TOWSON UNIVERSITY
COLLEGE OF GRADUATE STUDIES AND RESEARCH

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

Ashlee A. Harrington

Following an extensive literature review, an online tutorial was developed on the Auditory Steady State Response (ASSR). The literature review covers the following areas: auditory evoked potentials, history o the ASSR, neural generators of the ASSR, terminology unique to the ASSR, recording stimuli, stimulation techniques, analysis techniques for the ASSR, technical and recording parameters for the ASSR, subject factors, frequency and place specificity of the ASSR, clinical applications, calibration, and other considerations and future directions. The purpose of this website is to be a central information source of evidence-based practice for Doctor of Audiology (Au.D.) students and clinical audiologists with less than five-years experience with this auditory evoked potential. This website is easy to navigate, has animated figures describing various topics of the ASSR, and includes printer friendly downloads. The major topics of the website include: neural generators of the ASSR, terminology unique to the ASSR, stimuli utilized, stimulation techniques, analysis techniques, technical and recording parameters, subject variables, threshold estimation, calibration, and clinical applications.

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CHAPTER 1:

INTRODUCTION

A considerable amount of research as been conducted on the Auditory Steady State Response (ASSR). The ASSR is an auditory evoked potential, and is becoming a more widely known and accepted testing method to utilize when assessing hearing thresholds in difficult to test populations (i.e. children or persons that cannot actively participate in behavioral audiological testing). Although behavioral audiological testing is the gold standard for audiological evaluations, it requires a subjective response from the test subject; thus, there are clinical limitations. There is immense potential for ASSR testing in the populations that may provide unreliable behavioral responses, or are not able to provide a behavioral response. .

Galambos, Makeig, and Talmachoff (1981) first described an Event Related Potential (ERP) that repeated itself at a stimulus repetition rate of 40 per second, and coined this term the 40 Hz response. Following the initial research of Galambos and colleagues (1981), numerous research studies (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) have identified and discussed the initial limitations of the 40 Hz response, and developed testing parameters to control for these limitations. A thorough literature review of the ASSR was performed and includes the topics of: the history of the AEP, neural generators, specific terminology associated with the AEP, stimuli utilized, stimulation techniques, analysis techniques, technical and recording parameters, subject factors, frequency and place specificity, clinical applications (i.e. threshold estimation, bone conduction ASSRs, utilization for cochlear implant and hearing aid technologies), stimuli calibration, and future directions. The information included in this extensive literature review was condensed into a web-based tutorial for Doctor of Audiology (Au.D.) students and clinicians working with AEPs. The interactive web site provides the user with detailed information on various topics related to the ASSR, animated and narrated figures, stimuli sound clips, printer friendly resources, a self-test to assess understanding of the ASSR, and is in an easy to follow format.

CHAPTER 2:

LITERATURE REVIEW

Auditory Evoked Potentials (AEPs)

Evoked Potentials (EPs) are recordings of electrical activity occurring from either a human's or an animal's peripheral and/or central nervous system following sensory stimulation. Evoked Potentials may result from stimulation to the visual, somatasensory, and/or auditory systems. Evoked Potentials recorded following presentation of an auditory stimulus are appropriately named auditory evoked potentials (AEPs). In humans, many different types of AEPs can be recorded. To distinguish between the various types of AEPs, Picton (1990) has developed several classification systems based upon the function, anatomy, latency, and relationship to the stimulus (i.e. transient, steady-state, or sustained). Table 1 displays information regarding these classification systems.

Table 1

Classification of human auditory evoked potentials. Adapted from Stapells, D. R. (2009), p. 396.

Function	Anatomy	Latency	Relationship to stimulus		
			Transient	Steady-state	Sustained
Sensory	Cochlear and eighth nerve	First (0-5 ms)	Eighth nerve CAP ABR Waves I and II	Cochlear microphonic	Summating potential
	Brainstem	Fast (2-20 ms)	ABR (wave III, IV, and V)	FFR, >60 Hz ASSR	Pedestal of FFR
	Early cortical	Middle (10-100 ms)	MLR (Na, Pa, Nb)	~40 Hz ASSR	
	Cortical	Slow (50-300 ms)	Slow "vertex" potential (P1, N1, P2, N2)	<20 Hz ASSR	Cortical Sustained Potential
Processing-Contingent Potentials	Cortical	Late (150-1000 ms)	Mismatch negativity (MMN) Processing negativity (Nd) N2b P3a, P3b LAN, N400, P600		CNV

Note. CAP, compound action potential; ABR, auditory brainstem response; MLR, middle latency response; FFR, frequency following response; ASSR, auditory steady-state response; LAN, left anterior negativity; CNV, contingent negative variation

The most popular classification system for AEPs distinguishes among the responses according to their response latencies and the relationship of these latencies to the auditory system (Picton, 1990). Auditory EPs fall into five domains when being classified by latency: first (0-5 ms post-stimulus onset), fast (2-20 ms post-stimulus onset), middle (10-100 ms post-stimulus onset), slow (50-300 ms post-stimulus onset), and late (150-1000 ms post-stimulus onset) (Picton, 1990). A second classification scheme describes the presumed underlying neural generators of the responses: first AEPs are believed to be a cochlear response; fast AEPs are generated from the VIIIth Cranial Nerve and multiple areas of the brainstem; middle latency responses and slow AEPs are believed to be primarily cortical responses, and lastly late AEPs are cortical responses which have multiple generators within the brain (Picton, 1990; Stapells, 2009).

Auditory EPs can further be classified into either sensory EPs or processing contingent potentials (PCPs). Sensory AEPs are obligatory or exogenous responses that depend on the presence of a stimulus and are sensitive to changes in physical properties of the stimuli. For example, if the frequency of the stimulus changes from a high to a low frequency tone, then the latency of the various components in the response increases. In contrast, PCPs, or endogenous potentials, are responses that represent processing beyond the initial obligatory sensory stage (Picton, 1990). An example of a PCP is being able to successfully elicit a wave P3b in response to a frequency difference in the signals (e.g.,1000 and 2000 Hz tone bursts), which were presented in an oddball paradigm. The finding indicates that the subject was able to not only detect the energy in the acoustic signals (obligatory/sensory processing) but also was able to discriminate the acoustic difference between these two tones (additional/complex processing).

Another popular classification system for AEPs involves the temporal relationship of the response to the stimulus. This classification system labels potentials as transient, sustained or steady-state responses. Transient evoked potentials occur when an auditory stimulus is presented at a slow enough stimulus rate such that the response to the one stimulus ends before the response to the subsequent stimuli begins (Linden, Campbell, Hamel, & Picton, 1985). In contrast, sustained potentials occur in response to either repeated or continual stimulation (Picton, 1990). Lastly, steady-state responses are generated by rapidly repeating stimuli that are presented at stimulus rates which cause the response from one stimulus to overlap with the response to the previously presented stimulus within the same post-stimulus analysis window (Linden et al., 1985). The remainder of this literature review will focus on the Auditory Steady-State Response (ASSR), as this is the primary focus of the web-based tutorial.

History of the ASSR

The term “Auditory Steady-State Response” or ASSR has emerged from the auditory 40-Hz event-related potential (ERP), which was first described in the literature by Galambos, Makeig, and Talmachoff (1981). In this study, Galambos and colleagues (1981) simultaneously recorded the auditory brainstem response (ABR) and the middle latency response (MLR) to 500 Hz tonal stimuli, which were presented at stimulus rates ranging from 3.3 per second to 55 per second in awake adults with normal hearing sensitivity (Galambos et al., 1981). These investigators (1981) discovered that when a 500 Hz tone was presented at a stimulus presentation rate of 40 per second, wave V of the ABR and waves Na, Pa and Nb of the MLR repeated themselves every 25 milliseconds (ms) within the 100 ms post-stimulus analysis window (Panel A of Figure 1) (Galambos et al., 1981). The response recorded at this presentation rate resembled a series of four sine waves, which repeated every 25 ms, as shown by the arrows in the waveform located at the bottom of panel B of Figure 1. These investigators (1981) reported that this overlapping pattern of responses of the ABR Wave V followed by the components of the MLR (Na, Pa, Nb, Pb) (Panel C of Figure 1) was unique to the 40 Hz presentation rate (Galambos et al., 1981).

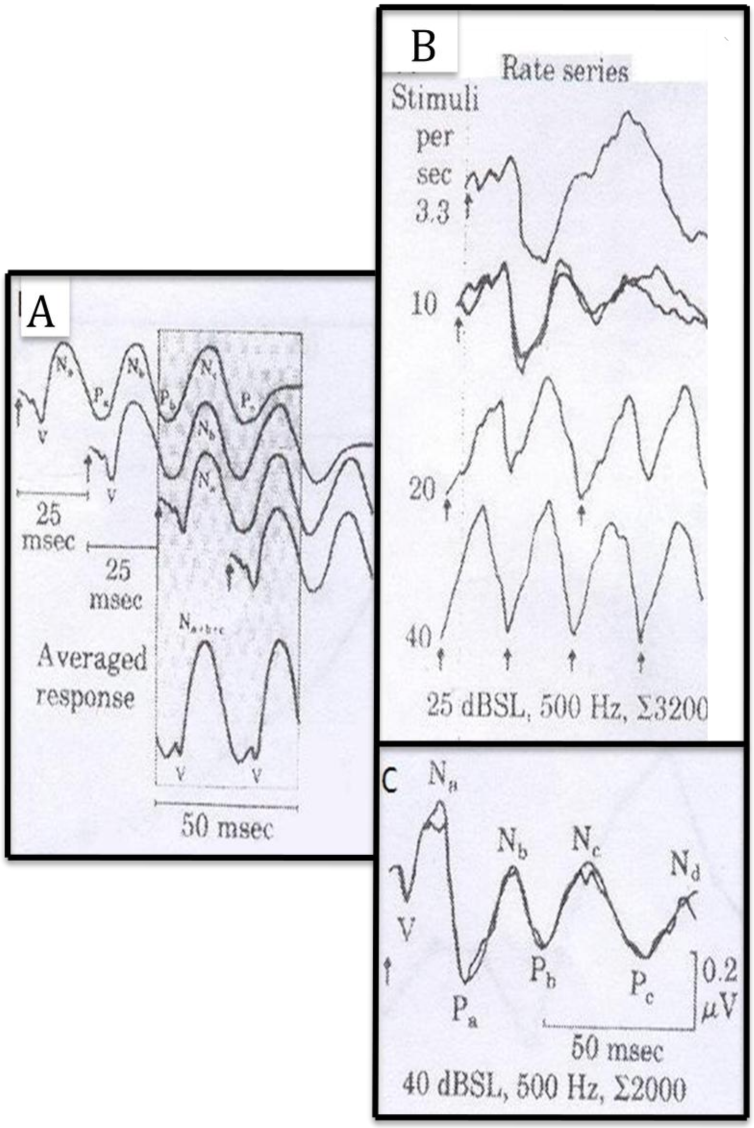

Figure 1. Panel A depicts the components of the ABR Wave V and MLR repeating themselves every 25 ms; coined the 40 Hz response as this pattern was unique only to the 40 per second stimulus presentation Panel B depicts the temporal waveforms of varied stimulus rates from 3.3 to 40 per second. A repeating pattern is apparent only at the 40 per second stimulus rate, as shown by the 4 arrows under the 40 per second waveform. Panel C depicts the 40 per second repeating pattern; the components of the ABR Wave V are followed by the components of the MLR (Na, Pa, Nb, Pb). Figure adapted from Galambos et al., (1981).

Galambos and colleagues (1981) plotted the amplitude of these ERPs as a function of presentation rate and found that the amplitude of the 40 Hz response was approximately two to three times larger in comparison to the amplitude of the responses at the other stimulus rates. This pattern is displayed in the adults' response labeled in Figure 2. As a result of these findings, Galambos and colleagues (1981) coined this term the "40 Hz response" to describe the unique properties of this response.

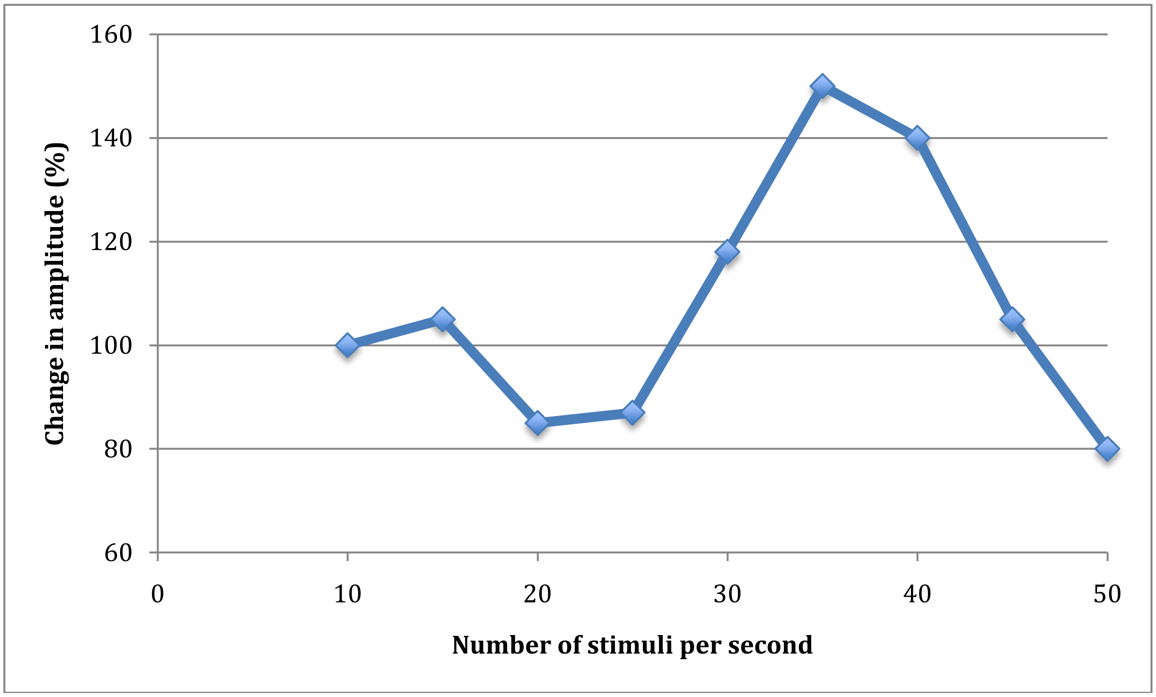

*Figure 2***.** Mean amplitudes of the 40 Hz ERP in adults plotted as a function of stimulus repetition rate. The peak response amplitude for adults is seen at the 40 Hz stimulus presentation rate. Figure adapted from Suzuki and Kobayshi (1984).

Galambos et al. (1981) reported on several interesting properties of this 40 Hz response. First, the 40 Hz ERP response can be elicited at several stimulus frequencies, including 250, 500 and 4000 Hz. Secondly, these 40 Hz ERP responses could be recorded at stimulus intensities very close to the subjects' behavioral thresholds. Thirdly, the amplitude of the 40 Hz response at threshold levels was considerably larger than ABR responses at similar intensities. Lastly, as the adult subjects drifted into a sleeping state, the amplitude of the 40 Hz response decreased by nearly half of its waking size (Galambos et al., 1981).

Stapells, Liden, Suffield, Hamel & Picton, (1984) conducted a replication of the initial Galambos et al. (1981) study. Stapells et al. (1984) reported that in normal hearing adults, the amplitude of the steady state response was the largest at stimulus repetition rates of 40 to 45 per second, while smaller responses occurred at slower and faster stimulus rates, similar to the results shown by Galambos and colleagues (1981). Stapells et al. (1984) also reported that as the frequency of the tonal stimulus increased, a decrease in the amplitude and latency of the response was observed. Lastly, the results of the Stapells et al. (1984) study indicated that the 40 Hz response could be used to estimate pure tone thresholds within a few decibels of the adult participant's true behavioral thresholds. These investigators, however, cautioned that although the 40-Hz ERP appeared to be recorded accurately in awake adults with normal hearing sensitivity, this response could not be generalized to all clinical populations (Stapells et al., 1984). Stapells et al. (1984) suggested that further research regarding the detectibility of the 40 Hz response in infants and young children, as well as the influence of varying subject state on this response was necessary.

In the mid to late 1980s, two research groups (Suzuki and Kobayshi, 1984 and Stapells, Galambos, Costello & Makeig, 1988) addressed this first issue of the detectability of the 40 Hz response in infants and young children. Suzuki and Kobayshi (1984) tested ten normal hearing infants and children (age 3 months to 6 years) and seven normal hearing adults (age 23 to 36 years), utilizing a click stimulus with modulation frequencies (MF) ranging from 10 to 50 Hz. All subjects were in a state of natural sleep. These researchers (1984) reported that the mean amplitude of the 40 Hz response in adults was similar to that previously reported by Galambos et al. (1981). In children, however, the response was significantly reduced at 40 Hz, and the peak amplitude of the response occurred at approximately 20 Hz (Suzuki & Kobayshi, 1984).

Stapells et al. (1988) also compared ERPs obtained from six sleeping adults (age 26 to 34 years) to the responses obtained from 18 infants and young children (age 3 weeks to 28 months) all of whom had normal hearing sensitivity. These investigators reported similar findings to Suzuki and Kobayshi (1984). The 40 Hz response obtained in the infants and children accounted for less than half the amplitude of the adult subjects at the same modulation frequency (Stapells et al., 1988). Collectively, the results of these two studies clearly demonstrated that the robust 40 Hz response seen in adults with normal hearing sensitivity could not be reliably recorded in the pediatric population. Rather, infants and young children revealed their most robust responses at stimulus rates between 20-30 Hz. Figure 3 shows the mean response amplitudes with the peak amplitude at 40 Hz in the adult subjects and from 20-30 Hz in the infant and young child subjects.

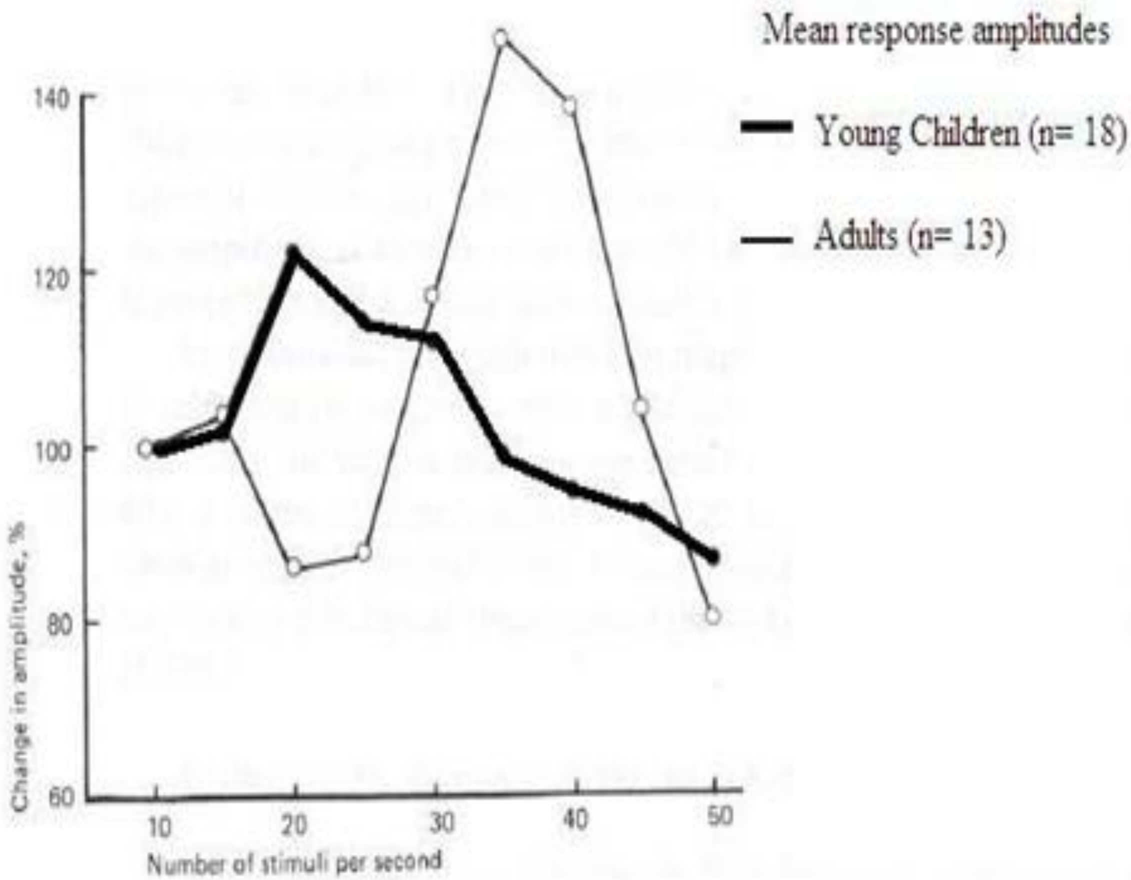

Figure 3. Mean amplitudes of the 40 Hz ERP in adults and young children plotted as a function of stimulus repetition rate. The peak response amplitude for adults is seen at the 40-Hz stimulus presentation rate, while the peak response amplitude for children is seen at approximately a 20 Hz stimulus presentation rate (Suzuki & Kobayshi, 1984).

The conclusions that the 40 Hz ERP was not a reliable measure for infants and young children led several investigators to speculate as to what might be the optimal stimulus rates for recording EPRs in the pediatric population (Aoyagi et al., 1993; Rickards et al., 1994). Specifically, Aoyagi et al. (1993) studied the differences in the steady state responses recorded in sleeping children to 1000 Hz tonebursts presented at stimulus modulation rates of 40 Hz, 80 Hz, and 100 Hz. These investigators (1993) reported that ASSRs were not detectable at 40 Hz in sleeping children, and was in agreement with the earlier findings (Aoyagi et al., 1993; Stapells et al., 1988; Suzuki & Kobayshi, 1984). When ASSRs were recorded at 80 Hz and 100 Hz modulation frequencies, however, the responses were robust and measurable in this pediatric population (Aoyagi et al., 1993). Consistent with the results reported by Aoyagi and colleagues (1993), Rickards et al. (1994) reported that frequency specific ASSRs can be recorded accurately in newborns (less than 7 days old) and in infants if stimulus repetition rates/modulation frequencies greater than 60 Hz are used. Collectively, the results of these two studies indicate that high modulation frequencies (approximately 70 - 110 Hz) are needed to elicit ASSRs in the pediatric population (Aoyagi et al., 1993; Rickards et al., 1994).

To address a second potential limitation in the ability to successfully record the 40-Hz ERP, and to better understand the characteristics of the steady-state response across various stages of natural sleep and wakefulness, Cohen, Rickards, and Clark (1991) examined 12 normal hearing adults with mixed modulated tones. The tones were presented at 250, 500, 1000, 2000, and 4000 Hz using varied modulation frequencies (MF), ranging from 30 to 190 Hz. These researchers reported that during wakefulness, subjects displayed larger response amplitudes at a 40 Hz MF than at higher MFs (≥70 Hz), regardless of the carrier frequency (CF), or stimulus intensity level (Cohen et al., 1991). However, when subjects were in a state of natural sleep, the largest ASSR response amplitudes occurred at higher MFs (70-190 Hz) compared to the lower 40 Hz MF (Cohen et al., 1991). Further, Cohen et al. (1991) reported that the amplitude of the response did not vary over the stages of natural sleep, although the integrity of the response was best during the rapid eye movement (REM) sleep stage. This is speculated to be a result of the lower levels of EEG noise recorded during the REM sleep stage as compared to deeper levels of sleep (Cohen et al., 1991).

Based on the collective findings discussed above, researchers have concluded that in awake adults the 40 Hz ERP can be used (Aoyagi et al., 1993; Cohen et al., 1991; Rickards et al., 1994; Stapells et al., 1988; Suzuki & Kobayshi, 1984); however, the 80 Hz response should be used in sleeping adults and in pediatric populations (Pethe, von Specht, Muhler, & Hocke, 2001; Picton, John, Dimitrijevic, & Purcell, 2003a). Researchers began to speculate that a leading reason for the varied behavior of the ASSR across age and sleep stages was based upon different underlying neural generators for responses recorded at lower (e.g., 40 Hz) versus higher (e.g., 80-100 Hz) MFs (Picton et al., 2003a). This issue will be explored in the next section of this literature review.

Neural Generators of the ASSR

Multiple human and animal studies have investigated which areas of the peripheral and central auditory nervous system are responsible for the neural generation of the auditory steady-state response (Giraud et al., 2000; Hari, Hamalainen, & Joutsiniemi, 1989; Herdman et al., 2002; Kuwada et al., 2002; Roβ, Borgmann, Draganova, Roberts & Pantev, 2000; Spydell, Pattee & Goldie, 1985). These studies have used various brain-imaging techniques, such as Brain Electric Source Analysis (BESA) Magnetoencephalography (MEG) and Functional Magnetic Imaging (fMRI) techniques. Studies have also investigated the neural generators of the ASSR in patients with known lesions in the auditory cortex and/or midbrain regions of the CANS and through conducting animal studies.

Brain Electric Source Analysis (BESA)

Using BESA to obtain far-field recordings for the origin of the ASSR response, Herdman et al. (2002) studied the correlation between stimulus/modulation frequency and the underlying neural generators of the response in ten adult subjects (mean age 30 years) with normal hearing sensitivity. Herdman et al. (2002a) presented click stimuli at three different stimulus rates/modulation frequencies: a low rate (12 Hz), a moderate rate (39 Hz), and a high rate (88 Hz). These authors (2002a) reported that the brainstem region was consistently active at all stimulus rates, however, the cortical regions of the brain were only active during presentation of slower stimulus rates (≤ 39 Hz) (Herdman et al., 2002a). In contrast, the neural generators responsible for the responses elicited at 88 Hz were only in the auditory pathways of the brainstem (Herdman et al., 2002a).

Magnetoencephalography (MEG)

A second brain–imaging technique used to study the neural generators of the ASSR was MEG. The MEG technique involves measuring magnetic fields produced by electric activity within the brain. Hari et al. (1989) used the MEG technique to investigate the intracerebral sources of the ASSR in a study conducted on 10 awake, normal hearing adult subjects. Hari and colleagues (1989) recorded the ASSR to stimuli presented at repetition/modulation rates ranging from 10.1 to 70.1 Hz. The results showed statistically significant differences in the amplitude of the response based on different modulation rates (Hari et al., 1989). The mean amplitude of the response was the largest at 40.1 Hz and was 2.7 times greater than the amplitude of the response at 30.1 Hz and 1.8 times greater than the amplitude of the response at 60.1 Hz. Furthermore, Hari and colleagues (1989) reported that the phase lag properties of the ASSR differed as a function of modulation frequency. Collectively, these findings led Hari and colleagues (1989) to conclude that there are slightly different neural generators located within the cortical regions of the brain for each of these modulation frequencies. The neural generators of the 40 Hz and 70 Hz modulation rates were not significantly different, and are located within the cortical structures located deep within the Sylvian fissure (Hari et al., 1989).

Roβ et al. (2000) also used MEG techniques to study the neural generators of the ASSR in young adults (22 to 32 years of age) with normal hearing sensitivity (≤ 10 dB HL) between 250 and 4000 Hz as identified by pure tone audiometry. In this study, ASSRs were recorded to 250, 500, 1000, 2000, and 4000 Hz CF tones presented at 70 dB SL utilizing stimulus repetition rates ranging from 10 to 100 Hz. The results reported by

Roβ and colleagues (2000) were similar to those of Hari et al. (1989), and showed that the auditory cortex responded to changes in stimulus repetition rates, thus suggesting cortical involvement. Furthermore, as the modulation frequency increased beyond 70 Hz, the time delay of the response decreased, suggesting brainstem activity at these higher modulation rates (Roβ et al., 2000).

Functional Magnetic Resonance Imaging (fMRI)

Another technique to investigating the underlying neural generators of the ASSR is via fMRI. The fMRI measures changes in blood flow in the brain that is related to neural activity (Giraud et al., 2000). Giraud and colleagues (2000) recorded fMRI in five normal hearing subjects to a white noise stimuli presented at varied repetition rates (4 to 256 Hz). The results indicated that the auditory cortex has a filtering system related to stimulus repetition rates in that the structures located higher in the central auditory nervous system (CANS) prefer low stimulus repetition rates (low MFs), while neural structures in the lower CANS prefer high stimulus repetition rates (high MFs) (Giraud et al., 2000).

Animal Studies

Further studies have examined the neural generators of the ASSR in animal subjects. Kuwada et al. (2002) obtained ASSR recordings from various locations on the surface of the brain in six un-anesthetized rabbits. The stimuli in this study were tone burstspresented at modulation rates ranging from 0 to 800 Hz. The rabbits were given injections meant to suppress the neural generators of the ASSR. Kuwada et al. (2002) reported that ASSRs recorded to low modulation rates (≤80 Hz) corresponded to neural generation sites primarily within the cortex, while ASSRs recorded to higher modulation rates (>150 Hz) corresponded to neural generation sites within the brainstem.

Collectively, the results of the studies employing neuro-imaging techniques (Giraud et al., 2000; Hari et al., 1989; Herdman et al., 2002a; Roβ et al., 2000) as well as the studies with animal lesions (Kuwada et al., 2002) suggest that there are multiple underlying neural generators for the ASSR. The location of these generators appears to be dependent on the modulation frequency of the stimulus. ASSRs recorded at low MFs (≤ 20 Hz) are generated primarily in the auditory cortex, those recorded at medium MFs (20-60 Hz), are generated in the auditory cortex, auditory midbrain and thalamus; and those recorded at high MFs (> 60 Hz) are generated in the brainstem region with contributions from the Superior Olivary Complex, Inferior Colliculus, and the Cochlear Nuclei (Giraud et al., 2000; Hari et al., 1989; Herdman et al., 2002a; Kuwada et al., 2002; Roβ et al., 2000; Spydell et al., 1985).

Terminology

In this section of the literature review, terminology used specifically in the ASSR literature and not related to other AEPs will be discussed and defined. In literature, ASSR is also referred to as the amplitude-modulation-following response (AMFR) (Aoyagi et al., 1993; Kuwada, Batra and Maher, 1986; Pethe et al., 2001; Riquelme, Kuwanda, Filipovic, Hartung and Leonard, 2006); the envelope-following response (EFR) (Dolphin, 1997); the steady-state evoked potential (SSEP) (Jerger et al., 1986); and the steady-state response (SSR) (Stach, 2002). Two important terms specific to the ASSR that audiologists/hearing scientists need to understand are *carrier frequency* and *modulation frequency*. These terms are defined below.

Carrier Frequency (CF)

Carrier frequency refers to the region of the cochlea where hair cells are activated during presentation of the tonal stimuli (GSI, 2001). The carrier frequency is what links the frequency of the stimulus tone to the particular region of the basilar membrane that is best tuned to that specific frequency, and is the test frequency of interest. For example, a 1000 Hz CF tone activates the portion of the basilar membrane that is best tuned to 1000 Hz, as shown in Figure 4. The typical CF tones used in ASSR testing are 500, 1000, 2000, and 4000 Hz.

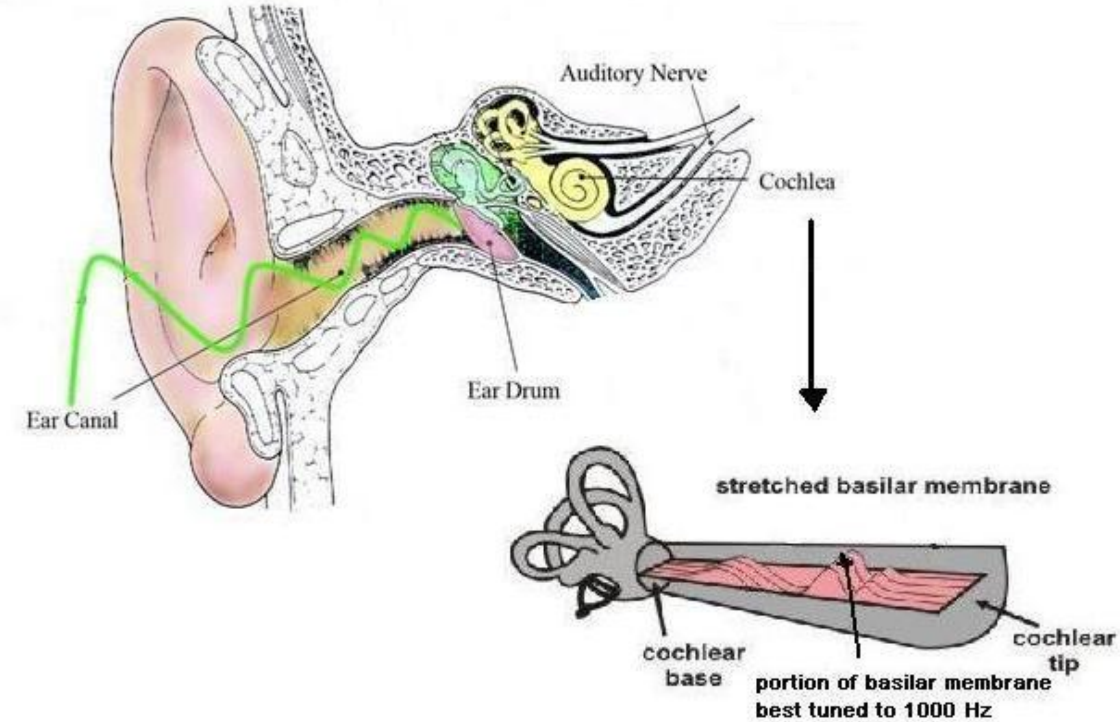

Figure 4. Depicts a 1000 Hz tone entering the ear canal with peak displacement at the region of the basilar membrane best tuned to 1000 Hz.

Modulation Frequency (MF)

A second term unique to the ASSR is modulation frequency (MF). The MF is the frequency at which the EEG activity is synchronized to fire (GSI, 2001). The MF is determined by calculating the period of the modulation frequency (period = 1 sec/MF). For example, if a 100 Hz MF is used with a 2000 Hz CF tone then the auditory nerve will synchronously fire every 10 ms (1000 ms/100 Hz = 10 ms), as shown in Figure 5. In its simplest analogy, the MF is similar to the stimulus rate.

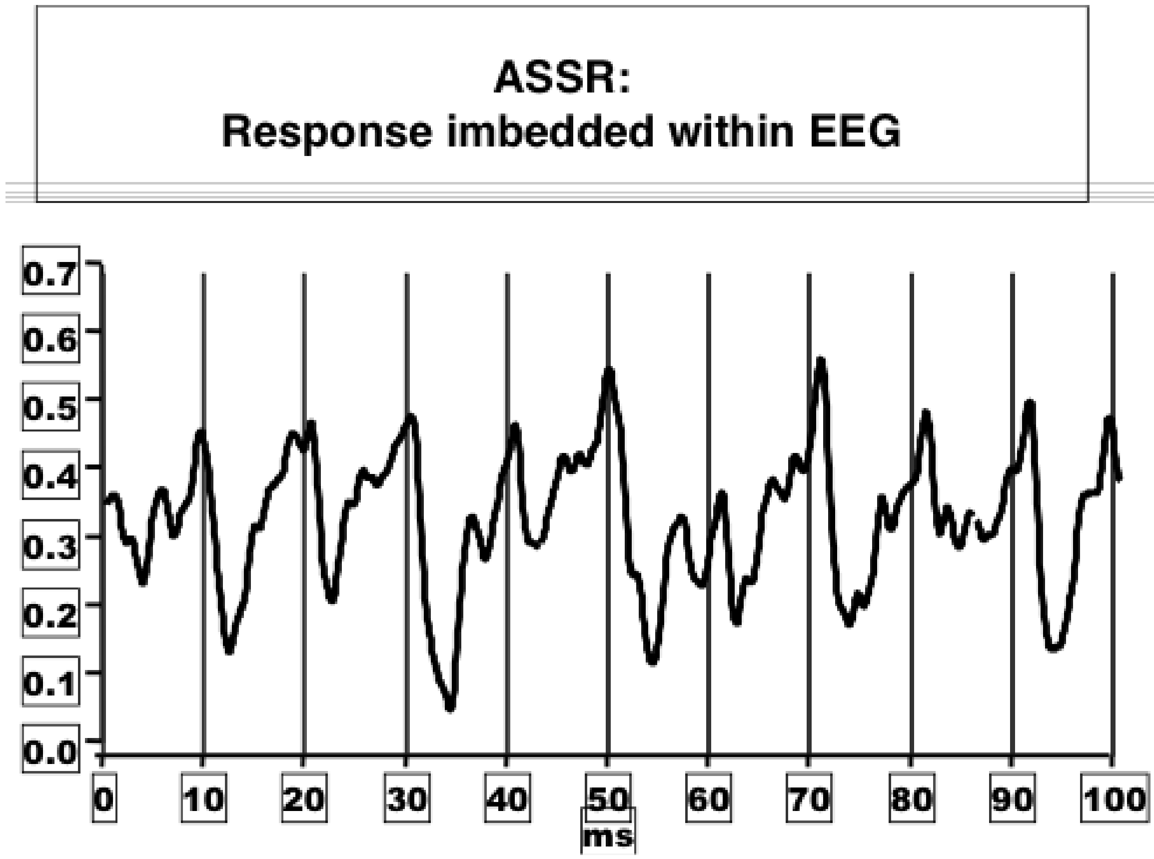

Figure 5. The neural firing of a 2000 Hz CF tone with a MF of 100 Hz. The vertical lines show neural firing every 10 ms, equal to the period of the MF (1000/100 ms = 10 ms) (GSI Brochure, 2001).

Further terminology that will be defined and discussed in greater detail later in this manual include the common types of stimuli used to elicit the ASSR (i.e., amplitude modulated tones, frequency modulated tones, mixed modulated tones, and repeated sequence tones), stimulation techniques (i.e., single frequency stimulation technique and multiple frequency stimulation technique), and response analysis techniques (i.e., phase coherence, Fast Fourier Transform [FFT], and F-Ratio application to FFT) for the ASSR. These are not the only types of stimuli, nor are they the only types of stimulation and/or response analysis techniques used with the ASSR, as will be described later in this literature review.

Stimuli

Historically, ASSRs have been recorded utilizing various types of stimuli. There are two main categories that each type of stimuli falls into: broadband (non-frequency specific) stimuli, or frequency-specific stimuli (Beck, Speidel, & Petrak, 2007). Broadband stimuli used to elicit the ASSR include clicks, noises, chirps, and amplitude modulated noise; whereas frequency specific stimuli used to elicit the ASSR include tone bursts, filtered clicks, band-limited chirps, narrow band noise, or amplitude and frequency modulated tones (Beck et al., 2007). According to Picton and colleagues (2003a) the primary difference between these two general types of stimuli are those that fall into the broadband category have energy at multiple frequencies across the acoustic spectrum, and thus activate broad regions of the basilar membrane. In contrast, frequency-specific stimuli activate limited areas of the basilar membrane that are best tuned to the specific characteristics of the presented stimulus (Picton et al., 2003a). Numerous authors (Beck et al., 2007; Hall, 2007; Picton et al., 2003a) have reported that the use of broadband stimuli for the ASSR are similar to conducting a click-evoked ABR as they can be used to quickly reach a rough estimation of the ASSR threshold. Once this approximate threshold estimation has been reached, utilizing frequency specific stimuli helps to narrow in on the true ASSR threshold. In general, however, broadband stimuli are not typically used in most clinical applications of the ASSR. Therefore, the remainder of this discussion of stimulus types will be limited to those commonly used in a clinical environment for eliciting the ASSR. These include: amplitude modulated tones, frequency modulated tones, mixed modulated tones, and repeating sequence tones.

Amplitude Modulated (AM) Tones

The most commonly used stimuli to record the ASSR are AM tones (Picton et al., 2003a). Amplitude Modulated tones represent a change in the amplitude of the stimulus over time. These amplitude changes occur within each cycle of the tonal stimulus. The change in the amplitude of the signal is referred to as the depth of modulation and is expressed as a percentage. For example, if a 4000 Hz tone has 100% AM, the amplitude changes from its baseline to its maximum amplitude. The temporal waveform shown in row A of Figure 6 shows that for this 4000 Hz AM tone, the baseline amplitude occurs at approximately 0 ms and reaches its maximum amplitude at approximately 5 ms. In the frequency domain, this AM stimulus has its peak energy located at the CF (4000 Hz) and has two side lobes of energy located at the CF-MF (4000 Hz – 100 Hz = 3900 Hz) and at the CF + MF (4000 Hz + 100 Hz = 4100 Hz), as shown under the frequency domain section of panel A, Figure 6. One advantage of using AM tones to record the ASSR is that they are very frequency specific (Picton et al., 2003a).

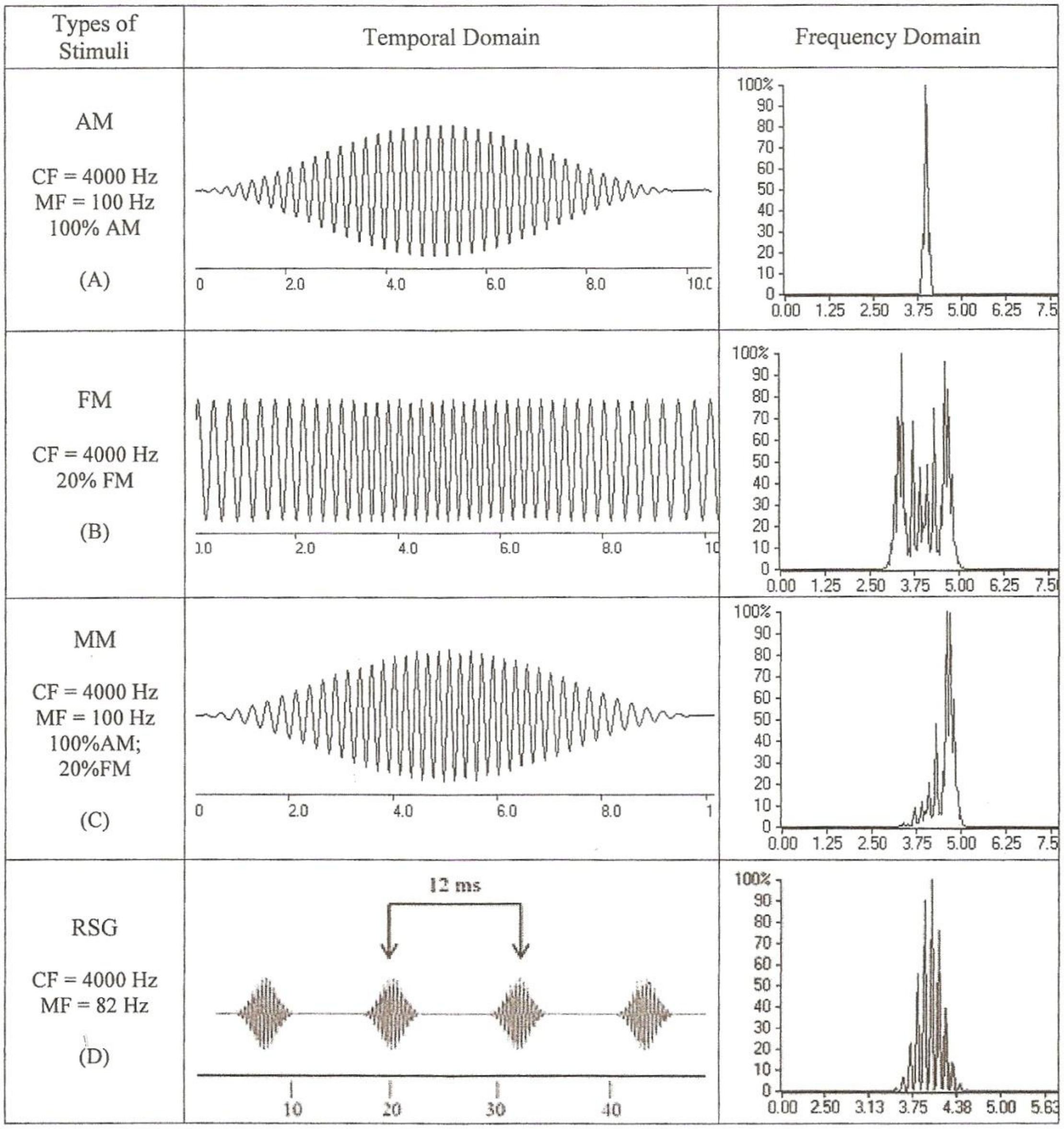

Figure 6. The most common types of stimuli utilized in the ASSR recording are shown in the temporal and frequency domain. Figure adapted from John & Purcell (2008) and Venema (2005).

Frequency Modulated (FM) Tones

In contrast, a FM tone represents a change in the frequency of the CF tone over time while the amplitude of the signal remains constant. The amount of frequency modulation of the stimulus that occurs is expressed as a percentage; the larger the percentage, the larger the frequency fluctuations around the CF (John, Dimitrijevic, van Roon, & Picton, 2001). Further, FM is described as the difference between the maximum and minimum frequencies divided by the carrier frequency. This equation is shown below:

$$\frac{\text{(maximum frequency-minimum frequency)}}{\text{carrier frequency}}$$

For example, if a 4000 Hz CF is frequency modulated by 20%, the frequency will change +/- 20% of the CF, which would be between 3200 and 4800Hz. This pattern of frequency change is seen in the temporal waveform shown in row B of Figure 6 as a lower frequency is apparent from approximately 0-3 ms and increases in frequency from approximately 4-7 ms. Panel B of Figure 6 also shows the frequency spectrum of this 4000 Hz FM tone, which is somewhat wider than that seen for the AM tone. The wider excitation of the basilar membrane for the FM tone in comparison to the AM tone occurs because FM tones stimulate the basilar membrane at the fundamental frequency as well as the second and third harmonics of the modulation frequency (Picton et al., 2003a; Venema, 2005).

Mixed Modulated (MM) Tones

Mixed modulated tones are a combination of amplitude and frequency modulation. Row C of Figure 6 shows a 4000 Hz MM tone with 100% AM and 20%

FM. The temporal waveform clearly shows a change in both the amplitude and frequency of the signal over time, as seen in row C of Figure 6. Looking at the right side of row C of Figure 6, the reader can see that the frequency spectrum of the MM tone is more narrow than the spectrum for the FM tone; thus, is a more frequency specific stimulus. The main lobe of energy in row C of this figure is located at the CF of 4000 Hz, while smaller lobes of energy are present at the CF ± MF, or at 3900 and 4100 Hz.

Two possible advantages of using MM tones are: (1) Picton and colleagues (2003) reported that MM tones have a dual effect on the cochlear generation site, and thus are more frequency and place specific than either AM or FM alone;(2) Venema (2005) has demonstrated that ASSRs recorded to MM tones in adults and children have larger amplitudes in comparison to ASSRs recorded to AM or FM tones alone. Larger response amplitudes aid the clinician in establishing ASSR thresholds in a more timely fashion.

Repeated Sequence Gated (RSG) Tones

The repeated sequence tonal stimuli are unique to the Intelligent Hearing System (IHS) ASSR software. In this software a series of *Blackman gated tones* are presented in a repeated sequence format with CFs ranging from 500 to 4000 Hz and MFs ranging from 77 to 101 Hz. The period of the MF of the tone determines the timing between stimulus repetitions. For example, if a 4000 Hz CF has a MF of 82 Hz, then the stimulus pattern repeats itself every 12 ms (4000/82 Hz) as shown in the temporal waveform in row D of Figure 6. If an ASSR is recorded, this will indicate that the auditory nerve was able to synchronously fire every 12 ms. The right side of row D of Figure 6 also shows the frequency domain of the RSG tone. The peak energy occurs at the CF (4000 Hz) and the side lobes of energy occur at the CF ± MF (i.e., 3918 Hz and 4082 Hz).

The IHS system generally uses Blackman gated tones to record ASSRs, however, other types of stimuli are available. The Blackman gated tone is a more complex trigonometric function than a linear gated tone. Gorga & Thorton (1989), speculated that the use of a Blackman gated tone results in a more frequency specific ABR in comparison to an ABR recorded to a linear-gated tone. When Blackman gated and linear gated tones of the same frequency are compared spectrally, three main differences become evident. First, the width of the main energy lobe of the Blackman gated tone is wider than that of the linear tone. Second, the side lobes of energy are much more apparent in the linear gated tones, and nearly absent in Blackman gated tones. On average, the side lobes of energy have amplitudes 27 dB below the peak energy in the main lobe for the linear gated tones, while the side lobes of energy are 58 dB below the peak energy for the Blackman gated tones. Lastly, because the side lobes of energy occur at much higher amplitudes in the linear tones, the rate of decay for the side lobes of energy is much steeper than compared to the Blackman gated tones (Gorga & Thorton, 1989). Oates and Stapells (1997) and Purdy and Abbas (2002) demonstrated that there are no significant differences in the frequency specificity of the ABR and/or MLR when recording these responses to either linear gated tones or Blackman-gated tones. Thus, both stimuli may be utilized to elicit frequency specific ABRs and ASSRs.

Stimulation Techniques

There are at least two possible stimulation techniques that can be used when recording the ASSR, a *single frequency (SF) stimulation technique* and a *multiple frequency (MF) stimulation technique* (Regan, 1982). The first, and easiest to understand is the *single frequency (SF) stimulation technique*. The SF technique consists of presenting a single CF tone at one stimulus intensity to one ear. Figure 7 displays this approach, showing a 1000 Hz CF tone being presented at 70 dB SPL to the subject's right ear with a modulation frequency of 95 Hz. This CF tone then stimulates the portion of the basilar membrane best tuned to 1000 Hz.

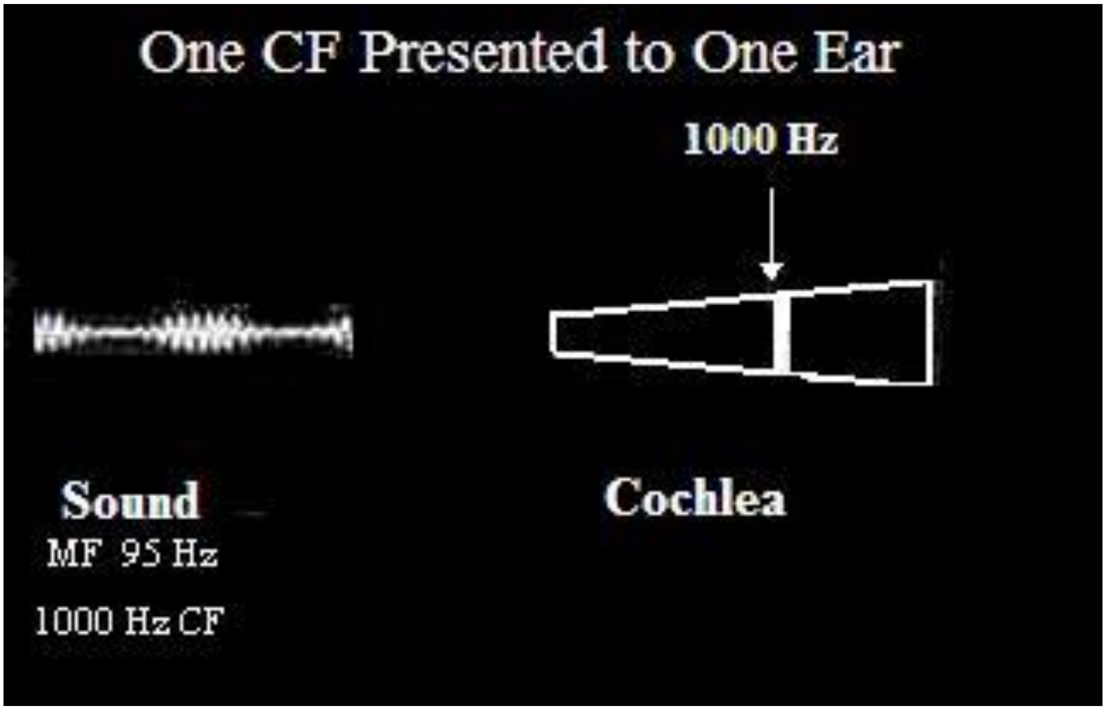

Figure 7. The SF stimulation technique; a 1000 Hz CF tone with 95 Hz MF is presented to one ear and stimulates the portion of the basilar membrane best tuned to 1000 Hz (Hall, 2007).

On the other hand, in the MF stimulation technique, up to four CF tones (typically 500, 1000, 2000, and 4000 Hz) are presented simultaneously to one or both ears. Figure 8 displays the MF stimulation technique which shows a complex tone waveform consisting of the sum of four CF tones (500, 1000, 2000 and 4000 Hz) being presented at 70 dB SPL in a monaural fashion to the subject's right ear. Further, each CF tone has its own unique modulation frequency which range from 84 to 91 Hz. When the four CFs are combined, a complex waveform is created that stimulates the frequency regions of the basilar membrane that are best tuned to these four frequencies, that is the 500, 1000, 2000 and 4000 Hz regions.

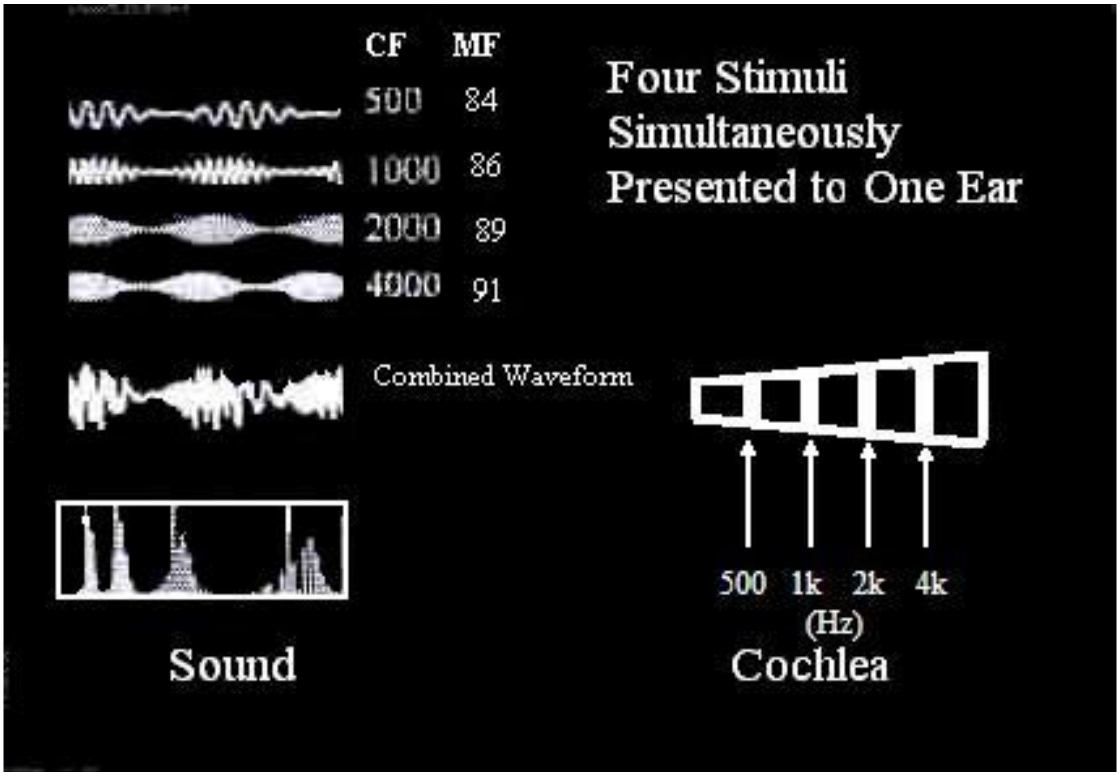

Figure 8. The MF stimulation technique; CF tones of 500, 1000, 2000, and 4000 Hz, with MF varying from 84 to 91 Hz are simultaneously presented to one ear, stimulating the portions of the basilar membrane best tuned to each specific CF (Hall, 2007).

The MF technique may also be used to present the stimuli in a binaural fashion. When utilizing a binaural MF stimulation technique, eight carrier frequency tones can be presented to both ears (four tones presented to each ear) simultaneously. In the binaural MF stimulation technique, each CF tone must have its own unique modulation frequency; these typically range from 82 to 106 Hz (Beck et al., 2007).

John, Lins, Boucher, and Picton (1998) reported that there are certain criteria for both the CF tones and the MFs that must be followed in order to obtain optimal MF ASSR recordings in a binaural mode. These criteria include the following principles: (1) each MF must be greater than 75 Hz; (2) each CF tone must have a presentation intensity level of 60 dB SPL or less; and (3) each CF tone must be at least one octave apart to prevent any significant reduction in the amplitude of the ASSR. When this set of criteria are followed, several investigators have reported that there is no decrease in ASSR response amplitudes for the binaural test condition in comparison to the monaural test condition and also no increase in the amplitude of the ongoing EEG noise (Canale, Lacilla, Cavalot, & Albera, 2005; John, Purcell, Dimitrijevic, & Picton, 2002b; Lins et al., 1996; Perez-Abalo et al., 2001).

There are several possible advantages of using the MF stimulation technique versus the SF stimulation technique. One advantage is that the MF stimulation technique gives the clinician the ability to test all four frequencies (500, 1000, 2000, & 4000 Hz) simultaneously in one or both ears without compromising the accuracy of threshold estimation as the level of EEG noise is consistent across all frequencies (Canale et al., 2005; John et al., 2002b; Lins et al., 1996; Perez-Abalo et al., 2001). Lins and Picton (1995) reported that there were not statistically significant differences in the accuracy of

ASSR threshold estimations made when they compared the results of the MF technique (either monaural or binaural) to the results obtained with the SF technique. A second considerable advantage of the MF stimulation technique is that it may substantially reduce the test taking time (Herdman and Stapells, 2001; John et al., 2002b).

One possible disadvantage of the MF stimulation technique is the upward spread of masking that may occur along the basilar membrane. Specifically, John et al. (2002b) reported that small interactions in the ASSR response may occur along the cochlear partition when utilizing a MF technique; however, these effects are not significant at stimulus intensities lower than 60 dB SPL, at modulation frequencies greater than 70 Hz (and more than 3 Hz apart), or are presented monaurally or by an octave frequency apart (Cone & Dimitrijevic, 2009; John et al., 2002b; Lins & Picton, 1995; Picton et al., 2003a). These investigators also suggest that MF technique is likely not the best choice if the client has an irregular shaped audiogram (i.e., steeply sloping, cookie-bite configuration) (John et al., 2002b)

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Analysis Techniques for the ASSR

Analysis of the ASSR is quite different from most other auditory evoked potentials in that it strictly relies on objective analyses techniques. This response analysis is not based upon subjective peak picking and measurements of absolute latency and/or peak-to-peak amplitude values, but instead is based on a computer algorithm that is applied to the recorded EEG signal to analyze the magnitude and phase of the EEG activity associated with the modulation frequency of the CF tone (GSI, 2001). There are two specific types of analyses utilized in recording the ASSR. These are: (1) a combination of Fast Fourier Transform (FFT) analysis and the F-Ratio and (2) phase coherence analyses. Below is a description of each of these techniques.

Fast Fourier Transform (FFT) and the F-Ratio

Fast Fourier Transform is a technique that converts the temporal waveform of the ASSR into the frequency domain. The results of this conversion are graphically represented on a frequency spectrum plot, which displays the energy (amplitude) component on the y-axis and frequency component on the x-axis.

When recording the ASSR, the FFT analysis technique analyzes the brain activity that occurs during auditory stimulation, and then plots the amplitude of the energy that occurs at the MFs present in the CF tone and compares that to the energy present in the ongoing EEG signal at frequencies both above and below the MF. Figure 9 illustrates the FFT results of both a SF stimulation technique (Panel A) and a MF stimulation technique (Panel B). Panel A of Figure 9 displays the ASSR to a 1000 Hz CF tone FM at 85 Hz. The FFT results show that the amplitude of energy at the MF (85 Hz) is substantially larger than the ongoing EEG noise that occurs in the 120 adjacent bins (60 bins above and 60 bins below the MF), as indicated by the dark bar.

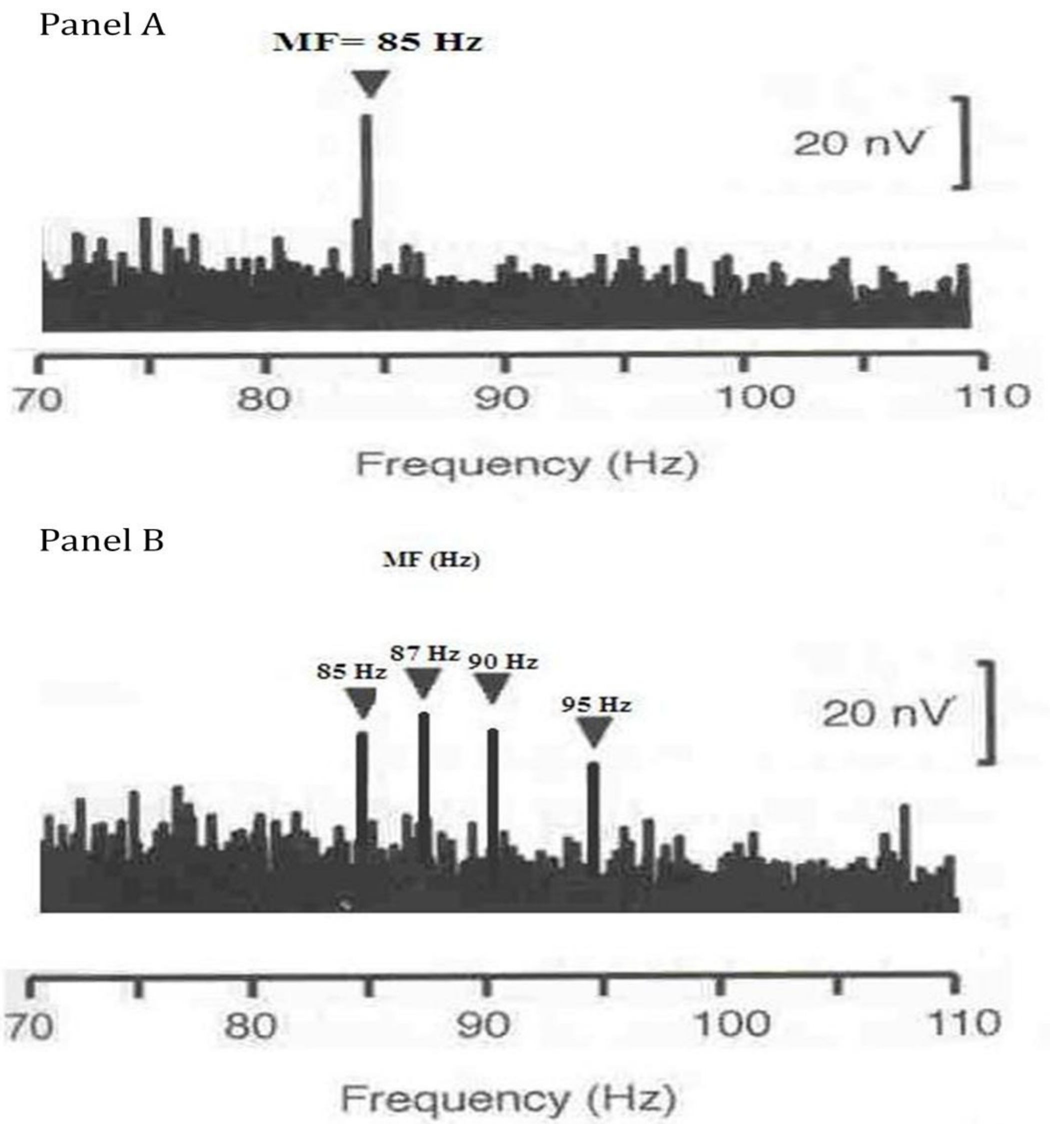


Figure 9. The FFT Analysis of a SF (Panel A-top) and MF (Panel B-bottom) stimulation technique. *Panel A* depicts the SF stimulation technique of a 1000 Hz CF with a MF of 85 Hz presented at an audible level as the response is standing out of the ongoing noise collected from the adjacent bins. *Panel B* depicts the MF stimulation technique of a 500 Hz CF with a MF of 85 Hz, 1000 Hz CF with a MF of 87 Hz, 2000 Hz CF with a MF of 90 Hz, and 4000 Hz CF with a MF of 95 Hz simultaneously presented to one ear. The arrowed bars represent a present response for each of the CFs as the MF is larger than the ongoing noise collected from the adjacent bins. Figure adapted from Picton et al. (2003).

In contrast, Panel B of Figure 9 shows the ASSR to the MF stimulation technique. The MF technique (Panel B) shows the response of a 500 Hz CF tone FM at 85 Hz, a 1000 Hz CF tone FM at 87 Hz, a 2000 Hz CF tone FM at 90 Hz, and a 4000 CF tone FM at 95 Hz. FFT results show the amplitude of energy that occurred at each of the MFs (i.e., 85, 87, 90, and 95 Hz), indicated by the four dark bars, is substantially larger than the energy present in the ongoing EEG noise in the 120 adjacent bins (60 bins above and 60 bins below the MF).

The F-Ratio becomes important when classifying whether an ASSR was present or absent for a particular CF tone at the stimulus intensity being assessed. Specifically, the ASSR EP software compares the amplitude of the energy present at the MF to the amplitude of the energy present in the ongoing EEG noise (Picton et al., 2003a). If the amplitude of the response at the MF is significantly larger than the amplitude of the ongoing EEG noise in the adjacent bins, then an ASSR is judged to be present for that CF tone at that stimulus intensity. Generally an alpha level of $p < 0.05$ is used to judge statistical significance (Picton et al., 2003). The combination of FFT analysis and F-Ratio technique is typically used with a multiple frequency stimulation technique (i.e., MASTER system), however it may also be used with a single frequency approach (i.e. AUDERA system).

Phase Coherence (PC)

Phase coherence is a different type of analysis technique that is employed with the ASSR. In this technique, the temporal waveform of ASSR is converted into the frequency domain using FFT. The amplitude and phase information provided by the results of the FFT is then plotted on a graph referred to as a polar plot, as shown in Figure

10. In this plot, the *magnitude* or amplitude of the ASSR at the MF is represented by the length of the vector, while the phase of the response at the MF is represented by the angle from the x-axis (0˚) measured counter-clockwise (GSI, 2001; Hall, 2007). The angle is thus labeled *phase angle*.

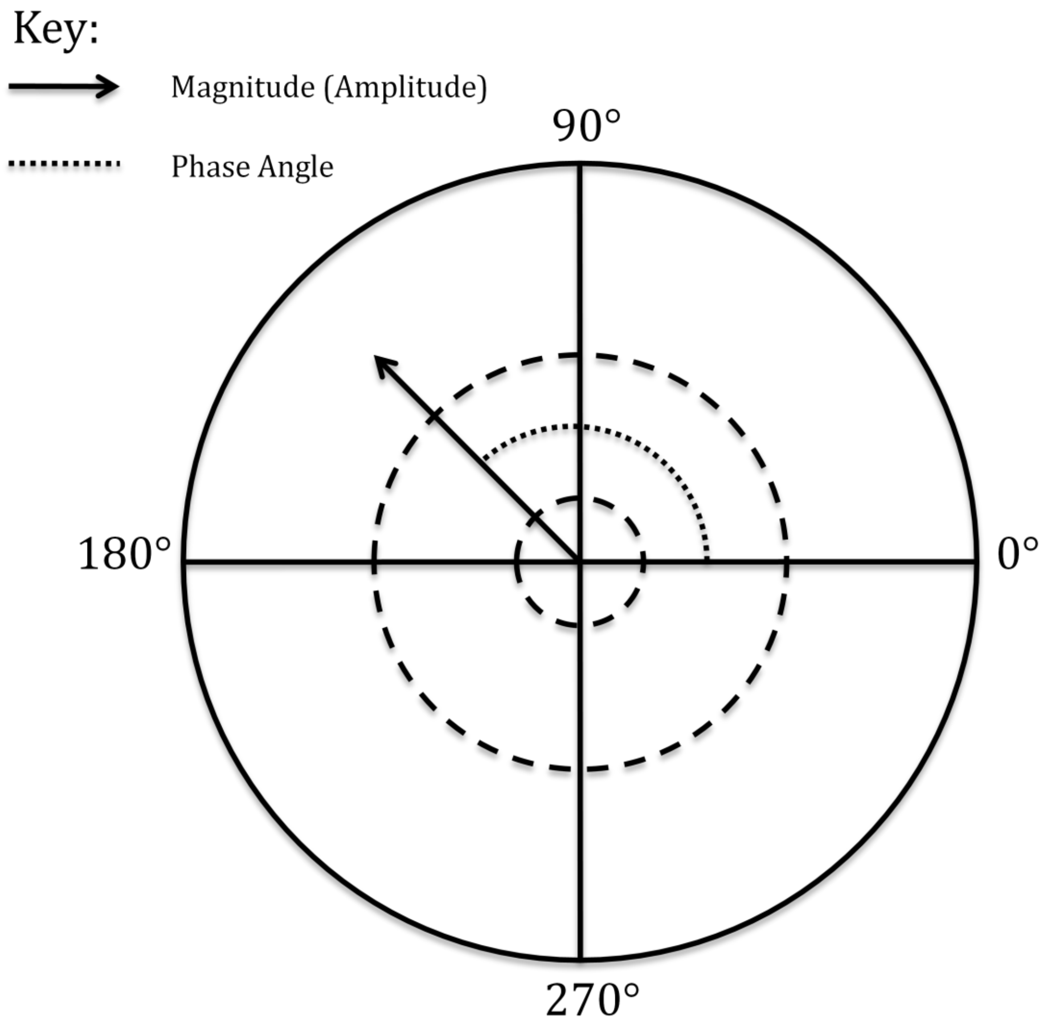


Figure 10. The polar plot is broken into four quadrants (I = 0°-90°; II = 90°-180°; III = 180°-270°; IV = 270°-360°). The magnitude (or amplitude) of the response is represented by the length of the vector (arrow) in quadrant II. The phase angle is represented by the closely dotted line extending from 0° to the vector in quadrant II.

This PC technique uses a measure called the Phase Coherence Squared (PC^2) value. This PC^2 value represents the strength of the phase relationship, and ranges from 0.0 to 1.0. The PC^2 value represents the probability that the energy present in the response is from a true ASSR surrounding the MF (GSI, 2001). The closer the PC^2 value is to 1.0, the higher the phase correlation, indicating that the magnitude of the response at the MF is significant and distinguishable from the ongoing background noise (Cone & Dimitrijevic, 2009). In contrast, a PC^2 value of 0.0 indicates low coherence and constitutes no ASSR, or a response consisting of only noise (Cone & Dimitrijevic, 2009).

While the ASSR test is being run, PC vectors are plotted in the polar plot and if these vectors all fall within the same quadrant of the plot, they form a cluster of responses (Cone & Dimitrijevic, 2009; GSI, 2001; Hall, 2007). This pattern is called *phase-locked.* In this pattern, the PC^2 value is high, and the ASSR is judged to be present for that CF tone at that stimulus intensity as is shown in Panel A of Figure 11. This pattern only occurs when the brain is accurately responding/firing to the temporal information present in the stimulus. In contrast, if the ASSR vectors on the polar plot have a random distribution throughout all four quadrants, the PC^2 value will be low (indicating low coherence), and the response is judged to consist of only noise, as shown in Panel B of Figure 11. Thus, the ASSR is absent for that particular CF tone at that stimulus intensity, and is labeled a *random* response. The PC analysis technique is typically used with SF stimulation technique and is present on the AUDERA clinical ASSR system.

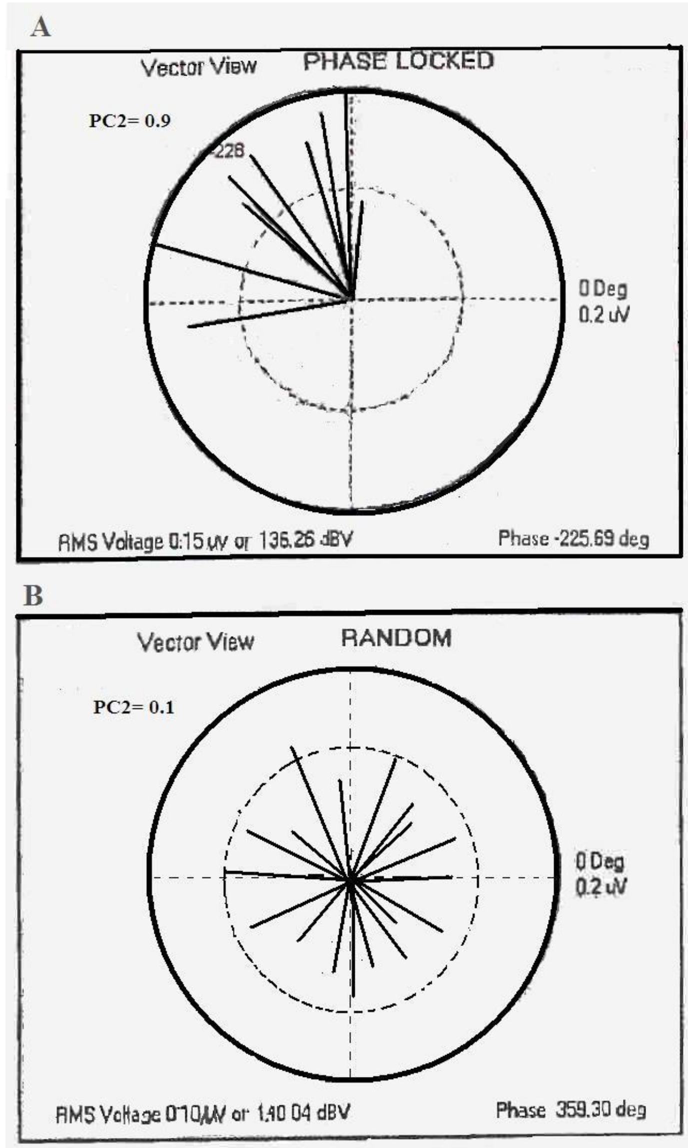


Figure 11. An illustration of the Phase Coherence Analysis. Panel A shows the audible signal as the response is "phase-locked" showing all vectors in the same quadrant with a high PC2 value (0.9). Panel B shows an absent response as the vectors are randomly located around the polar plot with a low PC2 value (0.1) (GSI, 2001).

Technical Parameters for the ASSR

There are numerous technical or recording parameters that may affect a successful recording of the ASSR. These parameters include: analog EEG band pass filter settings, stimulus artifact, artifact rejection, electrode montage, number of recording channels, the gain of the amplifier and objective stopping rules for signal averaging. Each of these technical recording parameters will be briefly discussed in the section below.

Analog EEG Band Pass Filter Setting

Filtering can be completed either through an off-line (digital) or on-line (analog) system, or through a combination of these two methods (Cone & Dimitrijevic, 2009). The main goal of band pass filtering is to increase the signal-to-noise ratio (SNR) through removal of any unwanted activity at frequencies other than the MF. The unwanted activity is the ongoing EEG noise, and comes from noise in the test environment, the test subject (moving, coughing, etc.), uncontrollable muscle movement, or possible electrical noise (Cone & Dimitrijevic, 2009).

The choice of the EEG band pass filter setting is determined by knowledge of the energy present in the response. In the case of the ASSR, the energy present in the response is determined by the modulation frequencies of the CF tones. Generally MFs for ASSR stimuli range from 70 -110 Hz, so the analog EEG band pass filter setting must be set to allow for these frequencies to be recorded and analyzed. In ASSR testing, a 30 Hz high-pass filter and a 300 Hz low-pass filter setting have been recommended in order to capture the energy present at the MFs (Cone & Dimitrijevic, 2009). The high-pass filter setting may be as low as 1 Hz to ensure this energy is accounted for; however, it is necessary to ensure the setting is no larger than 30 Hz as the filter setting may cause a dampened ASSR (Cone & Dimitrijevic, 2009; Hall, 2007; Picton et al., 2003a).

Stimulus Artifact

Physiologic or electromagnetic artifact may be present in the EEG response, and may result in falsely identifying an ASSR response (Hall, 2007). This is often seen when testing the ASSR via air conduction at high intensities (>95 dB HL), or at moderate intensities (>40 dB HL) if conducting bone conduction ASSR testing (Cone & Dimitrijevic, 2009; Hall, 2007). One way to control for artifact is by setting the *artifact rejection* parameters. Artifact rejection discards any samples that include an EEG response over a set amplitude/voltage value (i.e., 80 µV). This ensures that any activity within the EEG that has an abnormally large amplitude will be discarded and not recorded as a response, as most often this is artifact. The use of artifact rejection does have a downfall, as discarding of samples results in longer test times since more samples are needed for other analysis techniques such as averaging (Cone & Dimitrijevic, 2009).

A second way to control for artifact in the response is to set an anti-aliasing filter. *Aliasing* occurs when the signal is sampled at a rate lower than twice the highest frequency present in the response, and appears as spectral energy near the MF (Cone & Dimitrijevic, 2009; Hall, 2007). Setting a steep anti-aliasing (low-pass) filter ensures that the sampling rate is at an appropriate level and is at least twice the Nyquist frequency (Cone & Dimitrijevic, 2009; Hall, 2007). These methods are especially important to use in bone conduction testing, as stimulus artifact is more likely to impact the EEG recording at lower presentation levels.

Electrode Montage

The electrode montage utilized when recording the ASSR is the same 10-20 international system, as used with other AEPs. The non-inverting electrode should be placed on the vertex (Cz) or mid-frontal scalp (Fz), with the reference or inverting electrodes located on the mastoids, nape of the neck (Cv7), or inion, with ground at the shoulder or low forehead (Picton, 2007). The reader should be familiar with this electrode montage as it is the same as that used when recording other physiologic measures including the ABR.

The largest ASSR response amplitudes in adults occur when the reference electrode is placed at Cv7 or the ipsilateral mastoid (Cone & Dimitrijevic, 2009). However, physiologic noise produced from the subject's muscles most often occurs when an electrode is placed directly over a muscle, and is common to see when utilizing the nape of the neck (Cv7) electrode placement (Cone & Dimitrijevic, 2009). This muscle activity is problematic as it produces noise levels surrounding 20-50 Hz, which are close to the frequencies of the ASSR (Cone & Dimitrijevic, 2009). Conversely, the inion may be used as a good placement for the reference electrode in awake adult subjects, as this area is less contaminated by physiologic noise than the Cv7 placement (Stapells, 2009). When comparing results from 55 different electrode montages in infants (age 0 to 5 months), Van der Reijden, Mens, and Snik (2005) reported larger SNRs when the non-inverting electrode was placed on the vertex (Cz) with the reference electrode placed on the ipsilateral mastoid.

Number of Recording Channels

The number of recommended channels is dependent upon the stimulation technique utilized. For example, a two-channel recording must be utilized when recording the MF ASSR, while a one channel recording may be used for the SF technique. Generally, utilizing a two channel ASSR recording is recommended when using either the SF or MF stimulation technique, especially with adults. Small and Stapells (2008) reported very small differences (1 dB) in the mean air and bone conduction ASSR thresholds of adults recorded in the ipsilateral versus contralateral channels. However, in infants (age 2 to 11 months), ipsilateral channel recordings revealed larger ASSR amplitudes in comparison to contralateral channel recordings at 500 and 4000 Hz (Small and Stapells, 2008). In turn, better SNRs were observed with lower ASSR thresholds in the ipsilateral channel. The authors (2008) reported similar findings for bone conduction ASSRs, as thresholds were 13-15 dB poorer in the contralateral channel compared to the ipsilateral channel at 500 and 4000 Hz (Small & Stapells, 2008). The differences observed between ipsilateral and contralateral channel ASSRs in the infants may be attributed to the immature and under-developed auditory pathways, as these continue to develop until 5 years of age. Further, the un-fused skull structure seen in infants does not develop into the rigid and fused skull until adulthood, and may also contribute to the decreased contralateral bone conduction ASSR thresholds (Small & Stapells, 2008). This second theory is supported by data, as the interaural attenuation values for the infants varied from 10 to 30 dB, while adults had little to no interaural attenuation (Small & Stapells, 2008).

In conclusion, utilizing a two-channel recording of the ASSR is recommended, especially with adults (Small & Stapells, 2008). However, if differences between the two channels are observed, than the clinician should rely on the ASSR thresholds from the ipsilateral channel once all testing errors have been ruled out.

Stopping Rule for Averaging

The stopping rule for averaging is an automatic stopping measure for the maximum number of sweeps necessary to be obtained (for example, 64 for the AUDERA system) or for a specific response amplitude level to be reached (for example, $p<0.3$ for the AUDERA system) allowing the recording to cease when recording the EEG samples (GSI, 2001). The set number of sweeps or response amplitude level must be met in order for the sample to stop.

The Fsp technique was the first automatic stopping algorithm and was first described by Elberling and Don in 1984, as an automatic stopping method for the ABR. The Fsp algorithm calculates a variance ratio related to the F-distribution of the ongoing background noise, and is equated by dividing the averaged response (S) composed of the evoked potential and background noise by the variance of a single point (SP) (Elberling & Don, 1984). The equation is written as:

$$\text{Fsp} = \frac{\text{VAR(S)}}{\text{VAR (SP)}}$$

The Fsp algorithm thus dismisses the need for a predetermined number of sweeps to be obtained as long as the ongoing background noise is low enough. The Fsp algorithm analyzes the response in the frequency domain based upon the phase and amplitude of the ASSR response, and determines whether a response is present or absent based upon the amplitude of the response at the MF of each CF (Elberling & Don, 1984). When a response is present, the amplitude at the MF is much larger than the ongoing

EEG noise, and the recording of the AEP (in this case, the ASSR) ceases. When the Fsp algorithm criterion is met an ASSR response is determined to be present; thus, allows for a shorter test time, and improved SNR and quality of the AEP recording (Elberling & Don, 1984). The concept of an automatic stopping rule in EP recordings has been applied to ASSR testing for the obvious reason of time management during optimal recording sessions.

Cone and Dimitrijevic (2009) proposed several objective stopping rules for the ASSR averaging based upon either test time or residual noise levels. These include (1) stopping the ASSR recording at 3 to 5 minutes when a response is found to be significant; (2) stopping the ASSR recording at 12 to 15 minutes if no significant responses have occurred; (3) stopping the ASSR recording when residual noise levels are at 10 to 15 µV with the use of the 80 Hz MF or at 60 to 90 µV for MF of 40 Hz; and (4) stopping the ASSR recording after 12 minutes or when the average residual noise level is equal to 10 µV (Cone & Dimitrijevic, 2009). Although the authors (2009) suggest these four different stopping criteria, it is important for the audiologist to note which rule is used to ensure there is no confusion or misinterpretation of the results from the specific testing protocol (Cone & Dimitrijevic, 2009).

Subject Factors

There are also a few subject factors that may affect the accuracy of the ASSR. The following section will focus on the subject factors of age, subject state and subject attention.

Age

Although ASSRs can be accurately recorded in individuals of all ages, they are not reliable when recorded at MFs of 40 Hz in children and infants (Rickards et al., 1994). As discussed earlier in the *history of the ASSR* section, in order to accurately record an ASSR in children and infants, a high MF must be utilized. Lins and colleagues (1996) recorded ASSRs in healthy infants (age 1 to 10 months), adolescents with hearing loss, adults with normal hearing sensitivity and adults with simulated hearing loss at 500, 1000, 2000, and 4000 Hz carrier frequencies modulated between 75 to 110 Hz. Lins et al. (1996) concluded that ASSRs were elicited in all subject groups at MFs between 75 to 110 Hz; however, in infants response amplitudes were approximately one half that of adults.

Beyond differences in recording adult versus infant/child ASSRs, there has been some controversy in the literature regarding the adult aging process on the ASSR. Johnson, Weinberg, Ribary and Cheyne (1988) looked at ASSRs of elderly adults (mean age approximately 70 years) and young adults (mean age 38 years). These researchers (1988) reported no statistical differences in phase or amplitude of the ASSR response between the two groups when 40 Hz ASSRs with 1000 Hz CF tones were elicited (Johnson et al., 1988). Similarly, when comparing the response amplitudes of the 40 Hz ASSR, Boettcher, Poth, Mills, and Dubno (2001) reported no differences in response amplitude or phase for high (4000 Hz) or low (520 Hz) CF tones when recorded in three different adult age groups (22-29 years, 60-65 years, and 66-72 years). As a result, Boettcher et al. (2001) concluded there are no significant influences from the aging process on the 40 Hz ASSR.

On the other hand, Picton, Dimitrijevic, Periz-Abalo, & van Roon (2005) reported significantly smaller ASSR response amplitudes in elderly subjects (age 61 to 71 years) as compared to young adults (age 19 to 31 years). This reduced ASSR amplitude, however, did not affect the accuracy of the response (meaning threshold prediction) when utilizing a higher MF (80 Hz) (Picton et al., 2005). The controversies in the literature regarding the effect of the adult aging process on the amplitude of the ASSR response indicate further research is needed in this area to clarify the effects of aging.

Subject State

Picton (2007) recorded ASSRs with varied MFs in 20 young adults, age 22 to 47 years, while awake and asleep. When utilizing a 40 Hz, MF the ASSR amplitude was decreased by approximately fifty percent in the naturally sleeping subjects and was even more greatly reduced in subjects under anesthetics. The 80 Hz ASSR response amplitudes, however, were minimally affected by sleep (Picton, 2007). The decrease in response amplitude of the 40 Hz ASSR is believed to be related to the dominant contributions from the cortical regions of the brain at the lower MF. Picton (2007) reported that arousal state directly affects the amplitude of the ASSR recording in adults at modulation frequencies less than 80 Hz; however, the accuracy of the threshold prediction was unchanged. Although there was a decrease in the response amplitude, there was a greater decrease in the recorded EEG noise, presumably due to the body becoming quieter and more relaxed during sleep. Thus, the recorded response was not altered at the higher modulation frequencies (Picton, 2007).

Attention

Several studies have been conducted to better understand the effects of attention on the ASSR. For example, Ross, Picton, Herdman, Hillyard, and Pantev (2004) recorded ASSRs in 20 normal hearing adults (age 23 to 54 years) utilizing a monaurally presented 500 Hz CF tone amplitude modulated at 40 Hz. The ASSRs were recorded while the subjects were not attending to the stimuli and while they were attending via a button press. To map the structures of the brain that were active during each task MEG was utilized. The MEG results showed larger attention effects on the primary auditory cortex in the left hemisphere of the brain than the right, with contributions believed to be from deeper structures such as the thalamus (Ross et al., 2004). Further, Ross et al. (2004) reported greater changes in MEG activity within the auditory cortex while the subjects were attending to the task versus when the subjects were not attending to the task.

Frequency and Place Specificity of the ASSR

The next section of this literature review will focus on auditory thresholds estimated by the ASSR, as this is the primary application for the ASSR. Two factors that has a direct impact on the accuracy of behavioral threshold estimation by the ASSR is the *frequency specificity* and *place specificity* of the response. The *frequency specificity* of the response refers to how independent the threshold response is at one test frequency from contributions of the surrounding frequencies, while *place specificity* of the response refers to the correspondence between the location on the basilar membrane the response is coming from and the intended frequency threshold is to be predicted at (Oates & Stapells, 1997). For example, if one is trying to determine threshold at 4000 Hz and there is good place specificity of the response, then the response is primarily generated from the 4000 Hz region of the basilar membrane. Ideally, the frequency and place specificity of the response are in very good agreement, and will accurately predict the behavioral threshold. Further, it is important to note that the accuracy of the ASSR threshold estimation and the frequency and place specificity of the response are clearly related to the frequency and place specificity of the stimulus (Oates & Stapells, 1997).

Oates and Stapells (1997) examined the frequency and place specificity of the ABR and MLR in normal hearing adults utilizing linear gated and Blackman-gated tones presented at 500 and 2000 Hz. The tones were presented in quiet as well as simultaneously presented with high pass filtered broadband pink noise. Frequency specificity of the ABR and MLR was determined by a masking procedure known as the high pass noise/derived band (HPN/DR) technique. The results of this HPN/DR technique showed that ABRs and MLRs recorded to 500 and 2000 Hz linear gated and

Blackman gated tones presented at 80 dB SPL had good frequency and place specificity (Oates & Stapells, 1997). The derived band profiles revealed that the cochlear contributions to these two responses came from a narrow region of the basilar membrane (one-half octave above and below the stimulus frequency), and thus indicated these two AEPs had good place specificity (Oates & Stapells, 1997).

Herdman, Picton, and Stapells (2002b), reported similar results when utilizing the same HPN/DR technique to determine the place specificity of the ASSR in normal hearing adult subjects. Herdman and colleagues (2002b) utilized amplitude modulated CF tones ranging from 250 to 8000 Hz recorded using both a single frequency and a multiple frequency stimulation technique (Herdman et al., 2002b). The authors (2002b) reported that the ASSRs recorded to AM stimuli resulted from activation of a very narrow portion of the basilar membrane surrounding the CF tone and thus the ASSR had very good place specificity (Herdman et al., 2002b). This finding was true for both the SF and MF stimulation techniques.

One way to assess the frequency specificity of the ASSR is to see how well this response accurately predicts pure tone behavioral thresholds, especially in cases of sensorineural hearing loss. This issue will be addressed in the next section of this literature review.

Clinical Applications

The primary clinical application of the ASSR is for estimation of behavioral thresholds. The ASSR is able to determine not only the degree and configuration of the hearing loss, but also the type of hearing loss as both bone and air conduction testing can be performed. Further, use of the ASSR includes evaluations for hearing aids and cochlear implants, and cochlear implant mapping. Recent advances in complex stimuli have encouraged the potential use of the ASSR for speech perception and psychophysical abilities (Cone & Dimitrijevic, 2009). The following section outlines each of the potential applications for the ASSR in the clinical setting.

Threshold Estimation

The following section focuses on the use of ASSRs for threshold estimation, and the accuracy of the ASSR predicted threshold compared to behavioral thresholds in adults with normal hearing and those with sensorineural hearing loss. In discussing the correlation between the estimated ASSR threshold and the actual behavioral threshold, the term *difference threshold* or *difference score* is utilized. The difference threshold, or difference score, is determined by subtracting the pure tone behavioral threshold at a specific frequency from the predicted ASSR threshold at that same frequency (i.e., ASSR threshold – behavioral threshold). It should be noted that the smaller the difference score, the more accurate the estimated ASSR threshold is to the actual behavioral threshold. When discussing threshold accuracy, we will continue to use the term *mean difference score* as it is helpful in keeping a uniform comparison throughout the studies.

Adults with normal hearing.

Numerous studies have investigated the accuracy of the ASSR in estimating behavioral pure tone thresholds in normal hearing adults, and are shown in Table 2. Some of these studies have employed the SF stimulation technique (e.g., Herdman & Stapells, 2001; Luts & Wouters, 2005) while others have used a MF technique (e.g., Lins et al, 1996; Herdman & Stapells, 2001; Dimitrijevic et al., 2002; Johnson & Brown, 2005; Picton et al., 2005). Table 2 provides information regarding the types of stimuli, the stimulation techniques and the mean difference scores reported in each of these studies. The following is a brief discussion of these studies.

Table 2

ASSR mean difference scores for adults with normal hearing

Studies	**Stimuli**	**Stimulation Technique**	**Mean Difference Scores (±1 SD)**			
			500 Hz	*1000 Hz*	*2000 Hz*	*4000 Hz*
Herdman & Stapells, (2001)	AM	SF	7(13)	10(12)	12(10)	14(6)
Herdman & Stapells, (2001)	AM	MF	11(11) *14(10)	10(11) *8(7)	11(10) *8(9)	14(10) *15(9)
Lins et al., (1996)	AM	MF	*14(11)	*12(11)	*11(8)	*13(11)
Dimitrijevic et al., (2002)	MM	MF	*17(10)	*4(11)	*4(8)	*11(7)
Vander Werff & Brown	MM	MF	25(10)	18(9)	13(7)	13(8)

Note. Studies given by author, year, number of subjects, age range in years, type of stimuli (AM, FM, or MM), analysis technique (F test [FFT and F-Ratio] or Phase Coherence), mean difference scores with ± 1 standard deviation (SD). Studies are categorized by stimulation technique (SF, single frequency; MF, multiple frequency). AM= amplitude modulated tone, FM= frequency modulated tone, MM= mixed modulated tone. * Indicates a binaural MF stimulation technique.

Herdman and Stapells (2001) compared the mean difference scores for the ASSR recorded in ten normal hearing adults ranging from 21 to 42 years of age. Specifically these investigators (2001) studied the accuracy of the ASSR in predicting pure tone thresholds in three different test conditions: (1) the SF stimulation technique, (2) the monaural MF stimulation technique, and (3) the binaural MF stimulation technique (Herdman & Stapells, 2001). The stimuli utilized for this study were AM tones presented at four CFs: 500, 1000, 2000, and 4000 Hz. Herdman and Stapells (2001) reported that the mean difference scores ranged from 7 to 14 dB for the SF technique, from 11 to 14 dB for the monaural MF technique, and from 8 to 15 dB for the binaural MF technique. These authors (2001) reported that there were no significant differences in mean difference scores across these three techniques (Herdman & Stapells, 2001). Herdman & Stapells (2001) concluded that the binaural MF technique substantially reduced testing time without compromising the accuracy of the ASSR threshold in normal hearing adults.

Lins et al. (1996) investigated the accuracy of ASSR thresholds in estimating the pure tone audiogram in 20 normal hearing subjects ranging in age from 17 to 40 years. These authors (1996) recorded the ASSR using an AM tonal stimuli, which were presented simultaneously at CFs of 500, 1000, 2000 and 4000 Hz (Lins et al., 1996). These investigators (1996) reported that the mean difference thresholds ranged from 11 to 14 dB across the various CFs, with SD values ranging from 8 to 11 dB (Lins et al., 1996). As a result, Lins and colleagues (1996) concluded that ASSR thresholds accurately reflect behavioral pure tone thresholds in normal hearing adults.

Dimitrijevic et al. (2002) investigated the accuracy of ASSR threshold predictions obtained using a binaural MF stimulation technique in 14 normal hearing adults ranging in age from 23 to 63 years. The stimuli in this study were MM tones (100% AM and 20% FM) presented at CF tones of 500, 1000, 2000, and 4000 Hz (Dimitrijevic et al, 2002). Dimitrijevic and colleagues (2002) reported that their mean difference scores ranged from 4 to 17 dB across CF tones, with SD values ranging from 7 to 11 dB. Thus, Dimitrijevic et al. (2002) concluded that ASSR thresholds are on average 8 dB poorer than behavioral thresholds.

More recently, Vander Werff and Brown (2005) compared the accuracy of the ASSR in predicting pure tone thresholds recorded using a monaural MF stimulation technique. The subjects in this study were 10 normal hearing adults who ranged in age from 21 to 79 years. The mean difference scores ranged from 13 to 25 dB across the four CFs, with SD values ranging from 7 to 10 dB (Vander Werff & Brown, 2005). Vander Werff and Brown (2005) concluded that the results showed strong correlation between ASSR thresholds and behavioral thresholds, similar to the previous studies mentioned (Dimitrijevic et al., 2002; Herdman & Stapells, 2001; Lins et al., 1996).

Overall, the studies on adults with normal hearing sensitivity suggest the ASSR threshold is an accurate and reliable estimation of the behavioral threshold (Dimitrijevic et al., 2002; Herdman & Stapells, 2001; Lins et al., 1996). However, because these studies discussed above focused upon normal hearing adult subjects, the conclusions cannot be generalized to the pediatric population, or adults with varying degrees of hearing loss. The following section will further discuss the effects of sensorineural hearing loss on the correlation between the ASSR and behavioral thresholds.

Adults with sensorineural hearing loss (SNHL).

The following section looks at the mean difference scores of adults with hearing loss, specifically sensorineural hearing loss as this is most commonly reported over conductive pathologies. Later in this literature review, the reader will better understand the use of bone conduction testing using ASSR and how to determine a conductive from sensorineural pathology utilizing ASSR. All of the studies described below are outlined in Table 3 and are separated in categories of overall hearing loss, configuration of hearing loss, degree of hearing loss, and the effect of hearing loss on stimulation technique (SF or MF presentation). Overall, the majority of these studies are in agreement that ASSR testing is accurate within 10 to 15 dB of actual behavioral thresholds in adults with a sensorineural impairment (Dimitrijevic et al., 2002; Herdman & Stapells, 2003; Van Maanen & Stapells, 2005).

Table 3

ASSR mean difference scores for adults with sensorineural hearing loss

	Studies)	Stimuli	Stimulation Technique	Behavioral Threshold Degree of Loss	Hearing Loss Configuration	Mean Difference Scores (SD)			
						500 Hz	1000 Hz	2000 Hz	4000 Hz
Overall	**Dimitrijevic 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 (≥30 dB/octave)	13(13)	8(10)	12(10)	1(10)
	Herdman & Stapells (2003)	AM	MF	N/A	Flat/Shallow sloping (< 30 dB/octave)	15(13)	7(8)	7(11)	5(9)
	Vander Werff & Brown (2005)	MM	MF	Moderately severe	-Flat -High frequency	29(10)	23(11)	16(6)	15(10)
Degree	**Picton et al. (2005)**	MM	MF	Normal to mild	High frequency	21(14)	7(10)	11(7)	11.5(10)
	Picton et al. (2005)	MM	MF	Moderate to severe	N/A	11(18)	-4(9)	2.5(11)	5.3(12)
Stimulation	**Luts & Wouters (2005)**	MM	SF	Mild to profound	N/A	20(8)	14(7)	13(7)	14(13)
	Luts & Wouters (2005)	MM	MF	Mild to profound	N/A	*17(12)	*12(8)	*17)8)	*19(12)

Note. Studies given by author, year, number of subjects, age range in years, type of stimuli (AM, FM, or MM), analysis technique (F test [FFT and F-Ratio] or Phase Coherence), stimulation technique (SF or MF), mean difference scores with ± 1 standard deviation (SD). Studies are categorized by hearing loss overall, hearing loss by configuration, hearing loss by degree, and effects of hearing loss on stimulation technique. AM= amplitude modulated tone, FM= frequency modulated tone, MM= mixed modulated tone, SF= single frequency technique, MF = multiple frequency technique. * Indicates a binaural MF stimulation technique.

Overall hearing loss.

Dimitrijevic et al. (2002) looked at the overall effects that sensorineural hearing loss had on the accuracy of behavioral threshold prediction via the ASSR. These authors (2002) studied 31 adults with sensorineural hearing loss, which ranged from mild to severe and had configurations of loss described as flat, high frequency, or reverse sloping (Dimitrijevic et al., 2002). The ASSR was recorded to a MM stimulus (with 100% AM and 20% FM), presented at CF tones of 500, 1000, 2000, and 4000 Hz. Dimitrijevic and colleagues (2002) reported that their mean difference scores ranged from 5 to 13 dB across all CFs, with SD values ranging from 8 to 11 dB. The accuracy of threshold prediction was poorest at 500 Hz, and on average the ASSR thresholds were 8 dB poorer than behavioral thresholds (Dimitrijevic et al., 2002). Given these results, Dimitrijevic et al. (2002) concluded there was good correlation between the ASSR thresholds and behavioral pure tone thresholds in adults with sensorineural hearing loss.

More recently, Van Maanen and Stapells (2005) also investigated how well ASSR thresholds estimated pure tone behavioral thresholds in individuals with SNHL. Twenty-three adults with sensorineural hearing loss participated in this study and ranged in age from 45 to 80 years. Specific degrees and/or configurations of the hearing loss were not reported. The ASSR was recorded to a MM stimulus (100% AM and 20% FM), utilizing a MF stimulation technique, and were simultaneously presented at 500, 1000, 2000, and 4000 Hz. The mean difference scores ranged from 4 to 17 dB across all 4 CFs, with SD values ranging from 8 to 11 dB (Van Maanen & Stapells, 2005). Van Maanen and Stapells (2005) also concluded that the ASSR can be utilized to accurately predict sensorineural hearing loss in adults.

Configuration of hearing loss.

Herdman and Stapells (2003) compared mean difference scores in 18 adults with sensorineural hearing loss categorized as either steeply sloping (≥ 30 dB per octave) (n = 8) or flat/shallow (< 30 dB per octave) (n = 13); the degree of hearing loss was not reported in this study. A MF technique with an AM stimulus was utilized and presented at 500, 1000, 2000, and 4000 Hz simultaneously. Mean difference scores ranged from 1 to 13 dB with SDs ranging from 10 to 13 dB for the steeply sloping group, and from 5 to 15 dB with SDs ranging from 8 to 13 dB for the flat/shallow group across all presented frequencies (Herdman & Stapells, 2003). Herdman and Stapells (2003) concluded that ASSR thresholds are not affected by better hearing thresholds at adjacent frequencies; thus, confirming place specificity of the response in individuals with steeply sloping or flat/shallow hearing loss configurations.

Vander Werff and Brown (2005) also looked at the effects of hearing loss configuration on ASSR threshold accuracy. Ten adults with moderately-severe sensorineural hearing loss categorized as either flat or high frequency in configuration were participants in this study. A MF technique utilizing a MM tone with 100% AM and 20% FM presented at 500, 1000, 2000, and 4000 Hz simultaneously was utilized. The overall results revealed mean difference scores ranging from 15 to 29 dB with SDs ranging from 6 to 11 dB across all presented frequencies (Vander Werff & Brown, 2005). Results from both Herdman and Stapells (2003) and Vander Werff and Brown (2005) were in agreement that hearing loss configuration does not affect the accuracy of the ASSR threshold estimation in adults with sensorineural hearing loss.

Degree of hearing loss.

Picton et al., (2005) compared the mean difference scores of 10 elderly adults with sensorineural hearing loss levels ranging from normal to mild high frequency SNHL, to the mean difference scores of 10 elderly adults with a moderate to severe high frequency SNHL hearing loss. A MF stimulation technique was utilized to record the ASSR to a MM tone (100% AM and 20% FM). These MM tones were presented at 500, 1000, 2000, and 4000 Hz simultaneously. Mean difference scores for the group with a normal to mild high frequency loss ranged from 7 to 21 dB with SDs ranging from 7 to 14 dB, while the mean difference scores for the group with a moderate to severe high frequency loss ranged from -4 to 11 dB with SDs ranging from 9 to 18 dB across all presented frequencies (Picton et al., 2005). Picton and colleagues (2005) concluded that the variation between the two groups clearly demonstrated that the poorer an individual's behavioral hearing thresholds are, the more accurately the ASSR will predict the behavioral threshold.

Stimulation technique.

Luts and Wouters (2005) compared the mean difference scores of 10 adults with mild to profound sensorineural hearing loss obtained when the stimuli were presented using the SF versus MF stimulation techniques. A MM tone with 100% AM and 20% FM was utilized and presented at 500, 1000, 2000, and 4000 Hz. The SF technique was analyzed utilizing Phase Coherence, while the binaural MF technique was analyzed utilizing the FFT with F-Ratio. Mean difference scores ranged from 13 to 20 dB with SDs ranging from 7 to 13 dB for the SF technique and from 12 to 17 dB with SDs ranging from 8 to 12 dB for the binaural MF technique across all tested frequencies (Luts

& Wouters, 2005). The authors concluded that both the SF technique and binaural MF technique are reliable for obtaining ASSR thresholds, as no significant differences between trials was observed (Luts & Wouters, 2005).

Overall, the results of the studies (Dimitrijevic et al., 2002; Herdman & Stapells, 2003; Luts & Wouters, 2005; Picton et al., 2005; Van Maanen & Stapells, 2005; Vander Werff & Brown, 2005) conducted on individuals with sensorineural hearing loss are in agreement that the ASSR can be used to accurately predict the behavioral threshold in adults with SNHL regardless of hearing loss configuration or stimulation technique utilized. Degree of SNHL appears to have some impact on the accuracy of ASSR threshold estimation, as greater (poorer) hearing loss levels resulted in closer correlations between ASSR and behavioral thresholds (Picton et al., 2005). When looked at as a whole, sensorineural hearing loss can be determined by performing an ASSR.

Bone Conduction

Like conventional audiometry, the ASSR can be recorded to both air and bone conducted stimuli in order to determine the type (conductive, mixed or sensorineural) of hearing loss. Several investigators have reported that there are two general types of test methods that can be employed with bone conduction ASSR testing (Cone & Dimitrijevic, 2009; Picton et al., 2003a). In the first method, the bone conduction oscillator is placed on either the mastoid or the forehead and the same stimuli that are used in air conduction ASSR testing are employed. The second method involves using the sensory-neural acuity level (SAL) technique (Cone & Dimitrijevic, 2009; Picton et al., 2003). In the SAL technique, masking noise is presented through the bone conduction oscillator to determine the noise level needed to mask the air conduction response. The level of noise needed to effectively mask the air conduction response is then labeled as the bone conduction threshold (Ysunza & Cone-Wesson, 1987). Two studies (Dimitrijevic et al., 2002; Jeng, Brown, Johnson, & Vander Werff, 2004) in the ASSR literature have focused upon how accurate the ASSR is in determining air-bone gaps as compared to behavioral thresholds in adults with normal sensory hearing and an abnormal middle ear system. The first of these two reported studies evaluated 10 normal hearing subjects with a simulated conductive hearing loss (Dimitrijevic et al., 2002). This simulated conductive loss was created via placing a foam insert earphone into the ear canal. Both behavioral and ASSR air- and bone-conduction thresholds were determined with the foam insert earphone in place. On average, a pure tone average of 52 dB with a standard deviation of 4 dB was noted across the 10 subjects, with a flat configuration. In this study (Dimitrijevic et al., 2002), Dimitrijevic and colleagues (2002) placed the bone conduction oscillator on the subjects' forehead, and ASSRs were recorded to CF tones presented at 500, 1000, 2000, and 4000 Hz with MFs ranging from 80 to 95 Hz. The non-test ear was masked with 50 dB of white noise. Dimitrijevic and colleagues (2002) reported that their air-bone gaps ranged from 10 to 20 dB across the four CFs. Therefore, these authors (2002) concluded that air- and bone-conduction ASSRs could be used to effectively differentiate a sensorineural from a conductive pathology (Dimitrijevic et al., 2002).

Jeng et al. (2004) studied the effect of a simulated conductive hearing loss on 10 adult subjects with normal hearing sensitivity. These investigators also recorded the ASSR using the MF stimulation technique, with the stimuli being presented at CFs of 500, 1000, 2000, and 4000 Hz with MFs ranging from 78 to 92 Hz. During this study, the bone oscillator was placed on the forehead. The non-test ear was masked with 80 dB of white noise (Jeng et al., 2004).

Similar to the findings of Dimitrijevic et al. (2002), Jeng and colleagues (2004) reported that the air-bone gaps determined utilizing ASSR testing were within 10 dB of the air-bone gaps present in behavioral pure tone testing. Jeng et al. (2004) looked at two different methods of simulating a conductive hearing loss, either placing an epoxy material or lamb's wool over the tip of the insert ear-phone. The authors (2004) reported larger air-bone gaps (30 to 60 dB) when the epoxy material was used compared to the lamb's wool material (15 to 30 dB air-bone gaps) (Jeng et al., 2004). Based on these findings, Jeng and colleagues (2004) concluded that air- and bone-conduction ASSR thresholds can be used to effectively estimate behavioral thresholds and utilized to determine type (conductive, sensorineural, or mixed) of hearing loss in adult subjects..

Other factors that may affect bone conduction ASSR thresholds include bone oscillator coupling method, placement location, coupling force, and number of recording channels (see prior section for number of recording channels). Small, Hatton and Stapells (2007) looked at the effects of the coupling method and placement location of the bone oscillator in infants and adults. The authors looked at the variability in the amount of force applied to the oscillator in two coupling methods, either via elastic band or hand-held. Findings revealed that regardless of coupling method, there was no significant difference in coupling force applied to the oscillator (Small et al., 2007). This finding indicates that with a properly trained assistant the hand-held coupling method is equally effective as the elastic band method. Yang, Stuart, Stentrom, &Hollett (1991) reported that a coupling force of 400-450 gram is most efficient for obtaining accurate bone conduction thresholds via ABR testing. Small, Hatton and Stapells (2007) reported that both coupling methods could be used to achieve this recommended force level. The authors go on to state that a properly trained individual who hand holds the oscillator may be a clinically more effective approach in comparison to relying on elastic band coupling method without a verified force level, as the force of the band is often greater than the suggested levels (Small, et al., 2007). Further Small et al. (2007) found no significant difference between ASSR thresholds obtained using either coupling method in both adults and infants.

Small et al. (2007) also looked at the effects of bone oscillator placement on the ASSR threshold in infants. The oscillator was placed at either on upper temporal bone posterior to the upper pinna, the lower temporal bone (mastoid), or at the middle of the forehead. Results indicated no significant differences between infant ASSR thresholds when the oscillator is placed at either location on the temporal bone; however, significant threshold differences were recorded with the oscillator placed at the forehead (Small et al., 2007). For example, 18% of ASSR responses were absent in the forehead placement as compared to 5% of absent responses at either temporal location (Small et al., 2007). Further, as the stimulus frequency increased from 500 to 4000 Hz, the difference between both temporal locations and forehead placement became greater. These results from Small et al. (2007) are consistent with findings of behavioral adult studies indicating a significant difference between thresholds with oscillator placed at the mastoid process versus the forehead (Dirks, 1994). It should be noted, however, that greater differences are seen in infants ASSR bone conduction thresholds depending upon placement of oscillator than in the adult behavioral studies (Small et al., 2007). Thus, it may be concluded that when conducting a bone conduction ASSR threshold, a temporal location (directly behind pinna or on the mastoid process) should be utilized to ensure a more accurate ASSR bone conduction threshold.

Small and Stapells (2008) studied the effects of system maturation on the bone conduction ASSR response. Participants included two groups of normal hearing infants (group 1 aged 0.5-44 weeks; group 2 aged 12-24 months), and one group of normal hearing adults (aged 19-48 years). A MF stimulation technique was utilized to record the ASSR using the MASTER system. The stimulus was a MM stimulus, with 100% AM and 25% FM. The results of the Small and Stapells (2008) study indicate that there are clear maturational differences in the bone conduction ASSR responses across each of the three groups. Further, the ASSR response of young children did not become adult-like until approximately two-years of age (Small & Stapells, 2008). Small and Stapells (2008) also reported that significant changes in ASSR thresholds as a function of stimulus frequency occurred as the peripheral and central auditory nervous system matures. For example, at 500 and 1000 Hz, ASSR thresholds were significantly higher (poorer) for the adults in comparison to the two infant groups. The opposite pattern occurred at 2000 Hz. That is the ASSR thresholds at this higher stimulus frequency were significantly lower (better) for the adults versus the two infant groups (Small & Stapells, 2008). The clinician needs to be familiar with these normal maturational changes that occur in the ASSR bone-conduction responses in order to properly identify and interpret these responses.

Hearing Aids and Cochlear Implants

The ASSR can be useful in many clinical circumstances both pre and post hearing aid or cochlear implant fitting. ASSR thresholds are able to be obtained both aided and unaided, and would thus give the clinician important information regarding the benefit of the chosen amplification system for the auditory system (Dimitrijevic, John, & Picton, 2004). Utilizing the ASSR in this manner, to determine the benefit of amplification, is especially important in clinical populations that are not able to respond behaviorally to stimuli in the environment (i.e., infants). ASSR thresholds are also important in determining candidacy for cochlear implants, as it is possible to record the ASSR at considerably higher stimulus intensities than is possible for the ABR.

Several investigators have researched the practicality of utilizing an electrically evoked ASSR (EASSR) in cochlear implant recipients. These studies have been conducted on animals (i.e., Jeng et al., 2007; Jent et al., 2008) and humans (i.e., Hofmann & Wouters, 2010; Menard et al., 2004; Yang, Chen, & Hwang, 2008). Electrical artifact contamination was a significant recording problem across all of these studies, especially when recording at high stimulus intensities (Hofmann & Wouters, 2010; Jeng et al., 2007; Jeng et al., 2008; Menard et al., 2004; Yang et al., 2008). However, when the electrical artifact is accounted for, via an artifact removal process, EASSRs may be used to successfully assess the function of a cochlear implant (Hofmann & Wouters, 2010; Menard et al., 2004). Further, the estimated ASSR thresholds obtained were in good correlation to the behavioral thresholds, suggesting that the ASSR thresholds obtained in subjects with cochlear implants (adults and children) are reliable and accurate (Hofmann & Wouters, 2010; Menard et al., 2004; Yang et al., 2008). The overall conclusions do, however, suggest further research is necessary before clinical utilization begins (Hofmann & Wouters, 2010; Jeng et al., 2007; Jeng et al., 2008; Menard et al., 2004; Yang et al., 2008).

Calibration

Calibration of the ASSR equipment is critical to ensure that the estimated thresholds for this AEP are as near behavioral pure tone thresholds as possible. Although there is not yet a clear standard for calibration of the ASSR stimuli, current practice of calibrating the modulated ASSR stimuli is done in the same manner as when calibrating a pure-tone (via sound-level meter) (Cone & Dimitrijevic, 2009; Stapells, Herdman, Small, Dimitrijevic, & Hatton, 2005). This is because the continuous AM or MM tone used for the ASSR has a long-duration similar to a pure tone (Stapells et al., 2005). When calibration is carried out in dB HL units, the ANSI 1996 standards for SPL correction factor must be used. For example, when calibrating a 2000 Hz tone, the 0 dB HL level would equate to 2.5 dB SPL when the stimulus is present through insert earphones (Cone & Dimitrijevic, 2009). Most ASSR equipment is calibrated in dB HL, as the thresholds estimated by the AM or MM stimulus are very similar to puretones based upon their duration (Stapells et al., 2005).

However, when calibrating for the modulated tone used in ASSR, it is important to remember that the power of a modulated tone (i.e., stimulus used in ASSR testing) is actually much greater than that of a non-modulated tone (i.e., pure tone) (Cone & Dimitrijevic, 2009; Stapells et al., 2005). Thus, there will be a difference of approximately 2 to 3 dB when comparing the thresholds obtained via 100% AM tones to thresholds obtained via non-modulated pure tones (Cone & Dimitrijevic, 2009). Further, because the calibration of the HL measurement does not compensate for this discrepancy, the actual dB HL threshold obtained via ASSR may be dependent upon the amount of power (modulation) of the signal (Cone & Dimitrijevic, 2009). In order to better understand the effects of calibration of the modulated tone on the estimated ASSR threshold, especially in infants and young children and in cases of conductive or mixed hearing loss, further research is required (Stapells et al., 2005).

Other Considerations and Future Directions

It is important for the clinician to remember that the ASSR can only be utilized on patients with an intact auditory system and with a functioning auditory nerve. Thus, in the instances of Auditory Neuropathy Spectrum Disorder (ANSD), the ASSR should not be used (Rance et al., 2005). Rance and colleagues (2005) demonstrated that although behavioral thresholds of patients with ANSD may vary widely (ranging from normal to profound loss levels), the ASSR thresholds were consistently recorded at 85 to 90 dB HL regardless of CF. The authors (2005) reported only a 50% correlation between ASSR and behavioral pure tone thresholds in patients with ANSD as compared to a 97% correlation between these AEP and behavioral thresholds in patients with normal hearing (Rance et al., 2005). Thus, it was concluded that the ASSR should not be used to determine thresholds on individuals with, or suspected of having, ANSD (Rance et al., 2005). Similarly, Shinn and Musiek (2007) went on to describe that when discrepancies between ASSR and behavioral thresholds are obtained, there may be indication for a neural disorder. Overall, Shinn and Musiek (2007) reported that the discrepancies between ASSR and behavioral thresholds in patients with known brain lesions were much greater than those of patients with normal neurological systems. Therefore, if neural loss is suspected alternative AEPs should be selected.

Statement of Purpose

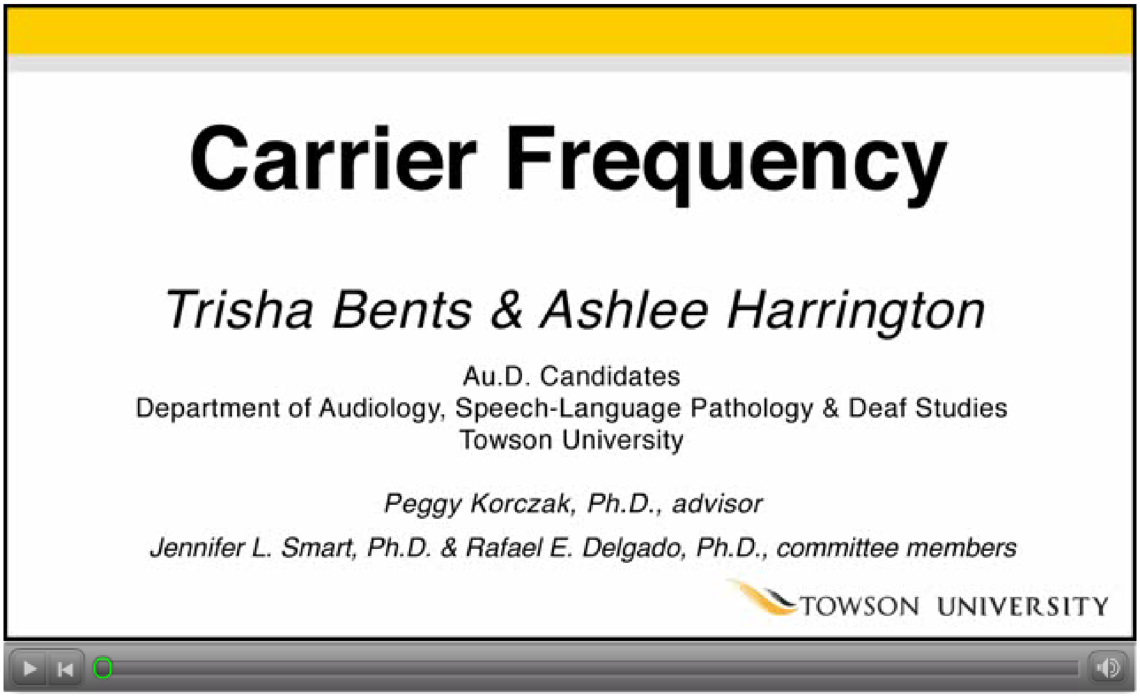
The ASSR is becoming a more widely known and accepted testing method to utilize when assessing hearing sensitivity in difficult to test clinical populations. Vast amounts of research in the area agree that the ASSR can be utilized to determine accurate and frequency specific threshold estimations in these difficult to test populations as well as normal hearing individuals. Further, within the ASSR literature, there are numerous terms unique to ASSR that are not used in discussing other AEPs. For these reasons, there is a need within our field for an easily accessible informational resource that helps define the terminology unique to the ASSR, as well as contains detailed information related to the stimuli, recording parameters, neural generators and threshold estimating capabilities of this response. This central information base should be up-to-date and should provide evidence-based resources for clinicians to adopt in the clinical setting. Further, this information should be presented on a level appropriate for Doctor of Audiology (Au.D.) students, recent Au.D. graduates, as well as audiologists within the field wishing to pursue ASSR testing. This project aims to create a web-based tutorial on the ASSR that will be easy to navigate and will be available to Au.D. students, recent Au.D. graduates and other professionals within the field interested in becoming more familiar with ASSR.

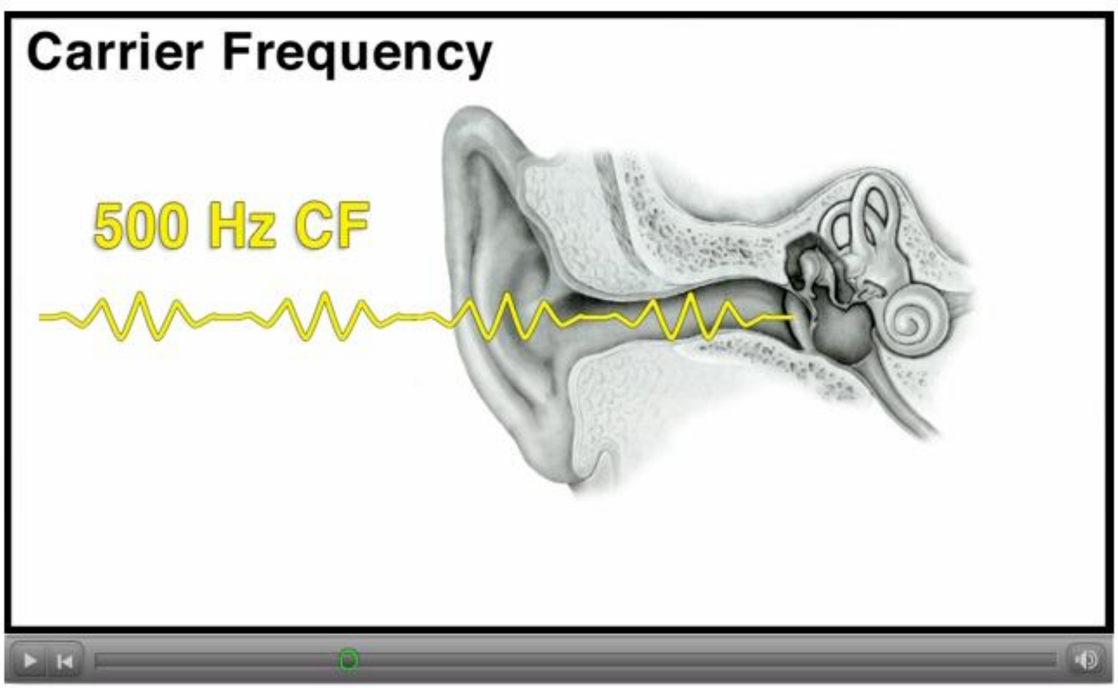
APPENDICES

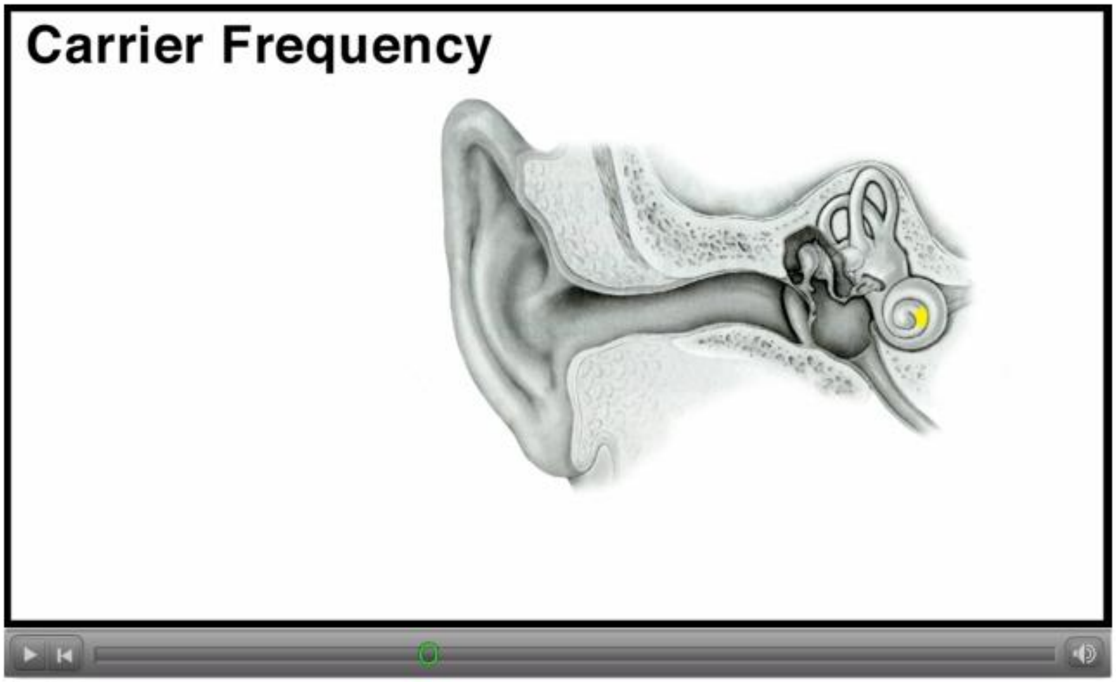
APPENDIX A

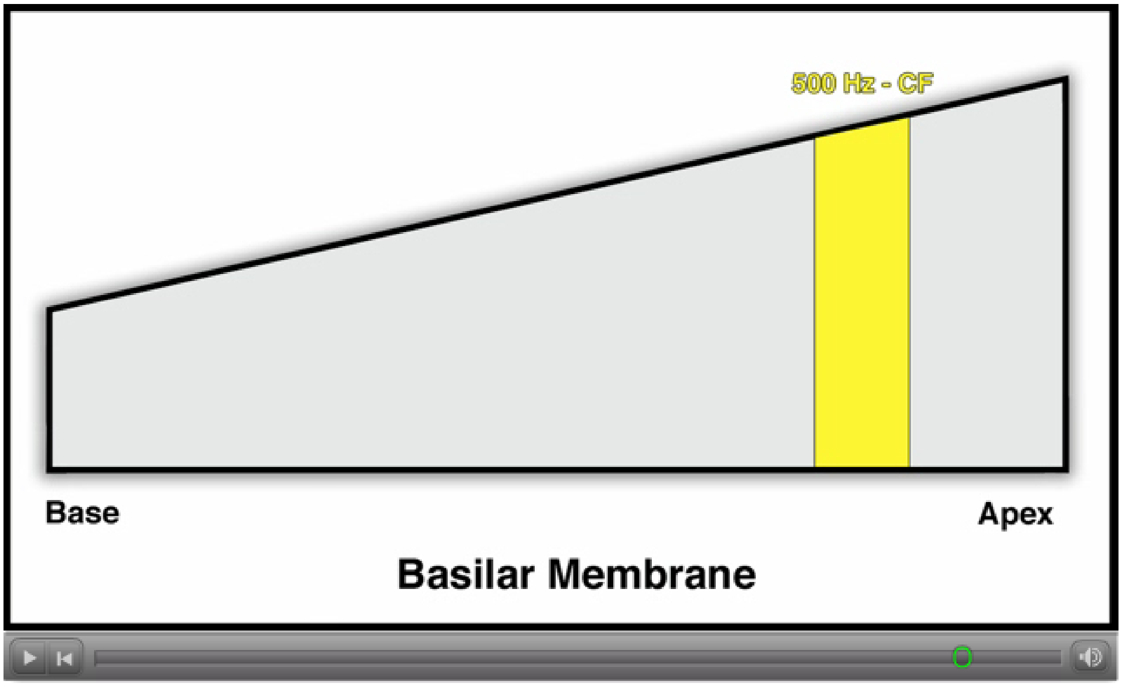
STILL SHOTS FOR ANIMATED FIGURES

Carrier Frequency






Carrier Frequency



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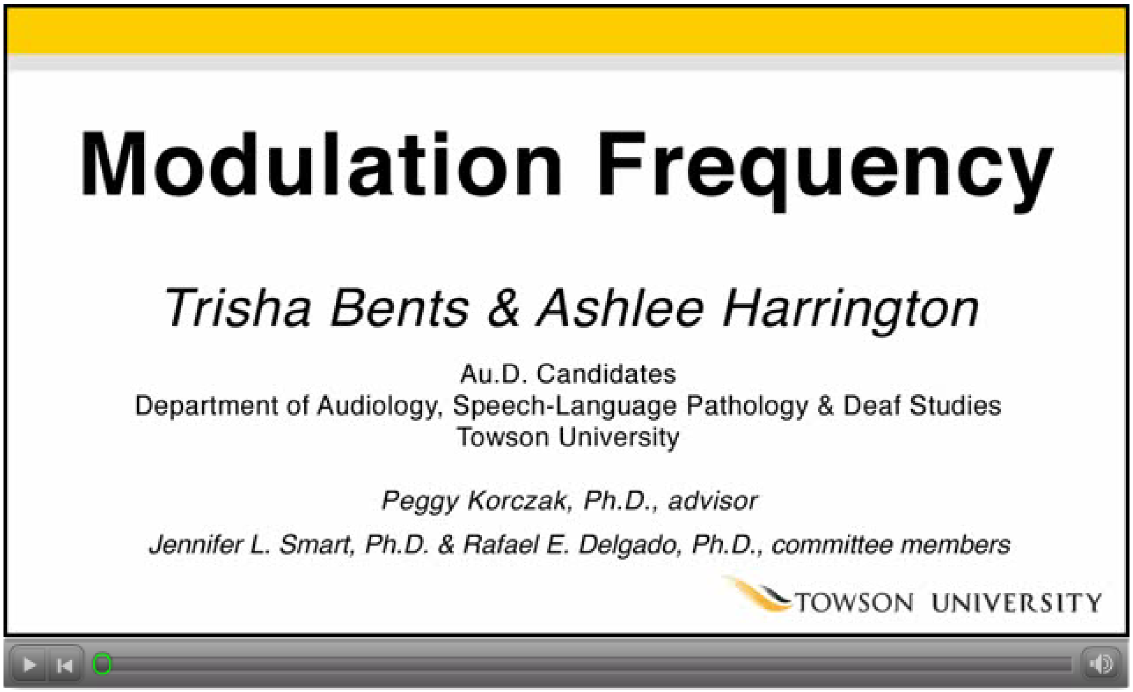
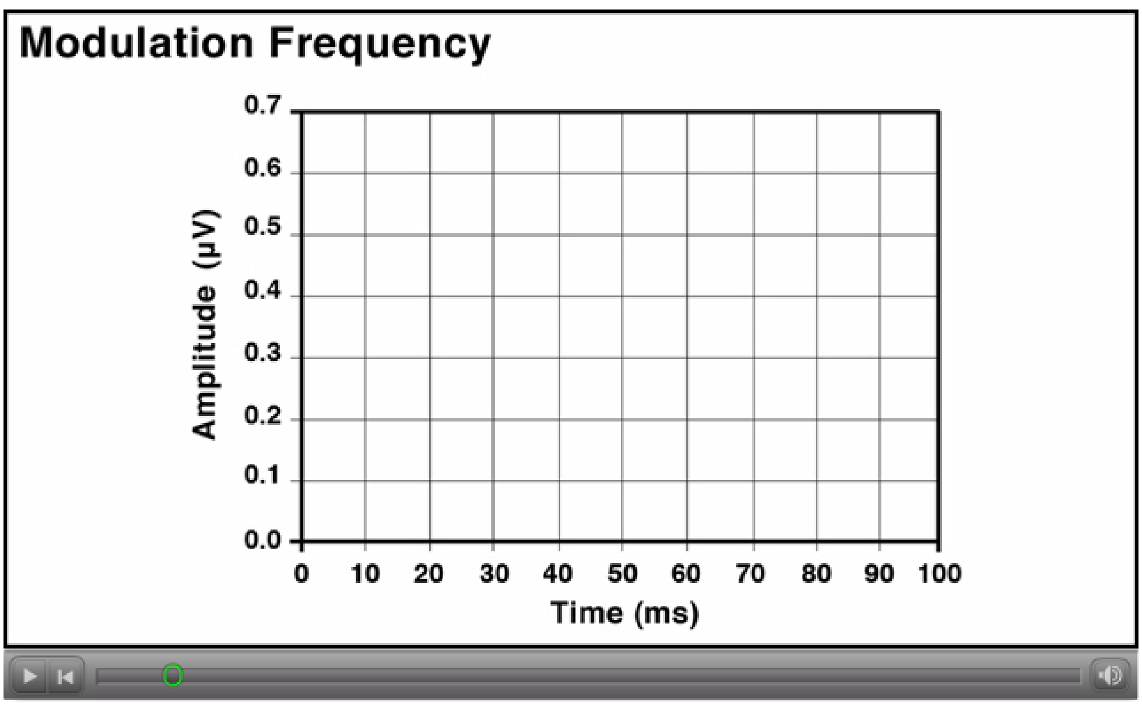
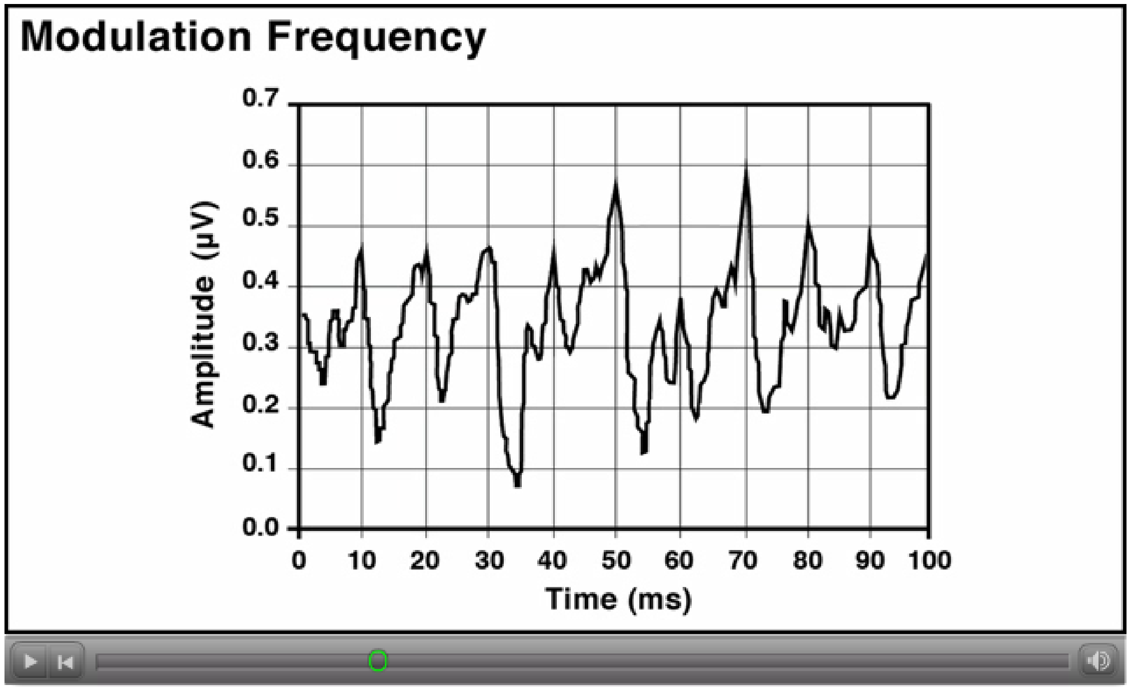
Herdman, A. T., Picton, T. W., & Stapells, D. R. (2002). Place specificity of multiple auditory steady-state responses. *Journal of the Acoustical Society of America, 112*, 1569-1582.

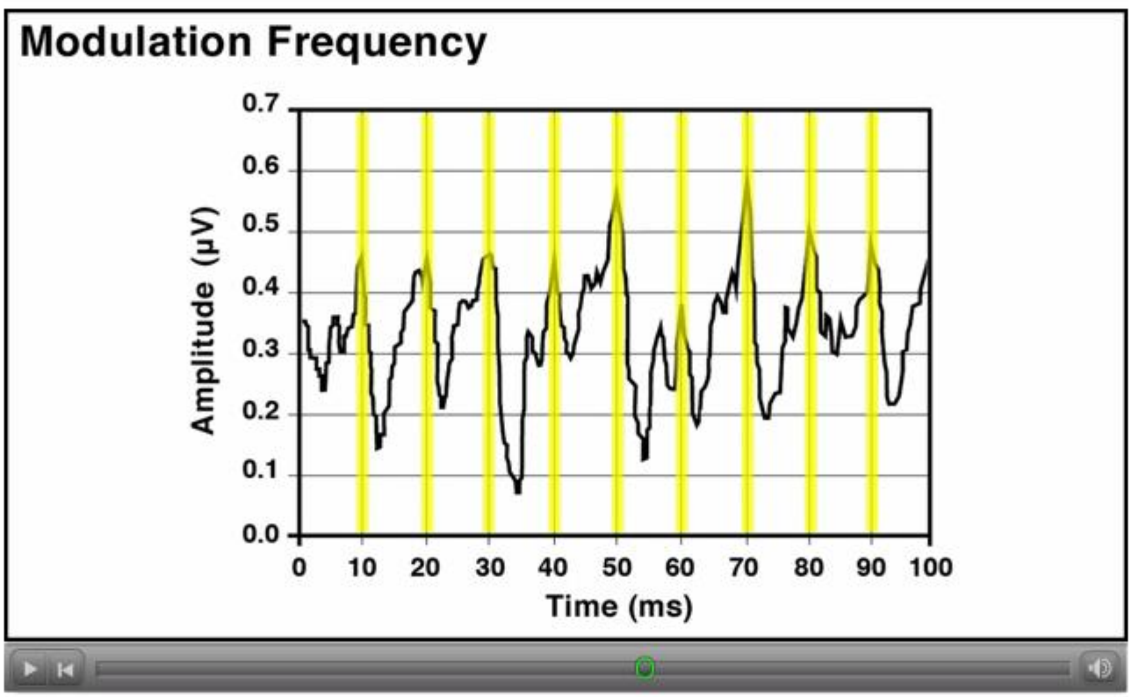
Stach, B. A. (2002). The auditory steady-state response: A primer. *The Hearing Journal, 55*, 10-18.

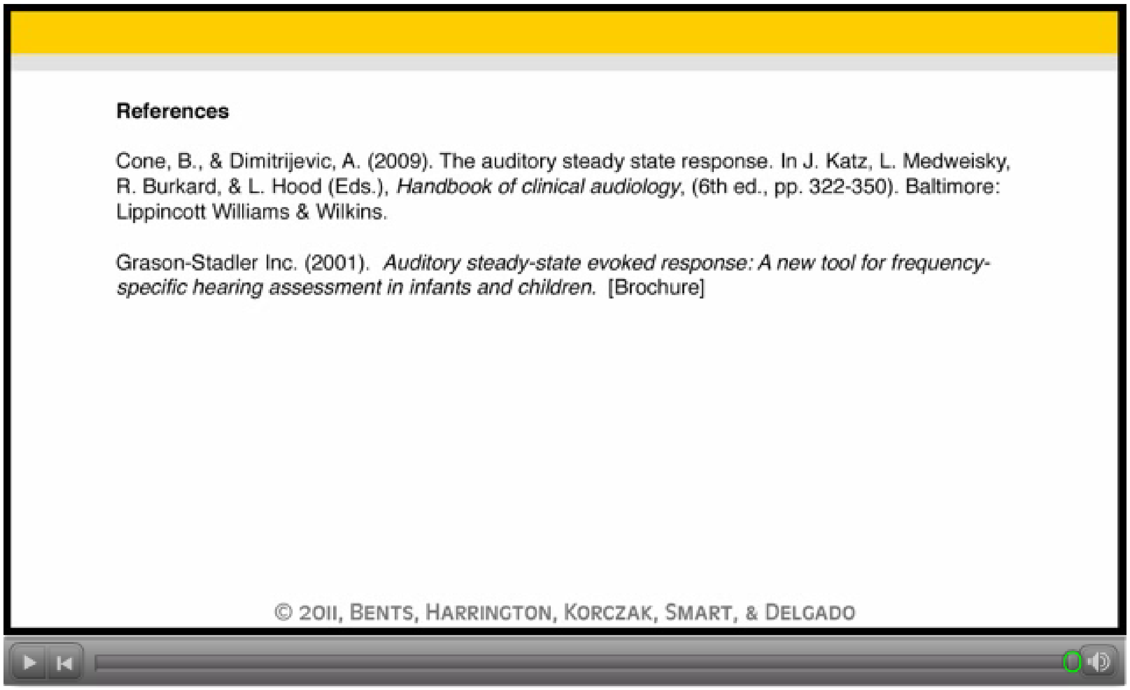
Modulation Frequency






Modulation Frequency
Amplitude (µV)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
10
20
30
40
50
60
70
80
90
100
Time (ms)


Modulation Frequency
Amplitude (µV)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
10
20
30
40
50
60
70
80
90
100
Time (ms)


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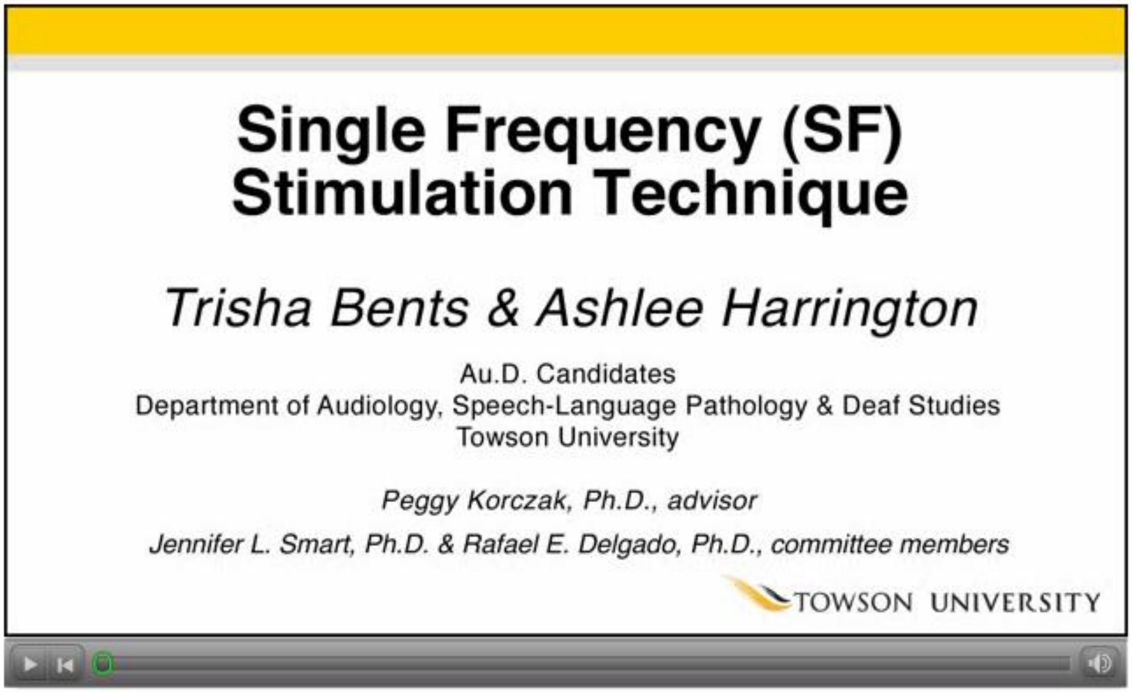
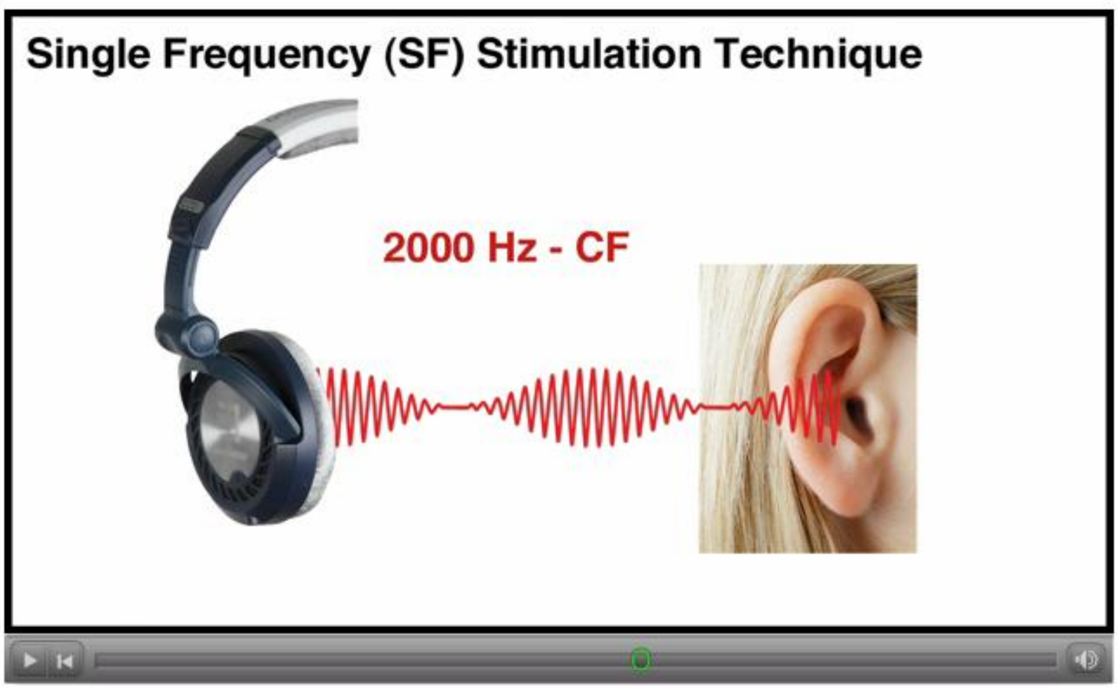
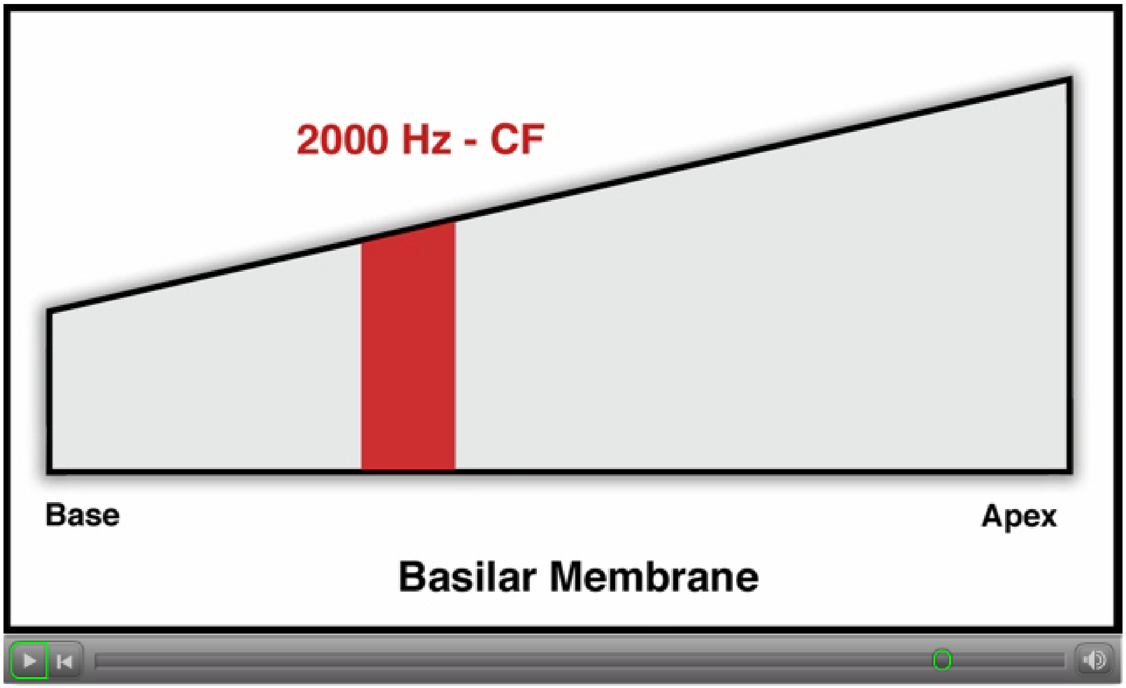
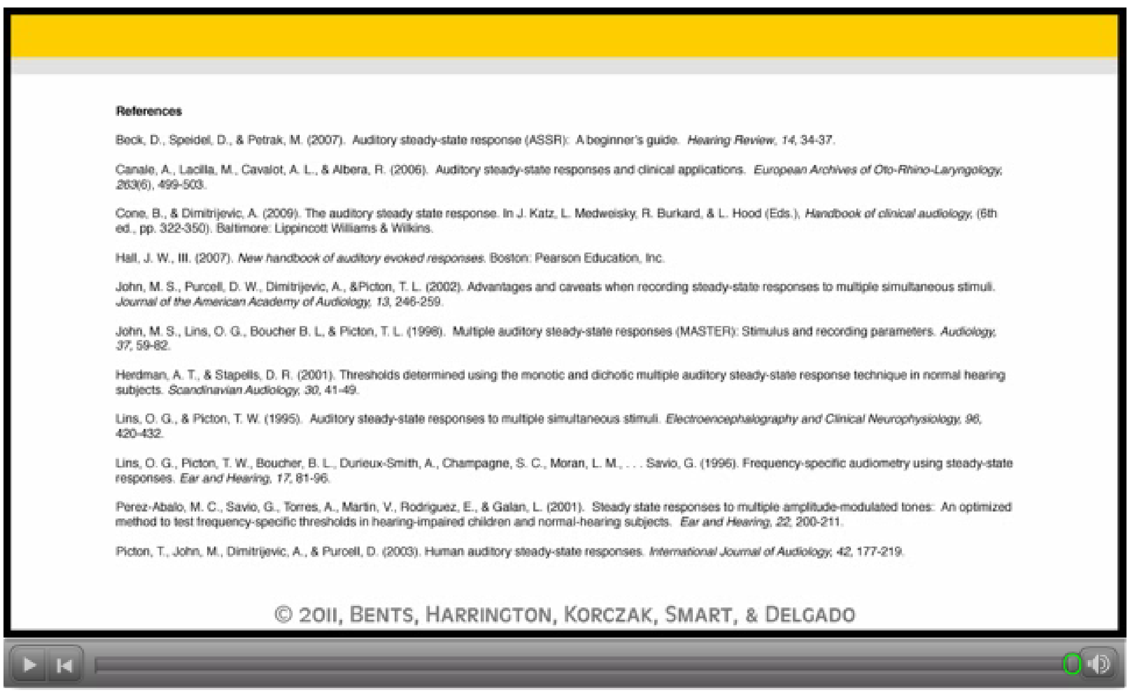
Single Frequence (SF) Stimulation Technique









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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.

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John, M. S., Purcell, D. W., Dimitrijevic, A., &Picton, T. L. (2002). Advantages and caveats when recording steady-state responses to multiple simultaneous stimuli. *Journal of the American Academy of Audiology, 13*, 246-259.

John, M. S., Lins, O. G., Boucher B. L, & Picton, T. L. (1998). Multiple auditory steady-state responses (MASTER): Stimulus and recording parameters. *Audiology, 37*, 59-82.

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.

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

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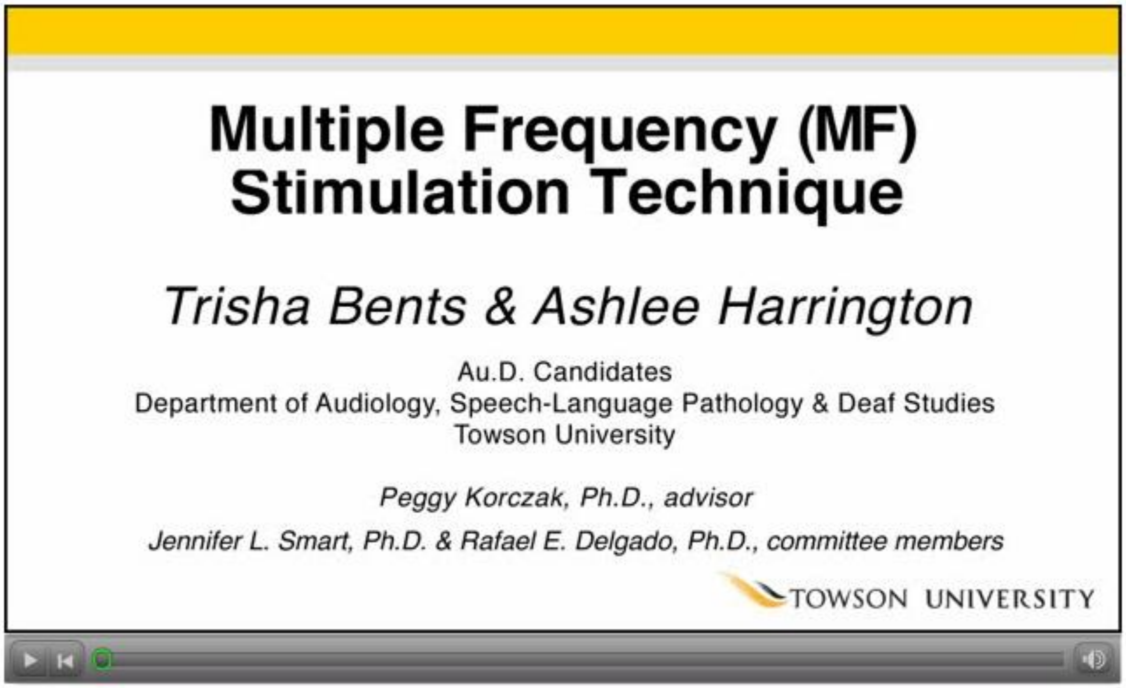
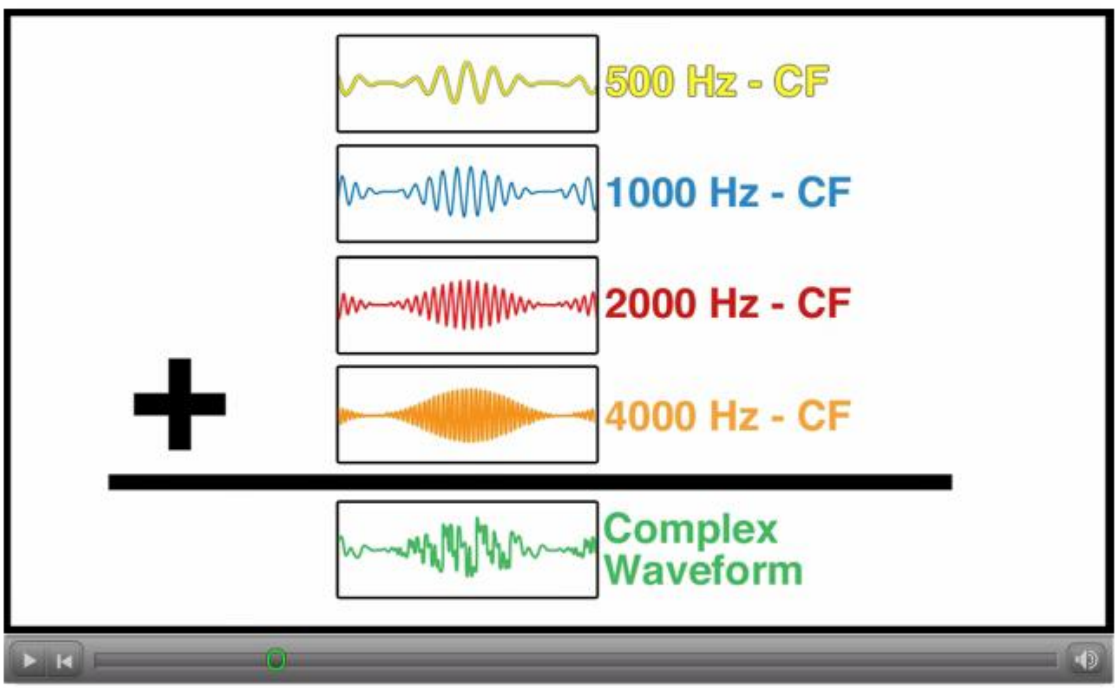
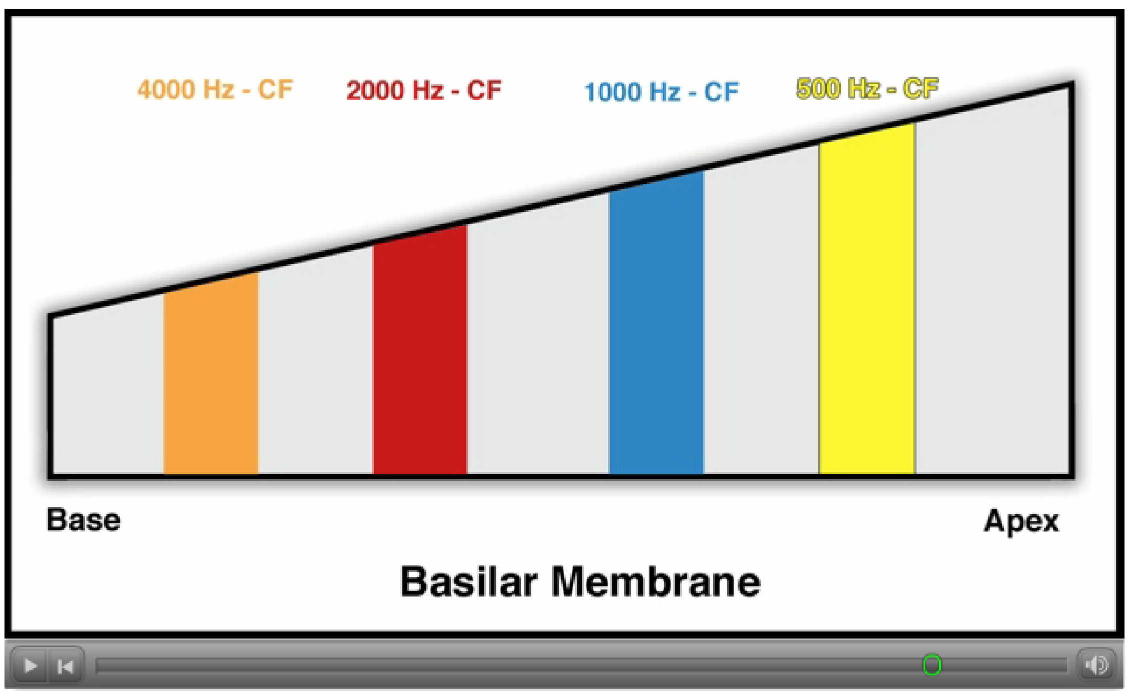
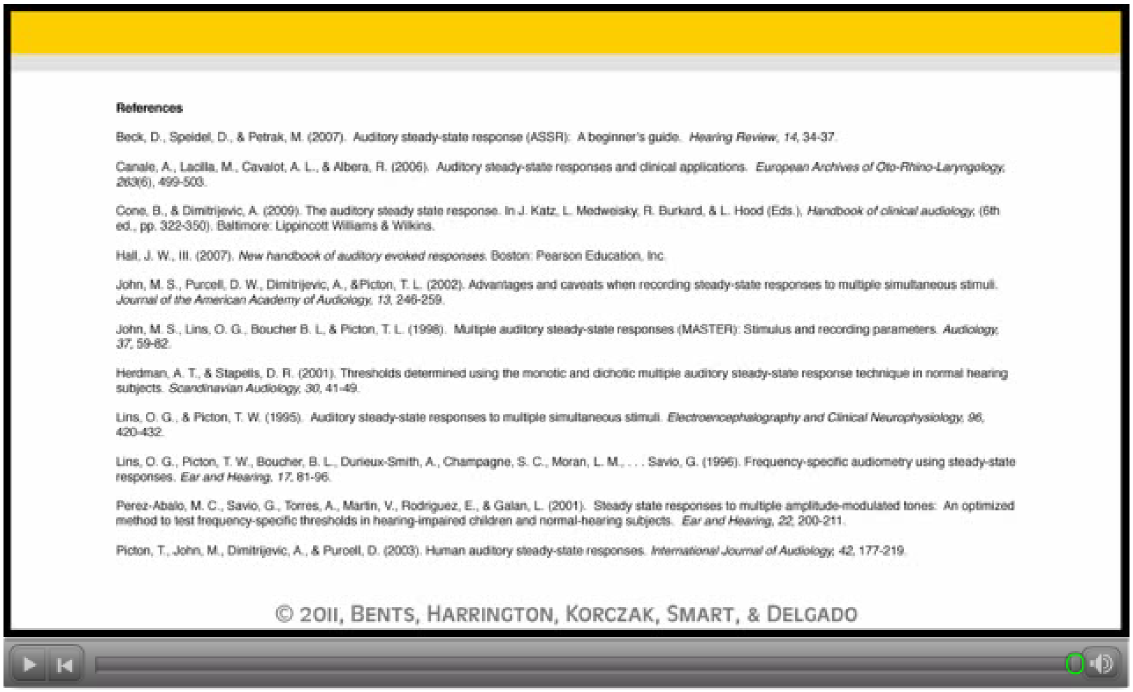
Picton, T., John, M., Dimitrijevic, A., & Purcell, D. (2003). Human auditory steady-state responses. *International Journal of Audiology, 42*, 177-219.

Multiple Frequency (MF) Stimulation Technique






4000 Hz - CF
2000 Hz - CF
1000 Hz - CF
500 Hz - CF
Base
Apex
Basilar Membrane



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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.

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

John, M. S., Purcell, D. W., Dimitrijevic, A., &Picton, T. L. (2002). Advantages and caveats when recording steady-state responses to multiple simultaneous stimuli. *Journal of the American Academy of Audiology, 13,* 246-259.

John, M. S., Lins, O. G., Boucher B. L, & Picton, T. L. (1998). Multiple auditory steady-state responses (MASTER): Stimulus and recording parameters. *Audiology, 37,* 59-82.

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.

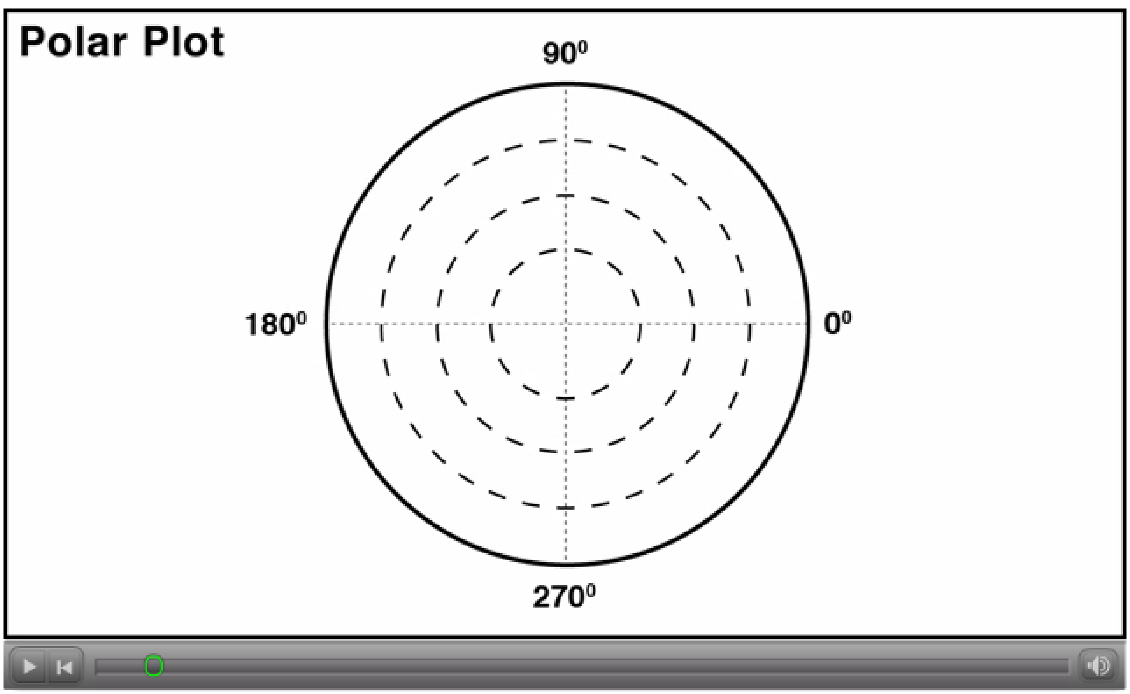
Lins, O. G., & Picton, T. W. (1995). Auditory steady-state responses to multiple simultaneous stimuli. *Electroencephalography and Clinical Neurophysiology, 96,* 420-432.

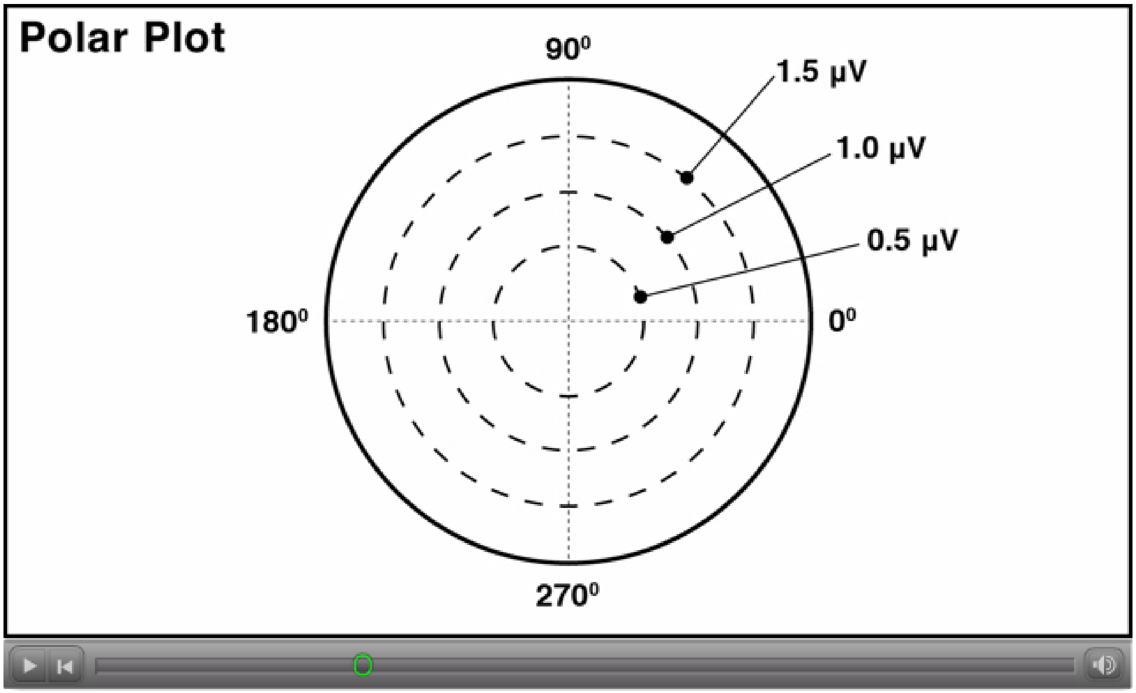
Lins, O. G., Picton, T. W., Boucher, B. L., Durieux-Smith, A., Champagne, S. C., Moran, L. M., . . . Savio, G. (1996). Frequency-specific audiometry using steady-state responses. *Ear and Hearing, 17,* 81-96.

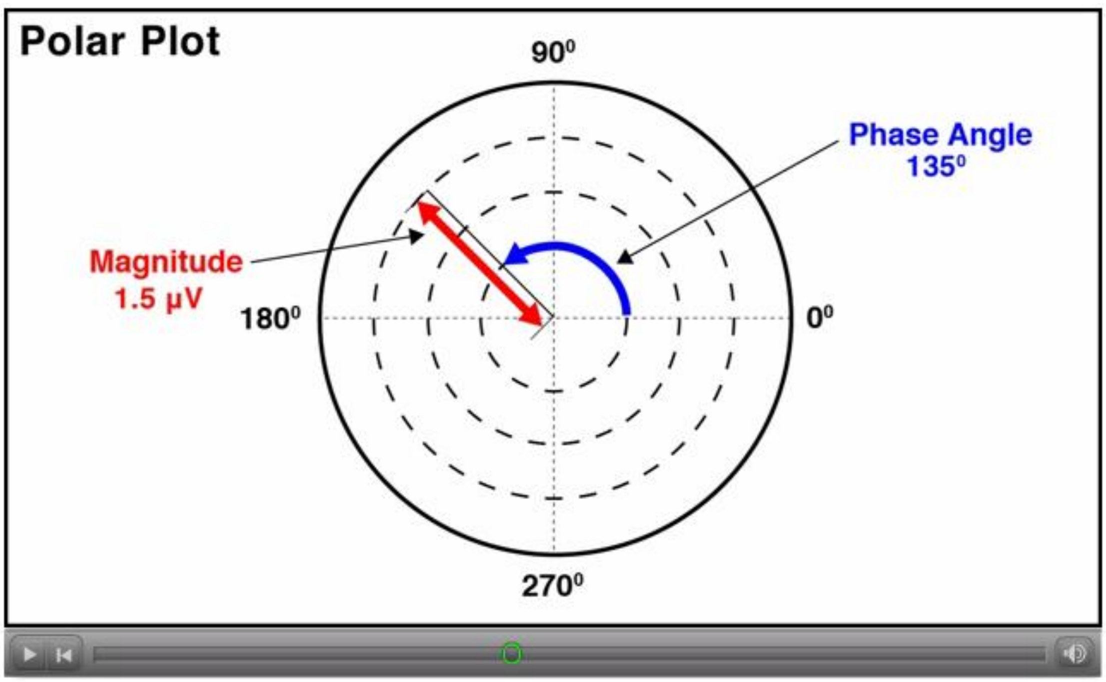
Perez-Abalo, M. C., Savio, G., Torres, A., Martin, V., Rodriguez, E., & Galan, L. (2001). Steady state responses to multiple amplitude-modulated tones: An optimized method to test frequency-specific thresholds in hearing-impaired children and normal-hearing subjects. *Ear and Hearing, 22,* 200-211.

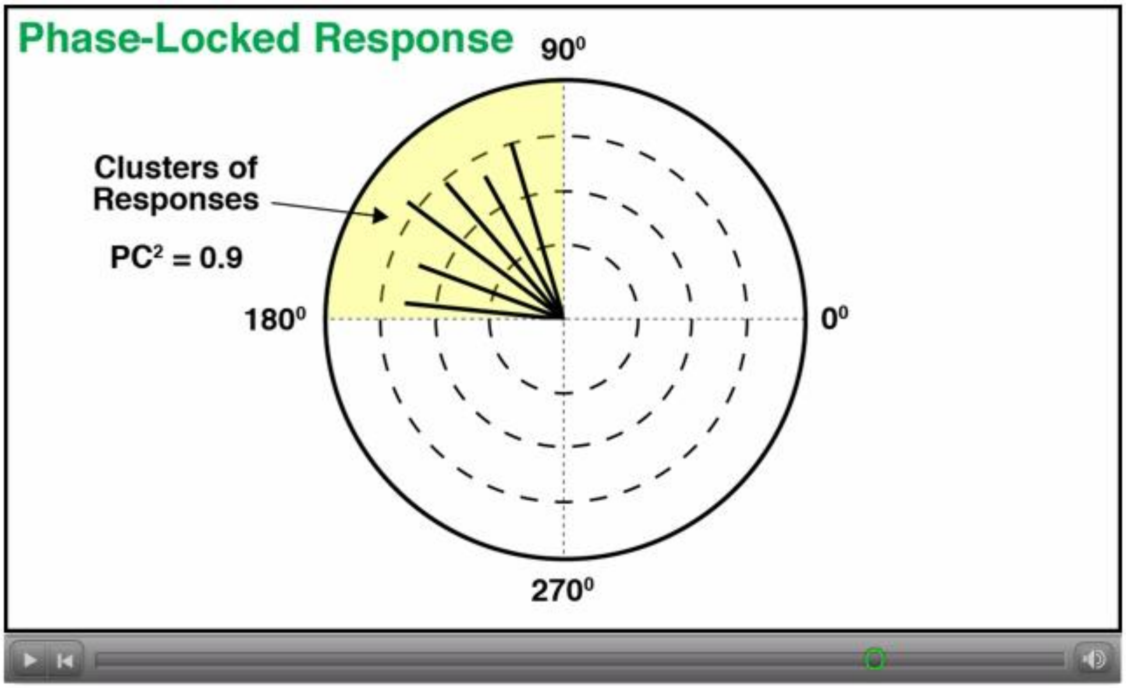
Picton, T., John, M., Dimitrijevic, A., & Purcell, D. (2003). Human auditory steady-state responses. *International Journal of Audiology, 42,* 177-219.

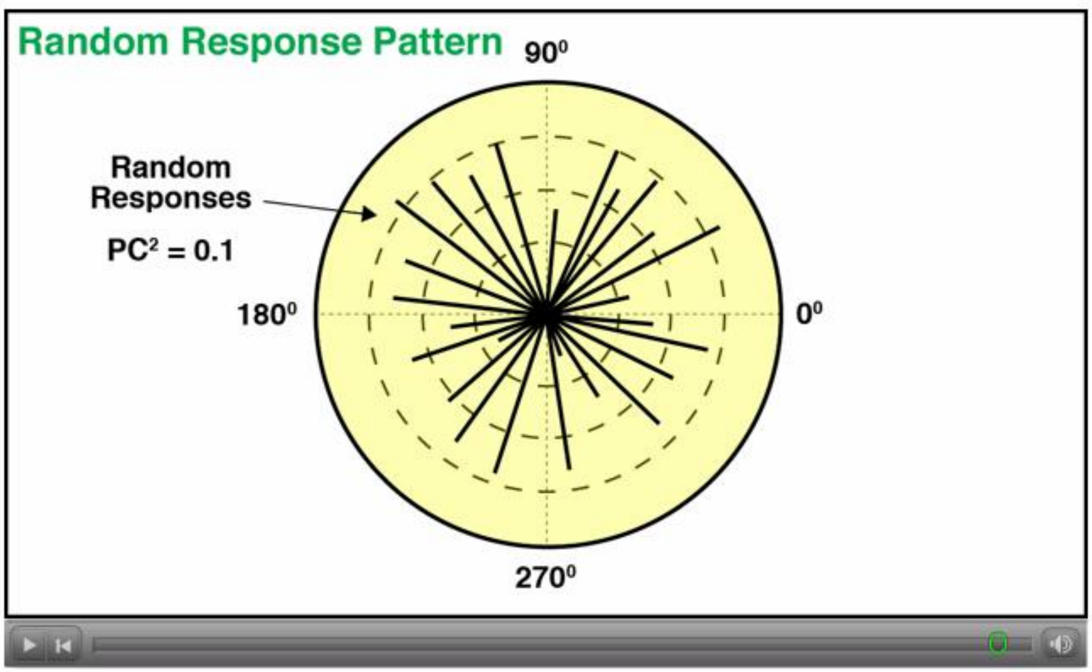
Phase Coherence

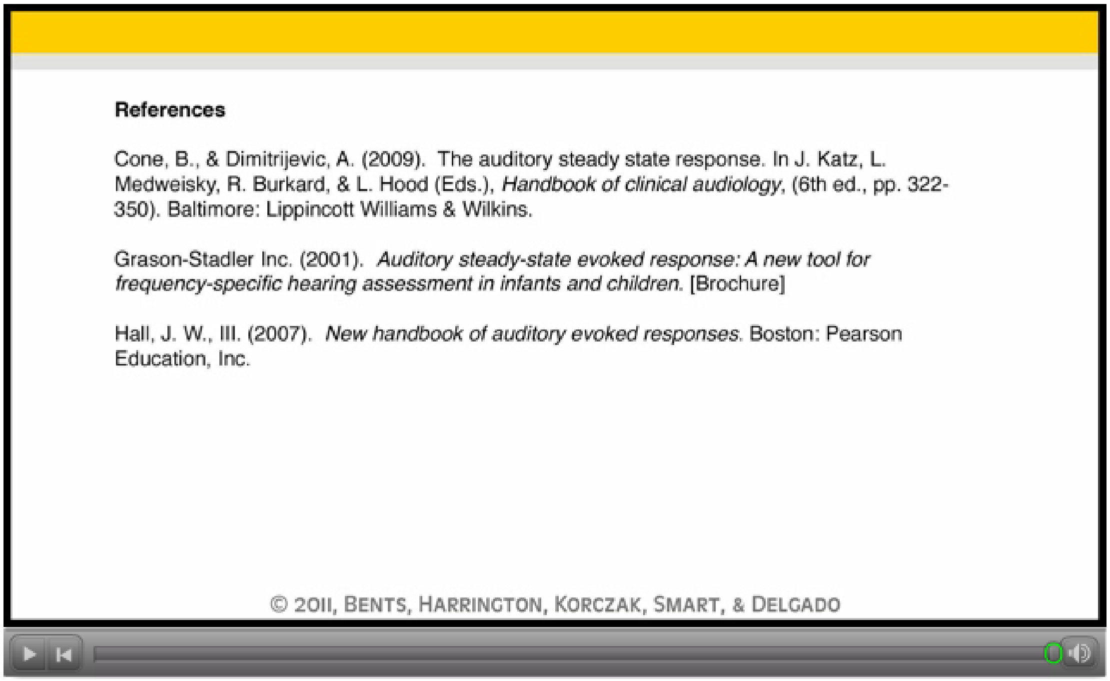



Polar Plot
90⁰
1.5 μV
1.0 μV
0.5 μV
180⁰
0⁰
270⁰


Polar Plot
90⁰
Phase Angle
135⁰
Magnitude
1.5 μV
180⁰
0⁰
270⁰


Phase-Locked Response
90⁰
Clusters of Responses
PC² = 0.9
180⁰
0⁰
270⁰


Random Response Pattern
90⁰
Random Responses
PC² = 0.1
180⁰
0⁰
270⁰


References
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.
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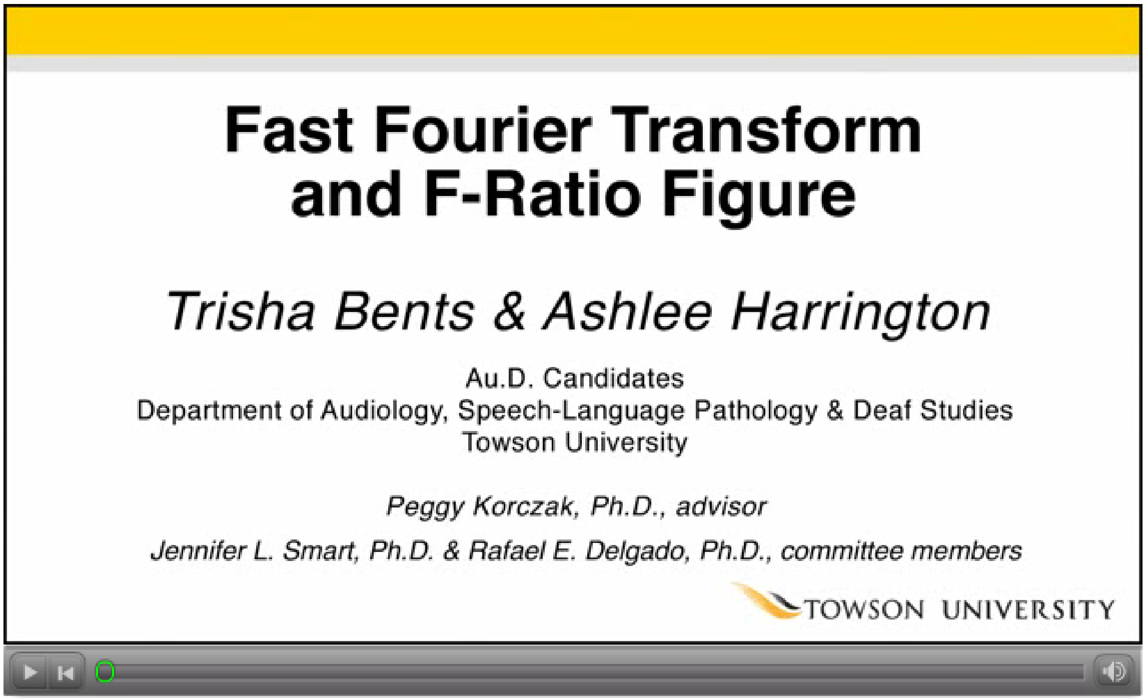
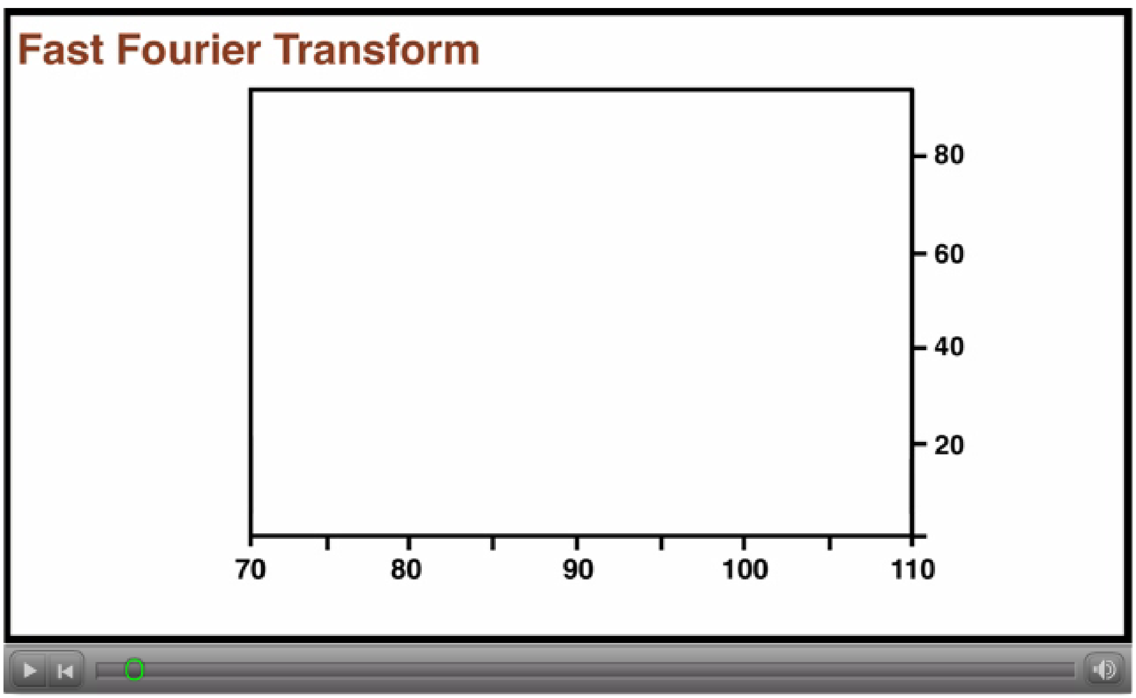
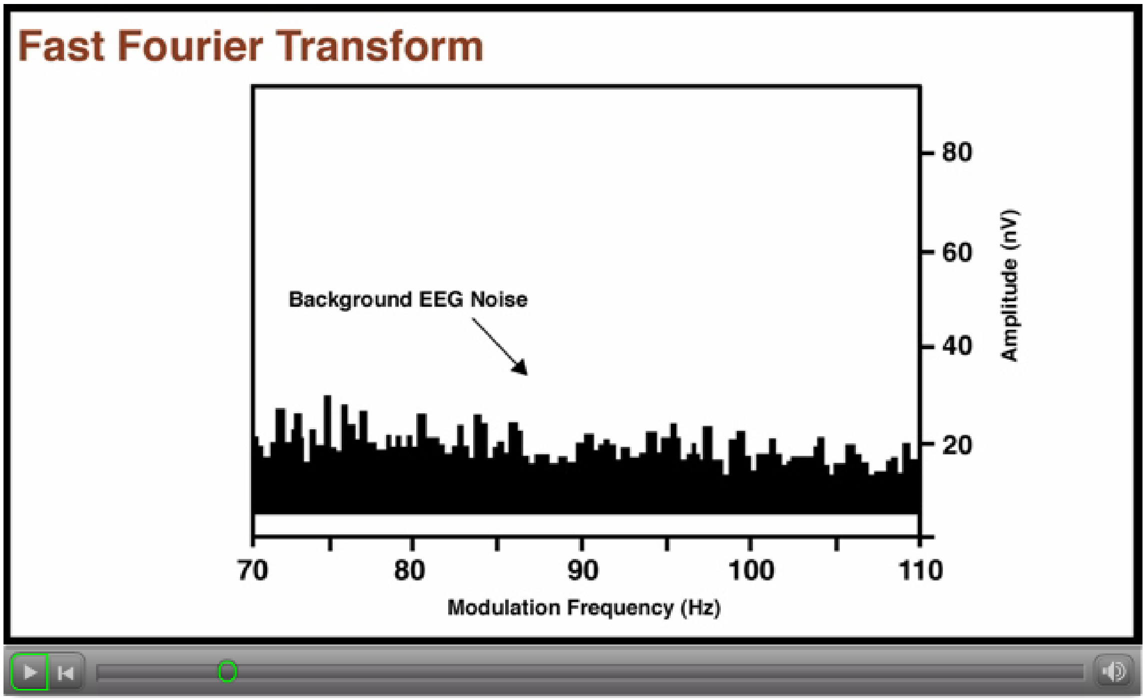
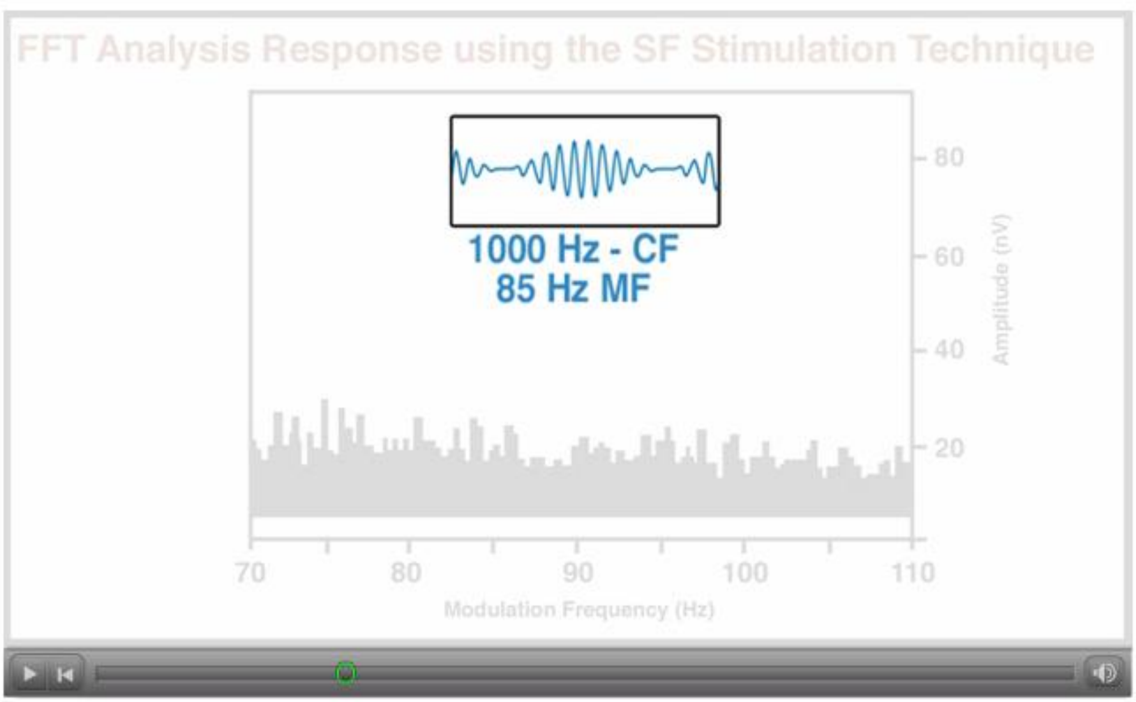
Fast Fourier Transform and F-Ratio Figure

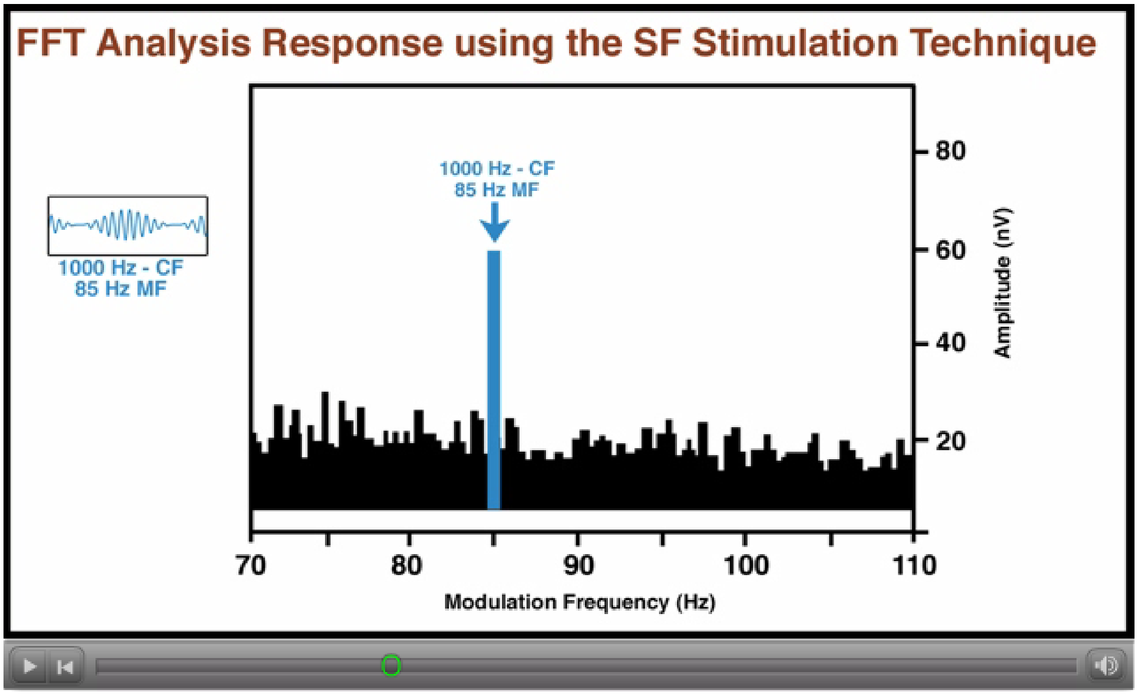


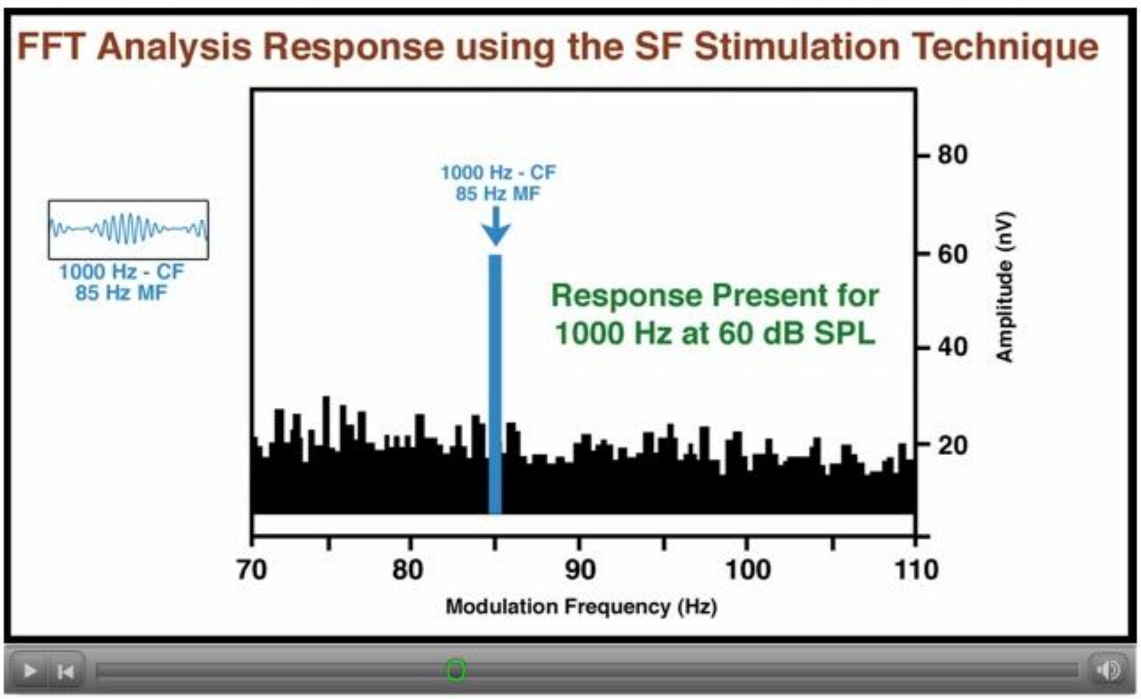


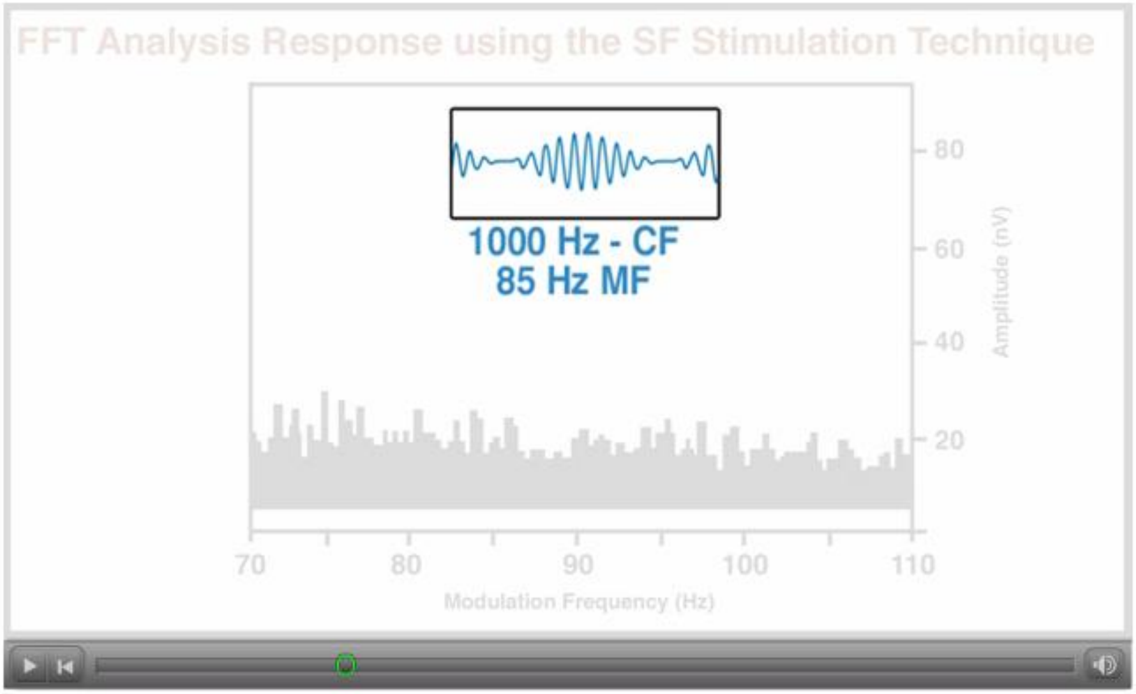

Fast Fourier Transform
Background EEG Noise
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

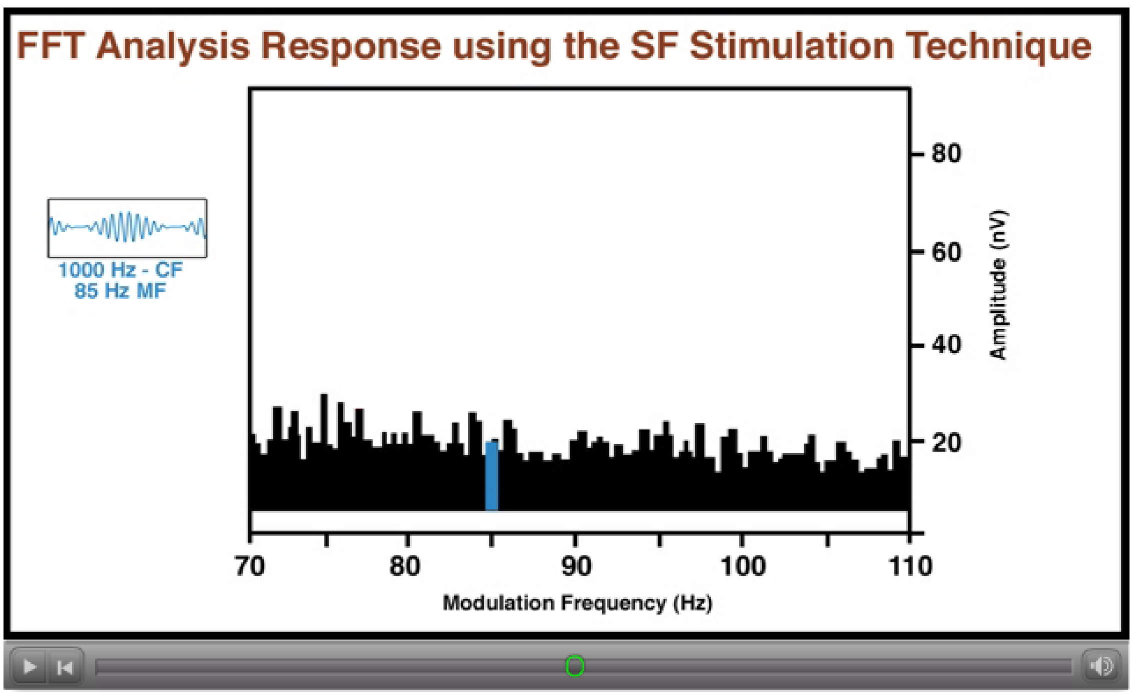
\

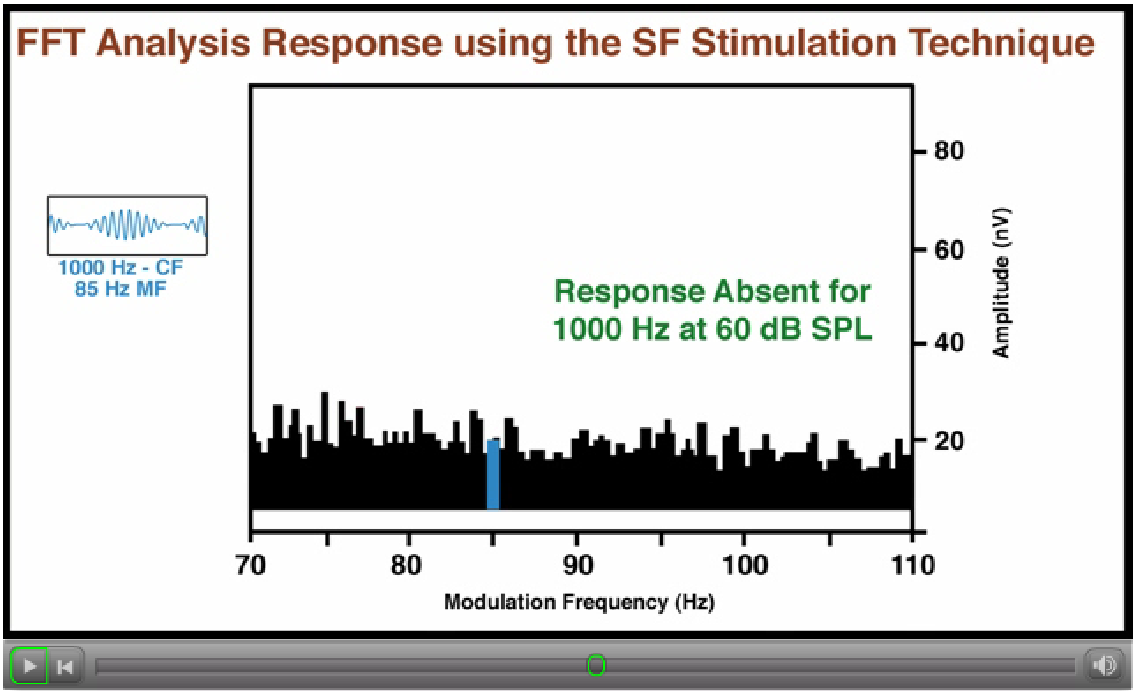

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

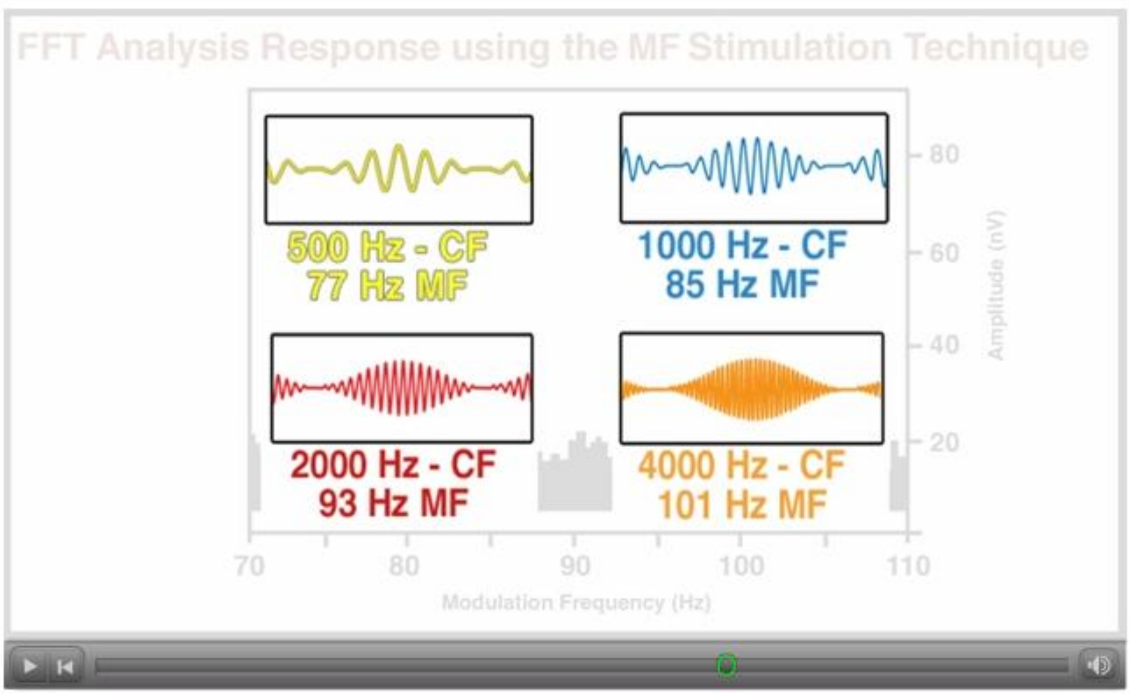

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
1000 Hz - CF
85 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

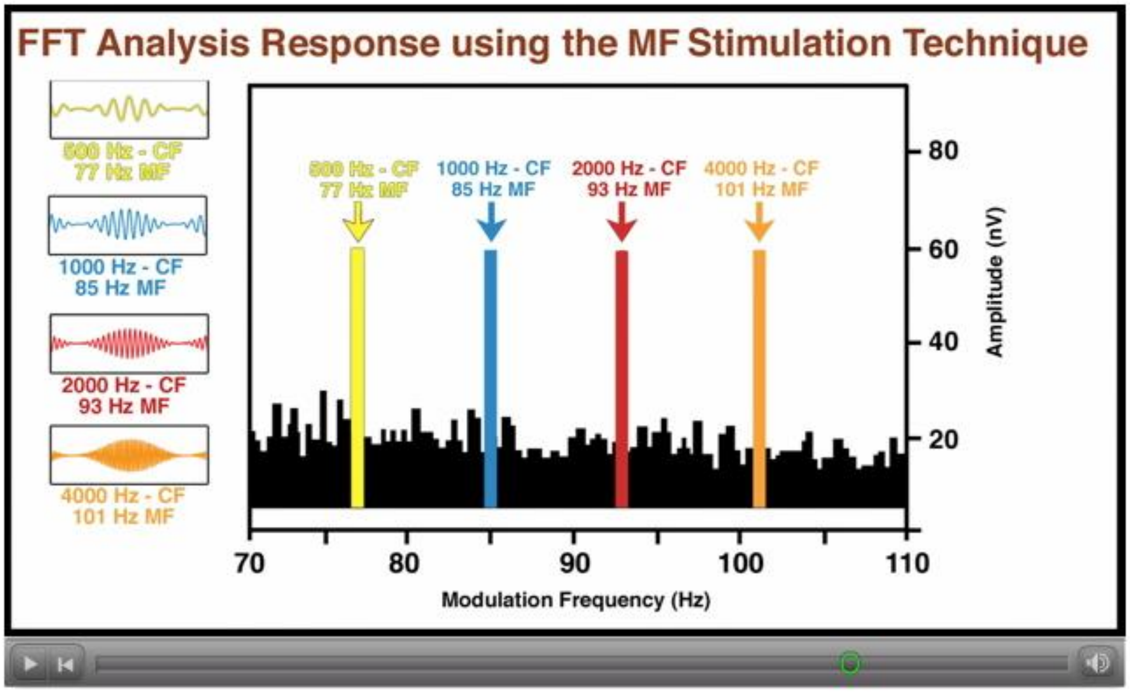

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
1000 Hz - CF
85 Hz MF
Response Present for
1000 Hz at 60 dB SPL
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

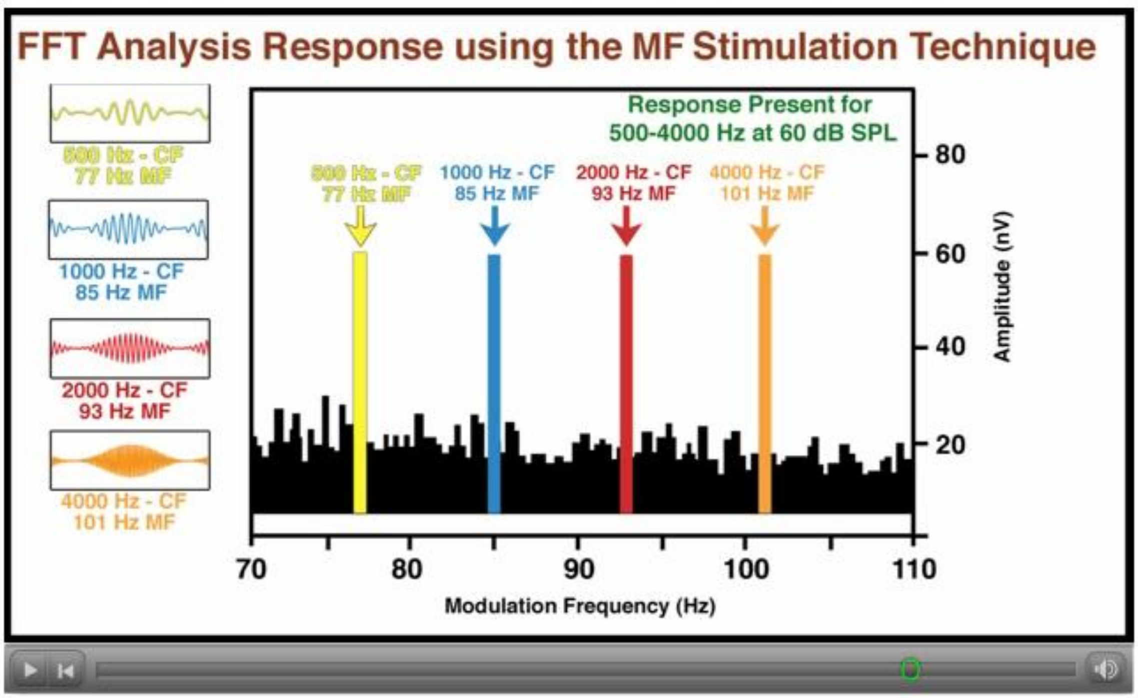

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

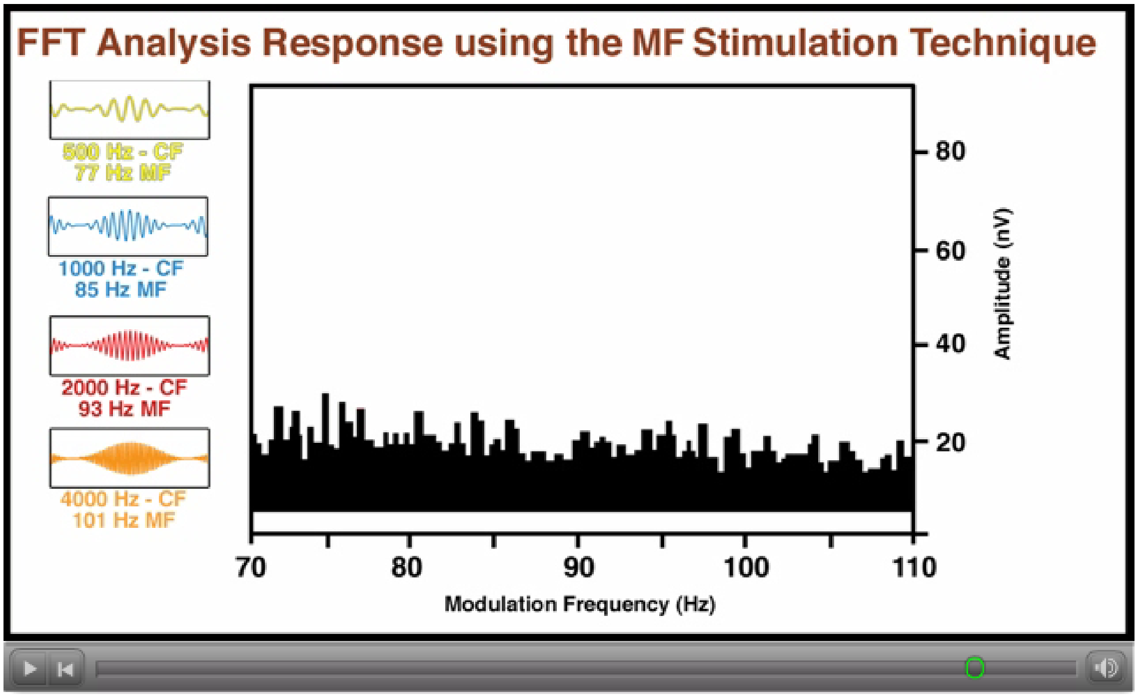

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

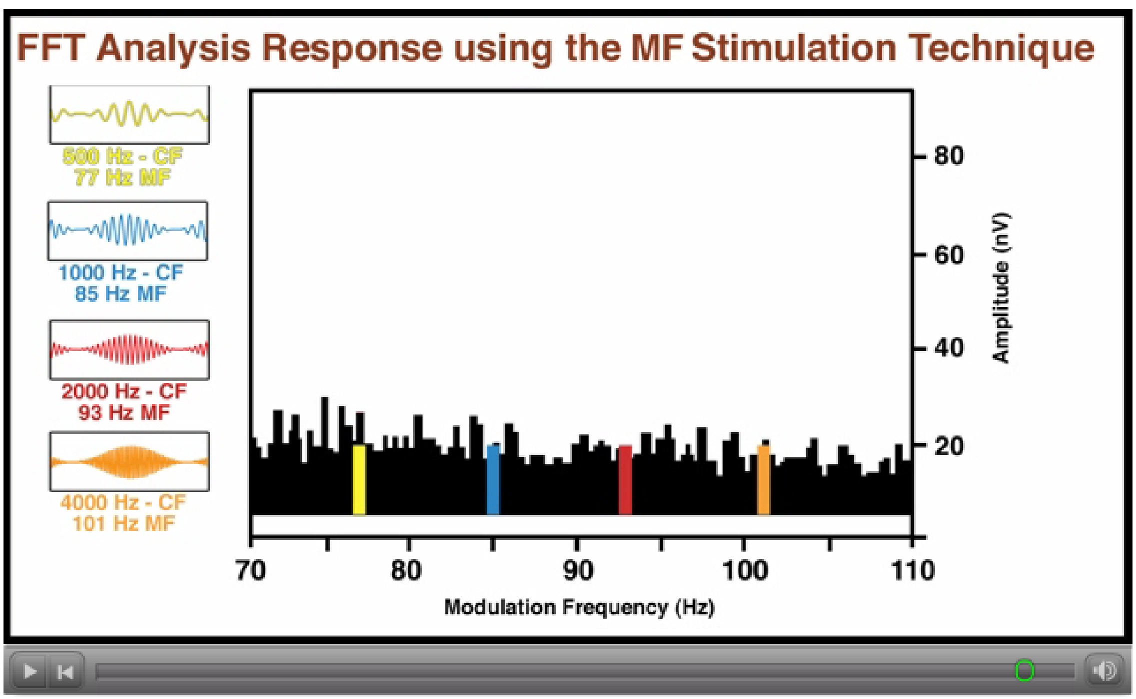

FFT Analysis Response using the SF Stimulation Technique
1000 Hz - CF
85 Hz MF
Response Absent for
1000 Hz at 60 dB SPL
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)

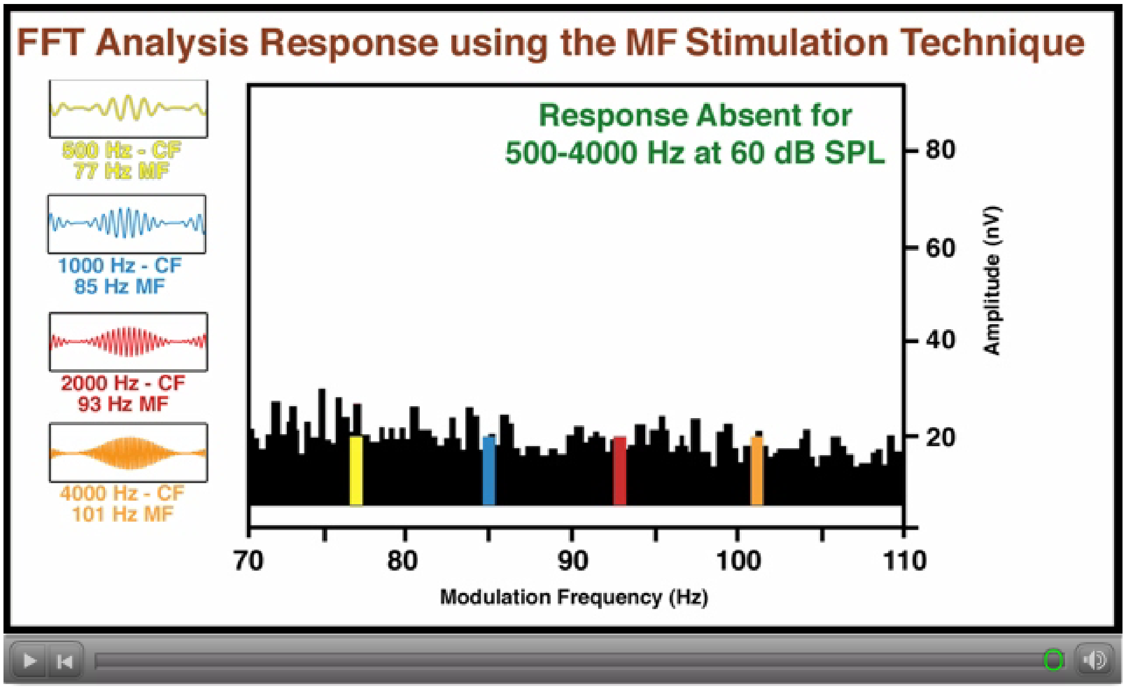

FFT Analysis Response using the MF Stimulation Technique
500 Hz - CF
77 Hz MF
1000 Hz - CF
85 Hz MF
2000 Hz - CF
93 Hz MF
4000 Hz - CF
101 Hz MF
80
60
40
20
Amplitude (nV)
70
80
90
100
110
Modulation Frequency (Hz)


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


FFT Analysis Response using the MF Stimulation Technique
500 Hz - CF
77 Hz MF
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
500 Hz - CF
77 Hz MF
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)



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.

APPENDIX B

DIALOGUE FOR ANIMATED FIGURES

Carrier Frequency

The Carrier Frequency (CF) of the tonal stimulus is the test frequency of interest. In this figure, the temporal waveform of a 500 Hz carrier frequency tone is highlighted in yellow. The carrier frequency tone enters the outer ear, travels through the middle ear and arrives at the inner ear. This carrier frequency tone only stimulates the region of the basilar membrane best tuned to 500 Hz.

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 carrier frequency tone stimulates the region of the basilar membrane best tuned to 500 Hz and is represented in yellow. 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

In this figure, we see the temporal waveform of a 2000 Hz carrier frequency 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 millisecond interval as shown by the vertical yellow lines. The interval of the firing pattern is determined by the period of the modulation frequency. In this example, the period equals

1 second divided by the modulation frequency, or 1000 milliseconds divided by 100 Hz; thus yielding a synchronous firing pattern every 10 milliseconds.

Single Frequency (SF) Stimulation Technique

The Single Frequency (SF) stimulation technique allows for only one carrier frequency tonal stimulus to be presented to one ear at a time. 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 carrier frequency 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.

Multiple Frequency (MF) Stimulation Technique

The Multiple Frequency (MF) stimulation technique presents up to four carrier frequency tonal stimuli to each ear either monaurally or binaurally. This figure illustrates four separate carrier frequency tones each being presented at 60 dB SPL: The 500 Hz carrier frequency tone is depicted in yellow, 1000 Hz carrier frequency tone is depicted in blue, 2000 Hz carrier frequency tone is depicted in red, and the 4000 Hz carrier frequency tone is depicted in orange being added together to form a complex waveform as displayed in green. 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 carrier frequency tones respective yellow, blue, red, and orange vertical lines on the figure of the basilar membrane.

Phase Coherence (PC) Analysis Technique

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 carrier frequency 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 represent 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, 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 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 synchronously 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 carrier frequency 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 in-synchronously 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) with F-Ratio Analysis Technique

Fast Fourier Transform (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 carrier frequency tone with an 85 Hz modulation frequency, presented at 60 dB SPL to the subject's right ear. In this figure, the amplitude of energy present at the modulation frequency 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 modulation frequency 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 carrier frequency tone with an 85 Hz modulation frequency being presented at 60 dB SPL. The FFT with F-Ratio analysis demonstrates that the amplitude of the response at the modulation frequency 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".

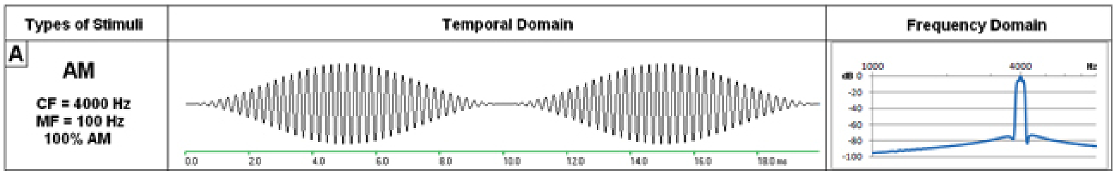
Now, this figure will demonstrate the FFT with F-Ratio technique utilizing a Multiple Frequency stimulation technique. Contrary to the Single Frequency approach, the Multiple Frequency stimulation technique consists of up to four separate carrier frequency tones, each with its own modulation frequency, being presented simultaneously to either one or both ears. The current figure will show an example of a present ASSR utilizing the multiple frequency FFT with F-Ratio analysis. Four carrier frequency tones of 500, 1000, 2000, and 4000 Hz are presented at 60 dB SPL to the subject's right ear. The 500 Hz carrier frequency tone has a 77 Hz modulation frequency and is highlighted in yellow, the 1000 Hz carrier frequency tone has an 85 Hz modulation frequency and is highlighted in blue, the 2000 Hz carrier frequency tone has a 93 Hz modulation frequency and is highlighted in red, and the 4000 Hz carrier frequency tone has a 101 Hz modulation frequency 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 modulation frequencies is approximately 60 nano-volts, and is statistically 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 modulation frequencies 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 modulation frequencies 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."

APPENDIX C

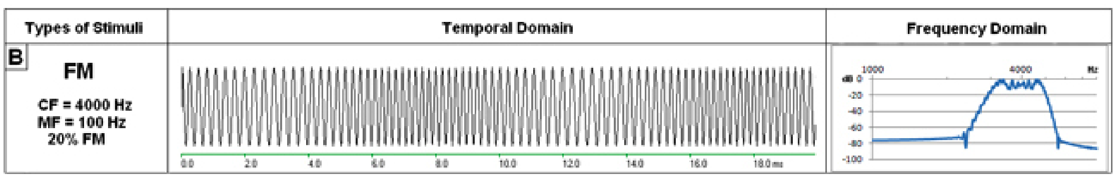
NON-ANIMATED FIGURES

Amplitude Modulated Tonal Stimuli



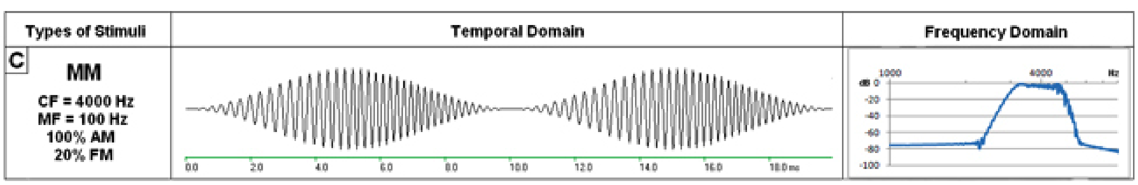
Listen to this AM Tone.

Frequency Modulated Tonal Stimuli



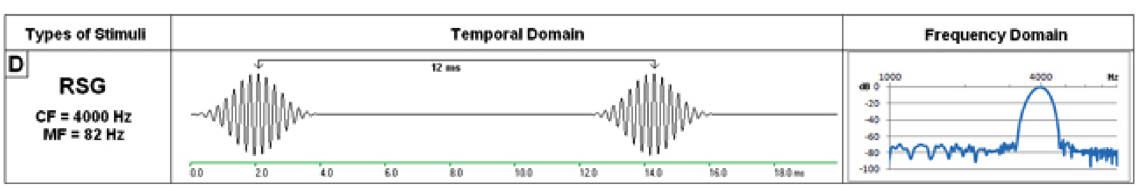
Listen to this FM Tone.

Mixed Modulated Tonal Stimuli



Listen to this MM tone.

Repeating Sequence Gated Tonal Stimuli



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)
A		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)
B	Multiple Frequency	Dimitrijevic et al. (2002)[55]	MF, Monotic	17(10)	4(11)	4(8)	11(7)
B	Multiple Frequency	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)
C		D'haenens et. al. (2008)[58]	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)
D	Monotic vs. Dicotic	Herdman & Stapells(2001)[56]	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 ($\geq$ 30 dB/octave)	15(13)	7(8)	7(11)	5(9)
			MF, Group B: Flat/Shallow ($\leq$ 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

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

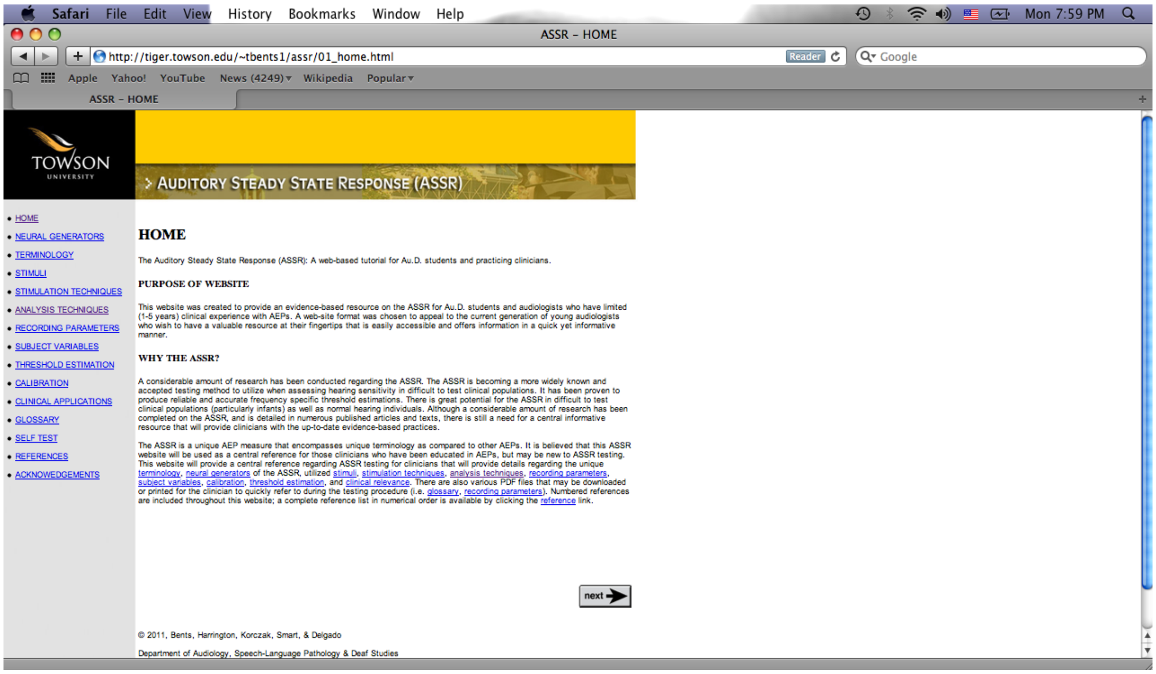
Key Terms	Carrier Frequency	Associated with the region in the cochlea where the hair cells are activated in response to the presentation of a stimulus[15,16].
	Modulation Frequency	The frequency at which electroencephalography (EEG) activity is synchronized to fire and can be derived by calculating the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

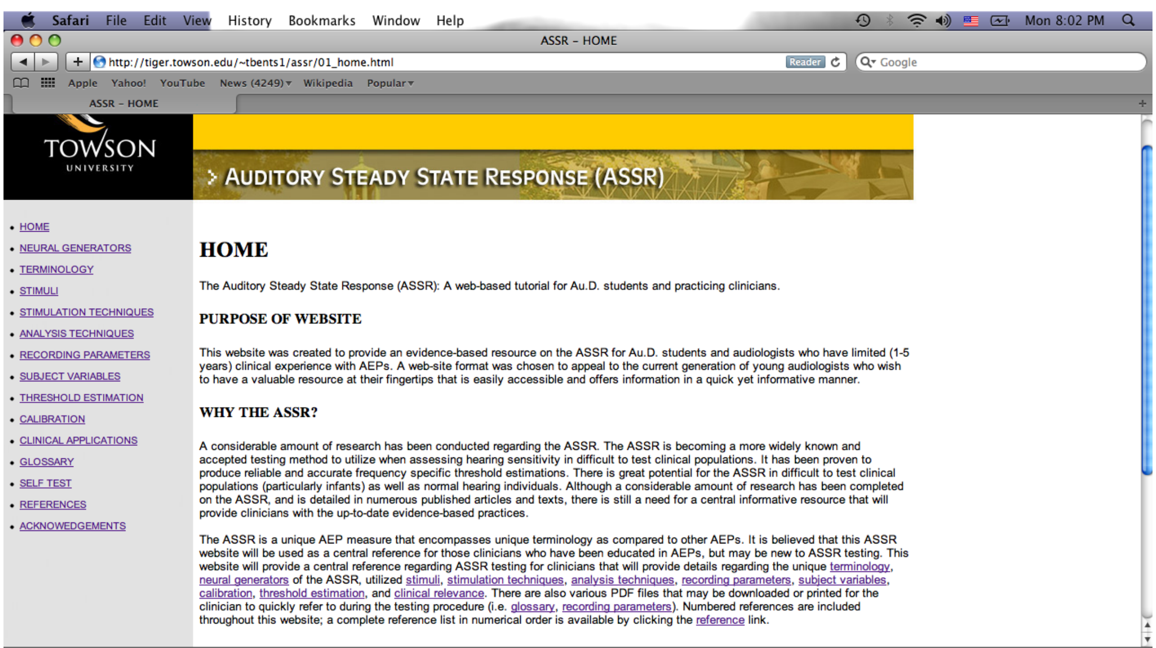
Analysis Techniques	Fast-Fourier Transform (FFT) Analysis	A computerized technique for separating a complex waveform consisting of multiple frequencies into its individual frequency components[74].
	Phase Coherence	Phase coherence "is related to the signal (response) –to-noise (background EEG and myogenic) 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

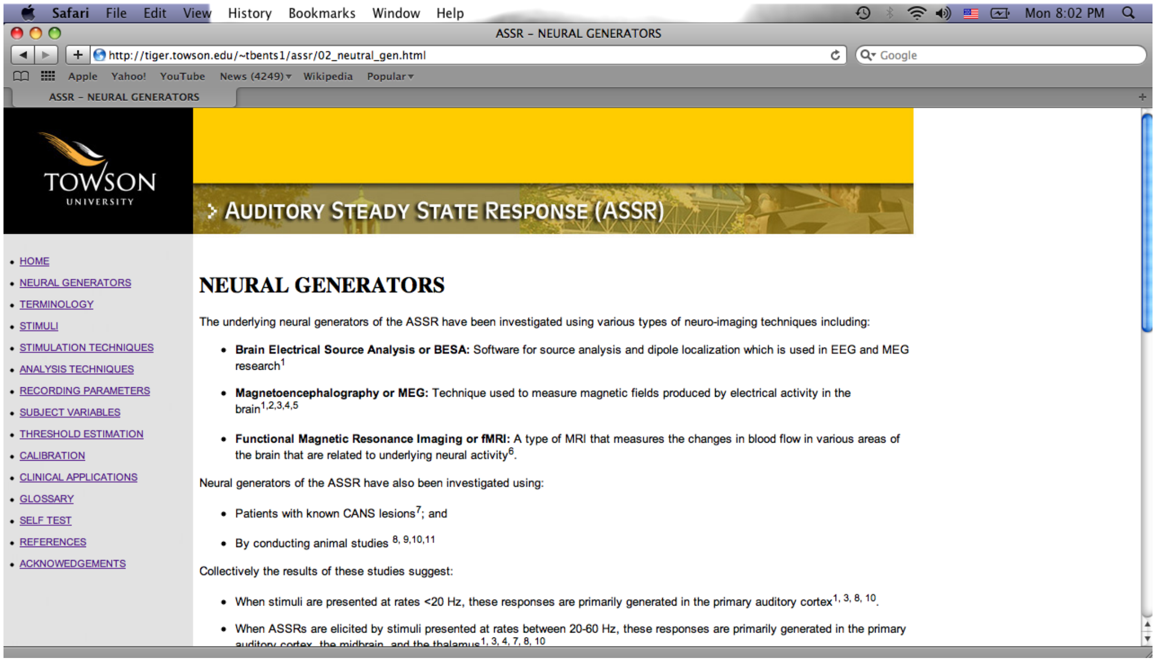
SAMPLE WEBPAGE SCREENSHOTS

Home Page

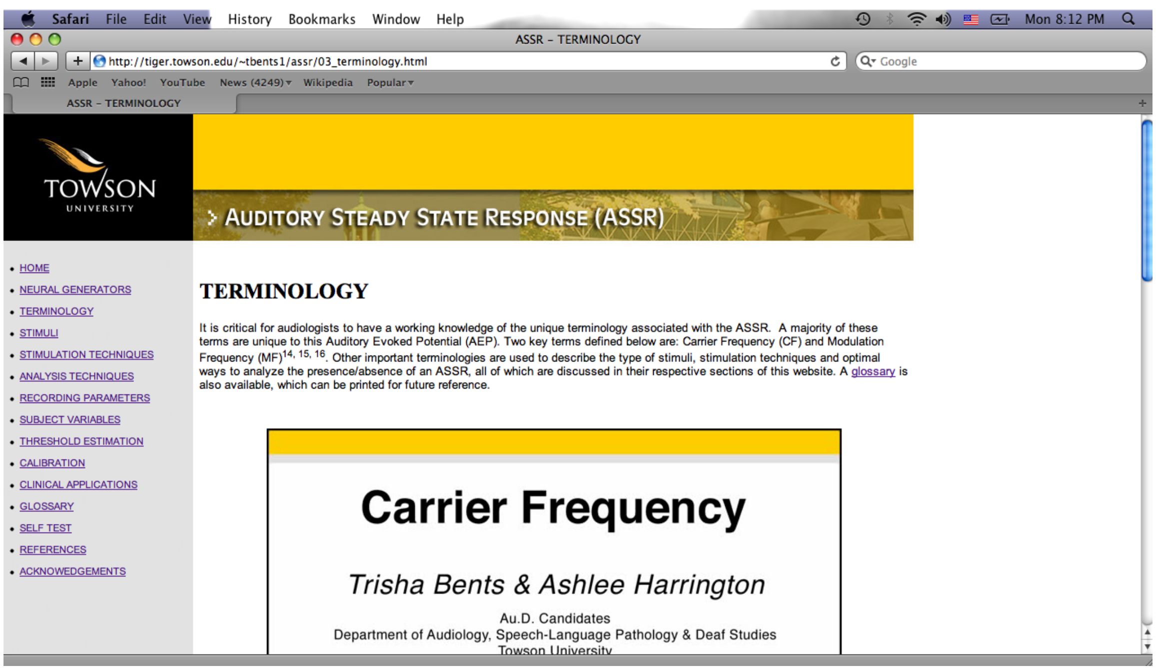




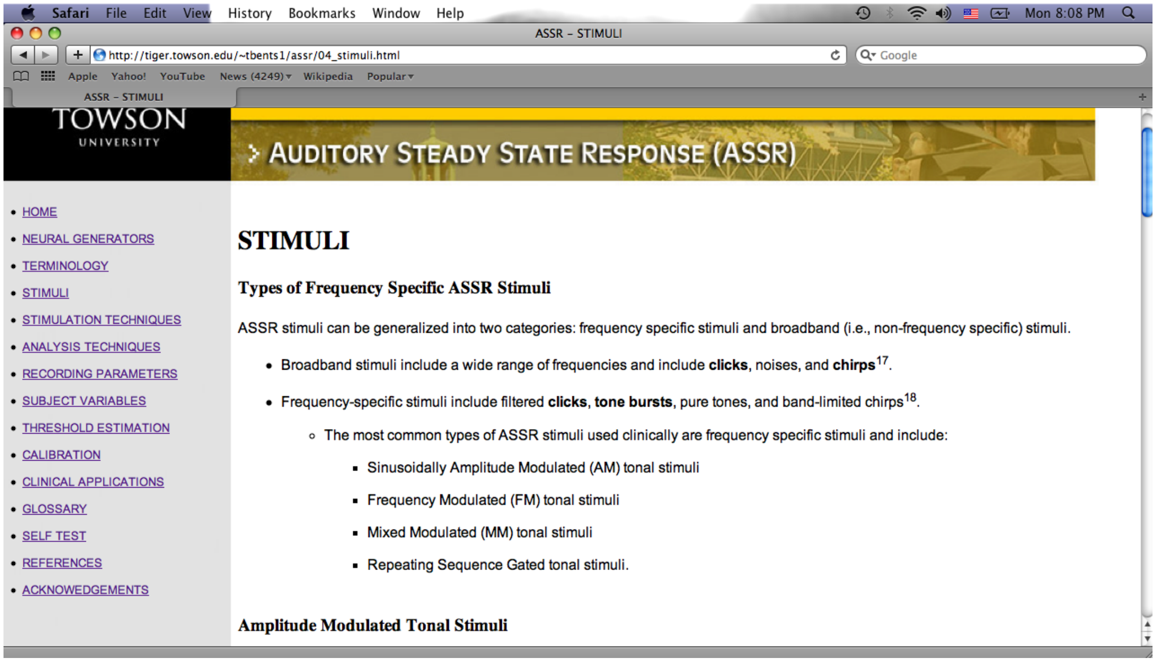
Neural Generators



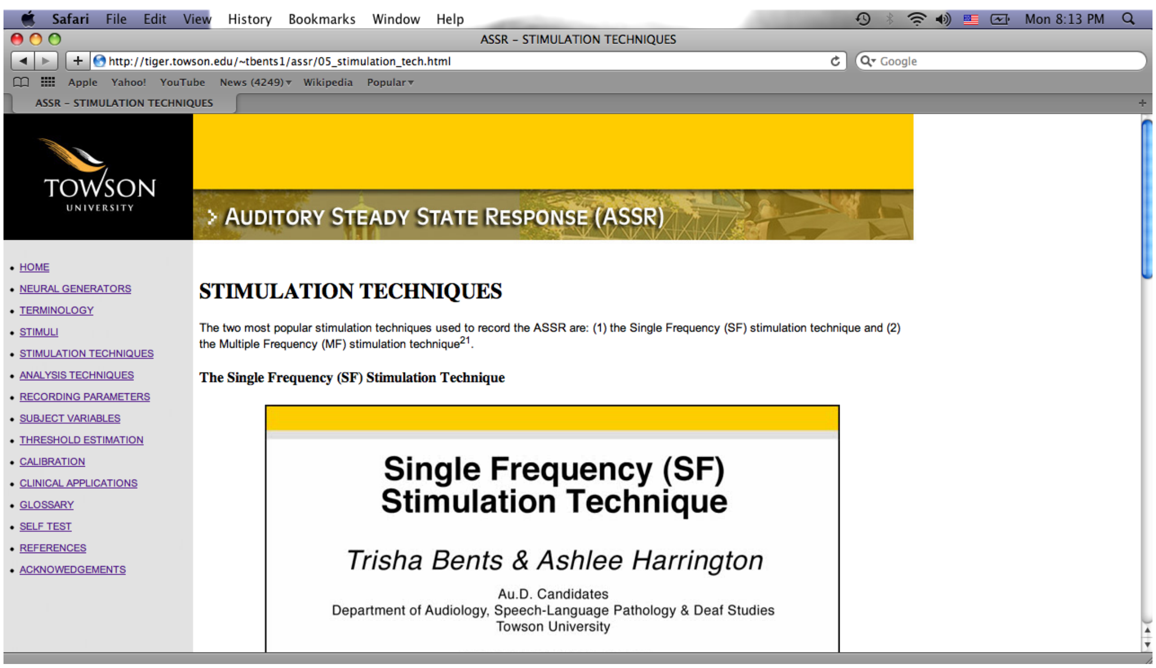
Terminology



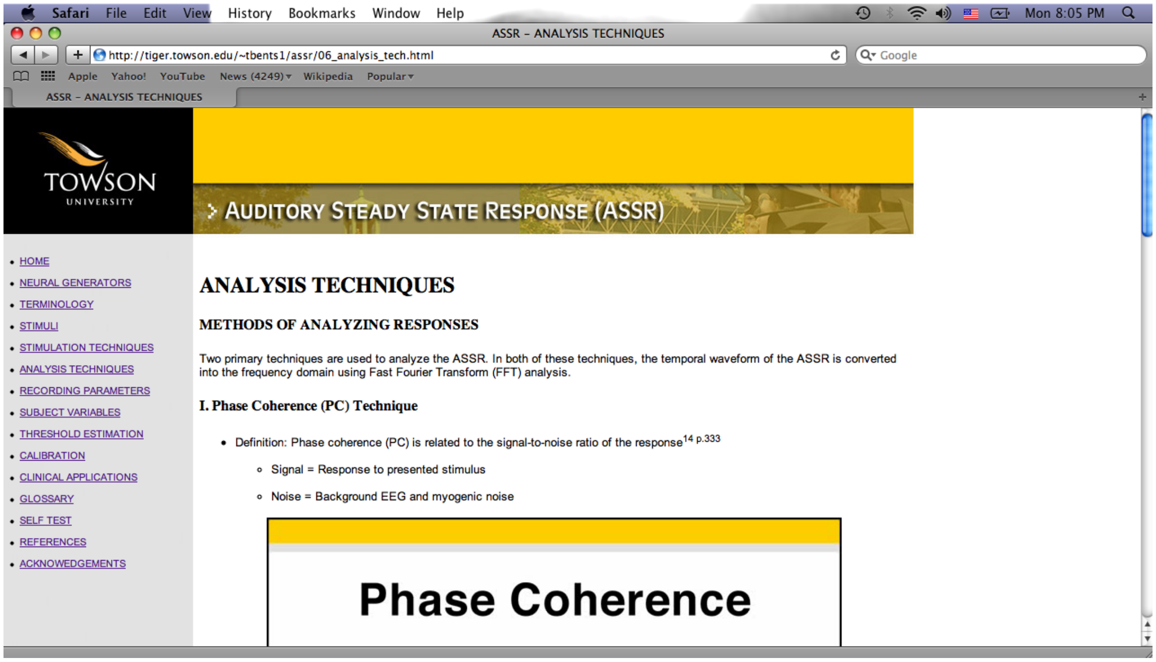
Stimuli



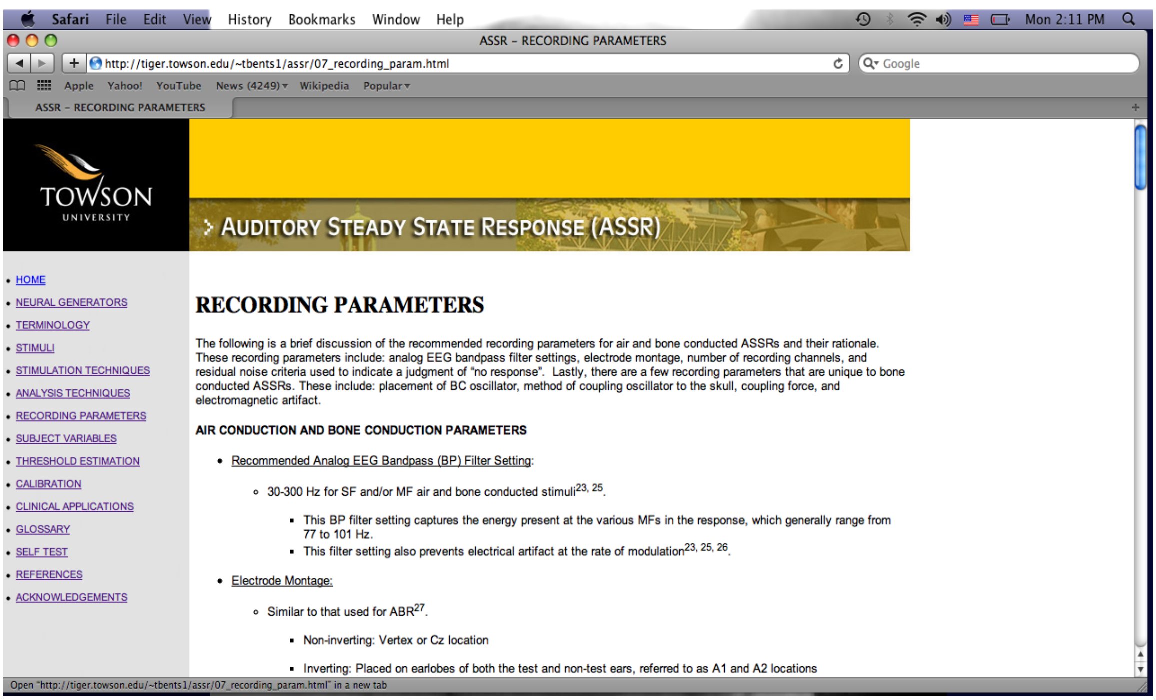
Stimulation Techniques



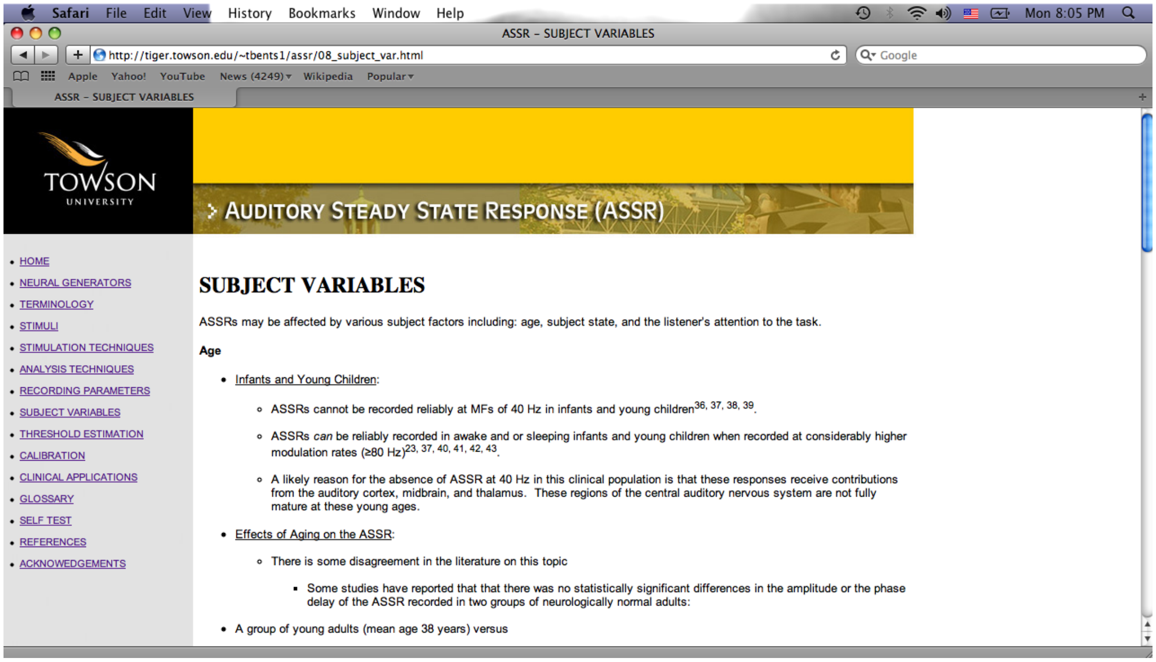
Analysis Techniques



Recording Parameters



Subject Variables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ASSR – SUBJECT VARIABLES

http://tiger.towson.edu/~tbents1/assr/08_subject_var.html

TOWSON UNIVERSITY

> AUDITORY STEADY STATE RESPONSE (ASSR)

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

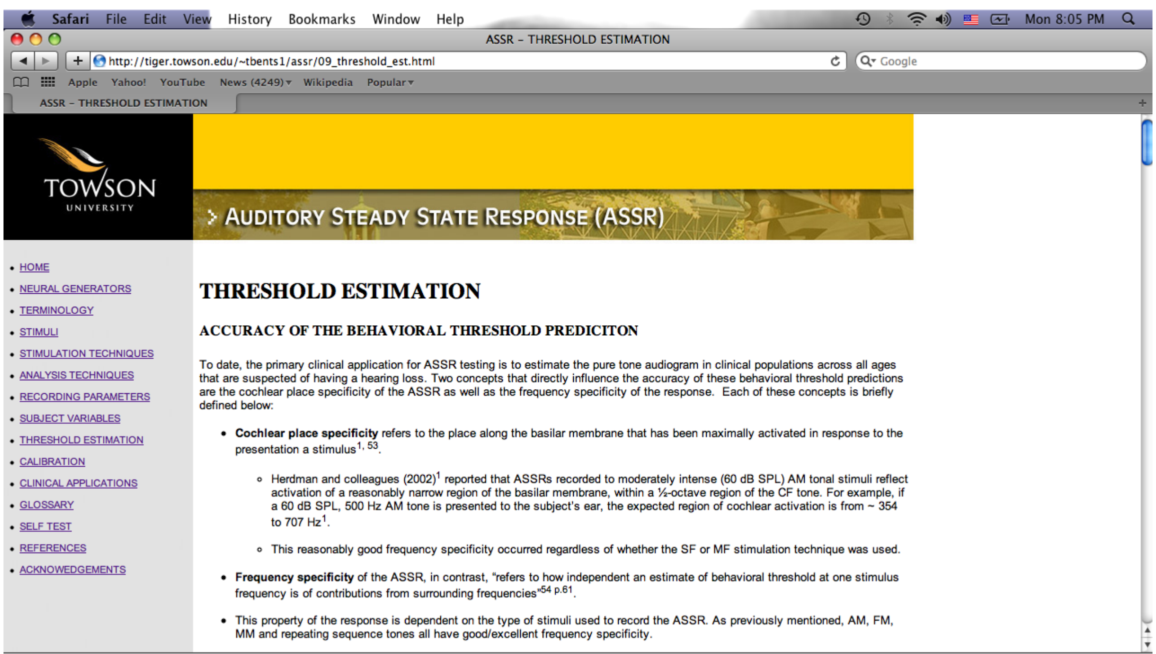
SUBJECT VARIABLES

ASSRs may be affected by various subject factors including: age, subject state, and the listener's attention to the task.

Age

- Infants and Young Children:
  - ASSRs cannot be recorded reliably at MFs of 40 Hz in infants and young children[36, 37, 38, 39].
  - ASSRs *can* be reliably recorded in awake and or sleeping infants and young children when recorded at considerably higher modulation rates (≥80 Hz)[23, 37, 40, 41, 42, 43].
  - A likely reason for the absence of ASSR at 40 Hz in this clinical population is that these responses receive contributions from the auditory cortex, midbrain, and thalamus. These regions of the central auditory nervous system are not fully mature at these young ages.
- Effects of Aging on the ASSR:
  - There is some disagreement in the literature on this topic
    - Some studies have reported that that there was no statistically significant differences in the amplitude or the phase delay of the ASSR recorded in two groups of neurologically normal adults:
- A group of young adults (mean age 38 years) versus

Threshold Estimation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ASSR – THRESHOLD ESTIMATION

http://tiger.towson.edu/~tbents1/assr/09_threshold_est.html

TOWSON UNIVERSITY

> AUDITORY STEADY STATE RESPONSE (ASSR)

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

THRESHOLD ESTIMATION

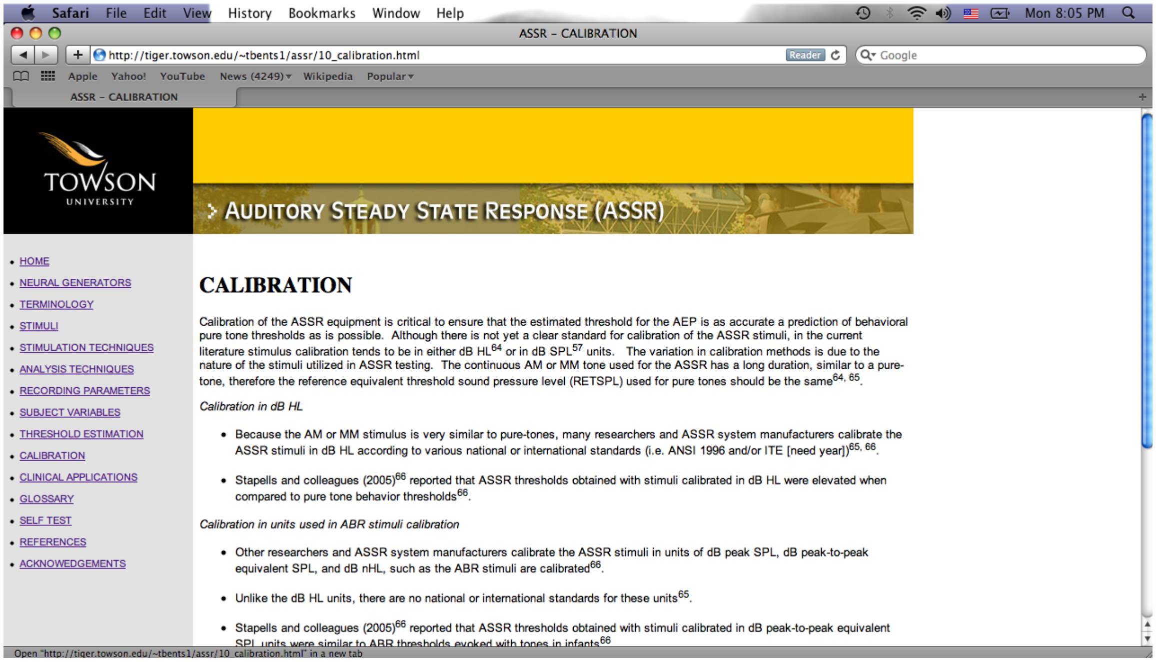
ACCURACY OF THE BEHAVIORAL THRESHOLD PREDICITON

To date, the primary clinical application for ASSR testing is to estimate the pure tone audiogram in clinical populations across all ages that are suspected of having a hearing loss. Two concepts that directly influence the accuracy of these behavioral threshold predictions are the cochlear place specificity of the ASSR as well as the frequency specificity of the response. Each of these concepts is briefly defined below:

- **Cochlear place specificity** refers to the place along the basilar membrane that has been maximally activated in response to the presentation a stimulus[1, 53].
  - Herdman and colleagues (2002)[1] reported that ASSRs recorded to moderately intense (60 dB SPL) AM tonal stimuli reflect activation of a reasonably narrow region of the basilar membrane, within a ½-octave region of the CF tone. For example, if a 60 dB SPL, 500 Hz AM tone is presented to the subject's ear, the expected region of cochlear activation is from ~ 354 to 707 Hz[1].
  - This reasonably good frequency specificity occurred regardless of whether the SF or MF stimulation technique was used.
- **Frequency specificity** of the ASSR, in contrast, "refers to how independent an estimate of behavioral threshold at one stimulus frequency is of contributions from surrounding frequencies"[54 p.61].
- This property of the response is dependent on the type of stimuli used to record the ASSR. As previously mentioned, AM, FM, MM and repeating sequence tones all have good/excellent frequency specificity.

Open "http://tiger.towson.edu/~tbents1/assr/09_threshold_est.html" in a new tab

Calibration



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CALIBRATION

Calibration of the ASSR equipment is critical to ensure that the estimated threshold for the AEP is as accurate a prediction of behavioral pure tone thresholds as is possible. Although there is not yet a clear standard for calibration of the ASSR stimuli, in the current literature stimulus calibration tends to be in either dB HL[64] or in dB SPL[57] units. The variation in calibration methods is due to the nature of the stimuli utilized in ASSR testing. The continuous AM or MM tone used for the ASSR has a long duration, similar to a pure-tone, therefore the reference equivalent threshold sound pressure level (RETSPL) used for pure tones should be the same[64, 65].

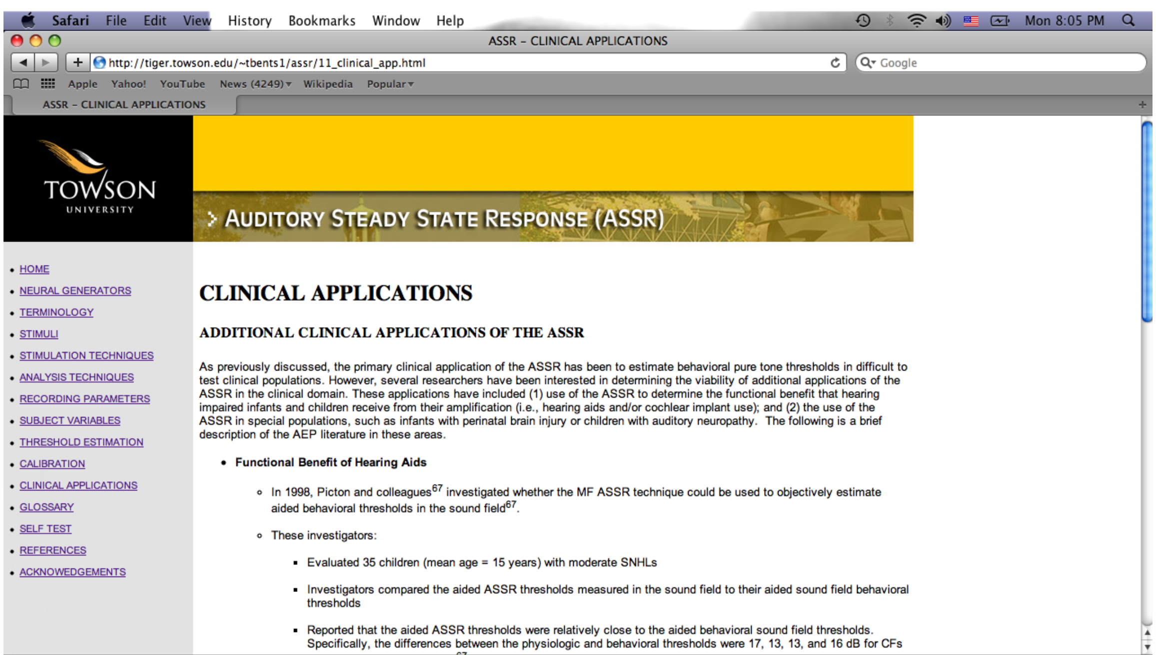
Calibration in dB HL

- Because the AM or MM stimulus is very similar to pure-tones, many researchers and ASSR system manufacturers calibrate the ASSR stimuli in dB HL according to various national or international standards (i.e. ANSI 1996 and/or ITE [need year])[65, 66].
- Stapells and colleagues (2005)[66] reported that ASSR thresholds obtained with stimuli calibrated in dB HL were elevated when compared to pure tone behavior thresholds[66].

Calibration in units used in ABR stimuli calibration

- Other researchers and ASSR system manufacturers calibrate the ASSR stimuli in units of dB peak SPL, dB peak-to-peak equivalent SPL, and dB nHL, such as the ABR stimuli are calibrated[66].
- Unlike the dB HL units, there are no national or international standards for these units[65].
- Stapells and colleagues (2005)[66] reported that ASSR thresholds obtained with stimuli calibrated in dB peak-to-peak equivalent SPL units were similar to ABR thresholds evoked with tones in infants[66]

Clinical Applications



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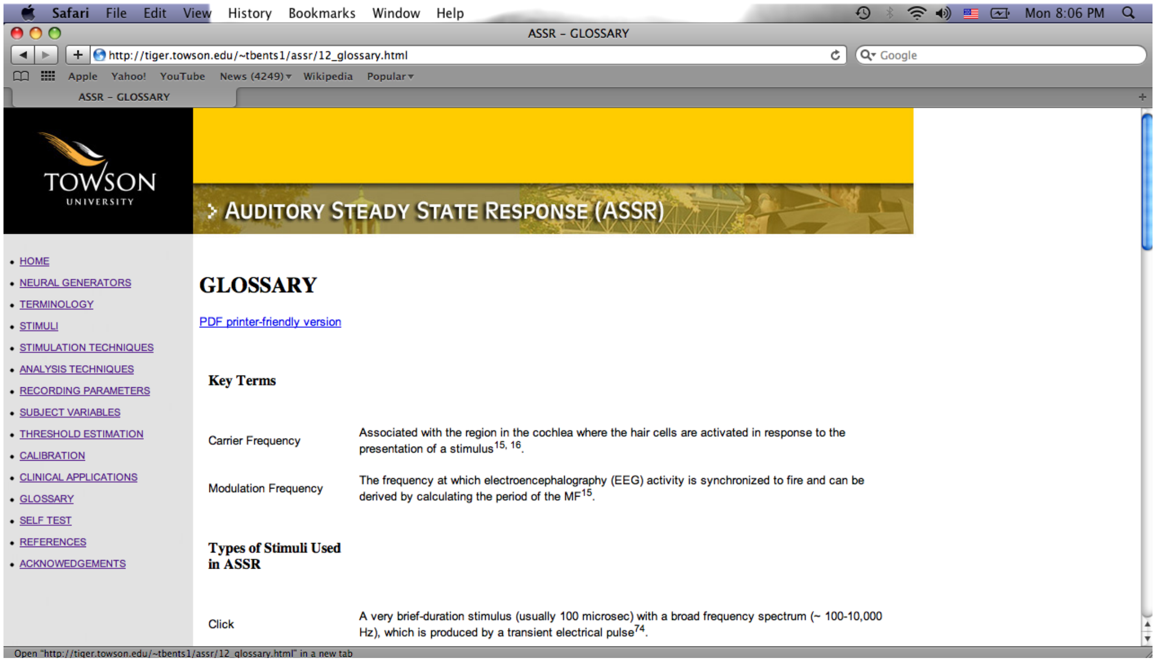
CLINICAL APPLICATIONS

ADDITIONAL CLINICAL APPLICATIONS OF THE ASSR

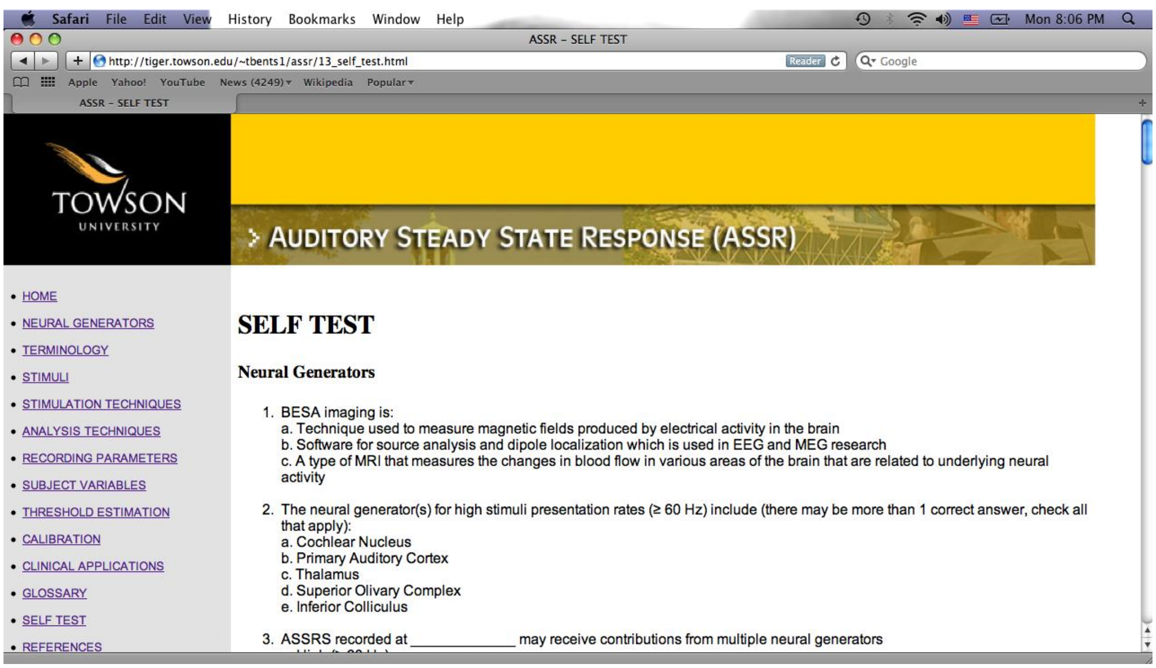
As previously discussed, the primary clinical application of the ASSR has been to estimate behavioral pure tone thresholds in difficult to test clinical populations. However, several researchers have been interested in determining the viability of additional applications of the ASSR in the clinical domain. 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

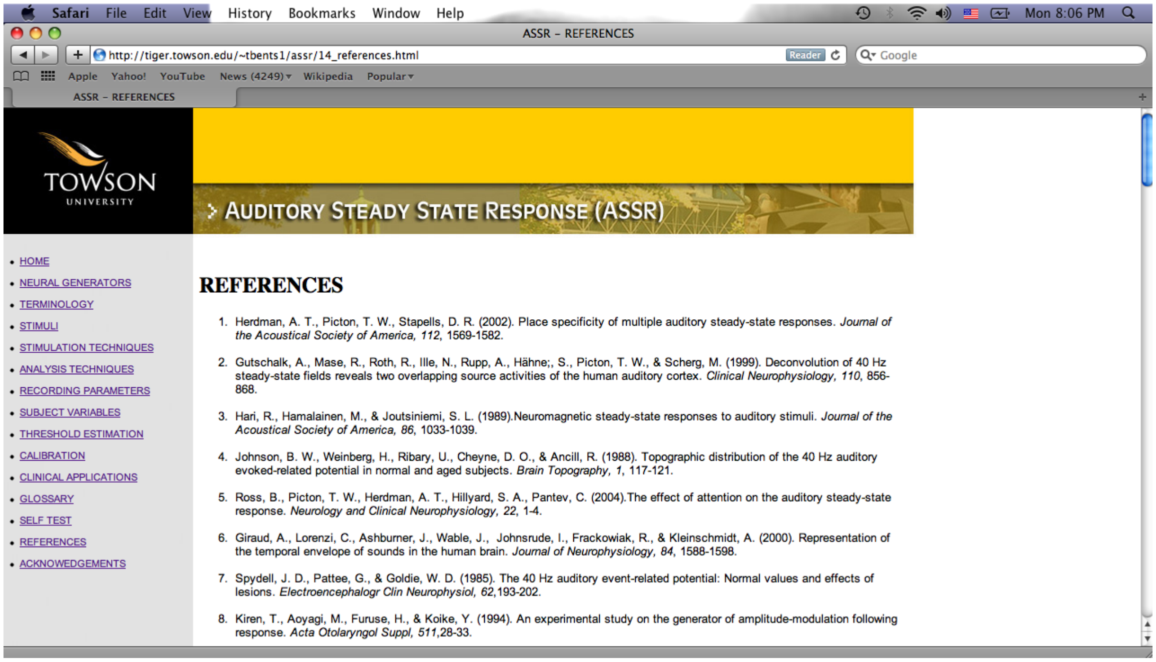
Glossary



Self Test



References



AUDITORY STEADY STATE RESPONSE (ASSR)

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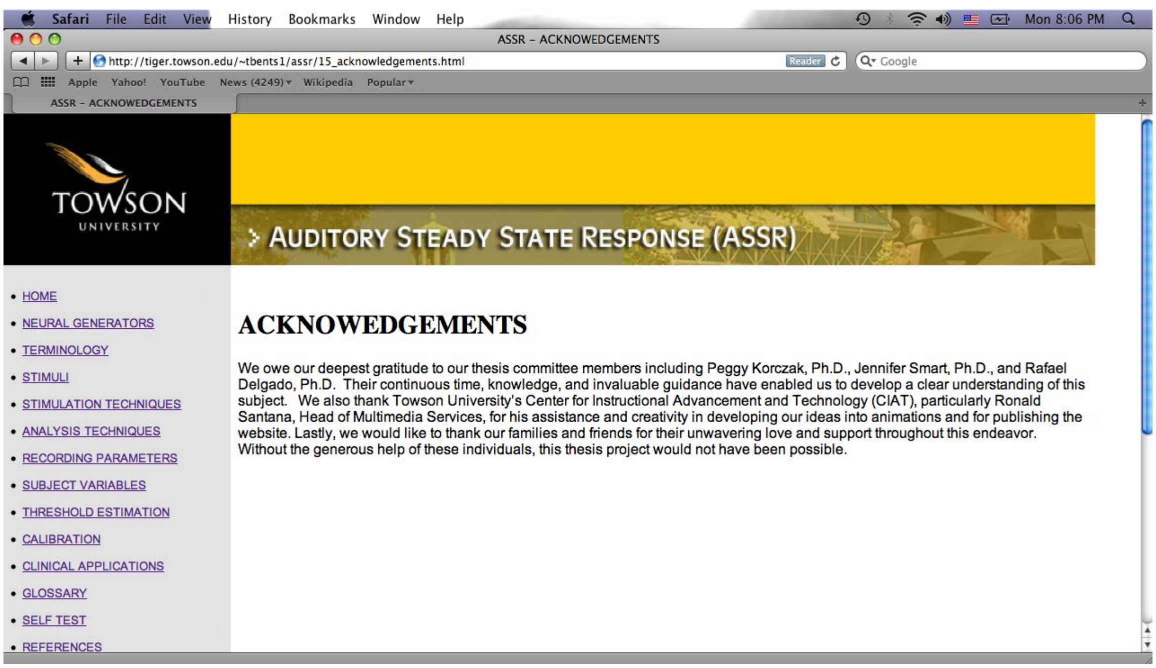
Acknowledgements



AUDITORY STEADY STATE RESPONSE (ASSR)

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We owe our deepest gratitude to our thesis committee members including Peggy Korczak, Ph.D., Jennifer Smart, Ph.D., and Rafael Delgado, Ph.D. Their continuous time, knowledge, and invaluable guidance have enabled us to develop a clear understanding of this subject. We also thank Towson University's Center for Instructional Advancement and Technology (CIAT), particularly Ronald Santana, Head of Multimedia Services, for his assistance and creativity in developing our ideas into animations and for publishing the website. Lastly, we would like to thank our families and friends for their unwavering love and support throughout this endeavor. Without the generous help of these individuals, this thesis project would not have been possible.

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- **Au.D., Doctor of Audiology,** Towson University, Towson, MD , *in progress*
  Thesis: *The Auditory Steady State Response: A Web Based Tutorial, in progress*
- **B.A., Communication Sciences and Disorders**, University of Maine, Orono, ME, 2008
  Capstone: *Sensorineural hearing loss resulting from perinatal infections*

Academic Honors and Awards

- Recipient, Starkey Outstanding Student Clinician Scholarship, Fall 2010
- Recipient, Towson University College of Graduate Studies and Research Fellowship, Fall 2010-Spring 2011
- Recipient, Dr. M. Barbara Laufer Award, Towson University, 2009
- Recipient, Communication Sciences and Disorders Achievement of Academic Excellence, University of Maine, 2008
- Recipient, Presidential Academic Achievement Award, University of Maine, 2008

Academic and Leadership Experience

Intern, York ENT Associates,York, PA, January 2011-Present

- Ear, Nose & Throat Specialists; Supervisor: Alisa Kauffman, M.S.
- Complete audiological assessment including diagnostic hearing and vestibular evaluations, immittance, auditory brainstem response, electrocochleography, and caloric's on diverse patient populations.
- Hearing aid assessment, selection, fitting, verification, validation, follow-up, trouble-shooting, and repairs on adult patients.

Intern, ENTAA Care, Annapolis, Columbia, & Glen Burne, MD, August 2010-December 2010

- Ear, Nose & Throat, Allergy, Audiology & Hearing Aid Center, Speech & Balance Center; Supervisor: Monica Davis, Au.D.
- Complete audiological assessment including diagnostic hearing and vestibular evaluations, immittance, otoacoustic emissions, auditory brainstem response, electrocochleography, vestibular evoked myogenic potential, caloric's, and auditory processing evaluations on a diverse patient population
- Hearing aid assessment, selection, fitting, verification, validation, follow-up, troubleshooting, and repairs on patients of all ages;

- Limited experience with cochlear implant evaluations and mapping on adult patients.

President, Towson University Student Academy of Audiology (TU-SAA), Towson, MD, July 2009-August, 2010

- Preside as chair over Board of Directors; serve as liaison between TU-SAA and National Board of Directors and TU-SAA chapter advisor.
- Organize University and community events
- Lead group of 25 students in fundraising and volunteer opportunities.

Graduate Assistant, Speech, Language & Hearing Center at Towson University, Towson, MD, August 2008-Present

- Routine inventory management of audiological supplies
- Organizational office skills including processing on- and off- campus student paperwork and assessments
- Hearing aid ordering, processing, trouble-shooting, and repairs
- Customer relations regarding the audiology branch of the SLHC, patient concerns regarding hearing aid issues and appropriate recommendations.

Intern, Healthy Hearing & Balance, Westminster, MD, May 2010-July 2010

- Private practice; Supervisor: Nancy Hart, Au.D.
- Audiological assessment including diagnostic hearing and vestibular evaluations (balanceback system), caloric's, tinnitus assessment, auditory brainstem response, and auditory processing evaluations on patients of all ages
- Hearing aid assessment, selection, fitting including real ear measurements, follow-up, troubleshooting, and repairs on patients across the life-span

Intern, Lincoln Intermediate Unit #12, York, PA, January 2010-May 2010

- Educational audiology; Supervisor: Rosalind Garfinkel, Au.D.
- Conventional audiology diagnostic procedures for pre-school and school-aged children normally developing and with multiple disabilities.
- Auditory Processing Disorder evaluations
- Soundfield testing of pediatric hearing aid and cochlear implant users
- Personal and soundfield FM System management, troubleshooting, and repair
- Part of a multi-disciplinary team approach to intervention services and developing Individualized Education Plans and/or 504 plans

Graduate Clinician, Towson University Speech, Language & Hearing Center, Towson, MD, January 2009-December 2009

- University Clinic; Supervisors: Tricia Ashby-Scabis, Au.D., Nicole Kreisman, Ph.D., Steven Pallett, Au.D., Jennifer Smart, Ph.D., Candace Robinson, Au.D., Elise Smith, Au.D., Bette Stevens, Au.D.
- Audiometric testing including complete diagnostic evaluations, hearing aid assessments, troubleshooting and repairs, auditory processing disorder evaluations, auditory brainstem responses, counseling, patient follow-up procedures and aural

rehabilitation.

- Hearing conservation program for necessary Towson University employees
- Hearing screening program for necessary Towson University students.

SLP Assistant, The Warren Center for Communication & Learning, Bangor, ME, June 2007-July 2008

- Assist SLP in pre-school therapy group
- Assist SLP in one-on-one treatment of pre-school and school-aged children
- Plan and prepare activities for treatment and therapy.

Summer Camp Assistant, Sign-N-Kids, Inc., Bangor, ME, Summer 2007

- Assist Deaf camp owner and founder in various summer camp activities including athletics, arts and crafts, life skills development, and educational trips.
- Communicate with D/deaf campers and parents in ASL and spoken English.

Volunteer Experience

- Special Olympics-Maryland Healthy Hearing; June, 2010
- Cherry Hill Health Care Initiative; June, 2009-May, 2010
- Maryland Academy of Audiology: September, 2009; September 2010
- American Academy of Audiology; April 2009; April 2010
- Maryland Audiology Awareness Day; January, 2009
- Special Olympics-Maine Healthy Hearing; June 2007; June 2008

Memberships

- American Academy of Audiology; September 2008-Present
- Student Academy of Audiology; May 2009-Present
- National Association of Future Doctors of Audiology; September 2008-May 2009

References

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