in turn initiates a traveling wave along the basilar membrane. The peak displacement of the traveling wave occurs at the portion of the basilar membrane that is best tuned to 1000 Hz (Cone & Dimitrijevic, 2009; Herdman, Picton, & Stapells, 2002).

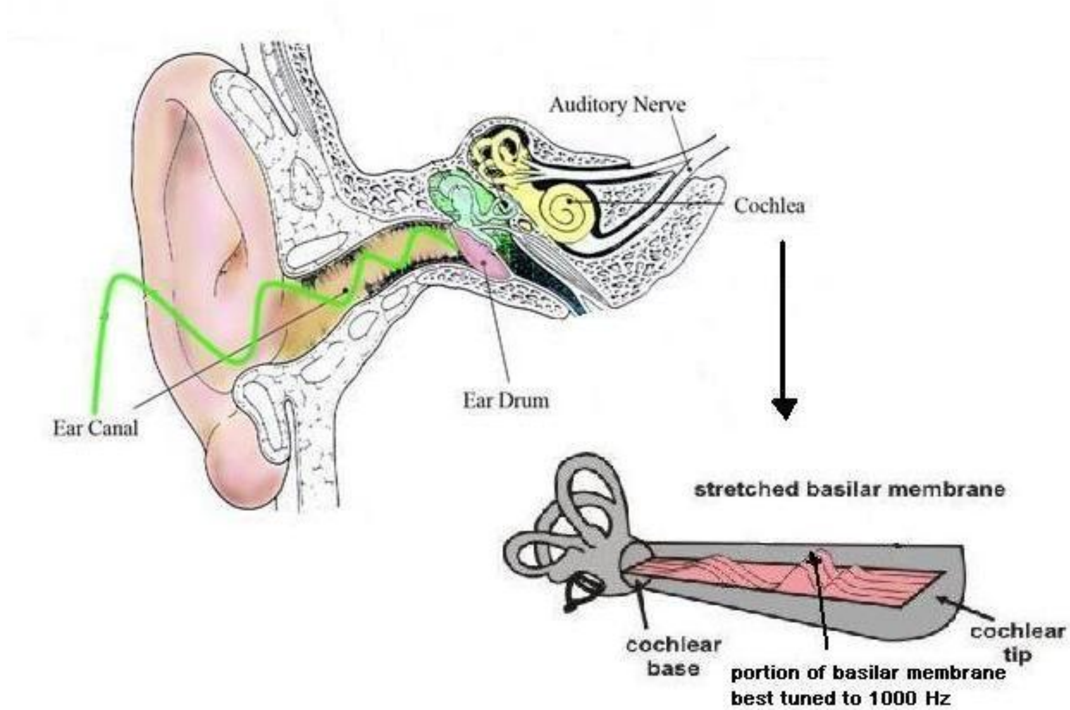


Figure 3. This figure demonstrates a 1000 Hz tone entering the ear canal. The peak displacement of the traveling wave is greatest at the portion of the basilar membrane best tuned to 1000 Hz.

A second term unique to ASSR testing is **modulation frequency (MF).** MF, in contrast, is the frequency at which the electroencephagraphy (EEG) activity is synchronized to fire (Cone & Dimitrijevic, 2009; Grason-Stadler Inc. [GSI] Brochure, 2001). It is derived by calculating the period of the MF. For example, if you have a 2000 Hz CF tone which has a 100 MF, then the EEG activity from the brain will synchronously fire every 10 ms. This occurs because the period of the 100 Hz MF is 10 ms [Period = 1sec/MF, so 1000 ms/100 Hz = 10]. This pattern of synchronized neural firing is clearly evident in Figure 4 below, where positive peaks in neural firing occur at 10 ms intervals (e.g., 10 ms, 20 ms, 30 ms, 40 ms etc) (GSI Brochure, 2001).

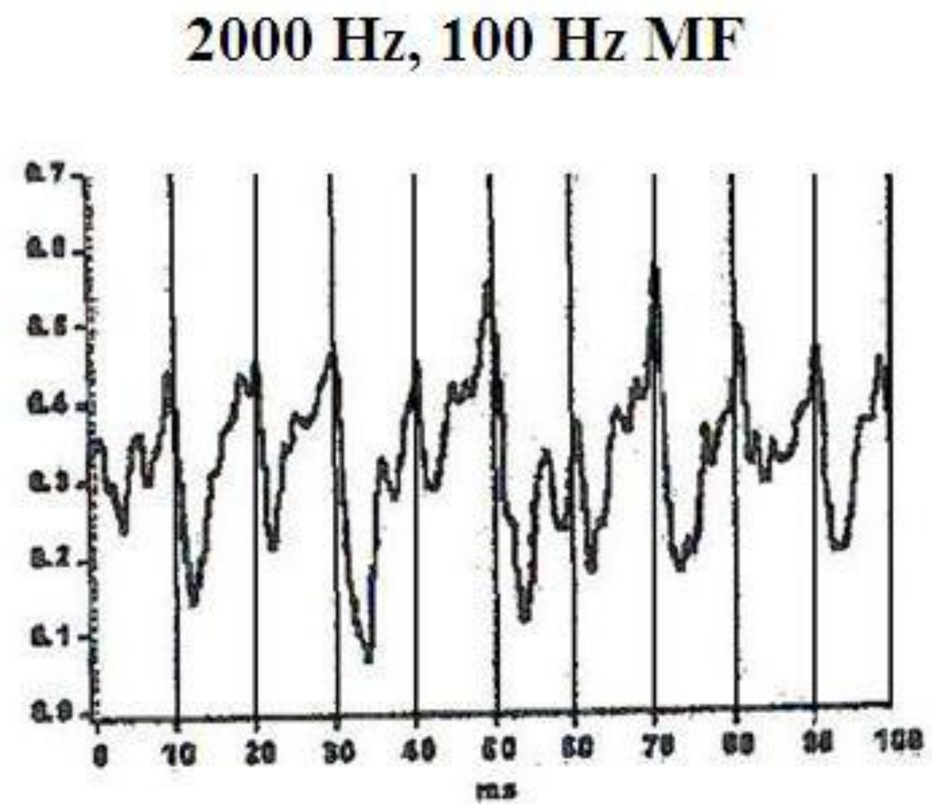


Figure 4. The neural firing of 2000 Hz CF that has a MF of 100 Hz is represented. The vertical lines depict the synchronously firing EEG that fires every 10 ms at the period of the MF (1000/100 ms= 10 ms). Figure adapted from GSI Brochure, 2001.

There are several types of stimuli, stimulation techniques, and analysis techniques that are used to not only elicit the ASSR but also to objectively determine if a response has occurred at a particular CF and stimulus intensity. The terminology associated with these stimuli and analysis techniques will be briefly introduced in this section.

The three most common types of stimuli used clinically to elicit frequency specific ASSRs are: **amplitude modulated (AM) tones**, **frequency modulated (FM) tones**, and **mixed modulated (MM) tones**. AM stimuli represent a change in the amplitude of the stimuli over time and these changes in amplitude are described in terms of the depth of modulation. In contrast, FM tones represent a change in the frequency of the stimulus over time. These changes in frequency result in a change in the site of stimulation along the cochlear partition. Lastly, MM tones are the result of a combination of both amplitude and frequency modulation, which results in a dual generation site along the basilar membrane (Beck, 2007).

Two stimulation techniques routinely used to elicit the ASSR are the **single frequency (SF) stimulation technique** and the **multiple frequency (MF) stimulation technique**. The SF stimulation technique involves the presentation of one CF tone to one ear. For example, a 2000 Hz CF tone, which has a 100 Hz MF, is presented to the subject's right ear. In contrast, in the MF technique up to four CF tones are presented simultaneously to either one or both ears (Beck, 2007). An example of a MF stimulation technique is simultaneously presenting 4 CF tones (500, 1000, 2000, and 4000 Hz) to the subject's right ear.

Lastly, there is terminology that is associated with various ASSR analysis techniques. These terms include: **Phase coherence, Fast Fourier Transform Analysis,**

and F-ratios. Phase coherence analysis is typically used for analyzing data obtained in a SF stimulation technique. Phase coherence evaluates the phase of each EEG sample in order to determine the probability that EEG samples obtained during the presentation of tonal stimuli are statistically different than those obtained when no stimulus is presented (GSI Brochure, 2001). Fast Fourier Transform (FFT) analysis is a technique in which the temporal waveform of the ASSR is converted into the frequency domain. This is done in order to measure the magnitude (amplitude) of energy in the response that is occurring at the modulation frequency. Lastly, the F ratio is a statistical technique used to determine whether the amplitude of energy at the MF is statistically larger than the amplitude of the energy in the ongoing EEG that is present in the neighboring frequency side bins. If the difference between these two amplitudes reaches a predetermined statistical criterion, usually an alpha level of $p < .05$, then the response is deemed present for that CF tone at that stimulus intensity. A combination of FFT analysis and F ratios are frequently used in MF stimulation techniques (Stach, 2002).

The terminology mentioned in this section will be discussed in greater detail in their respective sections throughout the remainder of this literature review.

Stimuli

Both non-frequency specific and frequency specific stimuli can be used to generate ASSRs. Non-frequency specific stimuli are broadband stimuli, which mean they contain energy across a broad range of frequencies. Examples of non-frequency specific stimuli include: clicks, noises, amplitude modulated noise, and chirps (Beck, 2007). In contrast, frequency specific stimuli have a concentration of energy at the test frequency of interest. Examples of frequency specific stimuli include: filtered clicks, band-limited chirps, narrowband noise bursts, tone bursts, amplitude modulated noise, narrowband noise, or amplitude and frequency modulated pure tones (Beck). While non-frequency specific stimuli do not produce frequency specific thresholds, they do produce robust response amplitudes in a short amount of time due to the broad stimulation across a majority of the basilar membrane. Picton and colleagues (2003) suggest that non-frequency specific stimuli can be used as a quick screening test of hearing sensitivity similar to how the click stimulus can be used in ABR testing. The following section will discuss the common frequency specific stimuli that are employed in a clinical setting. These stimuli include amplitude modulated tones, frequency modulated tones, and mixed modulated tonal stimuli.

Sinusoidally Amplitude Modulated (AM) Tones.

Picton and colleagues (2003) reported that AM tones are the most frequently utilized ASSR stimuli. Amplitude modulation refers to changes in the amplitude of the CF tone over time (Venema, 2005). The amount of variation in amplitude depends on the depth of the modulation, which is expressed as a percentage and is independent of the MF. Greater percentages of modulation result in larger changes in amplitude. For example, a 4000 Hz CF tone with a 100 Hz MF that is 100% AM means that the amplitude varies from zero to its peak amplitude. In panel A of Figure 5, the amplitude of the stimulus rises from 0 ms to reach a peak amplitude at approximately 5 ms, as shown in the middle panel. This pattern occurs in each cycle of the signal. In the frequency domain, the primary peak of energy in the stimulus is located at the CF (i.e., 4000 Hz) with two side lobes of energy occurring at the CF + the MF (4000 + 100 Hz = 4100 Hz) and at the CF – MF (4000 – 100 = 3900 Hz). The excellent frequency specificity of this stimulus is displayed in the right hand panel of Figure 5A.

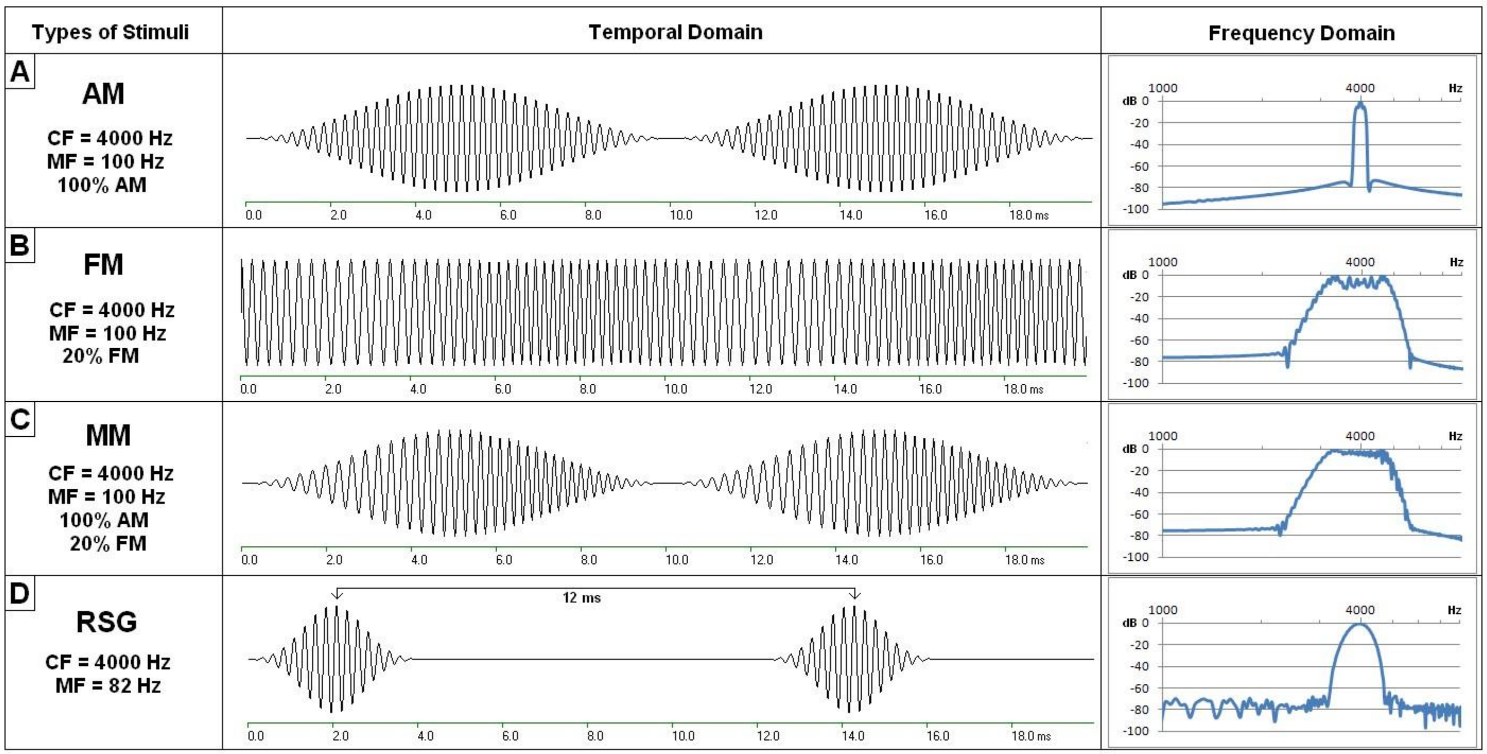


Figure 5. The most common types of ASSR stimuli are illustrated in the temporal and frequency domains. Figure adapted from John & Purcell (2008) and Venema (2005).

Frequency Modulated (FM) Tones

Frequency modulation (FM) in contrast, refers to a signal which changes in frequency over time, while the amplitude of the signal remains constant (Venema, 2005). The amount of modulation that occurs in the frequency domain is expressed as a percentage; larger percentages equate to larger frequency fluctuations around the CF. Figure 5, panel B depicts a 4000 Hz CF tone that has 20% FM. In the middle panel, the reader can see changes in the frequency of the signal that occurs during this 10 ms time window. The signal appears to have a lower frequency emphasis from approximately 0 – 3ms and then increase in frequency from approximately 4-7ms. In the frequency domain, the peaks of energy in this stimulus are located at the CF (4000 Hz) and at ± 10% of the CF (totaling 20%). Thus, this stimulus would contain energy from 3600 Hz (4000 – 400 Hz) to 4400 Hz (4000 + 400 Hz) (Venema, 2005; John & Purcell, 2008).

Mixed Modulated (MM) Tones

Mixed Modulated (MM) tones are the result of simultaneous frequency and amplitude modulation; therefore, both the amplitude and the frequency of the CF tone vary over time. Figure 5, panel C is an example of a MM 4000 Hz CF tone with a MF of 100 Hz. The amplitude has 100% AM and the frequency has 20% FM. The waveform seen in the temporal domain clearly shows both a change in the amplitude and the frequency of the signal over the 10 ms time window. The right side of panel 5C depicts the energy present in this MM signal as a function of frequency domain. The primary peak of energy is located at the CF (4000 Hz) with smaller side lobes of energy located on either side of the CF at ± MF [4000 Hz ± 100 Hz = 4100 Hz and 3900 Hz] (Beck, 2007).

When MM tones are utilized, phase disturbances can occur due to the interactions between the amount of amplitude and phase modulation. Therefore, careful consideration must be made when creating MM tones. In order to avoid phase disturbances, the maximum frequency should occur slightly after the maximum amplitude has been reached; however, the optimum frequency and amplitude relationships are dependent upon the carrier frequency (Picton et al., 2003). Most clinical systems have default settings for mixed modulated signals. For example, default mix modulated signals in the MASTERS software have a default frequency modulation of 20% and an amplitude modulation of 100% for each of the CFs with different respective MFs (Venema, 2005).

There are advantages and disadvantages to using either AM, FM, or MM signals related to the frequency specificity of the stimuli and the resulting amplitude of the ASSRs. Signals that are AM result in approximately the same frequency specificity as brief tone bursts (Picton, 2007). Signals that are 100% AM result in the most frequency specific response compared to any other percentage of a modulation regardless if it is amplitude, frequency, or mixed modulated (Venema, 2005). One potential disadvantage of using AM tones is that the amplitude of the ASSR tends to be relatively low as only a limited number of auditory neurons fire to the stimulus. FM tones have a slightly broader frequency spectrum in comparison to AM tones, as shown in the right hand side of panels A and B in Figure 5; however, the amplitude of ASSR elicited to FM signals alone result in amplitudes that are approximately 50% smaller than responses recorded to AM tones (Venema). MM, in contrast, produce response amplitudes that are substantially larger than those recorded to either AM or FM tones alone (John, Dimitrijevic, & Picton, 2002).

This finding is especially true at 1000 and 2000 Hz. Picton and colleagues (2003) reported that MM tones reduce the frequency specificity of the stimulus as compared to CFs that are solely AM or FM, however, this does not significantly affect the frequency specificity of the responses (Picton et al., 2003).

Repeating Sequence Tones

Repeating sequence tones are unique to the Intelligent Hearing Systems' Smart EP ASSR software. In this software, the Repeating Sequence Gated (RSG) tones consist of a series of Blackman-gated tones. Gorge and Thornton (1989) originally thought that Blackman-gated tones provided a more frequency specific response as compared to linear-gated tones due to the differences in acoustic energy present in these two different types of stimuli. The three differences between these two types of stimuli are: (1) that Blackman-gated tones have a wider lobe of main energy as compared to linear-gated tones, (2) the height of energy in the side lobes is larger for the linear-versus Blackman gated tones, and (3) linear-gate tones have a steeper rate of decay of their side lobes of energy when compared to Blackman-gated tones. While the spectral energy present in each of these two stimuli are different, both Oates and Stapells (1997) and Purdy and Abbas (2002) demonstrated that there were no significant differences in the frequency specificity of the response when either Blackman-gated or linear-gated tones were used to obtain either ABRs or MLRs. Therefore, it can be assumed that either Blackman-gated or linear-gated stimuli can be used to accurately elicit ASSRs.

The IHS system elicits the ASSR to a series of Blackman-gated tones that are presented in a repeating sequence format. This format is employed with CF tones ranging from 500 to 4000 Hz and with MFs ranging from 77 Hz to 101 Hz. These CF tones can be presented in either a SF or MF stimulation technique. The timing or duration between the tones is related to the period of the MF. Panel D shown at the bottom of Figure 5, depicts the temporal waveform of a 4000 Hz CF tone which has a MF of 82 Hz. This tonal pattern repeats 4 times within this 0 to 50 ms time window. The distance between the peaks of energy that occurs in each cycle is related to the period of the MF. In this example, the period of the MF is 12 ms (1000 ms / 82 Hz). This means that the auditory nerve will synchronously fire every 12 ms as long as the energy in the stimulus is audible to that individual. The right hand side of panel D displays the energy present in this repeating sequence tone as a function of frequency. The peak of energy is located at the CF (4000 Hz) with smaller side lobes of energy located at the CF ± the MF (4000 Hz ± 82= 3918 Hz and 4082).

Stimulation Techniques for the ASSR

Both the SF and MF stimulation technique have each been deemed as appropriate methods to elicit ASSRs. The following subsection will describe the differences between the SF and the MF stimulation techniques.

A SF stimulation technique, as briefly described in the terminology section, involves presenting one CF tone to one ear. Single frequency responses are regularly recorded to 500, 1000, 2000, and 4000 Hz CFs. Figure 6 illustrates the SF stimulation technique to a 1000 Hz CF tone, presented at a modulation frequency of 95 Hz. The CF tone stimulates the portion of the cochlea best tuned to 1000 Hz.

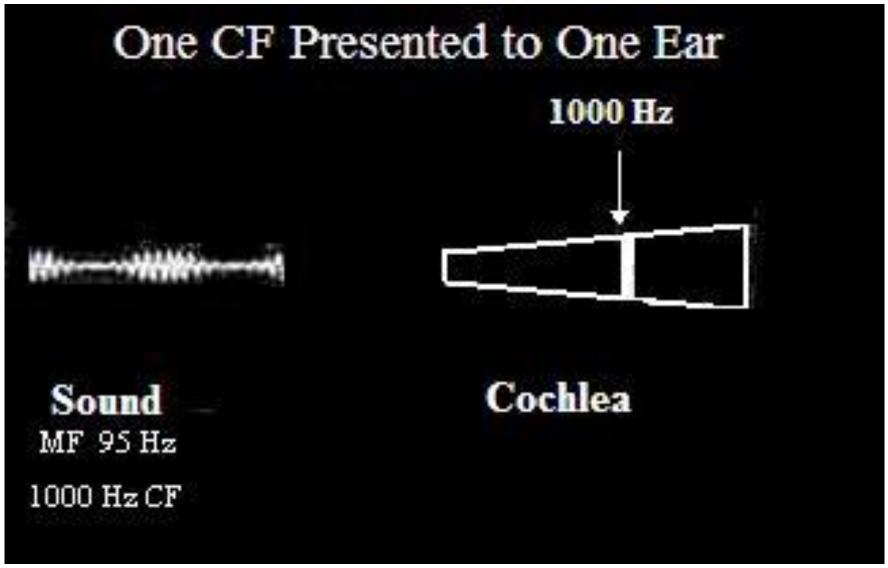


Figure 6. A SF stimulation technique is demonstrated. A 1000 Hz CF that has a 95 Hz MF is presented to one ear and stimulates the portion of the basilar membrane best tuned to 1000 Hz. Figure adapted from Hall, 2007.

The MF stimulation technique, in contrast, presents up to four CF tones (500, 1000, 2000 and 4000 Hz) to each ear either monaurally or binaurally. Each CF tone must have its own unique/signature MF. Figure 7 demonstrates an example of the MF stimulation technique in which the complex signal is being delivered in a monaural fashion to the subject's right ear. As seen in this figure, four CF tones (i.e., 500, 1000, 2000, and 4000 Hz) are being simultaneously presented to one ear. Each of the CF tones has a unique MF, which range from 84 to 91 Hz. When the four CF tones are added together they form a complex tone which is then delivered to the subject's ear. This complex tone stimulates the portions of the basilar membrane that are best tuned to 500, 1000, 2000 and 4000 Hz.

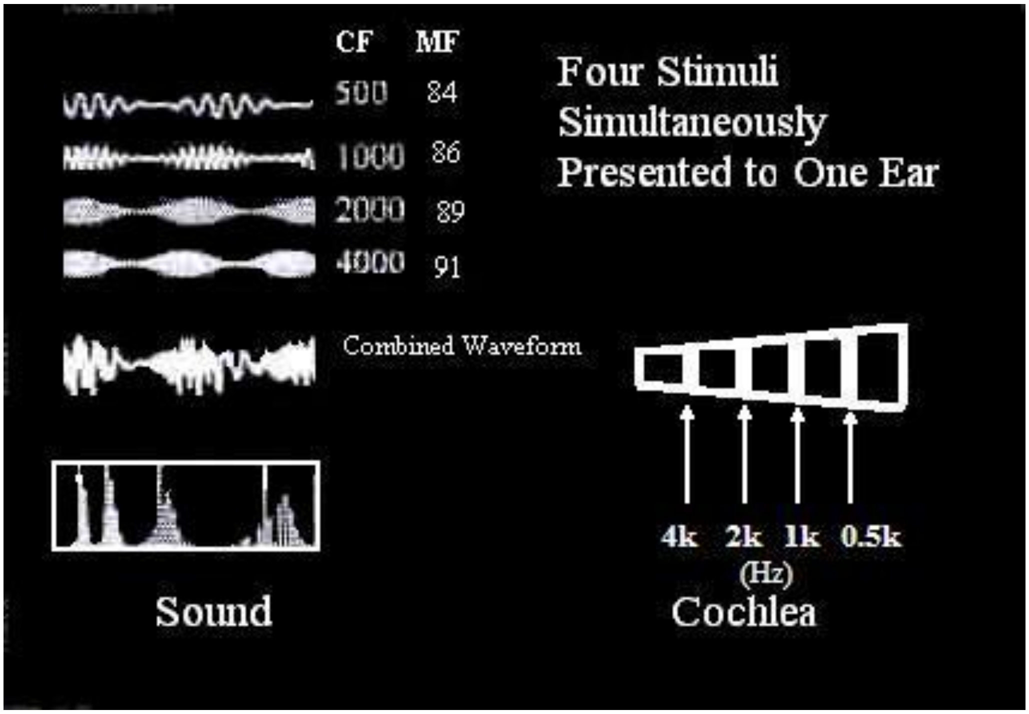


Figure 7. A MF stimulation technique is demonstrated. CFs including 500, 1000, 2000, and 4000 Hz are simultaneously presented to one ear which stimulates each portion along the basilar membrane that is best tuned to the individual CF. Figure adapted from Hall, 2007.

As mentioned above, this MF stimulation technique can also be presented in a binaural manner. Binaural stimulation allows the ASSR to be recorded for up to eight CF tones (four presented to each ear) simultaneously and each CF tone must have its own unique MF. Several investigators have demonstrated that the binaural MF stimulation technique can be successfully used without compromising the accuracy of behavioral threshold prediction given that the level of background EEG noise is consistent across all test frequencies (Canale et al., 2005; John, Purcell, Dimitrijevic, & Picton, 2002; Lins et al., 1996; Perez-Abalo et al., 2001).

When binaural MF stimulation techniques are used clinically, MFs between 82 Hz and 106 Hz are typically employed (Beck, Speidel, & Petrak, 2007). John, Lins, Boucher, and Picton (1998) clearly outline several guidelines that must be followed when conducting binaural MF ASSR recordings. These guidelines state the following: (1) that each MF must be greater than 70 Hz; (2) the intensity of the presentation level must be 60 dB SPL or less; and (3) the CF tones must be separated by at least one octave in frequency when presented to the same ear in order to prevent any significant reduction in ASSR amplitude. John and colleagues (1998) reported that when these specific caveats are followed, neither an increase in background EEG noise nor a decrease in ASSR amplitude significantly influenced test time or response detectability (John, Purcell, Dimitrijevic, & Picton, 2002).

Techniques for Analyzing the ASSR

There is no visual detection or measurement of peak latencies or amplitudes involved in the analysis of ASSR (Cone-Wesson, 2003). In contrast, in ASSR testing, the tonal signal is presented to the ear and stimulates the portion of the basilar membrane that is best tuned to the CF of the signal. The ASSR software then records both the neural activity related to the signal as well as the ongoing background EEG activity and displays this information in the temporal domain. Computer algorithms within the EP software then convert the temporal waveform into the frequency domain and the ASSR is displayed at the MF which corresponds to the CF tone. In order for an ASSR to be detected at any CF, the integrity of the cochlea and auditory nerve must be intact. The two primary techniques used to analyze the ASSR are: (1) Phase Coherence Analysis and (2) a combination of Fast Fourier Transform (FFT) Analysis and the F ratio. The following section of the literature review will discuss these two analysis techniques.

Phase Coherence Analysis

"Phase coherence (PC) is related to the signal (response)-to-noise (background EEG and myogenic) ratio" (Cone & Dimitrijevic, 2009, p. 333). Phase coherence is determined through using a computer algorithm which determines the magnitude and phase relationship of each EEG sample corresponding to the signal's MF and plots it as a vector. Each vector is graphed on a polar plot. Two parameters that are measured on these polar plots are: (1) the angle of the vector and (2) the length of the vector. The angle of the vector corresponds to the time delay between the presentation of the signal and the occurrence of the neural response and thus represents the synchronization of the EEG sample (Cone-Wesson, 2003). In contrast, the length of the vector reflects the magnitude of the EEG sample.

Generally two types of response patterns are seen for ASSR polar plots. In one pattern, the vectors are clustered in one quadrant of the polar plot, as shown in Figure 8A; while in the second pattern, the vectors are randomly spread across the four quadrants, as shown in Figure 8B. Statistical analysis is then performed to determine if the EEG samples are phase-locked, meaning that a true neural response has being obtained to this particular CF tone at this stimulus intensity. The phase of each vector is analyzed through an algorithm known as Phase Coherence Squared (PC^2) and is assigned a PC^2 value which ranges from 0.0 to 1.0. Values closer to 0.0 are the result of low phase coherence between the EEG sample and the signal's MF, while values closer to 1.0 are the product of high phase coherence between the EEG and the MF (Cone & Dimitrijevic, 2009). Phase Coherence Squared values are used in order to determine the probability or "p" value that the clusters of vectors obtained during the presentation of a modulated signal are statistically different than those vectors obtained when either no signal is presented or the modulated signal is not audible (GSI Brochure, 2001).

In Figure 8A the vectors all appear in the same quadrant and a PC^2 value of 0.9 has been assigned to this polar plot. This finding indicates that the CF tonal signal was audible to the brain and it has produced a phase-locked neural response and thus it is a true neural response. In contrast, Figure 8B demonstrates a modulated signal that is not audible to the brain; the EEG vectors appear scattered across the four quadrants of the polar plot and a low PC^2 value of 0.1 has been assigned. This finding indicates that there is no phase relationship occurring between the EEG sample and the MF; and thus no detectable response has occurred at this CF and stimulus intensity (Cone & Dimitrijevic, 2009; GSI Brochure, 2001; Hall, 2007).

The phase coherence analysis technique is often used with SF stimulation technique and is found on the AUDERA clinical ASSR system, manufactured by Grason and Stadler.

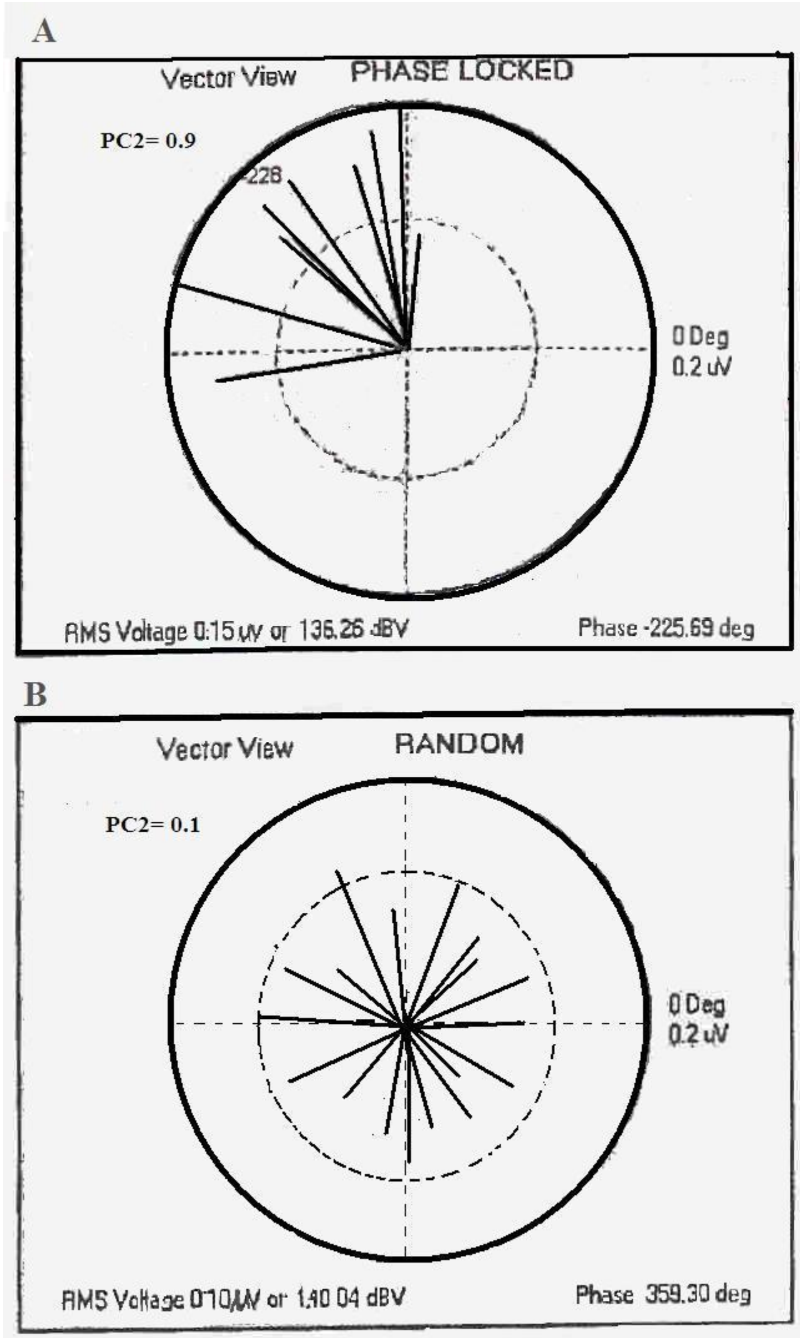


Figure 8. The Phase Coherence Analysis is illustrated. Panel A represents an audible signal as all vectors are located in the same quadrant and have a high PC2 value of 0.9. Panel B represents a signal that is not audible as the vectors are scattered around all four quadrants and have a low PC2 value of 0.1. Figure adapted from GSI Brochure, 2001.

Fast Fourier Transform (FFT) Analysis and F-ratios

A second method used to analyze the results of the ASSR employs a combination of Fast Fourier Transform (FFT) Analysis and the F-ratio. This technique can be used to analyze ASSR results obtained from either SF or MF stimulation techniques. In this technique, the temporal waveform of the ASSR is converted into the frequency domain, using FFT analysis techniques. The ASSR software then creates a graph of the energy present at the MFs and at the adjacent frequencies and these frequencies are plotted as frequency bins (Picton et al., 2003). Each frequency bin is depicted on the X axis while the y axis represents the amplitude of the response at each frequency. Figure 9 depicts the results of the FFT calculated on an ASSR recorded to a 1000 Hz CF tone with an 85 Hz MF using the SF stimulation technique. It is clearly evident that the energy present at the MF (85 Hz) is significantly larger than the energy present in the surrounding frequency bins.

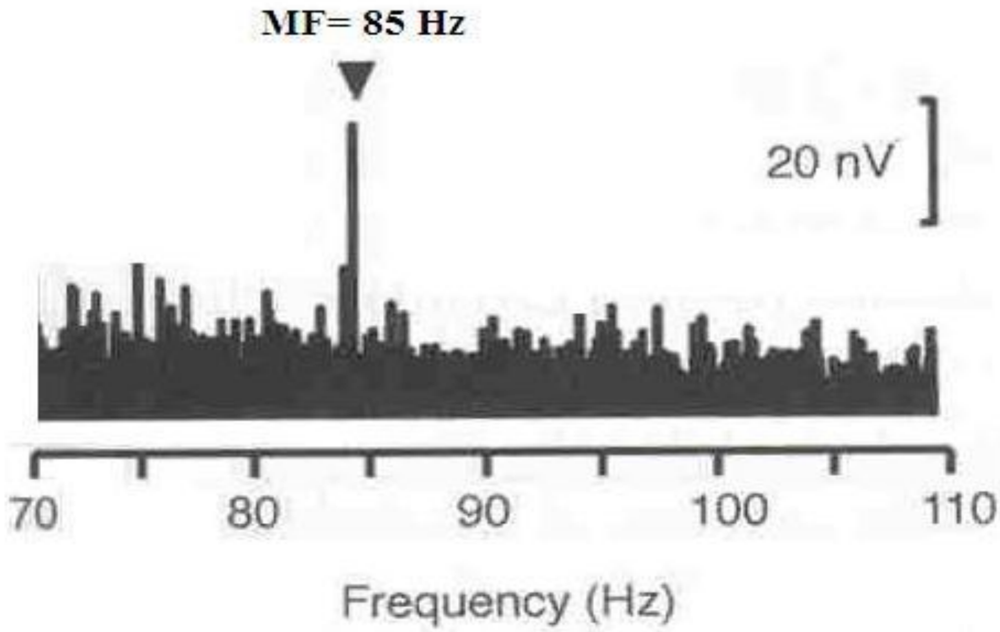


Figure 9. The FFT Analysis of a 1000 Hz CF with an 85 Hz MF that is presented at an audible level is illustrated.

In contrast, Figure 10 represents the results of an FFT conducted on an ASSR recorded using a MF stimulation technique. A 500 Hz CF with an 85 Hz MF, a 1000 Hz CF with an 87 MF, a 2000 Hz CF with a 90 Hz MF, and a 4000 Hz CF with a 95 Hz MF were simultaneously presented to one ear. Frequency bins at 85, 87, 90, and 95 Hz are larger than the surrounding bins representing a present ASSR at all of the CFs.

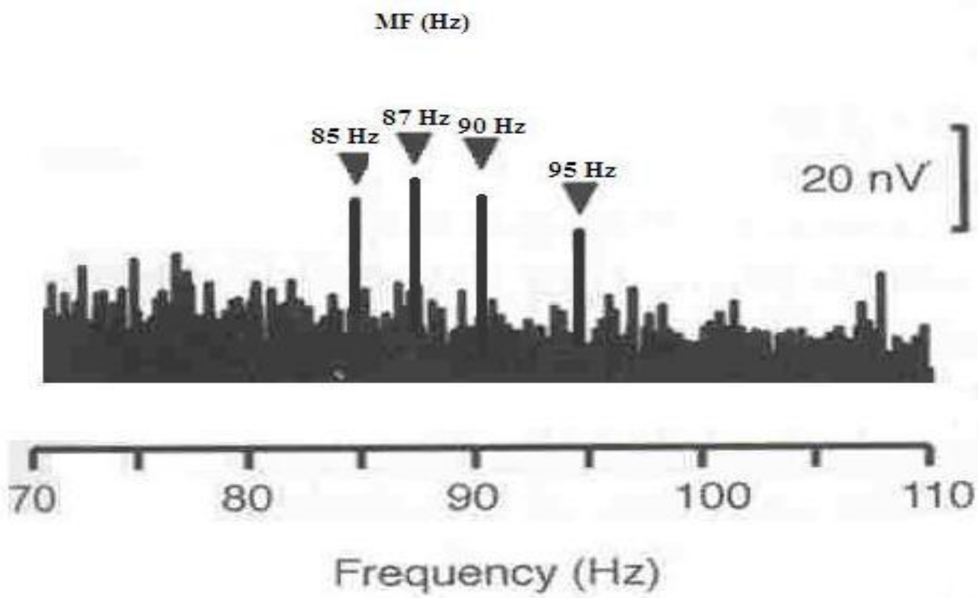


Figure 10. The FFT Analysis of a MF Stimulation technique is illustrated. A 500 Hz CF with an 85 Hz MF, a 1000 Hz CF with an 87 Hz MF, a 2000 Hz CF with a 90 MF, and a 4000 Hz with a 95 Hz MF were simultaneously presented at an audible level to one ear. Each CF is deemed present as the bin that represents each CF's MF is larger than surrounding bins or the background EEG noise.

Visual representation alone does not determine whether a response is deemed present or absent for either of the examples described above. A statistic known as the F-ratio, is used to calculate the power or statistical significance of the amplitude of the signal (energy at MF) divided by the amplitude of its surrounding frequencies (amplitude of the EEG noise) (Picton et al., 2003). Specifically, an F-ratio is calculated by comparing the responses at the MF of each CF tone to the 120 surrounding frequency bins surrounding the MF (± 60 frequency bins on either side of the MF) (Herdman & Stapells, 2001). Responses are considered significant at a predetermined "p value" that is typically an alpha level of $p \leq 0.05$. If the F-ratio does not reach this alpha level criterion than the response is determined absent as the amplitude of the signal at the MF is not deemed strong enough to be determined as a response (Picton, 2007).

ASSR Recording Parameters

A number of recording parameters can affect an audiologist's ability to successfully record an ASSR. These recording parameters include: EEG band pass analog filter settings, the gain of the amplifier, the electrode montage, the number of recording channels, and the stopping rules for averaging. Each of these recording parameters will be discussed in the following section.

EEG Analog Band Pass Filter Settings/ Gain of Amplifier

The goal of effective analog filter band pass settings is to remove ongoing background EEG noise at unnecessary frequencies from the response which, in turn, increase the response's signal to noise ratio (Cone and Dimitrijevic, 2009). In ASSR testing, a response is deemed present when the EEG signal is synchronized or phase locked to the MF of the response. Unwanted EEG noise is mostly generated in the brain, skin, eyes, tongue and the muscles of the scalp, face, and neck (Picton, John, Purcell, & Plourde, 2003).

The ASSR is deemed present or absent based on the amplitude of the response to the CF tone at the MF (Cone and Dimitrijevic). The MFs that are typically used in ASSR testing range from 70-110 Hz. Therefore the EEG analog band pass filter settings must be broad enough to keep the responses at the MFs intact in the EEG signal (GSI Brochure, 2001). Picton (2007) recommends that the routine use of EEG analog band pass filter settings of 30-300 Hz as they rid the response of some unnecessary noise from the EEG signal while still preserving the energy at the MFs (Cone & Dimitrijevic, 2009).

Since the amplitude of the ASSR is relatively small, the EEG needs to be amplified so that the signal can be converted from the analog to the digital form without the loss of information. The EEG signal is typically amplified by 50,000 times in order for a typical analog to digital range of plus or minus 5 V to be achieved (Picton, 2007).

Electrode Montage

ASSRs in adults are maximally recorded using an electrode located on the vertex (Cz) or mid frontal scalp as the non-inverting electrode with reference electrodes located on the mastoid, posterior neck, or inion (Picton, 2007). In adults, the largest response amplitudes occur when Cz is referred to the neck at the midline or ipsilateral to the ear stimulated. Responses that use the inion as the reference electrode tend to be slightly smaller than those that use cervical vertebrae 7 (CV7) on the lower neck. However, the inion is considered a good reference electrode when adult subjects remain awake as the lower neck is often contaminated by muscle activity (Picton, 2007).

In 2005, Van der Reijden, Mens, and Snik (2005) studied the effects that 55 different electrode montages had on the SNRs of ASSRs in infants (age 0 to 5 months). The researchers used either 500 Hz or 2000 Hz CF tones that were MM (100% AM and 20% FM) with a MF of either 90 Hz for the left ear or 94 Hz for the right ear. Their results demonstrated increased SNRs for infants occurred when the vertex electrode was used as the non-inverting electrode and the mastoid ipsilateral to the stimulated ear was used as the reference or inverting electrode placement.

Number of Recording Channels

Two channel recordings (ipsilateral and contralateral) are considered to be optimal for recording the ASSR. Small and Stapells (2008b) reported that in adults, there were very small (1 dB) differences in the mean ASSR thresholds recorded in the ipsilateral versus contralateral channels for both air- and bone- conduction testing.

In contrast, Small and Stapells (2008b) demonstrated that in infants (aged 2 to 11 months) ipsilateral air conduction recordings have greater response amplitudes in comparison to contralateral recordings. This results in better signal to noise ratios (SNRs) and lower ASSR thresholds in the ipsilateral channel. These investigators also reported that infants had bone conduction ASSR thresholds that were on average 13-15 dB poorer in the contralateral channel as compared to the ipsilateral channel. This pattern was true for both the 500 and 4000 Hz CF tones. Small and Stapells (2008b) attributed these threshold differences in ipsilateral and contralateral recordings in infants to the immature auditory pathways and skull structure of infants. The auditory pathway undergoes complex neuro-maturational changes until 5 years of age. The membranous, unfused structure of the skull that an infant is born with develops into a rigid, fused structure during adulthood. These neuro-maturational changes affect the interaural attenuation values for bone conducted stimuli. Small & Stapells (2008) reported that infants have interaural attenuation values of at least 10 to 30 dB, while most adults studies (ages 18-40 years) have little or no interaural attenuation.

In general, the use of two recording channels (ipsilateral and contralateral) is recommended for ASSR testing, especially with adults. If differences in ASSR threshold estimations between channels are seen during testing and audiologists have ruled out any testing errors, then audiologist should rely on information obtained from the ipsilateral channel.

Stopping Rule for Averaging

An automatic stopping rule for averaging allows for either a maximum number of sweeps to be obtained (i.e., 64 for the AUDERA software) or for a specific signal magnitude to be reached (i.e., $p<0.3$ for the AUDERA software) in order for the software to discontinue obtaining EEG samples (GSI Brochure, 2001). Either a preset number of sweeps and/or a preset amplitude of the response are the criteria that must be met in order to stop sampling. A preset number of sweeps prevents clinicians from obtaining an inordinate number of sweeps that does not necessarily increase the likelihood of the response achieving statistical significance (GSI Brochure, 2001).

Don, Elberling, and Waring (1984) originally investigated the idea of having an automatic objective stopping rule for averaging which could be applied to the auditory brainstem response (ABR) testing (Elberling & Don, 1987). The technique they developed was called the Fsp technique. The Fsp technique determines the presence/absence of a response by calculating data points along each sweep of the AEP.

Each data point's variance is analyzed in the ratio N*V2/V1. N equates to the number of sweeps averaged. V1 is a predetermined single point or position in which the variance of the EEG noise is measured for each sweep (i.e., the 20^{th} point in each sweep of 500 points is analyzed). V2 represents the variance of all points averaged within a designated time region of each response (i.e., 10 ms or where the response is expected). A response is determined to be present if the variance ratio (N*V2/V1) is greater than 1.0. In contrast, when no response occurs, the same variance ratio will equal 1.0. Various alpha levels can be used to signify the strength of the AEP. Alpha levels at 0.01 typically result in Fsp values of 3.1 while 0.05 alpha levels result in Fsp levels of 2.5 (Sininger & Hyde, 2009). Sininger and Hyde (2009) consider the Fsp variance ratio to be the most well established and powerful theoretical approach in determining the presence/absence of a response. These investigators also commented that the Fsp technique is clinically useful as it looks at more than just the residual noise levels present in the response.

The Fsp is equated to a stopping algorithm. This technique prevents the need for running a predetermined number of sweeps as long as the residual noise level is low enough. As soon as Fsp criterion is met, a response is considered positively detected, this, in turn, can significantly shorten test time. The algorithm associated with the Fsp technique not only provides an automatic stopping rule but also provides quality control for the AEP waveform and an improved signal-to-noise ratio (Elberling & Don, 1984).

Cone and Dimitrijevic (2009) propose several potential stopping rules for ASSR averaging that are either time based or based on the residual noise levels. These potential stopping rules include: 1) stopping the ASSR after 3 to 5 minutes when responses are found to be significant, 2) stopping averaging after 12 to 15 minutes for insignificant responses, 3) cease testing when averaged residual noise levels reach levels of 10 to 15 nV when 80 Hz MFs are utilized or levels of 60 to 90 nV when 40 Hz MFs are utilized, or 4) discontinue ASSR testing either after 12 minutes or when the average residual noise level equals 10 nV. To date, there has not been agreement in the literature regarding which objective stopping rule is optimal for ASSR testing.

Subject Factors

There are several subject factors that can affect the accuracy of the ASSR. This section of the literature review will focus on the effects that age, subject state and attention to task may have on the ASSR.

Age

ASSR responses can be obtained on individuals of all ages; however, ASSRs cannot be reliably recorded in infants using MFs of 40 Hz or less (Rickards et al., 1994). Lins et al. (1996) compared the response properties of ASSRs recorded to 500, 1000, 2000, and 4000 Hz CF tones in 4 clinical populations: well baby infants (ages 1-10 months), adolescents with identified hearing loss, adults with normal hearing sensitivity, and adults with a simulated hearing loss. The authors reported that the response amplitudes of the ASSRs were ~ 50% smaller in infants versus adults regardless of the CF of the tonal stimuli.

Luts, Desloovere, and Wouters (2006) compared the ASSR amplitudes and SNRs between two clinical groups (infants/young children versus adults). Specifically, one group consisted of 60 high-risk newborns and young children between the ages of birth and 4 years of age and the second group consisted of 10 adults with hearing within normal limits. The authors reported the newborns, with a mean age of 12 days old, had

ASSR thresholds that were elevated on average by 11 dB compared to the adult group and that the SNRs for the younger group were approximately 1.7 times smaller than for the adults.

John, Brown, Muir, and Picton (2004) reported that the amplitude of the ASSR increases over the first two to three months of life; therefore, they recommend performing ASSR testing at two months of age or older as it is easier and takes a shorter period of time when compared to testing a younger infant. Several studies have concluded that ASSRs can be reliably obtained on infants, children, and adults when MFs greater than 80 Hz are employed (Aoyogi et al., 1994; Lins et al., 1996; Luts, et al., 2006; Perez-Abalo et al., 2001).

Contradicting results have been reported in the literature regarding the effects of advanced aging on the ASSR. Johnson, Weinberg, Ribary, & Cheyne (1988) investigated the effects of advanced aging on the ASSR in two groups of neurologically normal adults: (1) 7 elderly adults with a mean age of 69.6 years; and (2) 5 younger adults with a mean age of 38.0 years. Johnson and colleagues elicited 40 Hz ASSRs using 1000 Hz CF tones presented binaurally. The researchers reported no statistically significant phase or amplitude differences between the ASSRs in the young versus elderly groups (Johnson et al., 1988). Boettcher and colleagues found similar results when comparing the amplitudes of the 40 Hz ASSRs in three different adult groups: 10 adults age 22-29 years, 7 adults aged 60-65 years, and 6 adults aged 66-72 years (Boettcher, Poth, Mills, & Dubno, 2001). Again, no significant differences in response amplitude or phase of the 40 Hz ASSRs were reported across the different age groups for either low (520 Hz) or high

(4000 Hz) CF tones. These researchers suggested that the normal aging process does not significantly affect the 40 Hz ASSR.

To the contrary, Picton, Dimitrijevic, Perez-Abalo, and Van Roon (2005) studied the effects of advanced aging of ASSRs recorded at a higher MF (80 Hz). The two groups of adult subjects in this study were: 10 adults' aged 19 to 31 years and 10 adults aged 61 to 71 years. These investigators reported that while no difference in the accuracy of the ASSR thresholds were found between the two groups, the amplitude of ASSR for the older adult group (aged 61-71 years) was significantly smaller than the ASSR amplitude for the younger adult group (age 19 to 31 years). Thus it appears that ASSR amplitudes are reduced in the elderly when higher MFs (80 Hz) are utilized as compared to younger adults. Given the disparity in findings across these studies, additional research is needed to clarify the effects of advanced aging on ASSRs.

Subject State

Picton (2007) reported that response amplitudes of the ASSR recorded to 40-Hz MFs are reduced by approximately 50% during natural sleep and are dramatically attenuated by most anesthetics. It is believed that these reductions in amplitude are due to the fact that the ASSR is dominated by contributions from the cortical regions of the brain at this lower MF. In contrast, ASSRs evoked to 80-Hz MFs are hardly affected by sleep. At this high MF, there is a dramatic reduction in the background EEG noise because the body becomes more relaxed and quieter during sleep (Picton, 2007). Therefore, subject state does not significantly affect ASSRs recorded to high MFs.

Linden, Picton, Hamel, and Campbell (1987) studied the effect that different types of attentional tasks had on the ASSR. In this study, 8 adult subjects (aged 27 to 40 years) had ASSRs recorded to 500 Hz CF tones presented at MFs ranging from 37 to 41 Hz. The ASSRs were monaurally recorded under two test conditions: an attending and an ignore condition. In the attending condition, the subjects were asked to count successive increments in stimulus intensity. In contrast, during the ignore condition the subjects were required to read a book and ignore the test stimulus. These researchers found no significant difference in the amplitude of the ASSR in either the attending or the ignore condition; Linden et al. (1987) also added a second test condition to their study. In this second condition, 10 normal hearing subjects (aged 22 to 38 years) were asked to attend to a dichotic listening task. The dichotic listening task required the subjects to count the number of changes in the frequency of the tonal stimuli (500 versus 1000 Hz) presented to one ear while ignoring the tones presented to the opposite ear over a 2 minute period. In this second test condition, Linden and colleagues reported no changes in the phase, amplitude, and/or threshold of the ASSR due to attentional effects. Linden and colleagues concluded that ASSRs recorded to 500 Hz tonal stimuli presented at MFs between 37 and 41 Hz are not influenced by the subjects' attention to the task for either monaural or dichotic listening conditions.

Ross and colleagues (2004) used MEG to explore if focused attention had an effect on the ASSR (Ross, Picton, Herdman, Hillyard, & Pantev, 2004). The investigators used 20 healthy, normal hearing adults (aged 23 to 54 years) and monaurally presented 500 Hz AM CF tones at a MF of 40 Hz. ASSRs were recorded under an attending and a non-attending test condition. The attending condition required the subject to discriminate a change in the MF (30 versus 40 Hz) and respond with a right handed press of a button. During the non-attending task, the subjects watched a slide show and counted the number of pictures in three categories: landscapes, animals, or humans. Ross and colleagues reported that the amplitudes of the ASSRs were enhanced during the attending task for 10 of the 12 subjects. The increase in amplitude occurred in the 200 to 500 ms post stimulus portion of the analysis window. This time window corresponds to the onset of the change in MF and is thought by the investigators to be the most relevant time interval for AM discrimination. Their MEG data showed larger effects of attention in the left hemisphere of the primary auditory cortex than in the right hemisphere.

Ross and colleagues (2004) speculated that their findings were different than those reported by Linden et al.'s (1987) due to the nature of the attention task. In the Linden et al. (1987) study, the attention task did not require their subjects to attend to the stimulus rhythm of the 40 Hz response and these researchers only utilized a single channel EEG recording. Therefore they were not able to distinguish between cortical and sub-cortical neural generators of the ASSR. The electrophysiological and MEG evidence provided by Ross et al. (2004) strongly suggests that changes in brain activity at the level of the primary auditory cortex occur when subjects are required to attend to the stimulus rhythm of the ASSR as compared to ASSRs recorded when subjects are not attending.

Frequency and Place Specificity of the ASSR

The ASSR is a considered both a frequency and place specific response. Frequency specificity refers to how independent the frequency or frequencies being tested are from contributions from surrounding frequencies while place specificity refers to the portion of the basilar membrane that is activated in response to the presentation of a stimulus (Oates & Stapells, 1997). Oates and Stapells (1997) investigated the frequency specificity of both the auditory brainstem response and middle latency response recorded to 80 dB peak SPL Blackman gated and linear gated tones. The researchers studied normal hearing adults (n=12). Both linear gated and Blackman gated tones were presented at 500 and 2000 Hz. Each tone was simultaneously presented with broadband pink noise. The ABR and MLR were recorded in quiet as well as in 9 different high pass noise test conditions. The researchers used a noise masking technique known as the high pass noise/derived response analysis (HPN/DR) technique to determine the frequency and place specificity of these two evoked potentials to the 500 and 2000 Hz tonal stimuli. These investigators reported that the center frequency of the derived bands for both the ABR and MLR showed that the primary contributions to these responses came from the primary test frequency with reduced cochlear contributions to the response coming from a ½ octave above and below the test frequency. Based on these findings, Oates and Stapells concluded that the ABR and MLR recorded to these 80 dB peak SPL 500 and 2000 Hz tones had good frequency and place specificity. These investigators also reported that there was no statistically significant difference in the frequency/place specificity of the responses to the Blackman versus linear gated tones (Oates & Stapells, 1997).

This same noise masking technique can be applied to study the frequency and place specificity of other AEPs, such as the ASSR. Herdman, Picton, and Stapells (2002) investigated the place specificity of the ASSR using this same HPN/DR technique. These researchers used both SF and MF stimulation techniques to obtained ASSRs for AM CFs ranging from 250 to 8000 Hz in 9 young adults (mean age= 18) with normal hearing (Herdman, Picton, & Stapells, 2002). Herdman and colleagues (2002) reported that the center frequency of the derived band for each CF tone was centered within one half of an octave of the CF tone. Herdman and colleagues (2002) also reported there were no significant differences in the derived band responses obtained using either the SF or MF stimulation technique. Therefore, these researchers concluded that the ASSRs to AM stimuli are the result of activation of a relatively narrow portion of the cochlea which is centered at the region of the basilar membrane best tuned to the CF tone, and thus the ASSR has good place specificity. Herdman and colleagues (2002) reported that this pattern is true regardless of whether the stimuli are presented individually in a SF stimulation technique or simultaneously in a MF stimulation technique.

A second way to assess the frequency specificity of an AEP is to see how accurately this AEP predicts behavioral pure tone thresholds. The next section of the literature review will discuss studies that have investigated how well the ASSR thresholds predict pure tone behavioral thresholds.

Threshold Estimation

The following section of this literature review will discuss the accuracy of the ASSR in predicting pure tone behavioral thresholds in two different clinical groups: (1) adults with normal hearing sensitivity and (2) adults with sensorineural hearing loss (SNHL). In order to accurately understand the ASSR literature in this area, the reader must understand the meaning of the term "difference scores". Difference scores are measured by subtracting an individual's behavioral pure tone threshold at one stimulus frequency from their ASSR threshold at the same test frequency (i.e., ASSR threshold- Behavioral Pure Tone Threshold= Difference Score). The smaller the difference score, the more accurate the ASSR threshold was in predicting the pure tone behavioral threshold. Calculation of mean difference scores allows investigators to quantify the level of accuracy that the ASSR threshold predicts the pure tone behavioral threshold at each carrier frequency. Secondly, it also allows investigators to compare their results to the findings reported in other published studies.

Adults with Normal Hearing

Several groups of researchers have investigated how well ASSR thresholds predict pure tone behavioral thresholds in adults with normal hearing sensitivity. Some of these studies have employed the SF stimulation technique for recording ASSRs, while others have used the MF stimulation technique. The mean difference scores as well as other associated details reported in these studies are summarized in Table 1. Below is a brief description of these studies.

Table 1

ASSR Mean Difference Scores for Adults with Normal Hearing

Study	**Stimuli**	**Stimulation Technique**	**Mean Difference Scores (+/- 1 SD)**			
			500 Hz	**1k Hz**	**2k Hz**	**4k Hz**
Herdman & Stapells (2001)	AM	SF (monaurally)	7(13)	10(12)	12(10)	14(6)
Cone-Wesson, Dowell, Tomlin et al. (2002a)	MM	SF	40(7)	-	-	15(9)
Lins, Picton, Boucher et al. (1996)	AM	MF	14(11)	12(11)	11(8)	13(11)
Herdman & Stapells (2001)	AM	MF (monaurally)	11(11)	10(11)	11(10)	14(10)
	AM	MF (binaurally)	14(10)	8(7)	8(9)	15(9)
Dimitrijevic, John, Van Roon et al. (2002)	MM	MF	17(10)	4(11)	4(8)	11(7)
Vander Werff & Brown (2005)	AM	MF	25(10)	18(9)	13(7)	13(8)
D'haenens, Dhooge, De Vel et al. (2007)	MM	MF	20(12)	14(9)	10(8)	12(8)

Note. The type of stimuli, stimulation technique, and mean difference scores with their standard deviations (SD) are given for each study. Mean difference scores are reported followed by (± 1 SD). AM is an amplitude modulated pure tone, and MM is both an amplitude and frequency modulated pure tone. SF is a single frequency and MF is a multiple frequency stimulation technique.

Herdman & Stapells (2001) recorded ASSRs to AM tones presented at carrier frequencies of 500, 1000, 2000 and 4000 Hz in 10 young adults (age range 21-42 years) with normal hearing sensitivity. The 4 carrier frequency tones were presented monaurally in a SF stimulation mode. Herdman & Stapells (2001) reported that their mean difference scores ranged from 7 to 14 dB, with slightly larger mean difference scores occurring at the higher (2000 and 4000 Hz) versus lower (500 and 1000 Hz) CFs as shown in Table 1. The variability in these difference scores, reflected in the SD values, was relatively similar across the 4 CFs.

Cone-Wesson and colleagues (2002a) recorded ASSRs to MM tones (100% AM and 10% FM) presented at carrier frequencies of 500 and 4000 Hz in 10 young, normal hearing adults (age range 20-35 years). The 2 CF tones were presented monaurally in a SF stimulation mode. Cone-Wesson et al. (2002a) reported a mean difference score of 15 dB at 4000 Hz and a mean difference score of 40 dB at 500 Hz, as seen in Table 1. The variability in these difference scores, reflected in the SD values, was comparable between both CFs. Both groups of researchers concluded that ASSRs recorded using the SF stimulation technique can be used to accurately predict behavioral audiograms in normal hearing adults.

Lins and colleagues (1996) recorded ASSRs to AM tones presented at CFs of 500, 1000, 2000, and 4000 Hz in 20 normal hearing subjects who ranged in age from 17-40 years. The AM stimuli in this study were presented in three conditions: 1) a SF stimulation technique presented monaurally, 2) a MF stimulation technique presented monaurally, and 3) a MF stimulation technique presented binaurally. The mean difference scores for each of these three test conditions were averaged together and reported as the general average. The mean differences scores in this study ranged between 11 to 14 dB, with minimal differences seen across CFs. The variability present in the difference scores, reflected in the SD values, was similar for each CF and ranged from 8 to 11 dB.

Herdman and Stapells (2001) replicated Lins et al.'s (1996) investigation. Under the same test conditions, these researchers evaluated 10 naturally sleeping, normal hearing adults. Their mean difference scores for the MF stimulation technique presented monaurally ranged from 10 to 14 dB; while their mean differences scores for the MF stimulation technique presented binaurally ranged from 8 to 15 dB, as shown in Table 1. The variability present in the difference scores was similar for the monaural versus binaural test conditions. Based on their test results, Herdman and Stapells concluded that the ASSR thresholds were on average between 5 and 15 dB of the pure tone behavioral thresholds for all 4 carrier frequencies. They also reported there were no significant differences in the accuracy of ASSR threshold prediction for the SF versus the MF stimulation techniques and secondly there was no significant difference in ASSR threshold prediction as a function of carrier frequency.

Dimitrijevic and colleagues (2002) investigated the accuracy of ASSR thresholds in predicting pure tone behavioral thresholds in 14 young normal hearing adults, ranging in age from 23-63 years (Dimitrijevic, John, Can Roon, Purcell, Adamonis, Ostroff, Nedzelski, & Picton, 2002). In this study, ASSR thresholds were established at 500, 1000, 2000, and 4000 Hz CFs using MM stimuli (100% AM and 20% FM) which were presented at MFs ranging from 80 to 95 Hz. A MF stimulation technique was employed and thus these four CF tones were simultaneously presented in a monaural fashion. Mean difference scores were calculated and ranged from 4 to 17 dB, with the smallest difference scores occurring at 1000 and 2000 Hz, as seen in Table 1. The variability in the data was essentially similar across CFs. Based on this data, Dimitrijevic and colleagues concluded that, on average, ASSR thresholds exceed behavioral thresholds by approximately 8 dB (Dimitrijevic et al., 2002).

Vander Werff and Brown (2005) examined 10 adults with normal hearing to determine the accuracy of ASSR thresholds in predicting pure tone thresholds at CFs of 500, 1000, 2000, and 4000 Hz. The stimuli in this study were 100% AM tones which were presented monaurally using a MF stimulation technique at MFs ranging between 78 and 92 Hz. Both ASSR thresholds and behavioral thresholds were obtained for both ears. These investigators reported that strong correlations occurred between the ASSR thresholds and the behavioral pure tone thresholds. The mean difference scores in this study ranged from 13 to 25 dB and SDs varying between 8 and 10 dB across frequencies, as seen in Table 1. A slightly poorer difference score of 25 dB was recorded at 500 Hz, compared to other higher CFs. These investigators reported that their mean difference scores were in good agreement with prior research which employed the MF technique (i.e., Picton et al., 2001; Dimitrijevic et al., 2002; Herdman and Stapells, 2001).

Lastly, D'haenens and colleagues (2007) published similar results. These investigators recorded ASSRs to MM stimuli using a MF stimulation technique in a relatively large group (n=51) of young adults with normal hearing sensitivity. The mean difference scores in this study ranged from 10 to 20 dB with SDs varying from 8 to 12 dB. The mean difference score at 500 Hz was slightly larger than at the remaining CFs. The variability in these difference scores was relatively similar across CFs.

In general, the mean difference scores reported in Table 1 reveal that ASSRs can produce reliable estimates of pure tone behavioral thresholds at 500, 1000, 2000, and 4000 Hz in adults with normal hearing sensitivity. The accuracy of this threshold prediction appears to be independent of whether a SF or a MF stimulation technique is employed.

Adults with Sensorineural Hearing Loss

The principle audiologic application of the ASSR is for threshold estimation in order to accurately diagnose hearing loss (Cone & Dimitrijevic, 2009). Mean difference scores reported in the ASSR literature provides investigators with a quantitative index of how well ASSR thresholds estimate pure tone behavioral threshold across the various frequencies. Several studies have investigated how accurately the ASSR predicts pure tone thresholds for adults with sensorineural hearing losses (SNHL). The issues addressed in these studies include: (1) the overall accuracy of threshold prediction in this clinical population; (2) the effect, if any, of configuration of the SNHL hearing loss on the accuracy of threshold prediction; (3) the effect, if any, of degree of SNHL on the accuracy of threshold prediction; and (4) the effect, if any, of ASSR stimulation technique (SF versus MF) on the accuracy of threshold prediction. The results of these studies are reported in Table 2, which is organized according to these four issues.

Table 2

ASSR Mean Difference Scores for Adults with Sensorineural Hearing Loss

	Study	Stimuli	Stimulation Technique	Degree of HL	Config.	Mean Difference Scores (± 1 SD) 0.5 Hz	1k Hz	2k Hz	4k Hz
Overall	Dimitrijevic, John, Van Roon et al. (2002)	MM	MF	Normal Mild Moderate Severe	Flat High- Frequency Reverse- Sloping	13(11)	5(8)	5(9)	8(11)
	Van Maanen & Stapells (2005)	MM	MF	n/a	n/a	17(11)	15(7)	19(9)	4(10)
Configuration	Herdman & Stapells (2003)	AM	MF	n/a	Steeply Sloping	13(13)	8(10)	12(10)	1(10)
		AM	MF	n/a	Flat	15(13)	7(8)	7(11)	5(9)
	Vander Werff & Brown (2005)	MM	MF	Moderately-Severe	High Frequency	18(8)	10(7)	8(6)	5(4)
					Flat	11(5)	8(4)	7(5)	6(5)
Degree	Rance, Rickards, Cohen et al. (1995)	MM	MF	Normal to Moderate	-	10(8)	9(7)	6(6)	5(4)
				Moderately-Severe to Severe	-	10(3)	6(4)	4(3)	5(4)
				Profound	-	6(5)	5(5)	4(3)	5(4)
	Picton, Dimitrijevic, Perez-Abalo et al. (2005)	MM	MF	Normal to Mild	High Frequency	21(14)	7(10)	11(7)	12(10)
		MM	MF	Moderate to Severe	n/a	11(18)	-4(9)	3(11)	5(12)
Stimulation Technique	Luts & Wouters (2005)	MM	SF	Mild to Profound	n/a	20(8)	14(7)	13(7)	14(13)
		MM	MF	Mild to Profound	n/a	17(2)	12(8)	17(8)	19(12)

Note. The type of stimuli, stimulation technique, and mean difference scores with their standard deviations (SD) are given for each study. When applicable, the degree and configuration (Config.) of the subjects' sensorineural hearing losses are provided. Mean difference scores are reported followed by (± 1 SD). AM is an amplitude modulated pure tone, and MM is both an amplitude and frequency modulated pure tone. SF is a single frequency and MF is a multiple frequency stimulation technique.

Overall Effects.

Dimitrijevic and colleagues (2002) studied the overall effects that SNHL has on how well ASSR thresholds predict pure tone behavioral thresholds. These researchers studied 59 ears in 31 adults with SNHL whose three-frequency pure tone averages ranged from normal to severe and hearing loss configurations varied from flat to high frequency losses and to low frequency losses. Auditory Steady-State Response thresholds were recorded using MM stimuli that were 100% AM and 25% FM. The ASSRs were obtained using a MF stimulation technique and the four CF tones (500 – 4000Hz) were presented at MFs ranging from 80 to 95 Hz. Dimitrijevic et al. (2002) reported that a strong correlation exists between ASSRs thresholds and behavioral pure tone thresholds. Mean difference scores for their participants with SNHL ranged from 5 to 13 dB across the 4 CFs, as shown in the top section of Table 2. The variability in these difference scores, reflected in the SD values, ranged from 8 to 11 dB. The mean difference scores were somewhat dependent on CF, with the smallest difference scores occurring at the mid frequencies (1000 and 2000 Hz). In general, the average ASSR thresholds collapsed across CFs were 8 dB higher than the pure tone behavioral thresholds (Dimitrijevic et al., 2002).

Van Maanen and Stapells (2005) also addressed this issue by determining ASSR thresholds in 23 adult subjects (age range from 45-80 years) with SNHL. Similar to the Dimitrijevic et al (2002) study, the ASSRs in the present study were recorded to MM stimuli using a MF stimulation technique with MFs ranging from 77 to 100 Hz. Van Mannen and Stapells reported that their mean difference scores ranged from 4 and 19 dB across the 4 CFs, with SD values ranging from 7-11, as shown in the top section of Table

2. The results of both the Dimitrijevic et al. (2002) and Van Maanen and Stapells (2005) studies clearly demonstrated that ASSRs can be used to accurately predict SNHL in adults.

Configuration.

Herdman and Stapells (2003) were interested in determining whether the configuration of the SNHL had an effect on the accuracy of behavioral thresholds estimation via ASSR thresholds. In address this question, these investigators determined ASSR thresholds on 31 adults with SNHL. Herdman and Stapells divided their subjects into two groups: (1) 13 individuals who had flat/shallow sloping SNHLs, meaning their hearing losses had a slope of < 30 dB/octave; and (2) 18 individuals who had steeply sloping SNHLs, meaning their hearing losses had a slope of ≥ 30 dB/octave. These investigators recorded the ASSRs to AM tones presented using a MF stimulation technique with MFs ranging from 77 to 100 Hz. Herdman and Stapells (2003) reported that their mean difference scores ranged from 5 to 15 dB for the flat/shallow sloping group and from 1 to 13 dB for the steeply sloping group, as shown in Table 2 in the panel labeled “configuration”. On average, the mean difference score for the 500 Hz CF tone was 3-4 dB greater than the mean difference scores for any of the other CFs (i.e., 1000-4000 Hz). Based on these findings, Herdman and Stapells concluded that the configuration of individuals’ SNHL can be accurately predicted by the ASSR. This is true for individuals with flat/shallow sloping SNHLs as well as those with sharply sloping SNHLs.

Vander Werff and Brown (2005) also compared the ASSR thresholds and behavioral pure tone thresholds of individuals with flat SNHLs to those with sloping high frequency SNHLs. In this study, ASSR were recorded to AM stimuli presented using a MF stimulation technique with MFs ranging between 78 to 92 Hz. These investigators reported that the mean difference scores for participants with flat SNHLs ranged from 6 to 11 dB across the 4 CFs, while those with high frequency SNHLs had mean difference scores that ranged from 5 to 18 dB across frequencies, as shown in Table 2. The variability in the difference scores, reflected in the SD values was essentially similar between the two groups of subjects. Vander Werff and Brown reported that there were no statistically significant differences in the mean difference scores for these two groups of subjects. Similar to Herdman and Stapells results from 2003, the largest mean difference scores were seen at 500 Hz in comparison to the remaining three CF tones. This finding was true for both the flat SNHL group as well as the high frequency SNHL group.

Collectively the results of these two studies suggest that ASSR thresholds can be used to accurately predict behavioral pure tone thresholds in patients with flat, shallow sloping, or steeply sloping SNHL. Based on their results, Herdman & Stapells (2003) concluded that ASSR thresholds for one frequency are not affected by better hearing thresholds at an adjacent frequency.

Degree.

Rance and colleagues (1995) examined the relationship between the accuracy of ASSR threshold prediction and behavioral pure tone thresholds in adults with varying degrees of SNHL (Rance, Rickards, Cohen, DeVidi, & Clark, 1995). The investigators recorded ASSRs in 35 adult subjects (age from 24-82 years), with hearing sensitivity ranging from normal hearing to a profound SNHL. The 35 subjects were divided into three groups based on the severity of their hearing loss: (1) behavioral thresholds between 0-55 dB HL, (2) behavioral thresholds between 60-85 dB HL, and (3) behavioral thresholds at 90 dB HL and above. ASSR thresholds were determined at CFs of 250, 500, 1000, 2000, and 4000 Hz. Rance et al. (1995) reported mean difference scores ranged from 5 to 10 dB for the subjects in group 1 (behavioral thresholds from 0-55 dB HL). The mean difference scores for the subjects in group 2 (behavioral thresholds from 60-85 dB HL) ranged from 4 and 10 dB, and the mean difference scores ranged from 4 to 6 dB for subjects in group 3 (behavioral thresholds at 90 dB HL and above). These findings are shown in Table 2 in the panel labeled “degree of HL”. The variability in the difference scores, reflected in the SD values, was greater for the individuals in group 1 (normal to moderate SNHL). These researchers reported that the difference scores in groups 1 and 2 were significantly different with larger difference scores being seen for group one. Lastly, in all subject groups, behavioral pure tone thresholds for higher frequencies were more closely predicted by the ASSR than lower frequency tones.

Picton and colleagues (2005) investigated the effects that varying degrees of SNHL had on the accuracy of ASSR threshold prediction (Picton, Dimitrijevic, Perez-Abalo, & Van Roon, 2005). The investigators recorded ASSRs in two elderly subject groups. One subject group consisted of 10 subjects, ranging in age from 64-86 years, with hearing sensitivity ranging from normal hearing to a mild SNHL. The second subject group consisted of 10 subjects, ranging in age from 61-77 years, with hearing sensitivity ranging from a moderate to severe SNHL. ASSR thresholds were determined at CFs of 500, 1000, 2000, and 4000 Hz. Picton et al. (2005) reported mean difference scores ranged from 7 to 21 dB across the 4 CFs for the elderly subjects in group 1 (normal hearing to a mild high frequency SNHL); while mean difference scores for the elderly subjects in group 2 (moderate to severe SNHL) ranged from -4 and 11 dB across the various CFs, as shown in Table 2 in the panel labeled “degree of HL”. The variability in the difference scores was similar for groups 1 and 2. The smaller mean difference scores reported for the individuals in group 2 clearly suggest that the more severe the degree of SNHL, the greater the accuracy of ASSR thresholds in predicting the degree of the hearing loss.

Stimulation technique.

Luts and Wouters (2005) compared the effects that the two types ASSR stimulation techniques (SF versus MF) had on the accuracy of ASSR threshold prediction. ASSR thresholds were obtained using a monaural SF stimulation technique via the GSI AUDERA software and using a binaural MF stimulation technique via MASTER software. The researchers used MM stimuli (100% AM and 20% FM) with MFs ranging from 74-110 Hz at the four CFs (500-4000 Hz). Luts and Wouters reported that the SF stimulation technique had mean difference scores ranging from 13-20 dB, with SD values between 7 to 13 dB; while the MF stimulation technique had mean difference scores ranging from 12 and 19 dB, with SDs varying between 8 to 12 dB, as seen in the bottom panel of Table 2. No statistically significant variability in difference scores between the two stimulation techniques was reported. Based on these findings, Luts and Wouters concluded that the SF and MF stimulation techniques estimate ASSR thresholds equally well for adults with SNHL (Luts & Wouters, 2005).

Bone Conduction

There are several ways in which bone conduction thresholds can be obtained via ASSR testing. The first, and more traditional method, presents the stimuli through the bone conduction vibrator and air conduction masking is used to isolate the cochlea (Dimitrijevic et al., 2002). The second method is called the sensorineural acuity level test (SAL) in which masking noise is presented through the bone oscillator to determine the amount of noise needed to mask the air conduction threshold (Cone & Dimitrijevic, 2009; Dimitrijevic et al., 2002; Jerger & Jerger, 1985;). Using the SAL technique, the ASSR bone conduction threshold is effective bone conduction masking level and air-bone gaps are determined by calculating the difference between the ASSR air conduction threshold and the bone conduction effective masking level (Cone & Dimitrijevic, 2002). To date, there are relatively few studies that have evaluated the accuracy of ASSR pure tone bone conduction thresholds; the studies described below ascertain that ASSR bone conduction thresholds can reliably predict the behavioral pure tone bone conduction thresholds in adults (Cone & Dimitrijevic, 2009). These findings are only reliable for adult subjects as the skulls of infants less than 1 year of age transduce bone conducted stimuli much differently than adults (Cone & Dimitrijevic, 2009). Infants less than 1 year of age will commonly appear to have air-bone gaps exceeding 10 to 15 dB due to the immaturity of the infant's skull (Cone & Dimitrijevic, 2009).

Adults with normal hearing.

Dimitrijevic and colleagues (2002) evaluated 16 adults (age 23 to 49 years) with normal hearing to examine the accuracy of ASSR in predicting pure tone bone conduction thresholds (Dimitrijevic, John, Van Roon, Purcell, Adamonis, Ostroff, Nedzelski, & Picton, 2002). A MF stimulation technique was used to obtain bone conduction thresholds and these were determined at CFs of 500 through 4000 Hz using MM tones presented at MFs ranging from 80 to 95 Hz. A Radioear model B-71 bone oscillator was placed on the middle of the forehead and held in place using an elastic strap with a force of 765 grams. Conductive hearing losses were simulated with the use of insert earplugs. Difference scores for the ASSR bone conducted thresholds were calculated. Mean difference scores were 22 ± 8 dB, 14 ± 5 dB, 5 ± 8 dB, and 5 ± 10 dB at 500, 1000, 2000, and 4000 Hz, respectively (Dimitrijevic et al., 2002).

Several years later, Small and Stapells (2005) evaluated the accuracy of ASSR bone conduction thresholds in estimating pure tone behavioral bone conduction thresholds in 10 normal hearing adults (age 20 to 48 years). Contrary to Dimitrijevic and colleagues (2002), Small and Stapells (2005) employed a mastoid placement for the bone oscillator as opposed to the former study's forehead placement. The Radioear model B-71 bone oscillator was secured using a Velcro headband and had an average coupling force of 450 to 550 grams. Using a MF stimulation technique, ASSRs were obtained for CFs of 500 through 4000 Hz using MFs ranging from 77 to 101 Hz. Mean difference scores were 22 ± 14 dB, 26 ± 3.5 dB, 18 ± 7.9 dB, and 18 ± 14 dB for 500, 1000, 2000, and 4000 Hz, respectively (Small & Stapells, 2005). In general, Small and Stapells (2005) mean difference scores were approximately 5 dB higher than those reported by Dimitrijevic et al. (2002) for normal hearing adults.

During the last 5 years, Small and Stapells conducted a series of studies to investigate how well ASSR bone conduction thresholds predicted behavioral bone conduction thresholds in infants. This series of studies addressed a number of developmental as well as technical parameters involved in recording these responses in the pediatric population. This issues included: (1) effect of neuro-maturation on the accuracy of the ASSR thresholds; (2) the effects of coupling method and placement of the bone oscillator on the ASSR; (3) the effect of number of recording channels and (4) the effect of stimulus artifact. The studies that addressed each of these issues will be briefly discussed below.

Effects of neuromaturation on the ASSR.

Small and Stapells (2006) compared ASSR bone conduction thresholds obtained from three subject groups: (1) 29 preterm infants (age 32 to 43 weeks post-conceptional age), (2) 14 full term infants (age 0 to 8 months) and (3) 10 normal hearing adults. ASSR bone conduction thresholds for all three subject groups were obtained using MM stimuli presented at CFs of 500 to 4000 Hz with MF from 77 to 100 Hz. Small and Stapells reported that a significant age effect was obtained such that poorer or higher ASSR thresholds were obtained for the premature infants as compared to the older infants and adults. This effect was true across all CFs. These investigators also reported that the average ASSR thresholds at the lower frequencies (i.e., 500 and 1000 Hz) were statistically better or lower for both groups of infants as compared to the adult group. For example, the two infant groups had average ASSR thresholds of approximately 15 and 9 dB at 500 and 1000 Hz, respectively, while the adults had average thresholds of 21 and 25 dB at these same two frequencies. In contrast, the adults had better or lower ASSR thresholds at the higher frequencies (i.e., 2000 and 4000 Hz) in comparison to both infant groups. In general, the premature infants had ASSR thresholds which were approximately 2.5 to 13 dB poorer or higher in comparison to the full term infants. This pattern was true across all four CFs. Small and Stapells (2006) speculated that, these small differences in ASSR thresholds between these two groups of infants were attributable to neuro-maturational changes in the infants' skulls and increased levels of ambient noise while testing the premature babies in the NICU.

Small and Stapells (2008) conducted a study to further investigate the neuro-maturational effects that can occur on ASSR pure-tone bone conduction thresholds. In this study, ASSRs were recorded to MM stimuli presented using a MF stimulation technique with MFs ranging between 77 to 100 Hz across the four CF tones. ASSR thresholds were recorded from three subject groups: (1) 35 young infants (age 0.5 to 44 weeks old) who passed their universal newborn hearing screening; (2) 13 older infants (age 12 to 24 months) who passed their universal newborn hearing screening; and (3) 18 adults (age 19 to 48 years) with normal hearing. These investigators reported that low frequency bone conduction ASSR thresholds increase with age while high frequency thresholds remained stable. Specifically, Small and Stapells (2008) reported that at a CF tone of 500 Hz, the youngest infants had ASSR thresholds which were 20 dB lower in comparison to the thresholds from the adult subjects and 10 dB lower in comparison to the older infant subjects. At a CF tone of 1000 Hz, adult ASSR bone conduction thresholds were 20 dB higher than both infant groups. A different pattern of results was seen for ASSRs to the higher frequency tones. At 2000 Hz, ASSR thresholds for the adults were 20 dB better than for both infant groups, while at 4000 Hz the ASSR thresholds were similar across all subject groups. Based on these findings, Small and Stapells (2008) reached two conclusions: (1) there are neuro-maturational changes that occur in the BC ASSR recorded from pre-mature and full term infants, and (2) differences in ASSR bone conduction thresholds occur across frequency for infants. Both of these factors must be accounted for when conducting ASSRs on both pre-mature and full term infants.

Effects of coupling method and bone oscillator placement.

Small, Hatton, and Stapells (2007) investigated how varying the method of coupling the bone oscillator to the skull as well as varying the location of the bone oscillator had on the accuracy of predicting BC behavioral thresholds using ASSR BC thresholds. Specifically in this study, these investigators compared the amount of force applied to the bone oscillator by an elastic headband coupling method versus a hand held coupling method. ASSRs were recorded for two patient groups in this study. These were normal hearing infants ranging in age from 0.5 to 38 weeks and normal hearing adults ranging in age from 20-39 years. Small and colleagues (2007) reported that there was no significant difference in the amount of force applied to the bone oscillator using these two coupling methods. These researchers then investigated whether there were any significant differences in ASSR bone conduction thresholds as a function of these two coupling methods in either subject group. Small, Hatton, and Stapells (2007) reported that for adults, the mean BC ASSR thresholds ranged from -0.3 to 11.5 dB for the elastic band coupling method and from 0.1 to 8.7 dB for the hand held method. Results of the statistical analyses revealed no significant main effect for type of coupling method for the adults. Similarly, Small and colleagues (2007) reported that for infants, the mean BC ASSR thresholds ranged from 6.0 to 26 dB for the elastic band coupling method and from 1.0 to 25 dB for the hand held method. The results of statistical analyses revealed that the infants' ASSR thresholds were not statistically different as a function of coupler method.

The second question addressed by Small and colleagues (2007) was the effect the location of the bone oscillator had on the accuracy of ASSR thresholds infants. ASSRs were recorded when the bone oscillator was at 3 different locations of the infant's skull. These locations were: (1) temporal bone, (2) mastoid, and (3) forehead. These investigators reported that significantly poorer or higher ASSR thresholds were recorded when the oscillator was located on the forehead in comparison to the other two locations. This finding was true across all four CFs. There was no significant difference in ASSR thresholds for the temporal bone versus mastoid placement (Small et al., 2007).

As a result of these findings, Small and colleagues (2007) concluded that either the elastic head band or the hand-held coupling methods are appropriate for clinical use when performed by properly trained professionals. Furthermore, forehead placements should be avoided when obtaining pure-tone bone conduction thresholds on premature infants as research shows that it regularly results in decreased amplitudes and increased threshold estimations. Since there were no differences in ASSR amplitudes or thresholds for either temporal or mastoid placements; either the temporal or the mastoid placement could be used when obtaining pure-tone ASSR bone conduction thresholds on premature infants (Small et al., 2007).

Effects of number of channel recordings.

Small and Stapells (2008b) recorded ASSR bone conduction thresholds using two-channel recordings in infants (age 2 to 11 months) and adults (age 18 to 40 years) to determine if asymmetries between ipsilateral and contralateral channels exist. Mean bone conduction thresholds in the infant subject group were 13 to 15 dB higher in the contralateral channel as compared to the ipsilateral channel for CF tones of 500 to 4000

Hz while there were no significant differences in ASSR thresholds between the two recording channels for adults. Therefore, based on the difference in ipsilateral and contralateral thresholds seen in infants, it was concluded that infants have an interaural attenuation at a minimum of 10 to 30 dB while adults have no interaural attenuation for bone conduction (Small & Stapells, 2008b).

Effects of Stimulus Artifact Rejection.

Stimulus artifact is often seen with air conduction ASSR testing at higher stimulus intensities (i.e., ≥ 95 dB HL) as well as at moderate intensities (≥ 40 dB HL) for bone conduction testing (Cone & Dimitrijevic, 2009; Hall, 2007). Stimulus artifact rejection is most often noted during bone conduction testing as it is more prominent at lower stimulus intensities as compared to air conduction testing. Stimulus artifact is a physiologic or electromagnetic artifact that may be present in the EEG response, and may result in an increase in a false-positive identification of an ASSR (Hall, 2007). Artifact rejection parameters are one available way in which to control for stimulus artifacts. There are two methods for reducing stimulus artifact. These are: (1) change the digital-to-analog conversion rate so that it is not a harmonic of the CF being tested, or (2) use a steep anti-aliasing (low pass) filter (Picton & John, 2004; Small & Stapells, 2005). Stimulus artifact rejection parameters eliminate any EEG samples that are elicited over a pre-determined or set amplitude (i.e., 80 mV). This prevents an EEG sample with an abnormally large amplitude from being averaged into the response. Since artifact rejection eliminates some EEG samples from being averaged, longer test times can result in attempt to retrieve enough samples for adequate signal analysis (Cone & Dimitrijevic, 2009). The following section will discuss the calibration of modulated stimuli.

Calibration

As with any audiometric procedure, precise calibration of the modulated tones is required in order to obtain accurate ASSR thresholds. Calibrating modulated tones is completed by measuring the sound pressure level (SPL) of the modulated tone the same way one would measure a pure tone (Cone & Dimitrijevic, 2009). Commercial sound level meters permit that user to select levels in either dB SPL or dB HL. The ASSR is typically calibrated in dB HL; however, Stapells, Herdman, and Small (2005) predict that this calibration trend will soon become a debate in the ASSR literature since ASSR thresholds reported in dB HL for infants and those with conductive or mixed hearing losses result in elevated ASSR thresholds relative to their behavioral thresholds. A modulated tone at 0 dB HL will have the same sound pressure level as a pure tone at 0 dB HL on an audiometer (Cone & Dimitrijevic, 2009). Cone and Dimitrijevic (2009) explain that modulated tones have less power than non-modulated tones. A difference of approximately 2 to 3 dB will occur when comparing the psychosocial threshold of a 100% AM tone to the psychosocial threshold of a non-modulated tone. This discrepancy between modulated and non-modulated tones is not compensated through the use of dB HL calibration. Calibration of these tonal stimuli is an area in need of additional research which might hopefully lead to the development of universal standards in this area.

Clinical Applications and Future Research

The following section of this literature review will discuss both the clinical application and future research needed for the clinical application of the ASSR. Currently, the primary application of the ASSR is to estimate hearing thresholds in infants, children, and adults who are suspected to have a hearing loss (Cone &

Dimitrijevic, 2009). As described earlier in this literature review, ASSRs can be used to accurately predict both air conduction and bone conduction thresholds. ASSRs can be beneficial as the presence/absence of a response can be determined objectively. The ASSR can provide objective measures regarding the appropriate fit and the benefit from amplification, albeit hearing aids or cochlear implants (Cone & Dimitrijevic, 2009). One advantage of the ASSR is that it can be obtained at stimulus intensity levels greater than ABR equipment is capable of producing. The high presentation levels of the ASSR allows for the accurate identification of more severe SNHLs and for the detection of residual hearing levels, both of which can aid in the decision making process for cochlear implantation. To date, limited research has also been completed on the clinical application of the electrically evoked ASSR to determine the action potentials of the eighth nerve which can also be used in determining cochlear implant candidacy and in cochlear implant mapping; however, continued research is required before the electrically evoked ASSR can be clinically relevant.

Several researchers have attempted to use supra-threshold ASSR stimuli in assessing patient’s word recognition and temporal processing abilities. Picton et al. (2003) predicts that studying the individual’s abilities to detect changes in modulation may predict how well those subjects are able to detect changes in amplitude and frequency that are important to speech discrimination. Word recognition was suspected to be correlated with ASSRs because both multiple modulated tones and speech quickly vary between intensity and frequency. Dimitrijevic and colleagues (2001) identified that the number of significant responses to 4 CFs (500-4000 Hz) presented in a MF stimulation technique binaurally correlated to word recognition scores when either the modulated tones or words varied in intensity for normal hearing adults (Dimitrijevic, John, Van Roon, & Picton, 2001). Similarly, in 2004, Dimitrijevic et al. demonstrated a strong correlation between word recognition scores and the number of ASSR components present in young adults with normal hearing, elderly with normal hearing, and elderly with hearing loss (Dimitrijevic, John, & Picton, 2004). The larger number of CFs determined present indicated a larger amount of acoustic stimuli available to the listener and the greater the word recognition score. The ASSR may also demonstrate the auditory systems ability to process changes in temporal cues (Picton et al., 2003). Future research is needed to identify if the auditory systems ability to detect rapid changes in acoustic information can be assessed by effects of modulation frequencies of the ASSR.

Statement of Purpose

A considerable amount of research has been conducted regarding the ASSR. The ASSR has been proven to produce reliable threshold estimations in a variety of clinical populations. There is great potential for the ASSR to be used to test difficult clinical populations, specifically infants, in order obtain reliable and accurate frequency specific threshold estimations. Although a considerable amount of research has been completed on the ASSR and is detailed in our literature review, there is still a need for a central informative resource that will provide clinicians with current evidence-based practices. The aim of this thesis project is to develop an ASSR website to be used as a clinical reference for Doctor of Audiology (Au.D.) students, recent Au.D. graduates, and audiologists that are not familiar with the current recommended evidence based ASSR testing protocol. Auditory Steady-State Responses are a unique AEP measure that encompasses unique terminology as compared to other AEPs. It is believed, that this

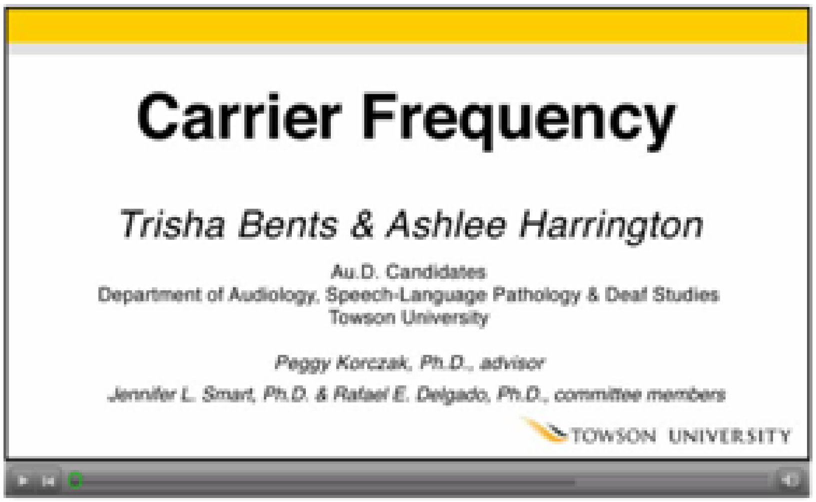
ASSR website will be used as a central reference for those clinicians who have been educated in AEPs, but may be new to ASSR testing. Still shots of the animations developed for use on the website can be found in Appendix A while Appendix B provides the scripts associated with the respective animations. Appendix C contains images of the non-animated figures. Appendix D and E contain images of the tables and printer friendly PDF, respectively, that are located throughout the webpages. Lastly, Appendix F contains samples of still shots from the published website. The published website can be viewed in its entirety at http://tiger.towson.edu/~tbents1/assr/.

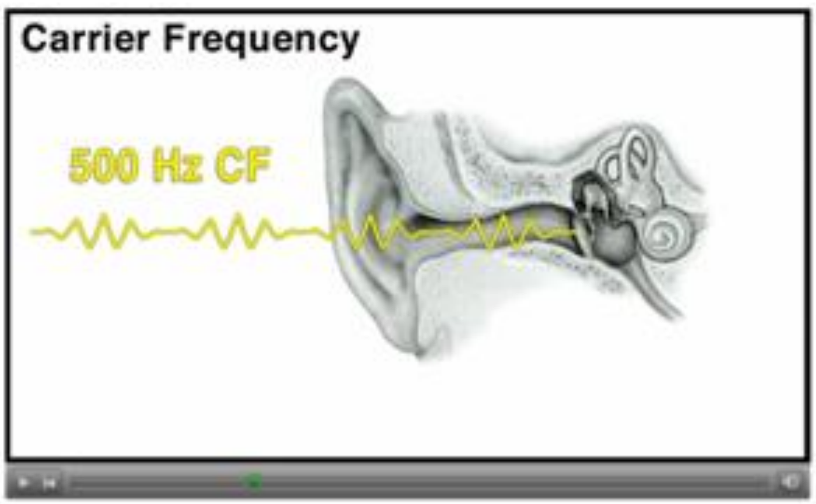
APPENDICES

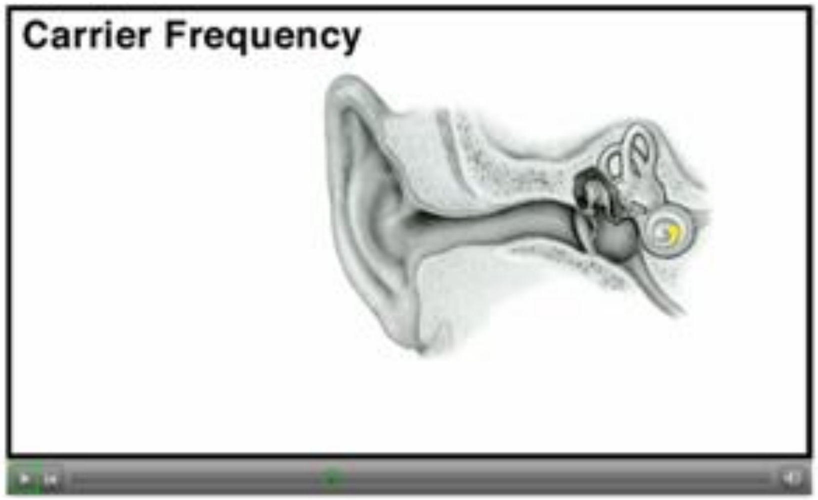
APPENDIX A

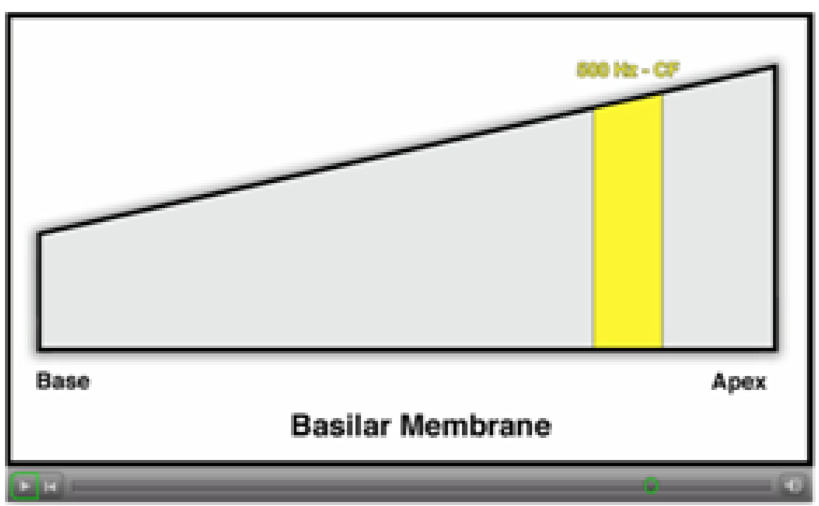
STILL SHOTS FOR ANIMATED FIGURES

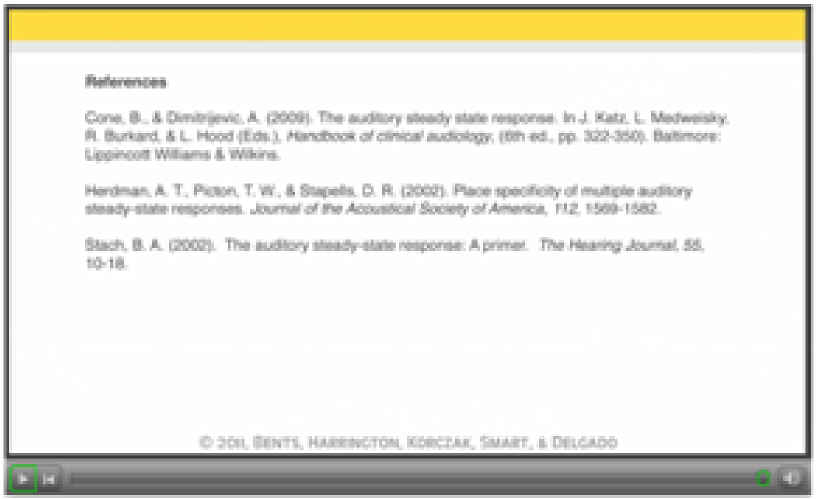
Carrier Frequency Animation Still Shots






Carrier Frequency


Base
Apex
Basilar Membrane


References
Cone, B., & Dimitrijevic, A. (2009). The auditory steady state response. In J. Katz, L. Medwetsky, R. Burkard, & L. Hood (Eds.), Handbook of clinical audiology, (6th ed., pp. 322-350). Baltimore: Lippincott Williams & Wilkins.
Herdman, A. T., Picton, T. W., & Stapells, D. R. (2002). Place specificity of multiple auditory steady-state responses. Journal of the Acoustical Society of America, 112, 1569-1582.
Stach, B. A. (2002). The auditory steady-state response: A primer. The Hearing Journal, 55, 10-18.
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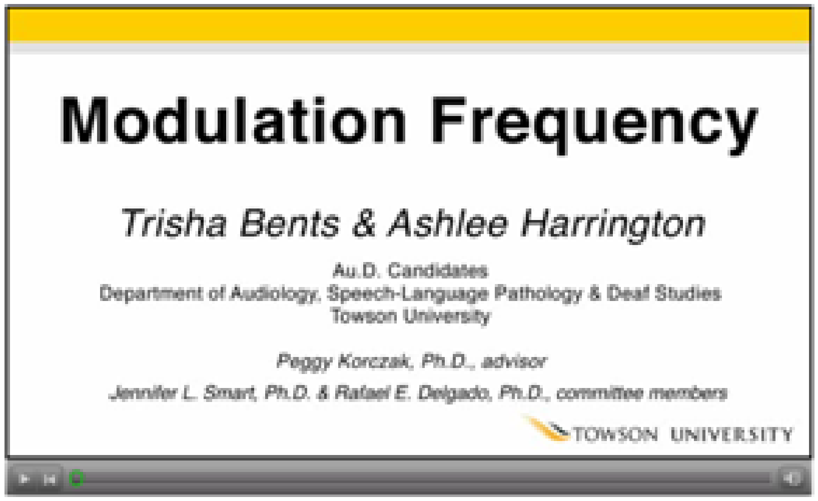
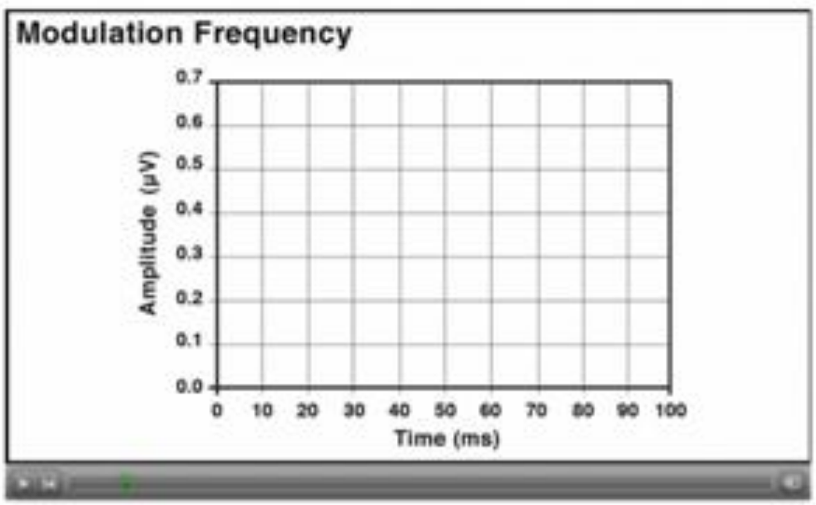
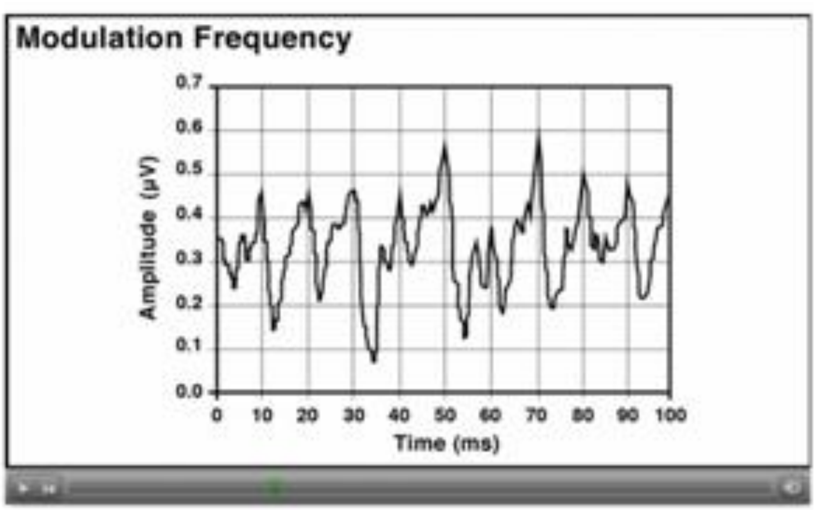
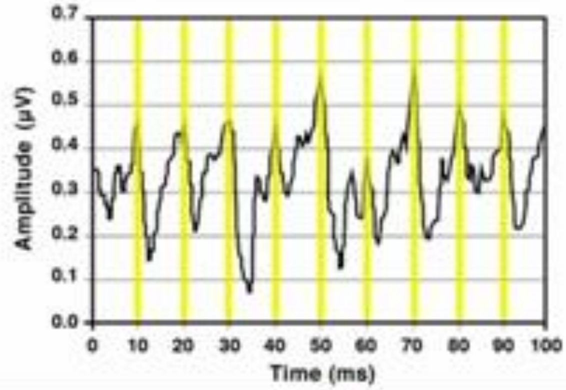
Modulation Frequency Animation Still Shots







Modulation Frequency

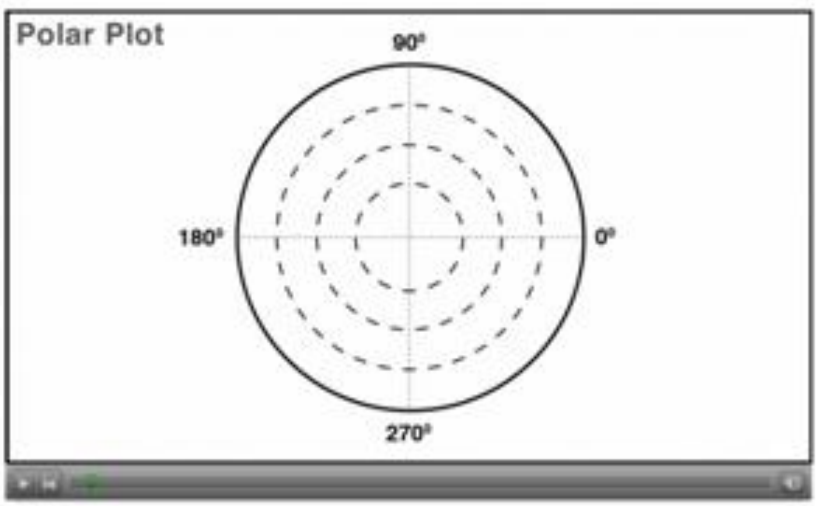


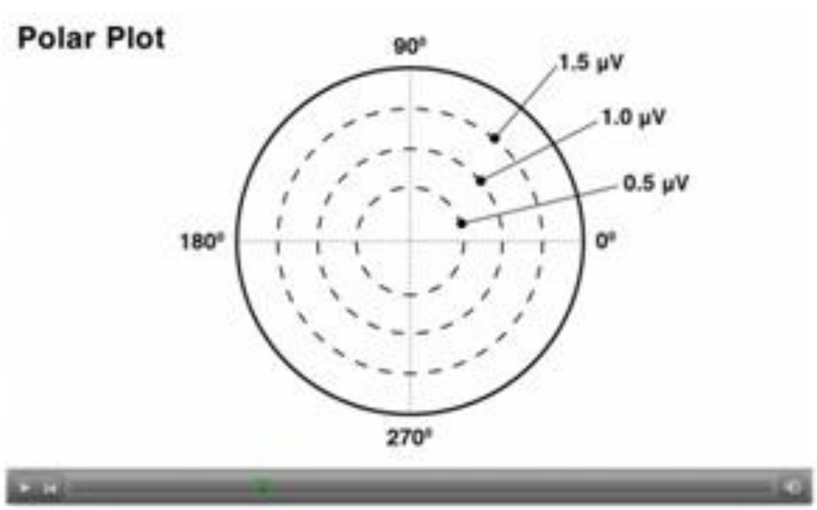
References

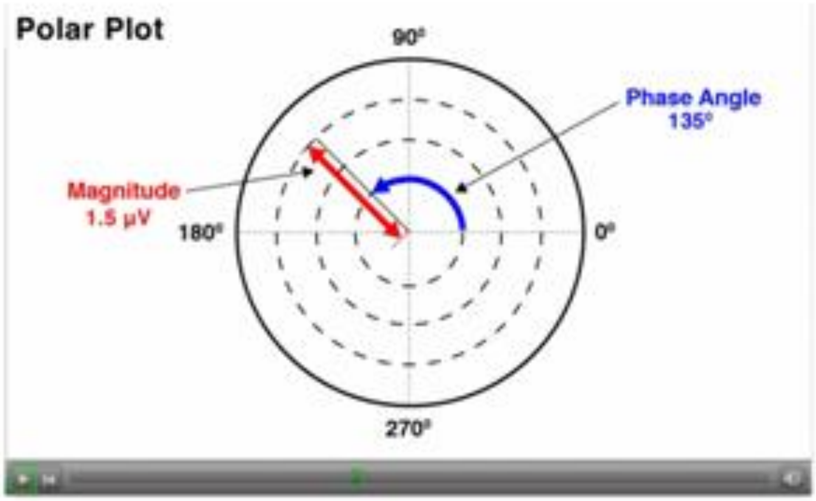
Cone, B., & Dimitrijevic, A. (2009). The auditory steady state response. In J. Katz, L. Medwetsky, R. Burkard, & L. Hood (Eds.), *Handbook of clinical audiology*, (6th ed., pp. 322-350). Baltimore: Lippincott Williams & Wilkins.

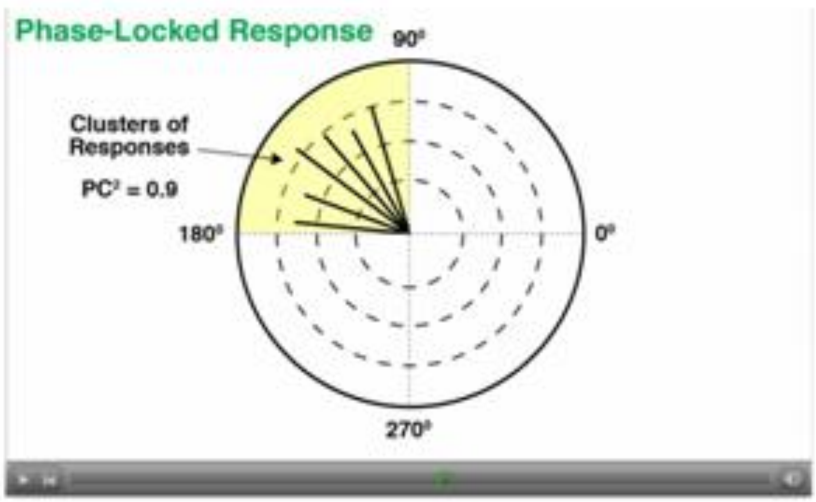
Grason-Stadler Inc. (2001). *Auditory steady-state evoked response: A new tool for frequency-specific hearing assessment in infants and children.* [Brochure]

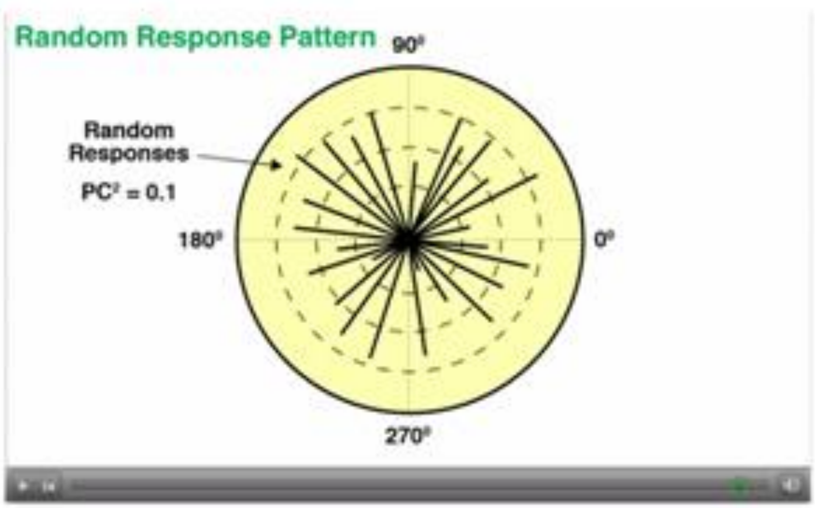
Phase Coherence Animation Still Shots



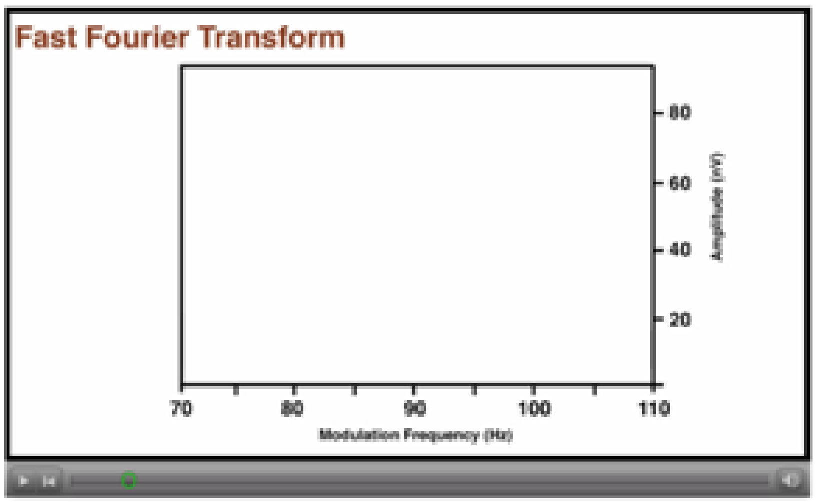


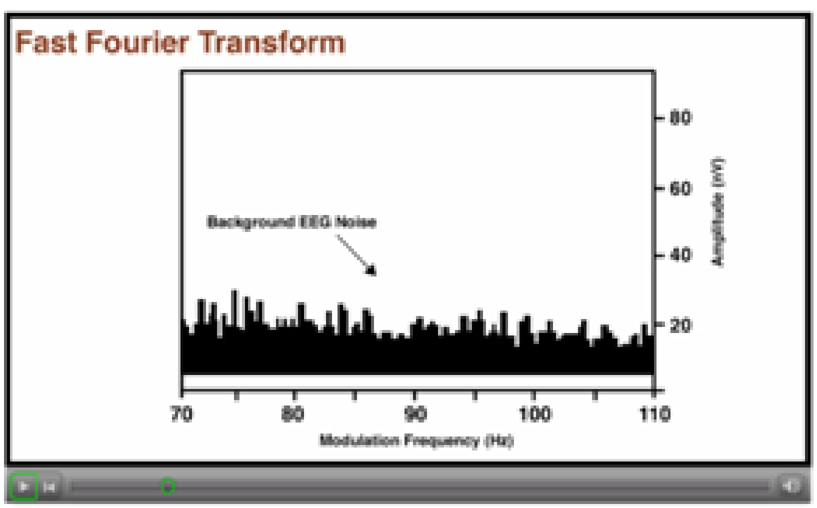

Polar Plot
90°
Phase Angle
135°
Magnitude
1.5 µV
180°
0°
270°

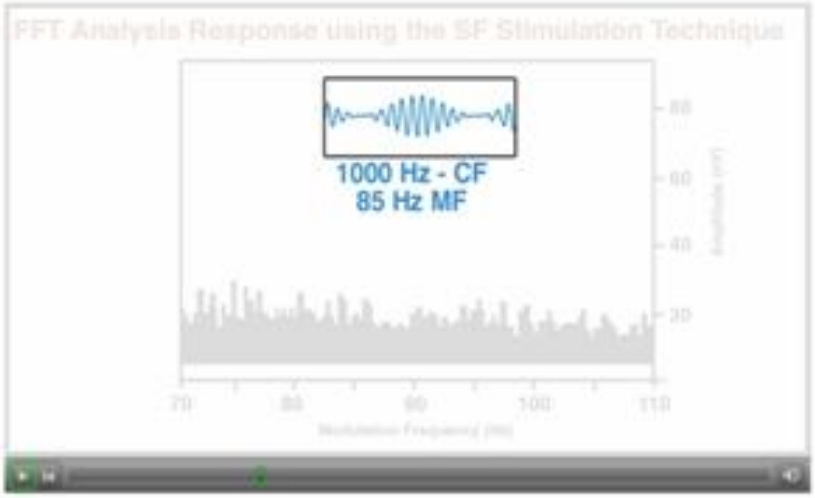

Phase-Locked Response
90°
Clusters of
Responses
PC² = 0.9
180°
0°
270°

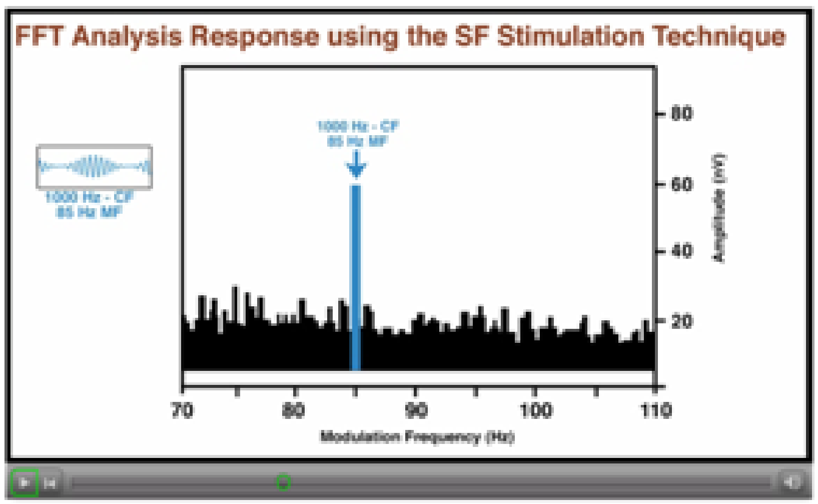

Random Response Pattern
90°
Random
Responses
PC² = 0.1
180°
0°
270°

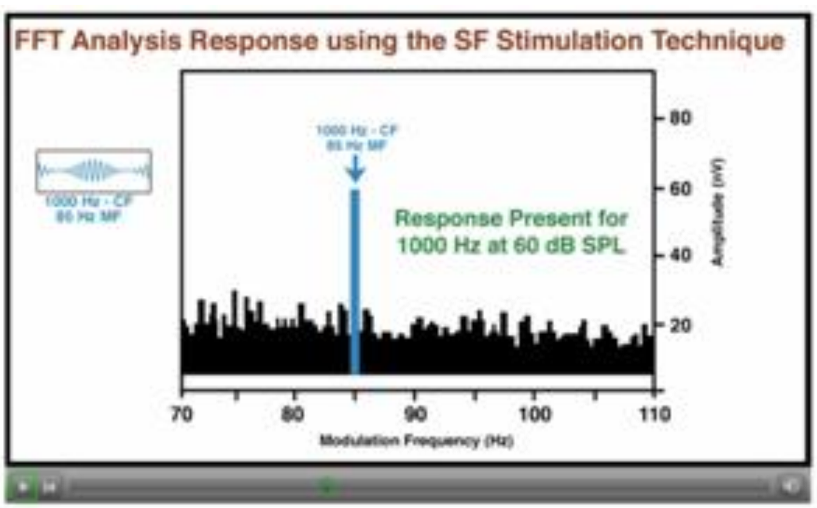
Fast Fourier Transform (FFT) and F- Ratio Animation Still Shots

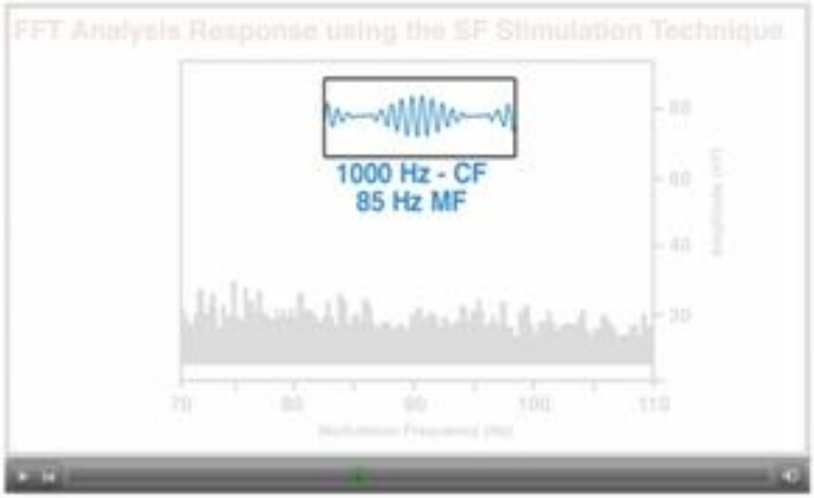


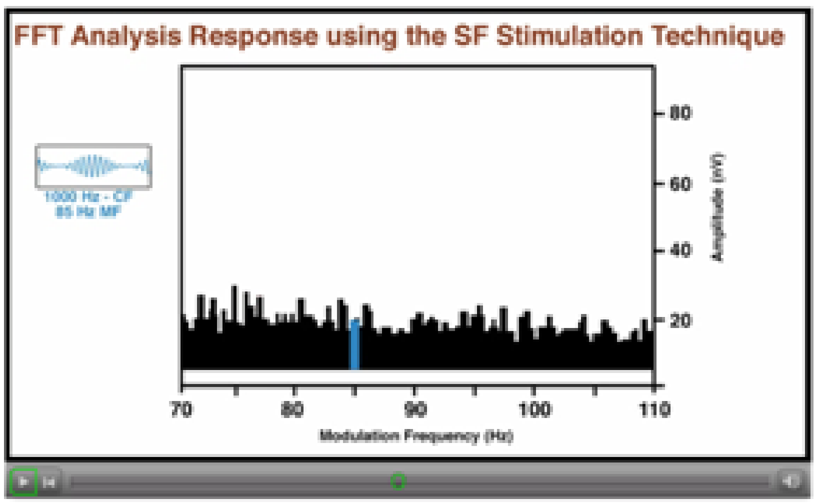


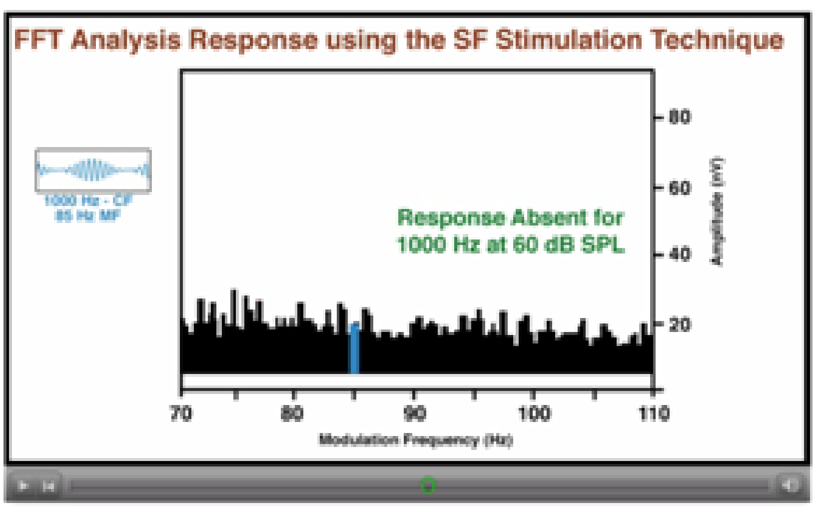

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
80
60
40
20
70
80
90
100
110
Modulation Frequency (Hz)
Amplitude (nV)

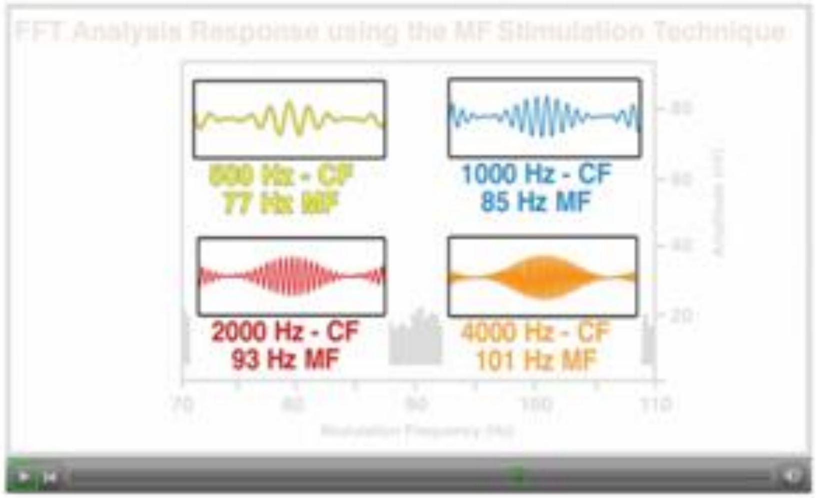

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
1000 Hz - CF
85 Hz MF
80
60
40
20
70
80
90
100
110
Modulation Frequency (Hz)
Amplitude (nV)

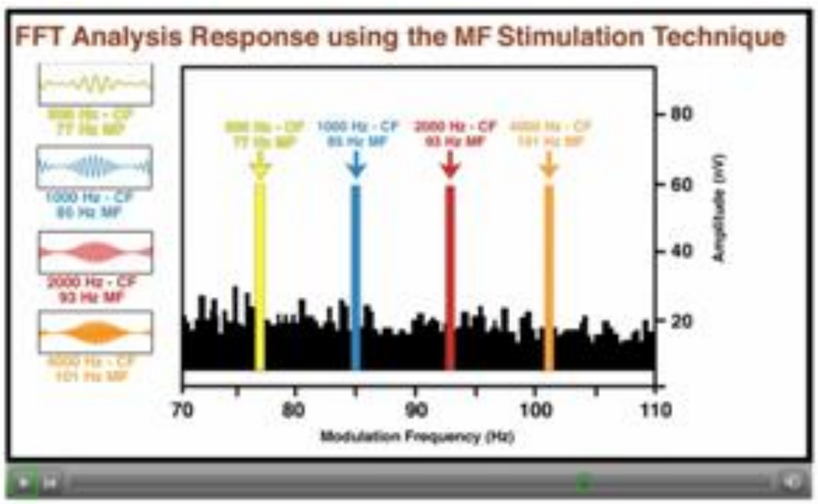

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
1000 Hz - CF
85 Hz MF
Response Present for
1000 Hz at 60 dB SPL
80
60
40
20
70
80
90
100
110
Modulation Frequency (Hz)
Amplitude (nV)

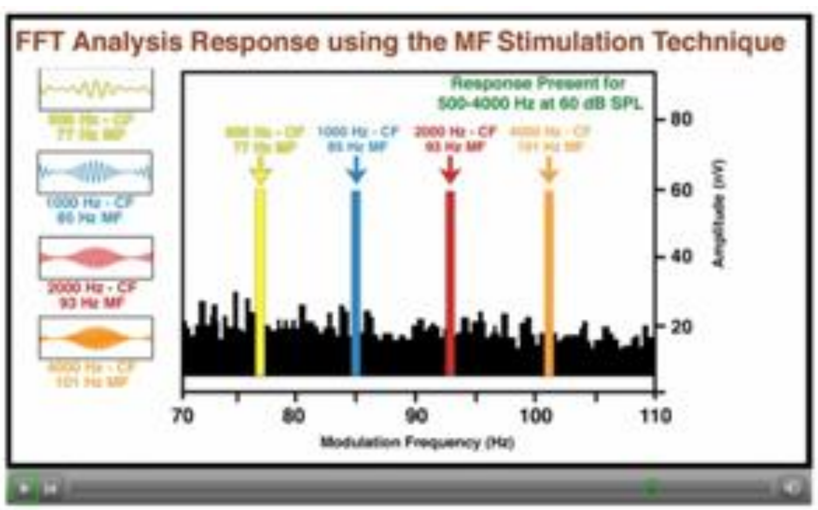

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF

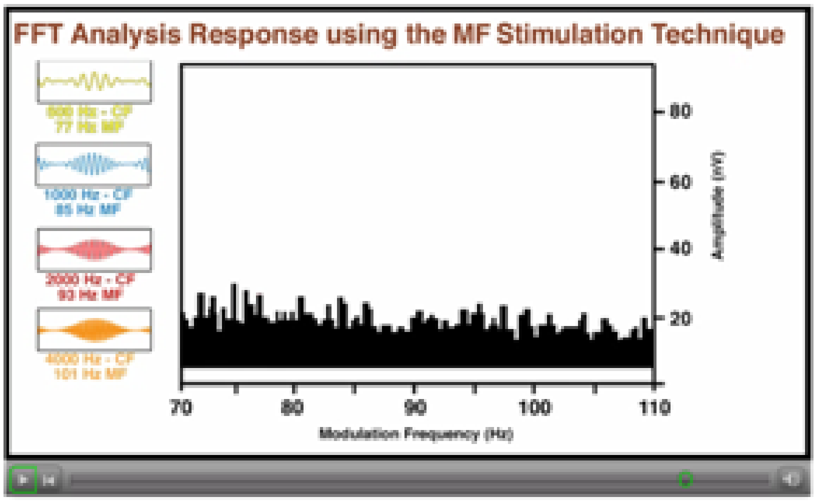

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

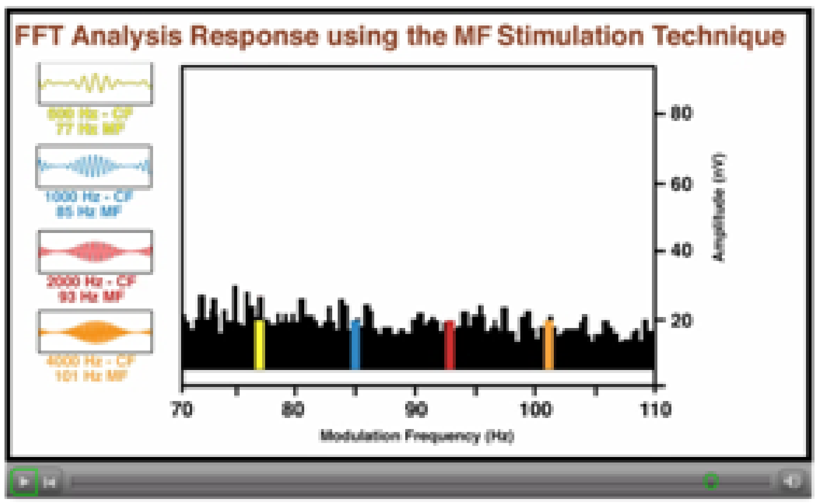

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
Response Absent for
1000 Hz at 60 dB SPL
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

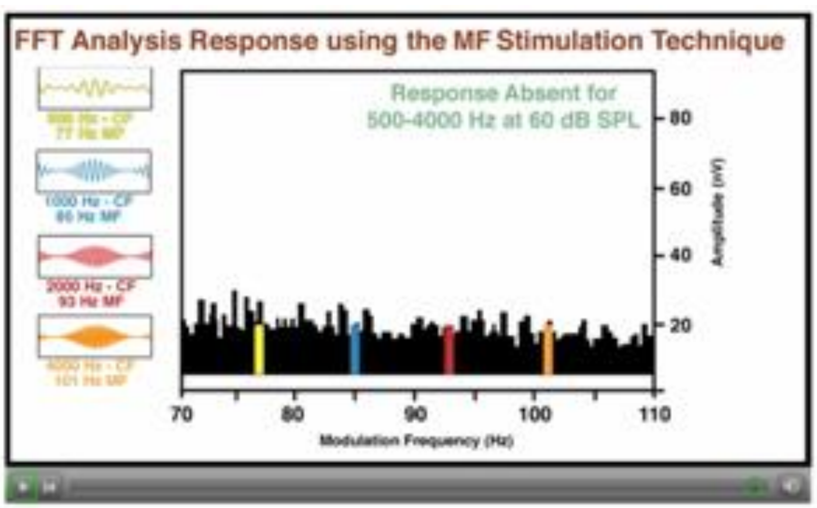

FFT Analysis Response using the MF Stimulation Technique
1000 Hz - CF
85 Hz MF
2000 Hz - CF
93 Hz MF
4000 Hz - CF
101 Hz MF

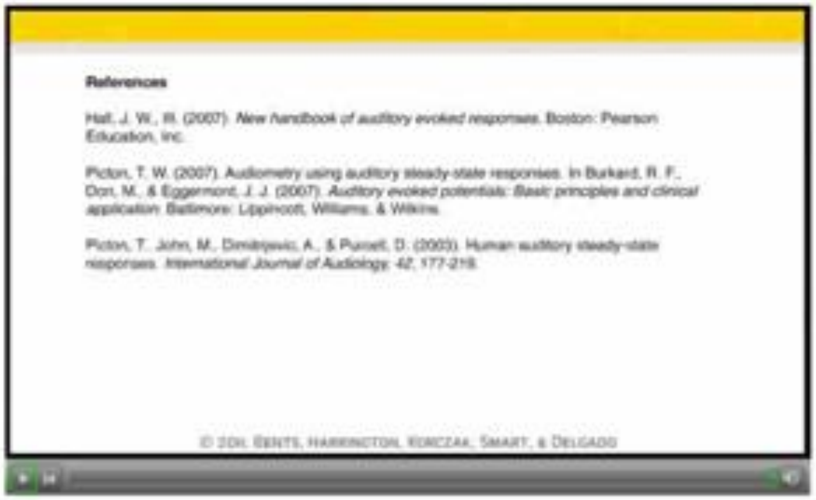

FFT Analysis Response using the MF Stimulation Technique
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)


FFT Analysis Response using the MF Stimulation Technique
Response Present for
500-4000 Hz at 60 dB SPL
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)


FFT Analysis Response using the MF Stimulation Technique
1000 Hz - CF
85 Hz MF
2000 Hz - CF
93 Hz MF
4000 Hz - CF
101 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)


FFT Analysis Response using the MF Stimulation Technique
1000 Hz - CF
85 Hz MF
2000 Hz - CF
93 Hz MF
4000 Hz - CF
101 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)


FFT Analysis Response using the MF Stimulation Technique
Response Absent for
500-4000 Hz at 60 dB SPL
2000 Hz - CF
93 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)


References
Hall, J. W., III. (2007). New handbook of auditory evoked responses. Boston: Pearson Education, Inc.
Picton, T. W. (2007). Audiometry using auditory steady-state responses. In Burkard, R. F., Don, M., & Eggermont, J. J. (2007). Auditory evoked potentials: Basic principles and clinical application. Baltimore: Lippincott, Williams, & Wilkins.
Picton, T., John, M., Dimitrijevic, A., & Purcell, D. (2003). Human auditory steady-state responses. International Journal of Audiology, 42, 177-219.
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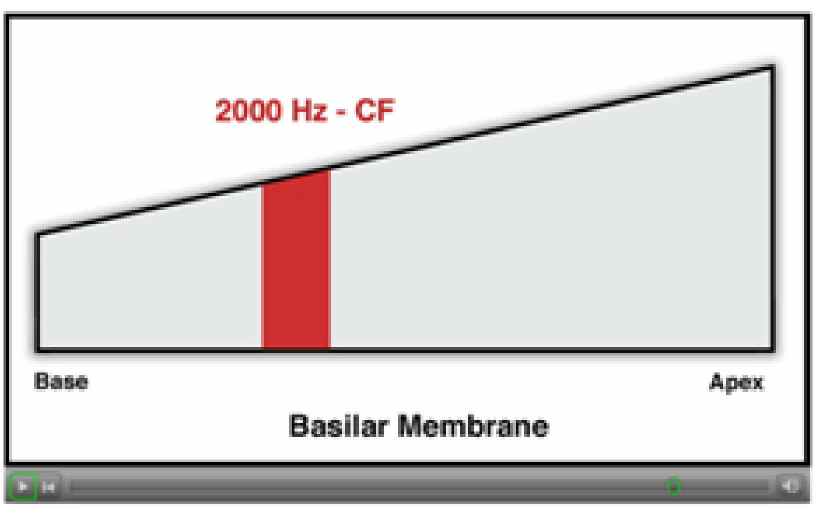
Single Frequency Stimulation Technique Animation Still Shots

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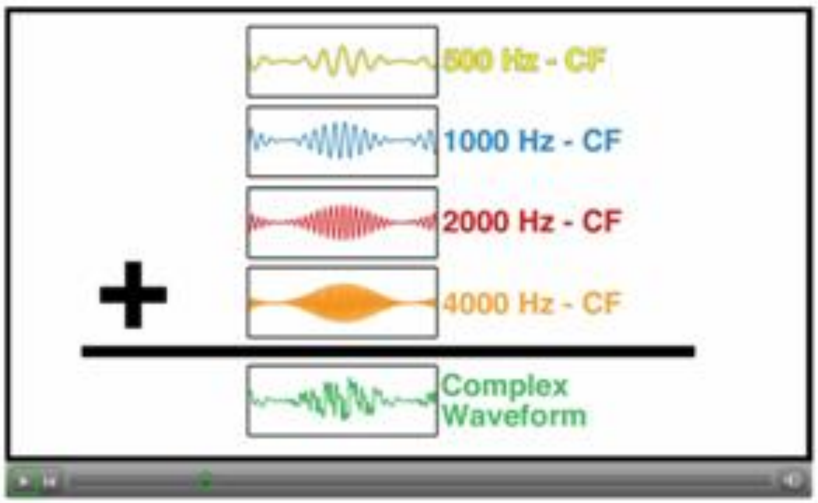
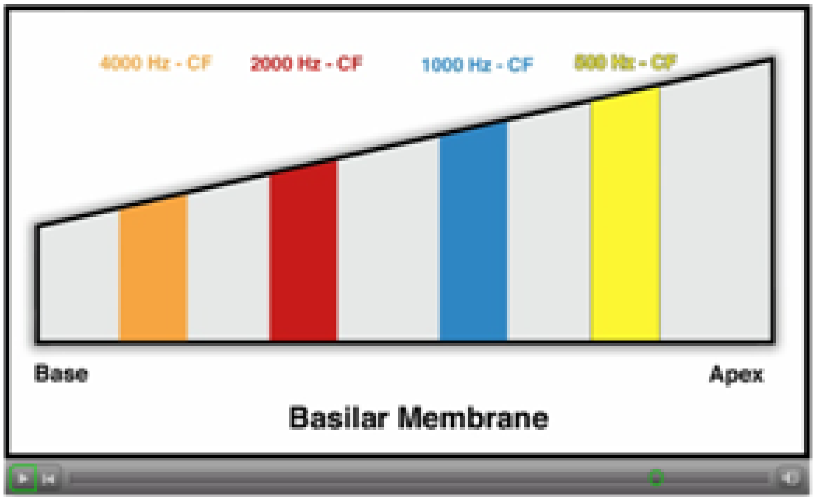
Multiple Frequency Stimulation Technique Animation Still Shots




4000 Hz - CF
2000 Hz - CF
1000 Hz - CF
Base
Apex
Basilar Membrane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APPENDIX B

SCRIPTS FOR ANIMATED FIGURES

Carrier Frequency Script

"The Carrier Frequency (CF) of the tonal stimulus is the test frequency of interest. In this figure, the temporal waveform of a 500 Hz CF tone is highlighted in yellow. The CF tone enters the outer ear, travels through the middle ear, and arrives at the inner ear. This CF tone only stimulates the region of the basilar membrane best tuned to 500 Hz (Cone & Dimitrijevic, 2009; Herdman et al., 2002; Stach, 2002)."

"This figure demonstrates the tonotopic organization of the uncoiled cochlea. The narrow, basal end of the basilar membrane is stimulated only by high frequency sounds while the broader, apical end is stimulated only by low frequency sounds. The traveling wave of the 500 Hz CF tone only stimulates the region of the basilar membrane best tuned to 500 Hz and is represented in yellow (Cone & Dimitrijevic, 2009; Herdman et al., 2002; Stach, 2002). The extent of the stimulation along the basilar membrane is dependent upon the stimulus intensity of the carrier frequency tone; a greater intensity level results in a larger peak displacement of the traveling wave."

Modulation Frequency Script

"In this figure, we see the temporal waveform of a 2000 Hz CF tone that is being presented at a modulation frequency of 100 Hz. This waveform is plotted on a graph, where time in milliseconds is located on the x-axis and amplitude in microvolts is located on the y-axis. If the brain is responding to the timing information present in this signal, then the auditory nerve fibers would synchronously fire at each 10 ms interval as shown by the vertical yellow lines (Cone & Dimitrijevic, 2009; GSI Brochure, 2001). The interval of the firing pattern is determined by the period of the MF. In this example, the period equals one second divided by the MF, or 1000 ms divided by 100 Hz, thus yielding a synchronous firing pattern every 10 ms (Cone & Dimitrijevic, 2009; GSI Brochure, 2001)."

Phase Coherence Script

"The phase coherence technique is one type of analysis measure which is used to determine whether an ASSR is present or absent for a particular CF tone at the stimulus intensity being evaluated. The results of this technique are plotted on a graph, known as a polar plot. The polar plot is broken into four quadrants. Quadrant I displays information from 0 – 90 degrees, quadrant II from 90 – 180 degrees, quadrant III from 180 – 270 degrees, and quadrant IV ranging from 270 - 360 degrees. Within the polar plot you also see concentric circles. Each of these circles represents a different amplitude measurement of the ASSR. For this polar plot, these amplitude values range from 0.5 to 1.5 microvolts."

"Two key pieces of information are plotted on these polar plots, using lines known as vectors. One is the length of the vector, which represents the amplitude, or magnitude, of the ASSR. In this figure, the length of the vector is shown by the red line and has an amplitude value of 1.5 microvolts. The second key piece of information is the phase angle. It is measured in a counter-clockwise direction starting at zero degrees (GSI Brochure, 2001; Hall, 2007). The phase angle of the ASSR provides information regarding the phase information or timing delay of the neural response. In this figure the phase angle is equal to 135 degrees, as indicated in blue."

“In this figure, the vectors in the polar plot are located in the same quadrant, as shown in yellow, and are described as a “cluster of responses” (Cone & Dimitrijevic, 2009; GSI Brochure, 2001; Hall, 2007). This analysis technique utilizes *Phase Coherence Values* to analyze the response. This measure is related to the signal–to-noise ratio of the response (Cone & Dimitrijevic, 2009). This technique assigns a *Phase Coherence Squared (PC^2)* value to measure the response. These PC^2 values can range from 0.0 to 1.0. The closer the value is to 1.0, the higher the coherence, indicating that the amplitude of the ASSR is significantly larger than the amplitude of the background noise. High PC^2 values only occur when the brain is accurately responding or firing in response to the temporal information present in the stimulus (Cone & Dimitrijevic, 2009). In this figure, the PC^2 value is 0.9 indicating that the auditory system is synchronous firing to temporal information present in the stimulus. This pattern of responses is labeled a *Phase-Locked Response,* and the ASSR is judged to be present for this CF tone at the stimulus intensity that it was presented.”

“A second pattern seen in the polar plots is a random configuration of vectors located throughout the four quadrants, as shown in yellow. In this figure, the PC^2 value is 0.1 indicating that the auditory system is firing insynchronously to the stimulus presented. This pattern is referred to as a *random response* and the ASSR is judged to be absent for this CF tone at the stimulus intensity that it was presented.”

Fast Fourier Transform (FFT) and F- Ratio Script

“Fast Fourier Transform or FFT analysis is a computerized technique for separating a complex waveform consisting of multiple frequencies into its individual frequency components (Hall, 2007). The results of the FFT are displayed on a graph with modulation frequency displayed on the x-axis and the amplitude of the response measured in nano-volts displayed on the y-axis. In this analysis technique, the statistical F-test is used to objectively determine whether the amplitude of energy present at the modulation frequency is statistically larger than the amplitude of the background EEG noise found in the surrounding 120 bins (Picton et al., 2003). Typically the F-test uses an alpha level of $p < 0.05$ to judge statistical significance. This figure will demonstrate a present and absent ASSR utilizing FFT with F-Ratio analysis for both a single frequency and a multiple frequency stimulation technique."

"The current figure shows the results of the FFT with F-Ratio analysis performed on the ASSR obtained using the single frequency stimulation technique, and will first show an example of a present ASSR. The ASSR was recorded to a 1000 Hz CF tone with an 85 Hz MF, presented at 60 dB SPL to the subject's right ear. In this figure, the amplitude of energy present at the MF of 85 Hz, shown as a blue vertical line, is approximately 60 nano-volts, and is statistically larger than the background EEG noise level located in the 120 adjacent bins to the MF that is present at approximately 20 nano-volts. Therefore, the ASSR is judged to be "present for 1000 Hz at 60 dB SPL."

"In contrast, this figure will now show an example of an absent ASSR for the same single frequency technique. Again, the ASSR was recorded to a 1000 Hz CF tone with an 85 Hz MF being presented at 60 dB SPL. The FFT with F-Ratio analysis demonstrates that the amplitude of the response at the MF of 85 Hz is approximately 20 nano-volts, and is not significantly larger than the amplitude of the ongoing EEG noise present also at approximately 20 nano-volts in the surrounding 120 bins. Therefore, this ASSR is judged to be "absent for 1000 Hz at 60 dB SPL."

“Now, this figure will demonstrate the FFT with F-Ratio technique utilizing a Multiple Frequency stimulation technique. Contrary to the Single Frequency approach, the Multiple Frequency stimulation technique consists of up to four separate CF tones, each with its own MF, being presented simultaneously to either one or both ears. The current figure will show an example of present ASSR utilizing the multiple frequency FFT with F-Ratio analysis. Four CF tones of 500, 1000, 2000, and 4000 Hz are presented at 60 dB SPL to the subject’s right ear. The 500 Hz CF tone has a 77 Hz MF and is highlighted in yellow, the 1000 Hz CF tone has an 85 Hz MF and is highlighted in blue, the 2000 Hz CF tone has a 93 Hz MF and is highlighted in red, and the 4000 Hz CF tone has a 101 Hz MF and is highlighted in orange. In this figure, the FFT with F-Ratio analysis demonstrates that the amplitude of energy present at each of the four MFs is approximately 60 nano-volts, and is significantly larger than the amplitude of the ongoing EEG energy present at approximately 20 nano-volts in the surrounding 120 bins. Therefore, this ASSR is judged to be” present for 500 through 4000 Hz at 60 dB SPL.”

“In contrast, this figure will now show an example of an absent ASSR for the same multiple frequency technique. Again, the four carrier frequency tones of 500 through 4000 Hz, with their respective MFs are presented to the subject’s right ear at 60 dB SPL. The FFT with F-Ratio analysis demonstrates that the amplitude of the responses at each of the four MFs is approximately 20 nano-volts, and is not significantly larger than the amplitude of the ongoing background EEG noise present also at approximately 20 nano-volts in the 120 adjacent bins. Therefore, this ASSR is judged to be “absent for 500 through 4000 Hz at 60 dB SPL.”

SF Stimulation Technique

"The Single Frequency (SF) stimulation technique allows for only one CF tonal stimulus to be presented to one ear at a time (Hall, 2007). This figure illustrates a 2000 Hz CF, highlighted in red, being elicited from a headphone at 60 dB SPL and entering the subject's right ear. The 2000 Hz CF tone enters the subject's right ear canal, and then stimulates the portion of the basilar membrane best tuned to 2000 Hz, which is portrayed by the red vertical line marked on the figure of the basilar membrane (Hall, 2007)."

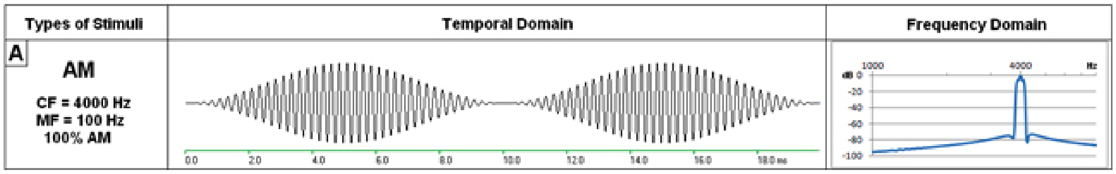
MF Stimulation Technique

"The Multiple Frequency (MF) stimulation technique presents up to four CF tonal stimuli to each ear either monaurally or binaurally (Canale et al., 2005; Hall, 2007; John, Purcell, Dimitrijevic, & Picton, 2002; Lins et al., 1996; Perez-Abalo et al., 2001). This figure illustrates four separate CF tones each being presented at 60 dB SPL: The 500 Hz CF tone is depicted in yellow, 1000 Hz CF tone is depicted in blue, 2000 Hz CF tone is depicted in red, and the 4000 Hz CF tone is depicted in orange being added together to form a complex waveform as displayed in green (Hall, 2007). This figure illustrates the complex waveform, in green, being elicited from a headphone at 60 dB SPL entering the subject's right ear. This complex waveform then stimulates the portions of the subject's basilar membrane best tuned to 500, 1000, 2000, and 4000 Hz as illustrated by the CF tones respective yellow, blue, red, and orange vertical lines on the figure of the basilar membrane (Hall, 2007)"

APPENDIX C

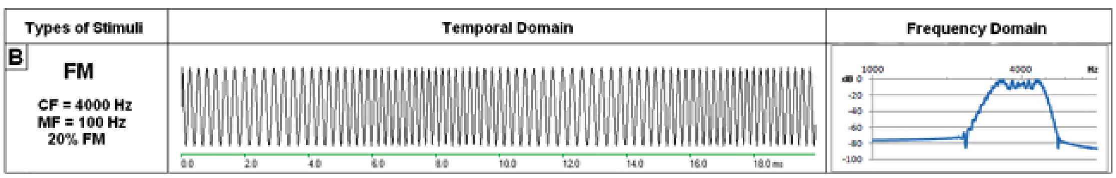
NON-ANIMATED FIGURES

Amplitude Modulated Tonal Stimuli



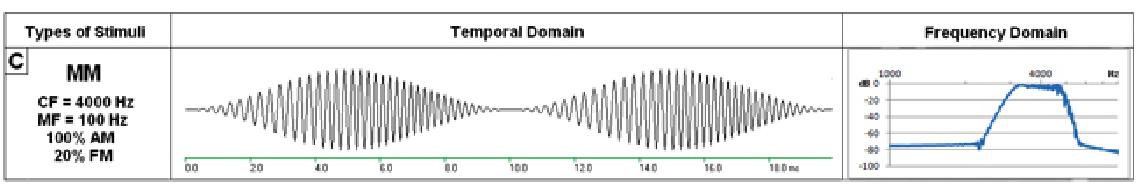
Listen to this AM Tone.

Frequency Modulated Tonal Stimuli



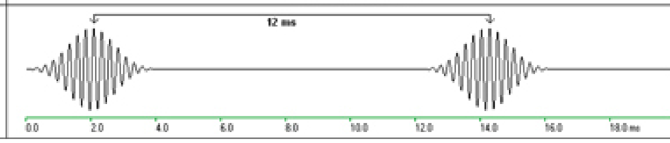
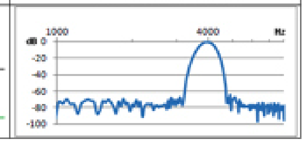
Listen to this FM Tone.

Mixed Modulated Tonal Stimuli



Listen to this MM tone.

Repeating Sequence Gated Tonal Stimuli

Types of Stimuli	Temporal Domain	Frequency Domain
D **RSG** CF = 4000 Hz MF = 82 Hz		

Listen to this RSG Tone.

APPENDIX D

WEBSITE TABLES

Neural Generators

Stimuli Presentation Rate	Neural Generator Site
< 20 Hz (Low)	Primary auditory cortex
20 – 60 Hz (Mid)	Primary auditory cortex Auditory midbrain Thalamus
> 60 Hz (High)	Superior olivary complex Inferior colliculus Cochlear nucleus

Technical and Recording Parameters

AIR AND BONE CONDUCTION PARAMETERS	
Analog EEG Bandpass Filter	30-300 Hz
Electrode Montage	Similar to ABR *Ground:* Fpz *Non- Inverting:* Vertex or Cz location *Inverting:* A1 and A2 locations
Number of Recording Channels	2 channels (ipsilateral and contralateral)
ADDITIONAL BONE CONDUCTION PARAMETERS	
Oscillator Placement	Upper temporal bone posterior to pinna OR Lower temporal bone (mastoid)
Coupling Method	Elastic band OR Hand-held if assistant properly trained
Coupling Force	400-450 grams

Air Conduction ASSR Results for Adults with Normal Hearing

Table 1			Description	Mean Difference Scores 500 Hz	1000 Hz	2000 Hz	4000 Hz
A		Cone-Wesson et al. (2002)[12]	SF, Monotic	-3.72 (15.0)	-0.45 (14.7)	1.67 (13.7)	-0.96 (15.0)
		Herdman & Stapells(2001)[56]	SF, Monotic	7(13)	10(12)	12(10)	14(6)
B	Multiple Frequency	Lins et al. (1996)[23]	MF, Monotic	14(11)	12(11)	11(8)	13(11)
		Dimitrijevic et al. (2002)[55]	MF, Monotic	17(10)	4(11)	4(8)	11(7)
		Herdman & Stapells(2003)[57]	MF, Monotic	11(11)	10(11)	11(10)	14(10)
C		D'haenens et. al. (2008)[58]	MF, Monotic ***Trial 1***	19(13)	14(10)	10(9)	13(10)
			MF, Monotic ***Trial 2***	19(11)	13(10)	12(9)	14(9)
D	Monotic vs. Dicotic	Herdman & Stapells(2001)[56]	MF, Monotic	11(11)	10(11)	11(10)	14(10)
			MF, Dichotic/ Binaural	14(10)	8(7)	8(9)	15(9)

Summary of the mean difference scores (and their SD values) for the four carrier frequencies tones reported across studies for adults with normal hearing sensitivity.

Air Conduction ASSR Results for Adults with SNHL

Table 2			Description	Mean Difference Scores (MDS)			
				500 Hz	1000 Hz	2000 Hz	4000 Hz
A		Lins et al. (1996)[23]	MF, Moderate SNHL	9(9)	13(12)	11(10)	12(13)
		Dimitrijevic et al. (2002)[55]	MF, Mild-Severe SNHL	13(11)	5(8)	5(9)	8(11)
B	Degree	Rance et al. (1995)[50]	SF, Degree of Loss: 0-55 dB HL	9.6	8.6	6.3	4.7
			SF, Degree of Loss: 60+ dB HL	7.9	5.6	3.8	5.0
C		Herdman & Stapells (2003)[57]	MF, Group A: Steeply Sloping (≥ 30 dB/octave)	15(13)	7(8)	7(11)	5(9)
			MF, Group B: Flat/Shallow (≤ 30 dB/octave)	13(13)	8(10)	12(10)	1(10)
D	SF vs. MF	Luts & Wouters (2005)[60]	SF, AUDERA	20(8)	14(7)	13(7)	14(13)
			MF, MASTER	17(12)	12(8)	17(8)	19(12)

Summary of mean difference scores (and SD values) between behavioral and ASSR thresholds for individuals with SNHL.

Bone Conduction ASSR Results for Adults and Children with Normal Hearing

A		Small & Stapells (2006)[41]	Infants (0.5-27 wks)	Post-term	13.6 (12.4)	2.1 (7.0)	26.4 (6.3)	22.1 (8.0)
			Adults (20-48 years)	Adults	21.0 (9.9)	25.0 (12.7)	18.0 (7.9)	16.0 (10.8)
B		Small & Stapells (2008a)[26]	Young Infants (0 –11 months)		14 (12.9)	4.9 (7.8)	25.7 (10.1)	13.7 (10.6)
			Older Infants (12-24 months)		22.3 (10.9)	13.1 (6.3)	26.2 (8.7)	13.1 (9.5)
			Adults		30.6 (15.1)	23.9 (13.8)	20.0 (7.7)	16.1 (10.9)
C	Coupling Method	Small, Hatton, & Stapells (2007)[31]	Infants (0.5-38 weeks)	Elastic Head Band	14.0 (14.3)	6.0 (8.43)	26.0 (9.7)	13.0 (11.6)
				Hand Held	14.0 (14.3)	1.0 (7.4)	25.0 (7.1)	22.0 (7.9)
			Adults (20-39 years)	Elastic Head Band	1.7 (3.7)	-0.3 (6.6)	11.5 (7.5)	-1.7 (5.5)
				Hand Held	1.5 (4.9)	2.3 (4.1)	8.7 (5.4)	0.1 (5.0)
D		Small, Hatton, & Stapells (2007)[31]	Infants (32-43 wks PCA)	Temporal Bone	16.0 (11.8)	16.7 (9.0)	34.6 (15.1)	33.3 (15.0)
				Mastoid	17.3 (13.3)	14.0 (9.1)	32.3 (19.6)	26.0 (12.9)
				Forehead	30.7 (16.2)	26.7 (13.5)	51.5 (13.6)	44.0 (9.7)
E	Recording Channels	Small & Stapells (2008b)[42]	Infants (2-11 months)	Ipsilateral	12.5 (12.9)	5.0 (5.2)	20.0 (12.8)	9.2 (7.9)
				Contralateral	24.6 (12.1)	13.0 (15.7)	33.6 (12.1)	22.5 (12.2)
			Adults (18-40 years)	Ipsilateral	31.3 (6.4)	17.5 (12.8)	20.0 (7.6)	10.0 (10.7)
				Contralateral	31.3 (6.4)	18.8 (11.3)	18.8 (8.4)	11.3 (8.4)

Table 3: Summary of mean (and SD) ASSR thresholds for infants and adults with normal hearing tested via bone conduction, based on the test results found in various Small and Stapells articles. PCA: Post-conceptional age

APPENDIX E

PRINTER-FRIENDLY DOWNLOADS

Technical and Recording Parameters

RECORDING PARAMETERS OF THE ASSR

AIR AND BONE CONDUCTION PARAMETERS	
Analog EEG Bandpass Filter	30-300 Hz
Electrode Montage	Similar to ABR *Ground:* Fpz *Non- Inverting:* Vertex or Cz location *Inverting:* A1 and A2 locations
Number of Recording Channels	2 channels (ipsilateral and contralateral)
ADDITIONAL BONE CONDUCTION PARAMETERS	
Oscillator Placement	Upper temporal bone posterior to pinna OR Lower temporal bone (mastoid)
Coupling Method	Elastic band OR Hand-held if assistant properly trained
Coupling Force	400-450 grams

Glossary

ASSR Glossary

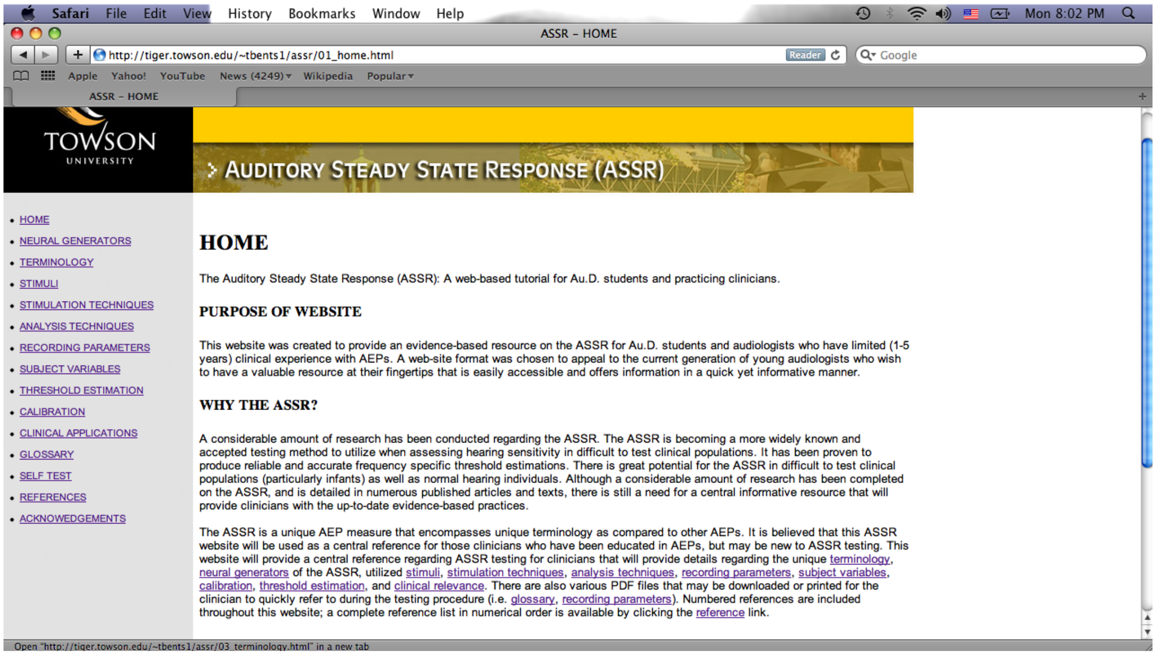
Key Terms	Carrier Frequency	Associated with the region in the cochlea where the hair cells are activated in response to the presentation of a stimulus[15,16].
	Modulation Frequency	The frequency at which electroencephalography (EEG) activity is synchronized to fire and can be derived by calculating the period of the MF[15].
Types of Stimuli Used in ASSR	Click	A very brief-duration stimulus (usually 100 microsec) with a broad frequency spectrum (~ 100-10,000 Hz), which is produced by a transient electrical pulse[74].
	Chirp	A type of stimulus that covers a broader range of frequencies than traditional modulated pure tones, activating more hair cells
	Toneburst	A brief (< 1 sec.) tonal stimulus which is frequency specific
	Sinusoidally Amplitude Modulated Tone	A pure tone that changes in amplitude during each cycle of the tone.
	Frequency Modulated Tone	A pure tone that changes in frequency during each cycle of the tone.
	Mixed Modulated Tone	A pure tone that changes in both frequency and amplitude over time.
	Repeating Sequence Gated Tone (RSG)	A series of gated tones which can be combined to form either a single frequency tone or a multiple frequency tone.
	Blackman-Gate Tone	Commonly used type of RSG tone. These tones differ from other RSG tones in three ways: 1) the width of the main peak of energy, 2) the height of the side-lobes of energy, and 3) the rate of decay for the side-lobes of energy.
Stimulation Techniques	Single Frequency	A method of stimulation that presents one carrier frequency tone at one MF to one ear at a time[74].
	Multiple Frequency	A method of stimulation that presents multiple carrier frequency tones (up to four in each ear) simultaneously[17]. These CF tones are presented to either one ear (monaural test condition) or to both ears (binaural test condition).

Analysis Techniques	Fast-Fourier Transform (FFT) Analysis	A computerized technique for separating a complex waveform consisting of multiple frequencies into its individual frequency components[74].
	Phase Coherence	Phase coherence "is related to the signal (response) –to-noise (background EEG and myogenic) ratio"[14 p.333].
	F-Test (a.k.a. F-Ratio)	A statistical method that is applied in ASSR testing to estimate the probability that the amplitude of an ASSR found at a particular MF is statistically different from the energy found at the surrounding frequencies which are attributed to the ongoing EEG noise[18,27,56].
Neuro-Imaging Techniques	Brain Electrical Source Analysis (BESA)	Software for source analysis and dipole localization which is used in EEG and MEG research
	Functional Magnetic Resonance Imaging (fMRI)	A type of MRI that measures the changes in blood flow in various areas of the brain that are related to underlying neural activity.
	Magnetoencephalography (MEG)	Technique used to measure magnetic fields produced by electrical activity in the brain.
Threshold Estimation	Mean Difference Scores (MDS)	The behavioral pure tone threshold minus the ASSR threshold equals the difference score. This is calculated separately for each CF.
	Frequency Specificity of the Response	"How independent a threshold at one stimulus frequency is of contributions from surrounding frequencies"[54 p. 61]. This refers to behavioral threshold estimations.
	Place Specificity	How precise the specific point on the basilar membrane is stimulated at the precise point that the frequency has its maximal activation[53].

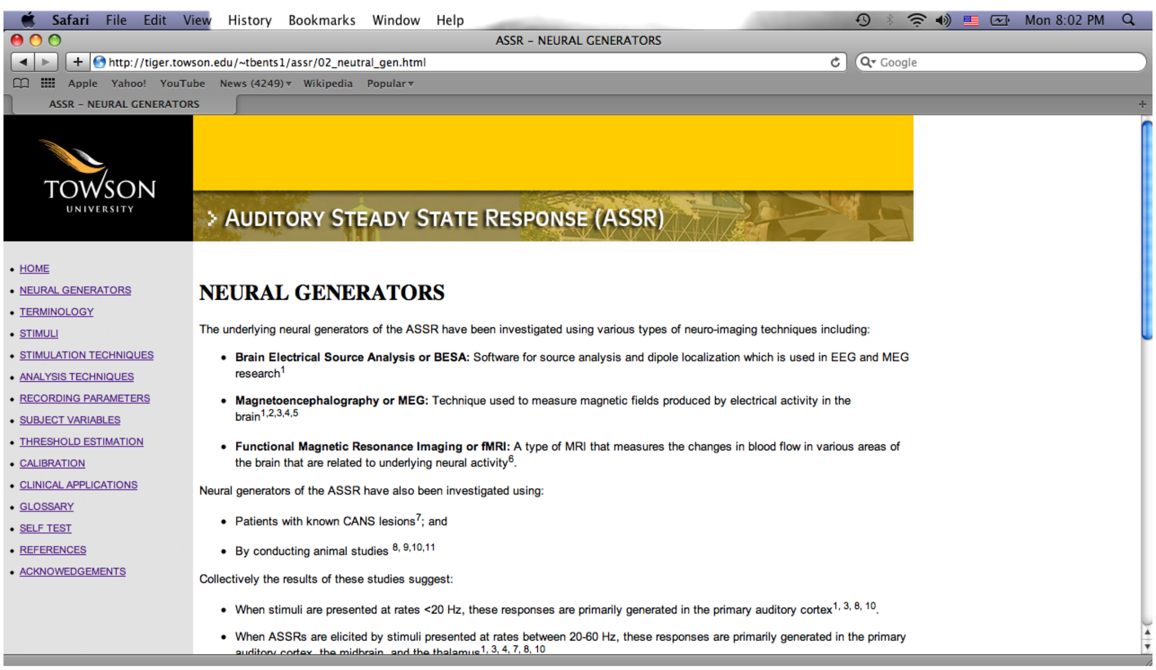
APPENDIX F

SAMPLE WEBPAGE SCREEN SHOTS

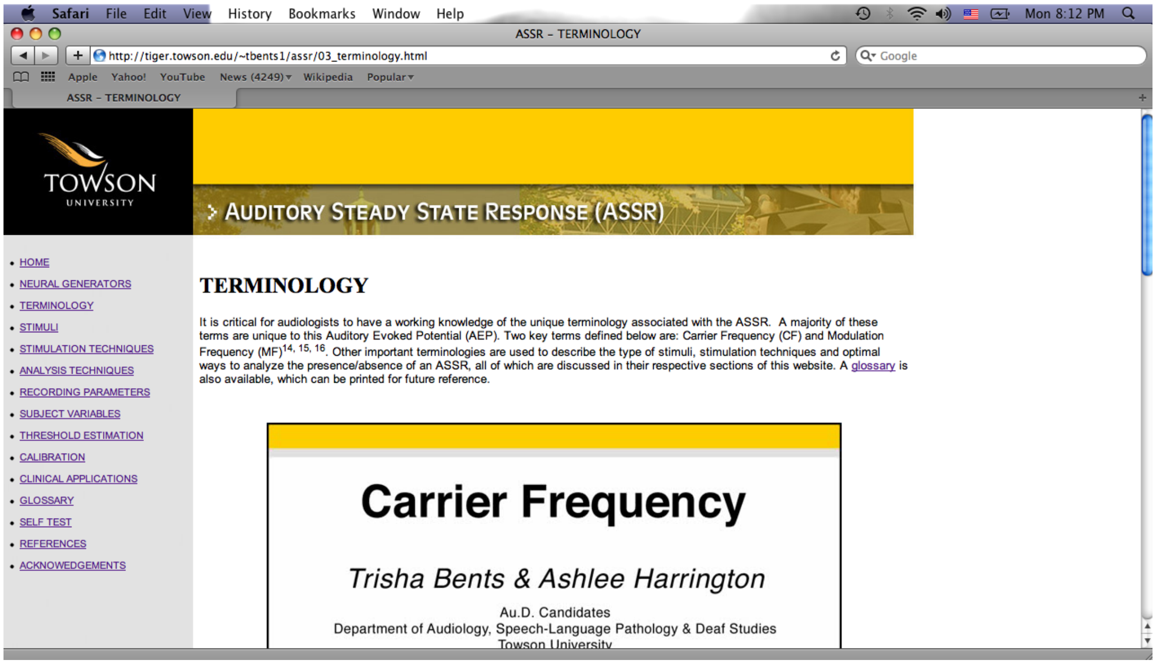
Home Webpage Screen Shot



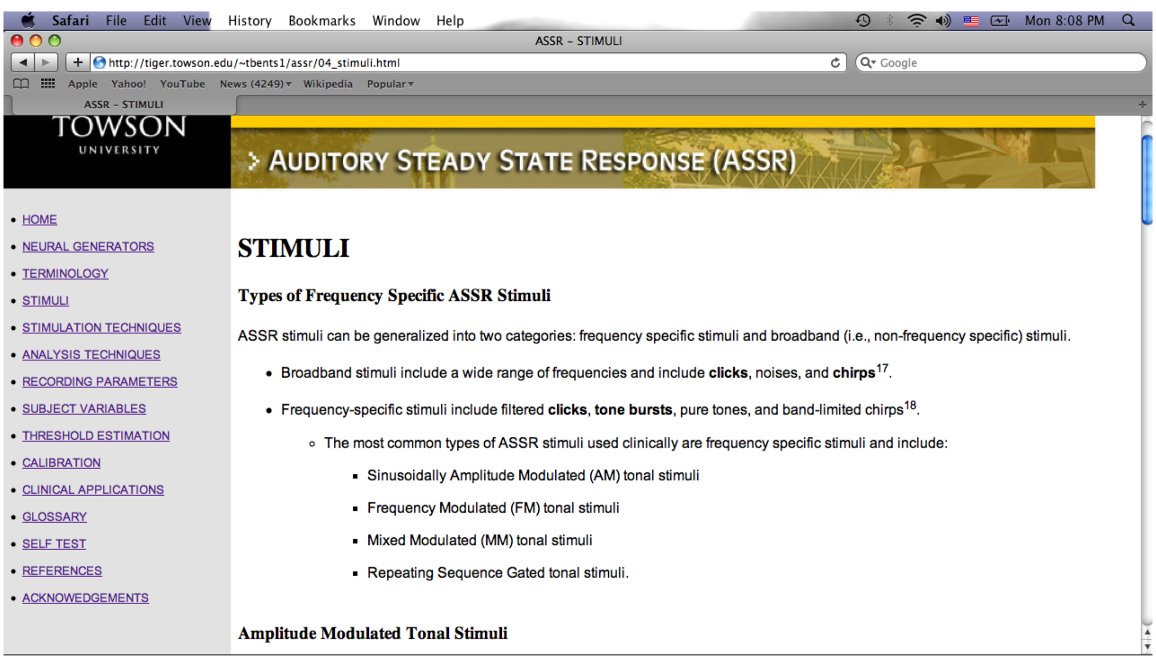
Neural Generators Webpage Screen Shot



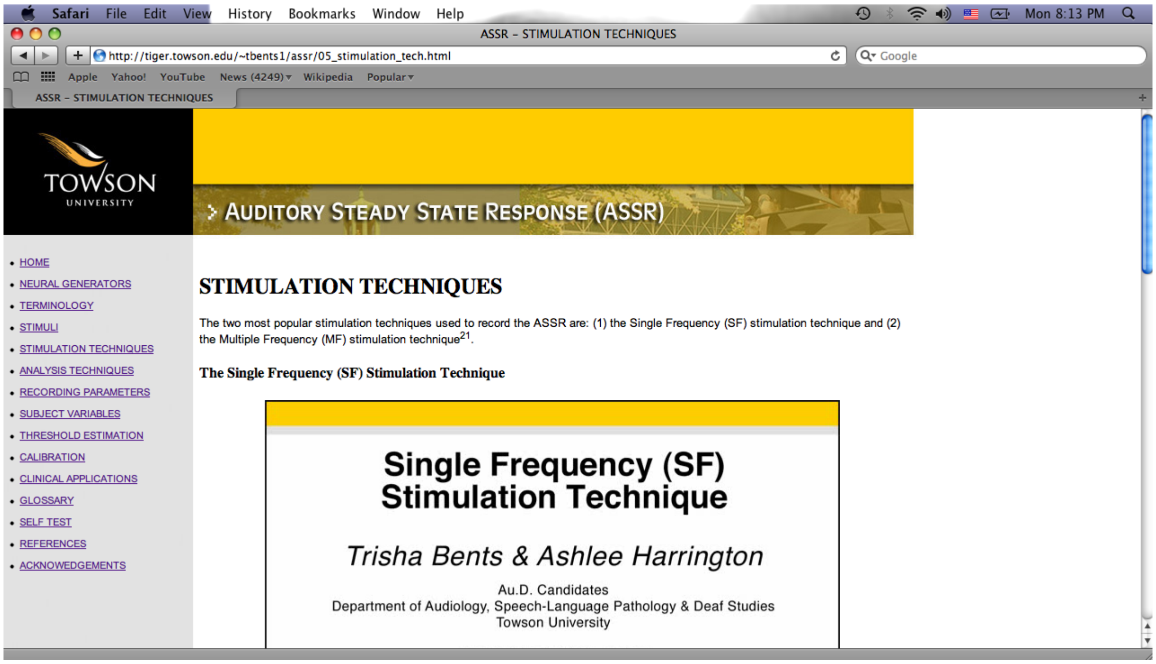
Terminology Webpage Screen Shot



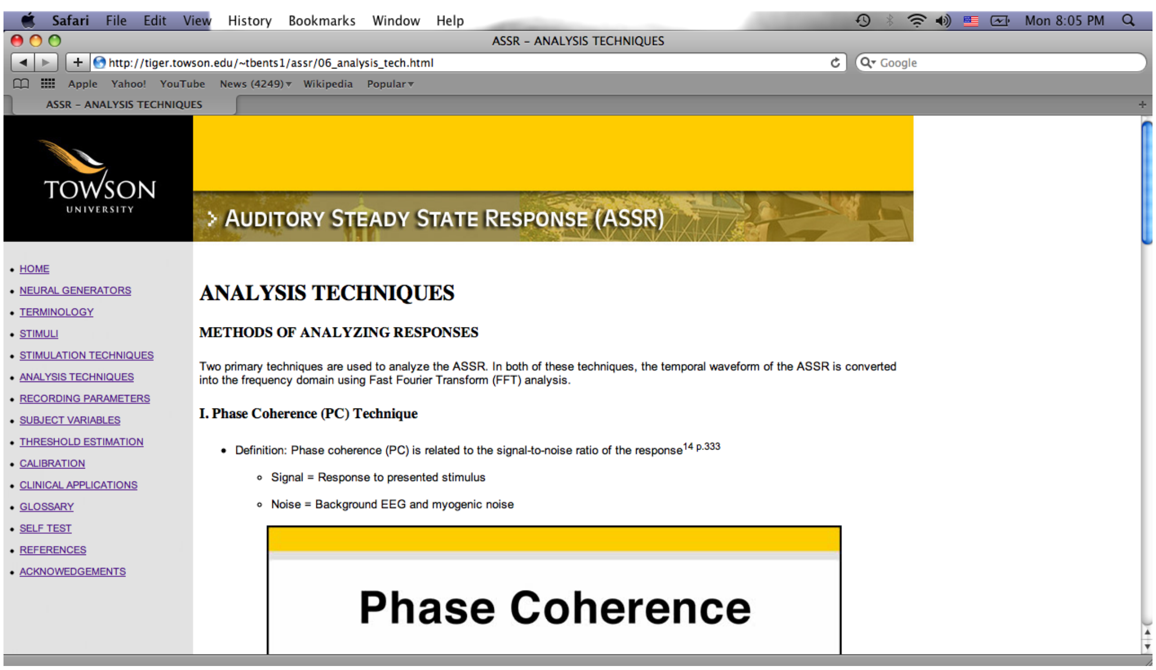
Stimuli Webpage Screen Shot



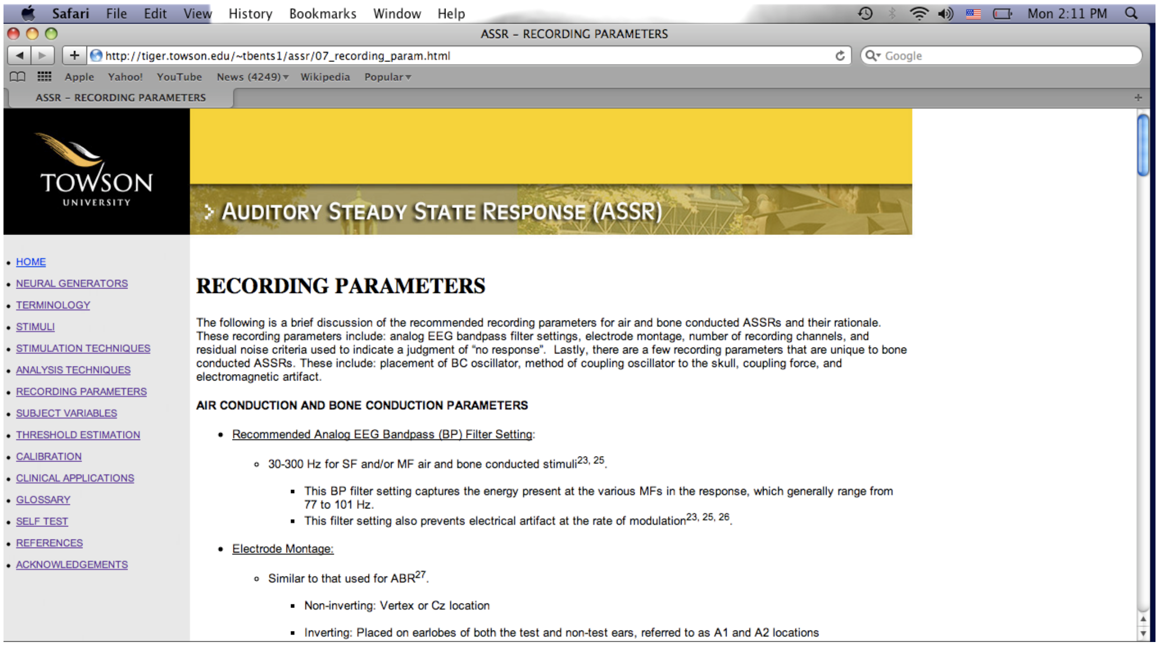
Stimulation Techniques Webpage Screen Shot



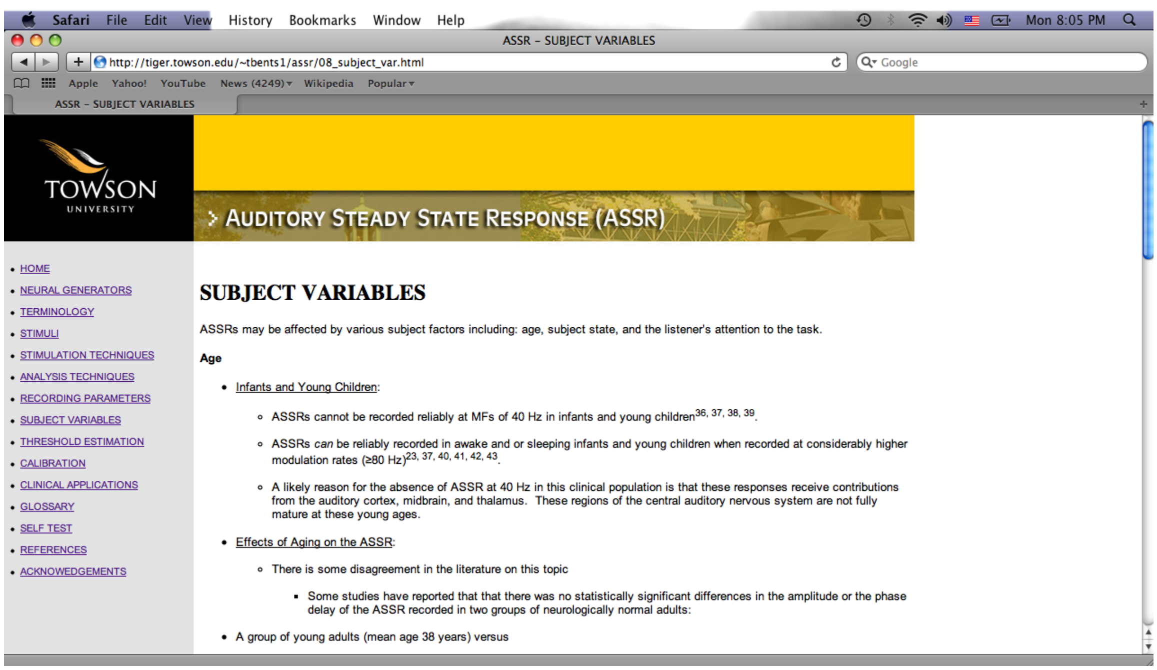
Analysis Techniques Webpage Screen Shot



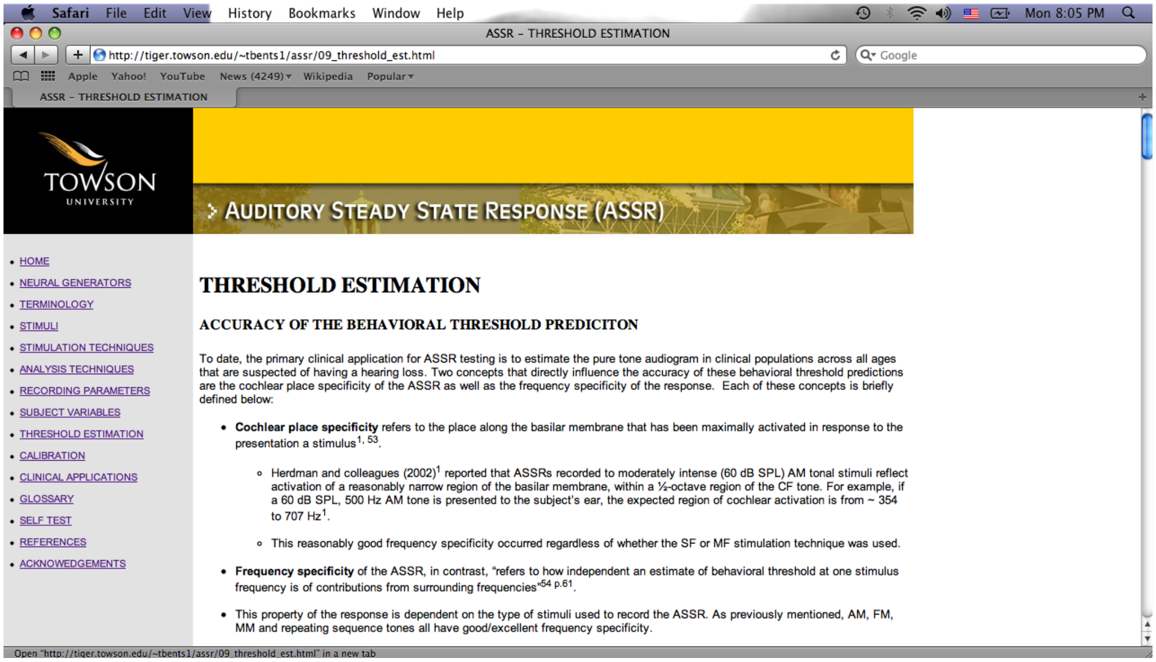
Recording Parameters Webpage Screen Shot



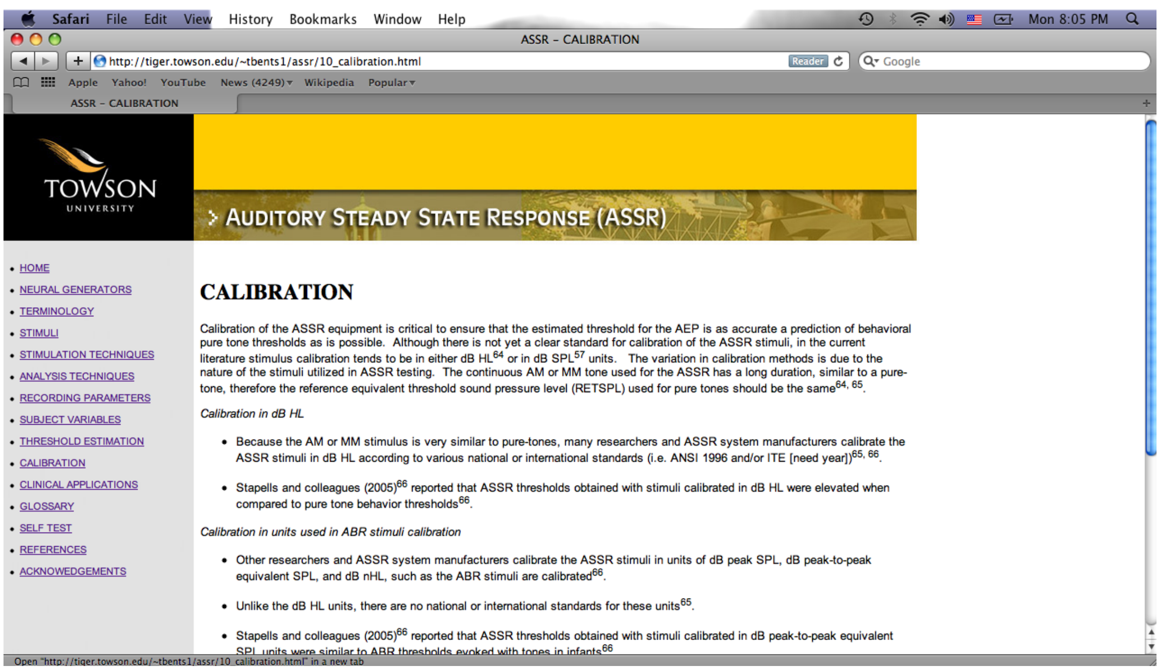
Subject Variables Webpage Screen Shot



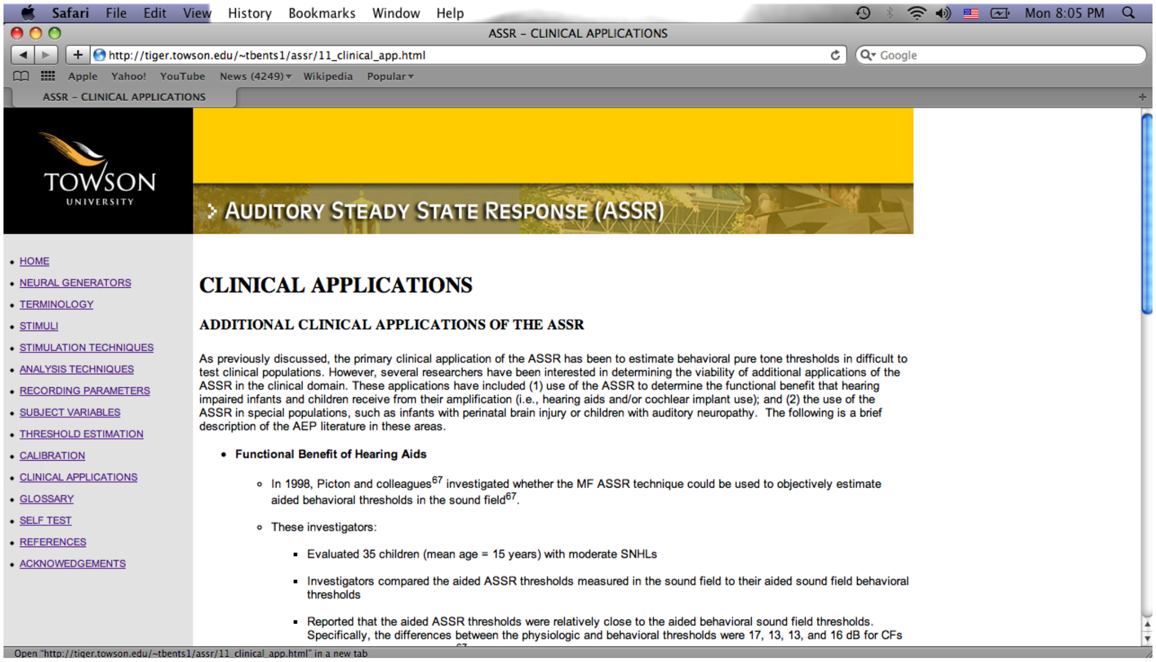
Threshold Estimation Webpage Screen Shot



Calibration Webpage Screen Shot



Clinical Applications Webpage Screen Shot



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ASSR – CLINICAL APPLICATIONS

http://tiger.towson.edu/~tbents1/assr/11_clinical_app.html

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AUDITORY STEADY STATE RESPONSE (ASSR)

- HOME
- NEURAL GENERATORS
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- STIMULI
- STIMULATION TECHNIQUES
- ANALYSIS TECHNIQUES
- RECORDING PARAMETERS
- SUBJECT VARIABLES
- THRESHOLD ESTIMATION
- CALIBRATION
- CLINICAL APPLICATIONS
- GLOSSARY
- SELF TEST
- REFERENCES
- ACKNOWEDGEMENTS

CLINICAL APPLICATIONS

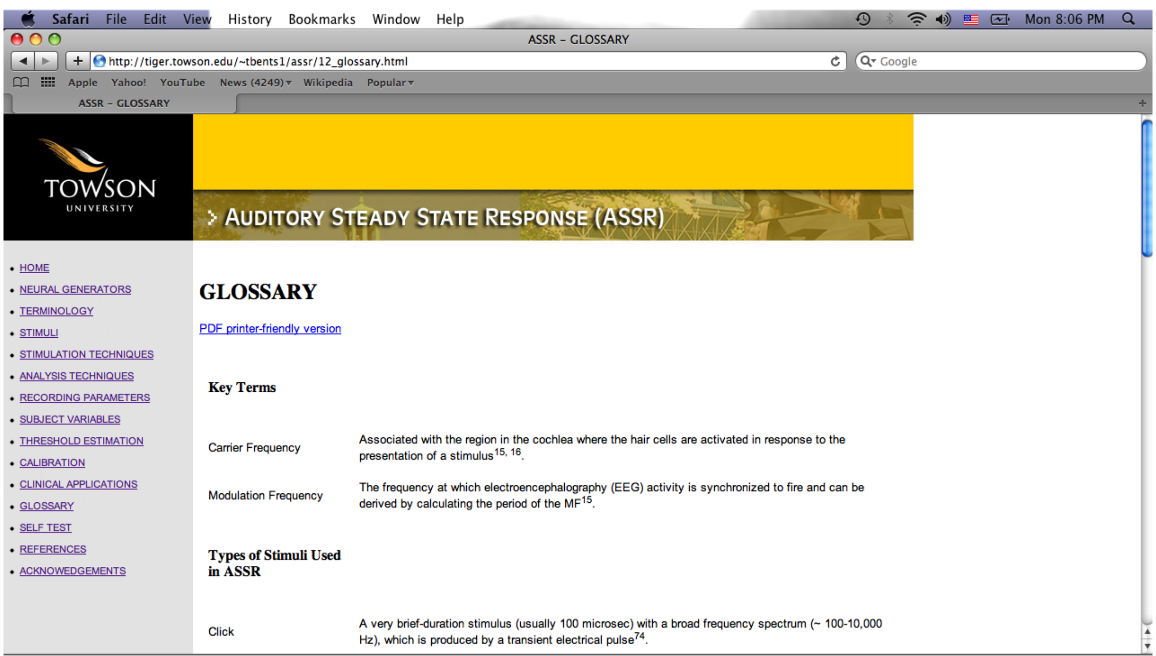
ADDITIONAL CLINICAL APPLICATIONS OF THE ASSR

As previously discussed, the primary clinical application of the ASSR has been to estimate behavioral pure tone thresholds in difficult to test clinical populations. However, several researchers have been interested in determining the viability of additional applications of the ASSR in the clinical domain. These applications have included (1) use of the ASSR to determine the functional benefit that hearing impaired infants and children receive from their amplification (i.e., hearing aids and/or cochlear implant use); and (2) the use of the ASSR in special populations, such as infants with perinatal brain injury or children with auditory neuropathy. The following is a brief description of the AEP literature in these areas.

- **Functional Benefit of Hearing Aids**
  - In 1998, Picton and colleagues[67] investigated whether the MF ASSR technique could be used to objectively estimate aided behavioral thresholds in the sound field[67].
  - These investigators:
    - Evaluated 35 children (mean age = 15 years) with moderate SNHLs
    - Investigators compared the aided ASSR thresholds measured in the sound field to their aided sound field behavioral thresholds
    - Reported that the aided ASSR thresholds were relatively close to the aided behavioral sound field thresholds. Specifically, the differences between the physiologic and behavioral thresholds were 17, 13, 13, and 16 dB for CFs

Open "http://tiger.towson.edu/~tbents1/assr/11_clinical_app.html" in a new tab

Glossary Webpage Screen Shot



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ASSR – GLOSSARY

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AUDITORY STEADY STATE RESPONSE (ASSR)

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- STIMULI
- STIMULATION TECHNIQUES
- ANALYSIS TECHNIQUES
- RECORDING PARAMETERS
- SUBJECT VARIABLES
- THRESHOLD ESTIMATION
- CALIBRATION
- CLINICAL APPLICATIONS
- GLOSSARY
- SELF TEST
- REFERENCES
- ACKNOWEDGEMENTS

GLOSSARY

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Key Terms

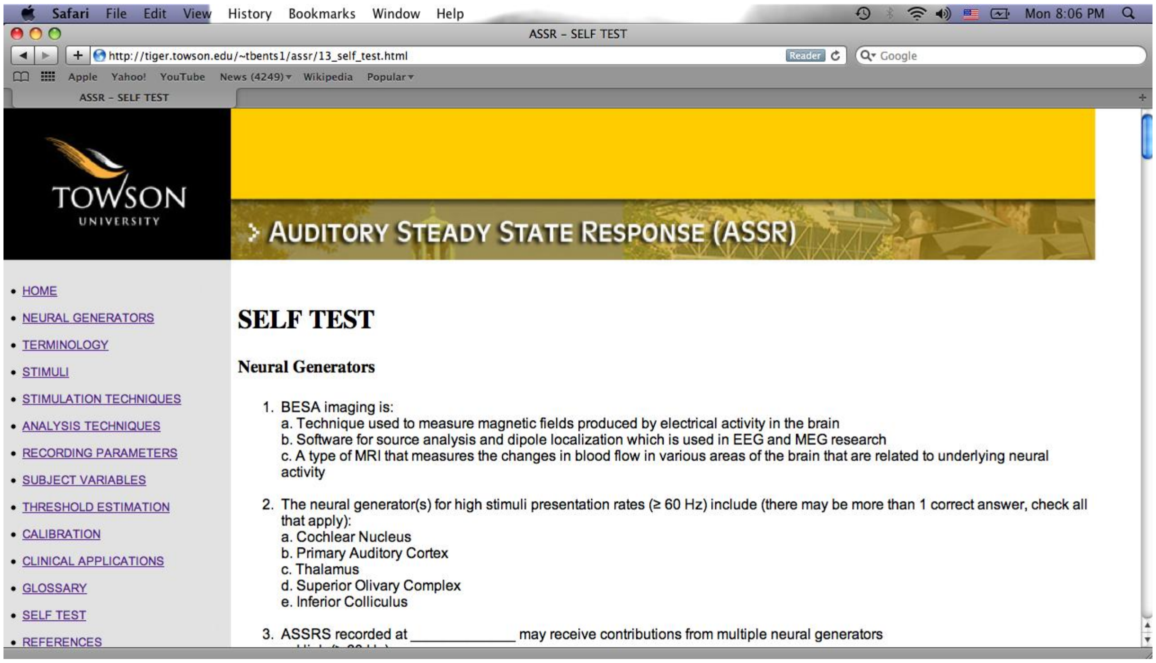
Carrier Frequency	Associated with the region in the cochlea where the hair cells are activated in response to the presentation of a stimulus[15, 16].
Modulation Frequency	The frequency at which electroencephalography (EEG) activity is synchronized to fire and can be derived by calculating the period of the MF[15].

Types of Stimuli Used in ASSR

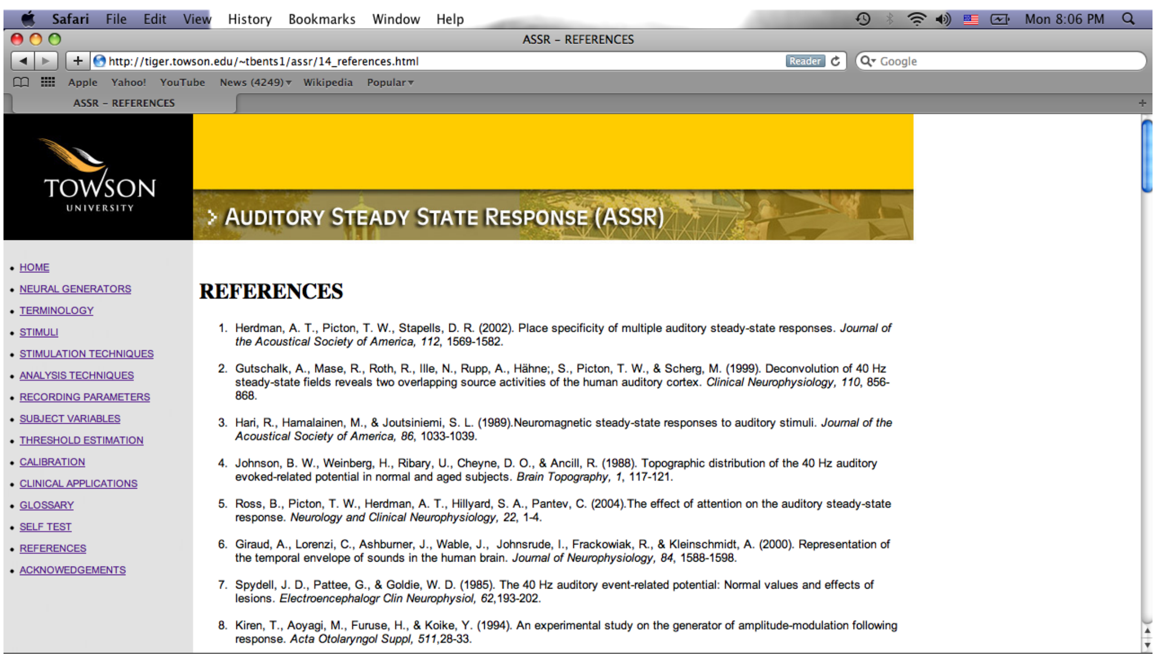
Click	A very brief-duration stimulus (usually 100 microsec) with a broad frequency spectrum (~ 100-10,000 Hz), which is produced by a transient electrical pulse[74].

Open "http://tiger.towson.edu/~tbents1/assr/12_glossary.html" in a new tab

Self Test Webpage Screen Shot



References Webpage Screen Shot



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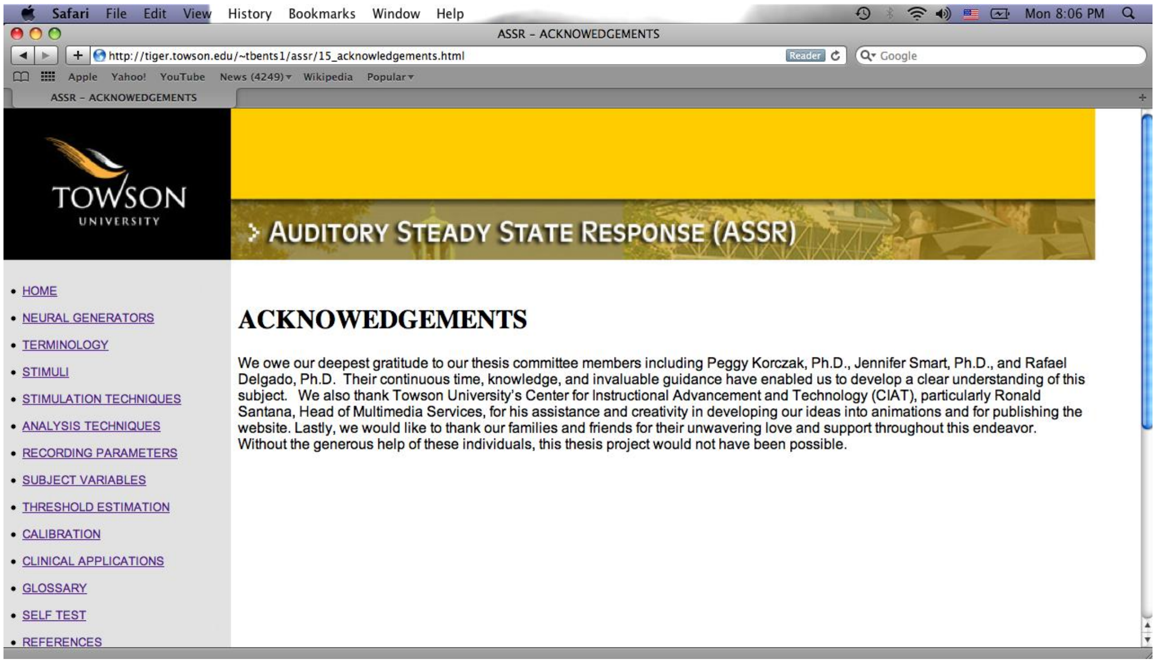

REFERENCES

Aoyagi , M., Kiren, T., Kim, Y., Suzuki, Y., Fuse, T., & Koike, Y. (1993). Optimal modulation frequency for amplitude modulation following response in young children during sleep. *Hearing Research, 65*, 253-261.

Aoyagi, M., Kiren, T., Furuse, H., Fuse, T., Suzuki, Y., Yokota, M., & Koike, Y. (1994). Pure-tone threshold prediction by 80-Hz amplitude-modulation following response. *European Archives of Oto-Rhino-Laryngology(Suppl), 511*, 7-14.

Beck, D., Speidel, D., & Petrak, M. (2007). Auditory steady-state response (ASSR): A beginner's guide. *Hearing Review, 14*, 34-37.

Boettcher, F. A., Madhotra, D., Poth, E. A., & Mills, J. H. (2002). The frequency-modulation following response in young and aged human subjects. *Hearing Research, 165*, 10-18.

Boettcher, F. A., Poth, E. A., Mills, J. H., Dubno, J. R. (2001). The amplitude-modulation following response in young and aged human subjects. *Hearing Research, 153*, 32-42.

Canale, A., Lacilla, M., Cavalot, A. L., & Albera, R. (2006). Auditory steady-state responses and clinical applications. *European Archives of Oto-Rhino-Laryngology, 263*(6), 499-503.

Cone, B., & Dimitrijevic, A. (2009). The auditory steady state response. In J. Katz, L. Medweisky, R. Burkard, & L. Hood (Eds.), *Handbook of clinical audiology*, (6th ed., pp. 322-350). Baltimore: Lippincott Williams & Wilkins.

Cone-Wesson, B. (2003). Electrophysiologic assessment of hearing in infants: Compound nerve action potential, auditory brainstem response, and auditory steady state response [Monograph]. *The Volta Review, 103*(4), 253-279

Cone-Wesson, B., Dowell, R., Tomlin, D., Rance, D., & Ming, W. (2002a). The auditory steady-state response: Comparisons with the auditory brainstem response. *Journal of the American Academy of Audiology, 13*, 173-187.

Cone-Wesson, B., Parker, J., Swiderski, N., & Rickards, F. W. (2002b). The auditory steady-state response: full term and premature neonates. *Journal of the American Academy of Audiology, 13*, 260-269.

Cohen, L. T., Rickards, F. W., & Clark, G. M. (1991). A comparison of steady-state potentials to modulated tones in awake and sleeping humans. *Journal of the Acoustical Society of America, 90*, 2467-2479.

D'haenens, W., Dhooge, I., De Vel, E., Maes, L., Bockstael, A., & Vinck. (2007). Auditory steady-state responses to MM and exponential envelope AM^2/FM stimuli in normal- hearing adults. *International Journal of Audiology, 46,* 399-406.

Dimitrijevic, A., John, M. S., Picton, T. W. (2004). Auditory steady-state responses and word recognition scores in normal hearing and hearing-impaired adults. *Ear and Hearing, 25*, 68-84.

Dimitrijevic, A., John, M. S., Van Roon, P., Picton, T. E. (2001). Human auditory steady-state responses to tones independently modulated in both frequency and amplitude. *Ear and Hearing, 22*, 100-111.

Dimitrijevic, A., John, M. S., Van Roon, P., Purcell, D. W., Adamonis, J., Ostroff, J., . . . Picton, T. W. (2002). Estimating the audiogram using multiple auditory steady-state responses. *Journal of the American Academy of Audiology, 13,* 205-224.

Don, M., Elberling, C., & Waring, M. (1984). Objective detection of averaged auditory brainstem responses. *Scandinavian Audiology, 13*, 219-228.

Elberling, C., & Don, M. (1987). Threshold characteristics of the human auditory brain stem response. *Journal of the Acoustical Society of America, 81*, 115-121.

Galambos, R., Makeig, S., & Talmachoff, P. J. (1981). A 40 Hz auditory potential recorded from the human scalp. *USA, 78, 2643-2347.*

Giraud, A., Lorenzi, C., Ashburner, J., Wable, J., Johnsrude, I., Frackowiak, R., & Kleinschmidt, A. (2000). Representation of the temporal envelope of sounds in the human brain. *Journal of Neurophysiology, 84*, 1588-1598.

Grason-Stadler Inc. (2001). *Auditory steady-state evoked response: A new tool for frequency-specific hearing assessment in infants and children.* [Brochure]

Gutschalk, A., Mase, R., Roth, R., Ille, N., Rupp, A., Hähne, S., . . . Scherg, M. (1999). Deconvolution of 40 Hz steady-state fields reveals two overlapping source activities of the human auditory cortex. *Clinical Neurophysiology, 110,* 856-868.

Hall, J. W., III. (2007). *New handbook of auditory evoked responses.* Boston: Pearson Education, Inc.

Hari, R., Hamalainen, M., & Joutsiniemi, S. L. (1989). Neuromagnetic steady-state responses to auditory stimuli. *Journal of the Acoustical Society of America, 86*, 1033-1039.

Herdman, A.T., Lins, O., Van Roon, P., Stapells, D.R., Scherg, M., & Picton, T.W. (2002). Intracerebral sources of human auditory steady-state responses. *Brain Topography, 15,* 69-86.

Herdman, A. T., Picton, T. W., & Stapells, D. R. (2002). Place specificity of multiple auditory steady-state responses. *Journal of the Acoustical Society of America, 112*, 1569-1582.

Herdman, A. T., & Stapells, D. R. (2001). Thresholds determined using the monotic and dichotic multiple auditory steady-state response technique in normal hearing subjects. *Scandinavian Audiology, 30*, 41-49.

Herdman, A. T., & Stapells, D. R. (2003). Auditory steady-state response thresholds of adults with sensorineural hearing impairments. *International Journal of Audiology, 42*, 237-248.

Jerger, J., Chmiel, R., Frost, J. D., & Coker, N. (1986). Effect of sleep on the auditory steady state evoked potential. *Ear and Hearing, 7,* 240-244.

Jerger, J., & Jerger, S. (1965). Critical evaluation of SAL audiometry. *Journal of Speech and Hearing Research, 8*, 103-127.

John, M. S., Brown, D.K., Muir, P. J., & Picton, T. W. (2004). Recording auditory steady-state responses in young infants. *Ear and Hearing, 25,* 539-553.

John, M. S., Dimitrijevic, A., van Roon, P., & Picton, T. W. (2001). Multiple auditory steady-state responses to AM and FM stimuli. *Audiology and Neuro-otology, 6*, 12-27.

John, M. S., Dimitrijevic, A., & Picton, T.W. (2002). Auditory steady state responses to exponential modulation envelopes. *Ear and Hearing, 23*, 106-117.

Johnson, B. W., Weinberg, H., Ribary, U., Cheyne, D. O., & Ancill, R. (1988). Topographic distribution of the 40 Hz auditory evoked-related potential in normal and aged subjects. *Brain Topography, 1*, 117-121.

Kaf, W. A., & Danesh, A. A. (2008). Air-conduction auditory steady-state response: Comparison of interchannel recording using two modulation frequencies. *Journal of the American Academy of Audiology, 19*, 696-707.

Kuwada, S., Anderson, J. S., Batra, R., Fitzpatrick, D. C., Teissier, N., & D'Angelo, W. R. (2002). Sources of scalp-recorded amplitude modulated following response. *Journal of the American Academy of Audiology, 13*, 188-204.

Linden, R. D., Campbell, K. B., Hamel, G., & Picton, T. W. (1985). Human auditory steady state evoked potentials during sleep. *Ear and Hearing, 6*, 167-174.

Linden, R. D., Picton, T. W., Hamel, G., & Campbell, K. B. (1987). Human auditory steady-state evoked potentials during selective attention. *Electroencephalography and Clinical Neurophysiology, 66*, 145-159.

Lins, O. G., & Picton, T. W. (1995). Auditory steady-state responses to multiple simultaneous stimuli. *Electroencephalography and Clinical Neurophysiology, 96*, 420-432.

Lins, O. G., Picton, T. W., Boucher, B. L., Durieux-Smith, A., Champagne, S. C., Moran, L. M., . . . Savio, G. (1996). Frequency-specific audiometry using steady-state responses. *Ear and Hearing, 17*, 81-96.

Luts, H., & Wouters, J. (2005). Comparison of MASTER and AUDERA for measurement of auditory steady-state responses. *International Journal of Audiology, 44*, 244-253.

Oates, P., & Stapells, D. R. (1997). Frequency specificity of the human auditory brainstem and middle latency responses to brief tones. II Derived response analyses. *Journal of the Acoustical Society of America*, *102,* 3609-3619.

Perez-Abalo, M.C., Savio, G., Torres, A., Martin, V., Rodriguez, E., & Galan, L. (2001). Steady state responses to multiple amplitude-modulated tones: An optimized method to test frequency-specific thresholds in hearing-impaired children and normal-hearing subjects. *Ear and Hearing, 22,* 200-211.

Pethe, J., von Specht, H., Muhler, R., & Hocke, T. (2001). Amplitude modulation following responses in awake and sleeping humans—a comparison for 40 Hz and 80 Hz modulation frequency. *Scandinavian Audiology*, *30*(Suppl 52), 152-155.

Picton, T. W. (1990). Auditory evoked potentials. In D. Daly & T. Pedley (Eds.), *Current Practice of Clinical Electroencephalography.* (pp. 625-678). Baltimore, MD: Lippencott, Williams & Wilkins.

Picton, T. W. (2007). Audiometry using auditory steady-state responses. In Burkard, R. F., Don, M., & Eggermont, J. J. (2007). *Auditory evoked potentials: Basic principles and clinical application.* Baltimore: Lippincott, Williams, & Wilkins.

Picton, T. W., Dimitrijevic, A., Perez-Abalo, M. C., & Van Roon, P. (2005). Estimating audiometric thresholds using auditory steady-state responses. *Journal of the American Academy of Audiology, 16*, 140-156.

Picton, T., & John, M. (2004). Avoiding electromagnetic artifacts when recording auditory steady-state responses. *Journal of the American Academy of Audiology, 15*, 541-554.

Picton, T., John, M., Dimitrijevic, A., & Purcell, D. (2003). Human auditory steady-state responses. *International Journal of Audiology*, *42*, 177-219.

Picton, T. W., John, M. S., Purcell, D. W., & Plourde, G. (2003). Human auditory steady-state responses: The effects of recording technique and state of arousal. *Anesth Analg, 97*, 1396-1402.

Purdy, S. C., & Abbas, P. J. (2002). ABR thresholds to tonebursts gated with blackman and linear windows in adults with high-frequency sensorineural hearing loss. *Ear and Hearing*, *23*, 358-368.

Rance, G., Rickards, F. W., Cohen, L. T., De Vidi, S., & Clark, G. M. (1995). The automated prediction of hearing thresholds in sleeping subjects using auditory steady-state evoked potentials. *Ear and Hearing*, *16,* 499-507.

Rance, G., Roper, R., Symons, L., Moody, L., Poulis, C., Dourlay, M., & Kelly, T. (2005). Hearing threshold estimation in infants using auditory steady-state responses. *Journal of the American Academy of Audiology*, *16*, 291-300.

Rickards, F.W., Tan, L.E., Cohen, L.T., Wilson, O.J., Drew, J.H., & Clark, G.M. (1994). Auditory steady state evoked potentials in newborns. *British Journal of Audiology, 28,* 327-337.

Roß, B., Borgmann, C., Draganova, R., Roberts, L. E., & Pantev, C.(2000). A high precision magnetoencephalographic study in human auditory steady state response to amplitude modulated tones. *Journal of the Acoustical Society of America, 108*, 679-691.

Ross, B., Picton, T. W., Herdman, A. T., Hillyard, S. A., Pantev, C. (2004). The effect of attention on the auditory steady-state response. *Neurology and Clinical Neurophysiology, 22*, 1-4.

Sininger, Y. S., & Hyde, M. L. (2009). Auditory Brainstem Response in Audiometric Threshold Prediction. In J. Katz, L. Medweisky, R. Burkard, & L. Hood (6th ed.), *Handbook of clinical audiology*, (pp. 293-321). Baltimore: Lippincott Williams & Wilkins.

Small, S. A., Hatton, J. L., & Stapells, D. R., (2007). Effects of bone oscillator coupling method, placement, location, and occlusion on bone-conduction auditory steady-state responses in infants. *Ear and Hearing, 28*, 83-96.

Small, S. A., & Stapells, D. R. (2005). Multiple auditory steady-state responses to bone-conduction stimuli in adults with normal hearing. *Journal of the American Academy of Audiology, 16*, 172-183.

Small, S. A., & Stapells, D. R. (2006). Multiple auditory steady-state responses to bone-conduction stimuli in young infants with normal hearing. *Ear and Hearing, 27,* 219-228.

Small, S. A., & Stapells, D. R. (2008a). Maturation of bone conduction multiple auditory steady-state responses. *International Journal of Audiology, 47*, 476-488.

Small, S. A., & Stapells, D. R. (2008b). Normal ipsilateral/contralateral asymmetries in infant multiple auditory steady state-responses to air- and bone-conduction stimuli. *Ear & Hearing, 29,* 185-198.

Stach, B. A. (2002). The auditory steady-state response: A primer. *The Hearing Journal, 55*, 10-18.

Stapells, D. (2009). In J. Katz, *Handbook of clinical audiology.* Baltimore, MD: Lippencott, Williams & Wilkins.

Stapells, D. R., Galambos, R., Costello, J., & Makeig, S. (1988). Inconsistency of auditory middle latency and steady state responses in infants. *Electroencephalography Clinical Neurophysiology, 71,* 289-295.

Stapells, D. R., Linden, D., Suffield, J. B., Hamel, G., & Picton, T. W. (1984). Human auditory steady state potentials. *Ear and Hearing, 5,* 105-113.

Supin, A. Y., & Popov, V. V. (1995). Envelope-following response and modulation transfer function in the dolphin's auditory system. *Hearing Research, 92*, 38-46.

Suzuki, T., & Kobayashi, K. (1984). An evaluation of 40-Hz event related potentials in young children. *Audiology*, *23,* 599-604.

Van Maanen, A., & Stapells, D. R. (2005). Comparison of multiple auditory steady-state responses (80 versus 40 Hz) and slow cortical potentials for threshold estimation in hearing-impaired adults. *International Journal of Audiology, 44*, 613-624.

Van der Reijden, C. S., Mens, L. H., & Snik, F. M. (2005). EEG derivations providing auditory steady-state responses with high signal-to-noise ratios in infants. *Ear and Hearing, 26*, 299-309.

Vander Werff, K. R., & Brown, C. J. (2005). Effect of audiometric configuration on threshold and suprathreshold auditory steady-state responses. *Ear and Hearing, 26*, 310-325.

Venema, T. (2005). The ASSR revisited: A clinical comparison of two stimuli. *Hearing Review, 12*, 54-5.

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