Tutorial

Auditory Steady-State Responses

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Abstract

Background: The auditory steady state response (ASSR) is an auditory evoked potential (AEP) that can be used to objectively estimate hearing sensitivity in individuals with normal hearing sensitivity and with various degrees and configurations of sensorineural hearing loss (SNHL). For this reason, many audiologists want to learn more about the stimulus and recording parameters used to successfully acquire this response, as well as information regarding how accurately this response predicts behavioral thresholds across various clinical populations.

Purpose: The scientific goal is to create a tutorial on the ASSR for doctor of audiology (Au.D.) students and audiologists with limited (1–5 yr) clinical experience with AEPs. This tutorial is needed because the ASSR is unique when compared to other AEPs with regard to the type of terminology used to describe this response, the types of stimuli used to record this response, how these stimuli are delivered, the methods of objectively analyzing the response, and techniques used to calibrate the stimuli. A second goal is to provide audiologists with an understanding of the accuracy with which the ASSR is able to estimate pure tone thresholds in a variety of adult and pediatric clinical populations.

Design: This tutorial has been organized into various sections including the history of the ASSR, unique terminology associated with this response, the types of stimuli used to elicit the response, two common stimulation methods, methods of objectively analyzing the response, technical parameters for recording the ASSR, and the accuracy of ASSR threshold prediction in the adult and pediatric populations. In each section of the manuscript, key terminology/concepts associated with the ASSR are bolded in the text and are also briefly defined in a glossary found in the appendix. The tutorial contains numerous figures that are designed to walk the reader through the key concepts associated with this response. In addition, several summary tables have been included that discuss various topics such as the effects of single versus multifrequency stimulation techniques on the accuracy of estimating behavioral thresholds via the ASSR; differences, if any, in monaural versus binaural ASSR thresholds; the influence of degree and configuration of SNHL on ASSR thresholds; test-retest reliability of the ASSR; the influence of neuro-maturation on ASSR thresholds; and the influence of various technical factors (i.e., oscillator placement, coupling force, and the number of recording channels) that affect bone conducted ASSRs.

Conclusion: Most researchers agree that, in the future, ASSR testing will play an important role in clinical audiology. Therefore, it is important for clinical audiologists and Au.D. students to have a good basic understanding of the technical concepts associated with the ASSR, a knowledge of optimal stimulus and recording parameters used to accurately record this response, and an appreciation of the current role and/or limitations of using the ASSR to estimate behavioral thresholds in infants with various degrees and configurations of hearing loss.

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uditory evoked potentials (AEPs) are often used in clinical audiology to estimate behavioral pure tone thresholds in certain populations including infants, young children, and individuals with intellectual disabilities. An AEP is a response that can be recorded from the brain following presentation of auditory stimuli, such as clicks, tone bursts, and/or speech. In many audiology centers, the auditory brainstem response (ABR) is the AEP of choice for estimating behavioral pure tone thresholds, due to the high test-retest reliability of this response (Lauter and Loomis, 1986, 1988; Lauter and Karzon, 1990a, b, c; Hood, 1998; Hall, 2007) and the well-established normative database for using this response to estimate behavioral thresholds in infants, young children, and adults (e.g., Stapells et al, 1990, 1995; Munnerley et al, 1991; Beattie and Kennedy, 1992; Stapells, 2000, 2011). However, more recent developments in the field suggest that a relatively new method of recording AEPs, known as the auditory steady state response (ASSR), is comparable to the ABR with respect to the accuracy of estimating pure tone thresholds and the potential to reduce testing time. (For a general review of AEPs and their clinical applications see Burkard et al [2007], Hall [2007], and Picton [2011]. Additionally, any term that appears in bold below can be found in the glossary in Appendix A.)

**HISTORY OF THE ASSR**

Occasional reports of steady state responses to auditory stimuli recorded from the human scalp have appeared in the AEP literature in the 1960s (Geisler, 1960) and in the 1970s (Campbell et al, 1977). However, the ASSR was first described in detail in the literature by Galambos et al (1981). In this study, Galambos and colleagues (1981) recorded auditory brainstem responses and middle latency responses to 500 Hz tonal stimuli presented at stimulus rates ranging from 3.3 to 55/sec in adults with normal-hearing sensitivity. These investigators demonstrated that when the stimuli were presented at a rate of 40/sec, an overlap in the positive and negative peaks of the response occurred at approximately 25 msec intervals within the 100 msec poststimulus analysis window (see Fig. 1A). Galambos and colleagues plotted the amplitude of this ASSR as a function of stimulus rate and demonstrated that for adults the largest amplitude of this response occurred at 40 Hz (see Fig. 1B). Therefore, these investigators named this response the 40 Hz event-related potential (ERP); however, this response has also been referred to as the steady state evoked potential (Stapells et al, 1984; Linden et al, 1985; Cohen et al, 1991; Rickards et al, 1994; Rance and Rickards, 2002).
Galambos et al’s (1981) data revealed several useful characteristics of the 40 Hz response. First, this response was present at intensity levels near behavioral thresholds and thus could be used to predict hearing sensitivity for these adult subjects. Second, the 40 Hz response was easy to identify. Third, the amplitude of the 40 Hz response remained relatively large even close to threshold.

Subsequent research in the mid-to late 1980s, however, identified two critical limitations of the 40 Hz ERP. One limitation was that the 40 Hz response could not be reliably recorded in infants and young children as the peak amplitude of their ASSR occurred at rates of approximately 20 Hz as shown in Figure 1B (Suzuki and Kobayashi, 1984; Stapells et al., 1988). Secondly, the presence of the 40 Hz response was dependent upon subject state and could only be reliably recorded in awake subjects (Linden et al., 1985; Jerger et al., 1987; Kuwada et al., 1986; Cohen et al., 1991). These limitations posed a problem for the clinical feasibility of recording this response especially in the pediatric population who are often tested while asleep or sedated.

Restored interest in the 40 Hz ERP for adults transpired years later when Cohen et al (1991) proved that the ASSR could be reliably recorded in adults during various states of arousal when testing at higher stimulus/modulation rates (≥70 Hz). Several pediatric studies have also demonstrated that the ASSR can be successfully recorded in either awake or sleeping infants and young children using fast (≥70 Hz) stimulation rates (Aoyagi et al., 1993; Rickards et al., 1994; Rance et al., 1995). As a result of these discoveries, reference to the 40 Hz ERP was dismissed for infants and young children, and this AEP was now generally referred to as the ASSR. Considerable interest, however, remained in the clinical application of the 40 Hz response in adults.

In 2004, Pethe and colleagues sought to determine what modulation frequency (40 or 80 Hz) would yield the best signal-to-noise ratios (SNR) for recording ASSRs in young children, aged 2 mo to 14 yr. Specifically these investigators recorded responses to 1000 Hz carrier frequency (CF) tones with modulation frequencies (MFs) of 40 and 80 Hz presented at stimulus intensities ranging from 10 to 50 dB nHL. Pethe et al (2004) reported that for infants below 1 yr of age, the amplitude of the 40 Hz response was approximately the same as the amplitude of the 80 Hz response. However, by 13 yr of age, the amplitude of the 40 Hz response was almost twice as large (i.e., at 50 dB nHL, the amplitudes of the responses were ∼150 nV and ∼80 nV for the 40 and 80 Hz responses, respectively). Since the amplitude of the residual background electroencephalography (EEG) noise is significantly higher at 40 Hz than at 80 Hz (van der Reijden et al, 2001), then the SNR for ASSRs in younger children is considerably better for the higher (80 Hz) versus lower (40 Hz) MFs. Based on this data, Pethe and colleagues (2004) concluded it appears that 13 yr of age is a critical time when the optimal MF changes from a high- to a low-frequency range.

Given the substantial differences in the response properties of the ASSRs generated at lower (i.e., 40 Hz) versus higher (i.e., ≥70 Hz) stimulation rates, researchers began to speculate as to why these differences occurred. One leading explanation for these rate-sensitive differences was that the ASSR was receiving contributions from different underlying neural generators in the peripheral and/or central auditory nervous system when elicited at lower rather than higher stimulus rates.

**NEURAL GENERATORS OF THE ASSR**

The underlying neural generators of the ASSR have been investigated using various types of neuroimaging techniques including **Brain Electrical Source Analysis, or BESA** (Herdman et al, 2002); **magnetoencephalography, or MEG** (Johnson et al., 1988; Hari et al., 1989; Ross et al., 2000), and **functional magnetic resonance imaging, or fMRI** (Giraud et al, 2000). The neural generators of the ASSR have also been investigated using patients with known lesions in the auditory cortex and/or midbrain regions of the CANS (Spydell et al., 1985) and by conducting animal studies (Mäkelä et al., 1990; Kiren et al, 1994; Kuwada et al., 2002).

Collectively, the results of these neural generator studies suggest that when ASSRs are elicited by stimuli

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**Figure 2.** 500 Hz carrier frequency tone moves through the outer and middle ear into the cochlea. The point on the basilar membrane that is best tuned to 500 Hz is then activated.
presented at rates less than 20 Hz, these responses are mainly generated by activity in the primary auditory cortex (Hari et al., 1989; Mäkelä et al., 1990; Herdman et al., 2002). When ASSRs are elicited by stimuli presented at rates between 20 and 60 Hz, the underlying neural generators are mainly located in the primary auditory cortex, auditory midbrain, and thalamus (Spydell et al., 1985; Johnson et al., 1988; Hari et al., 1989; Mäkelä et al., 1990; Kiren et al., 1994; Herdman et al., 2002). Lastly, when ASSRs are elicited by stimuli presented at rates greater than 60 Hz, these responses are generated primarily by contributions from the superior olivary complex, inferior colliculus, and cochlear nucleus (Hari et al., 1989; Mäkelä et al., 1990; Kiren et al., 1994; Cone-Wesson, Dowell, et al., 2002; Herdman et al., 2002; Picton et al., 2003). The results of these neural generator studies also demonstrated that ASSRs recorded at any of these stimulation/modulation rates receive contributions from multiple generators. However, recording parameters such as stimulus rate and EEG bandpass filter settings can suppress contributions from certain underlying neural generators to the final averaged response.

Knowledge of the changes in the underlying neural generators of the ASSR as a function of stimulus/modulation rate helps to explain the two primary limitations that were discovered in the early research conducted on the 40 Hz response. Galambos and his colleagues (1981) were able to successfully record robust 40 Hz responses in awake adults with normal hearing sensitivity, as their auditory cortices were fully mature and intact. In contrast, the 40 Hz response was not observable in awake infants and young children because their auditory cortices are not fully mature. When ASSRs are elicited using high (i.e., ≥70 Hz) stimulus/modulation rates, the primary neural generators occur within the auditory brainstem region, similar to the ABR, and thus are not affected by subject state and age.

TERMINOLOGY ASSOCIATED WITH THE ASSR

In addition to understanding the neural generators of the ASSR, it is also important for audiologists to have a working knowledge of the terminology associated with this response. Two primary terms associated with the ASSR are carrier frequency (CF) and modulation frequency (MF). The CF of the tonal stimulus is the test frequency of interest. The CF is associated with the region in the cochlea where the hair cells are activated in response to the presentation of a stimulus (Hall, 2007). For example, if a 500 Hz CF tone is used to elicit the ASSR, the portion of the basilar membrane that is activated is the one best tuned to 500 Hz (see Fig. 2). The extent of basilar membrane excitation that occurs in this area is dependent on stimulus intensity, such that higher intensity stimuli produce a larger area of cochlear excitation. Typical CF tones used to record the ASSR are 500, 1000, 2000, and 4000 Hz.

The MF, in contrast, is the frequency at which the EEG activity is synchronized to fire. This can be derived by calculating the period of the MF. For example, if a 2000 Hz CF tone is presented with a 100 Hz MF, then the response follows the MF at 100 Hz resulting in a peak every 10 msec (see Fig. 3). This 10 msec interval corresponds to the period of the MF that can be determined by calculating the period (T) of the modulation frequency ($T = \frac{1}{f} = \frac{1}{\text{MF}} = \frac{1000 \text{msec}}{100 \text{Hz}} = 10 \text{msec}$). Audiologists can think of MF as similar to stimulus rate.

Several other terms are used with the ASSR to describe the type of stimuli, the stimulation techniques, and the way the response is analyzed. The majority of these terms are fairly unique to this AEP and can be found in Appendix A. Some of the common terms used to describe the types of stimuli are frequency modulated tones, amplitude modulated tones, and mixed modulated tones and are discussed in the section labeled “Types of Stimuli.” Terms typically associated with the stimulation techniques used to elicit the ASSR are the single frequency stimulation technique and the multifrequency stimulation technique, and these are discussed in the section labeled “Stimulation Techniques.” Lastly, the terminology associated with analyzing the response includes terms such as phase-coherence, fast Fourier transform (FFT) analysis, and F-test, and these are discussed in the section labeled “Methods of Analyzing Responses.”

TYPES OF STIMULI

There are several types of stimuli used to record ASSRs. These stimuli can be generalized into two categories: broadband (i.e., non-frequency specific) stimuli and frequency-specific stimuli. Broadband stimuli

**Figure 3.** ASSR response to a 2000 Hz CF tone with a 100 Hz MF. The response follows the MF at 100 Hz resulting in a peak every 10 msec (modified from Grason-Stadler Inc, 2001).
encompass a range of frequencies and include clicks, noises, and chirps. In contrast, frequency-specific stimuli include filtered clicks, tone bursts, pure tones, and band-limited chirps (Beck et al, 2007). The most common types of stimuli used in clinically recording the ASSR are sinusoidally amplitude modulated tonal stimuli, frequency modulated tonal stimuli, mixed modulated tonal stimuli, and repeating sequence gated tonal stimuli. The following is a discussion of the temporal and frequency characteristics of these four types of stimuli.

Amplitude modulated (AM) tones are tones that change in amplitude over a period of time, and they are the most common type of stimuli used to evoke the ASSR (Picton et al, 2003). Amplitude-modulated tonal stimuli are created when a sinusoidal function is used to modulate the primary tone. Generally, the higher frequency signal is the carrier frequency (CF) tone, and the lower frequency signal serves as the MF (Lins and Picton, 1995). The degree of change in the amplitude of the signal is referred to as the depth of modulation and is reported as a percentage, with a larger number (90–100%) indicating a greater change in the amplitude of the response in comparison to a smaller number (30–40%). For example, if the carrier frequency is 4000 Hz, the MF is 100 Hz, and the tone is amplitude modulated by 100%, then the amplitude of the signal will change over time within each cycle, as shown in the temporal waveform (see Fig. 4A). In the frequency domain, this AM signal has its primary energy at the CF (4000 Hz) and has two sidebands of energy, one at the CF – MF (3900 Hz) and the other at the CF + MF (4100 Hz).

A frequency modulated (FM) tone is a stimulus in which only the frequency content of the stimulus changes over the duration of the tone (see Fig. 4B). Frequency modulated tonal stimuli are formed by modulating both the frequency and the phase of the CF tone. Frequency modulation looks at the maximum and minimum frequencies present and how they relate to the CF (John et al, 2001). For example, if the CF is 4000 Hz and it is frequency modulated by 20%, then the maximum and minimum frequency values will differ by ±20% from the CF, and thus the frequencies will vary from 3200 (CF – 800 Hz) to 4800 (CF + 800 Hz) (as seen in the temporal waveform). In the frequency domain, an FFT analysis conducted on the FM stimulus shows that the primary energy is at the carrier frequency (4000 Hz) and extends to 800 Hz above and below the CF.

A third way to modulate the stimuli used in ASSR is mixed modulation (MM) tone is a stimulus that involves a combination of amplitude and frequency modulation. For example, if the CF is 4000 Hz, the MF is 100 Hz, and there is 100% AM and 20% FM (see Fig. 4C), then one would expect to see changes in both the amplitude and frequency of the tonal stimulus within each cycle, as shown in the temporal waveform. For this example, in the first cycle of the stimulus, the amplitude increases from baseline to a maximum value at approximately 5 msec, and it is evident that the frequency changes from a lower frequency signal at approximately 1 msec to a higher frequency signal in the range of 4 to 6 msec. In the frequency domain, there is a spread of energy from approximately 3200 to 4800 Hz; thus,

Figure 4. Most common types of stimuli used to elicit an ASSR response as seen in the temporal and frequency domains. Figure concept modified from John and Purcell (2008).
the MM stimulus is less frequency specific than the AM tonal stimulus.

The final stimulus commonly used to elicit the ASSR is a repeating sequence gated (RSG) tone. RSG tones can include various types of tonal stimuli such as linear-gated tones, cosine squared gated tones, and Blackman-gated tones. As the name implies, these RSG tones have a regular repeating pattern (as seen in Fig. 4D). This pattern can also be seen mathematically by calculating the period of the MF. In the example shown in Figure 4D, the CF = 4000 Hz and the MF = 82 Hz; therefore, the period of the modulation frequency = 12 msec (T = \frac{1}{f} = \frac{1}{82} \text{sec} = 12 \text{msec}). In Figure 4D, we see that the time difference between the maximum positive peaks of the repeating stimuli is 12 msec. In the frequency domain, the primary peak of energy is located at the CF, with side lobes of energy extending from approximately 3500 to 4500 Hz.

At least one commercial ASSR system (i.e., the Intelligent Hearing System [IHS] SmartEP-ASSR) uses brief tonal stimuli, such as Blackman-gated tones, presented at durations ranging from 4 to 8 msec, as their default stimuli. Recently, Mo and Stapells (2008) investigated the effect of stimulus duration on single frequency and multifrequency ASSRs elicited to 500 and 2000 Hz CF Blackman-gated tones. These tonal stimuli were presented at 75 dB SPL and had stimulus durations ranging from 0.5 to 12 msec. These investigators reported that for the single frequency technique, ASSR amplitudes increased as stimulus duration decreased for both 500 and 2000 Hz; however, the duration of the stimuli needed to be quite brief (2 msec for 2000 Hz and 6 msec for 500 Hz). In contrast, for the multifrequency technique, response interference tended to reduce the ASSR amplitudes, and at 500 Hz there was no change in amplitude of the ASSR as stimulus duration decreased. Based on these findings, Mo and Stapells (2008) concluded that brief-tone stimuli may not be optimal for ASSR threshold estimation, due to the compromise in frequency specificity that accompanies the use of very brief tonal stimuli.

Overall, there are some advantages and disadvantages for using each type of stimulus. The AM tone is the most frequency specific stimuli of these four types of stimuli. In contrast, the MM tone is the least frequency specific tone of these four types of stimuli; however, large response amplitudes are elicited with this type of stimulus (John et al., 2002, 2003). A unique aspect of the MM stimulus is that it is affected by the phases of the AM and FM components, and this can alter the frequency spectra of the tone (Dimitrijevic et al., 2002). When the AM and FM components are out-of-phase by 180°, the peak of the spectra will skew to the lower frequencies and potentially decrease the amplitude of the response (Dimitrijevic et al., 2002). In contrast, when the AM and FM components are in-phase, reaching their maximum amplitude at the same time, the peak of the MM spectra will skew to the higher frequencies while increasing the amplitude of the response (Dimitrijevic et al., 2002; John and Purcell, 2008).

Recently, John and Purcell (2008) reported that the amplitudes of the ASSRs recorded to MM tones, with in-phase AM and FM components, are approximately 20% larger than those recorded to either AM tones or FM tones and the responses still remain fairly frequency specific. Therefore these investigators suggested that the use of a MM tone to elicit the ASSR may provide audiologists with the most easily detected responses (John and Purcell, 2008).

**STIMULATION TECHNIQUES**

There are two primary stimulation techniques used to record the ASSR, a single frequency stimulation technique and a multifrequency stimulation technique (Regan, 1982). The single frequency stimulation technique presents one carrier frequency tone to one ear using one MF. For example, a 2000 Hz CF tone presented at a MF of 95 Hz is delivered to the client’s right ear. In contrast, the multifrequency stimulation technique is unique in its ability to test many carrier frequency tones presented simultaneously in either one or both ears. The typical carrier frequencies used in the multifrequency technique are 500, 1000, 2000, and 4000 Hz. In the multifrequency stimulation technique, the ASSR software assigns a unique MF between 75 and 110 Hz to each of the carrier frequency tones. Figure 5 displays an example of a monaural multifrequency stimulation technique. In this example, four CF tones (500, 1000, 2000, and 4000 Hz) are delivered simultaneously to one of the subject’s ears. The compound stimulus being delivered to the ear contains energy at each one of these carrier frequencies (as shown in bottom left side of this figure). The corresponding modulation frequencies assigned to these CF tones are 76 Hz (500), 82 Hz (1000), 95 Hz (2000), and 101 Hz (4000). These unique modulation frequencies are necessary for the processing of the stimuli to remain independent through the auditory system and up to the brain. The four CF tones in turn activate the four regions of the basilar membrane that are best tuned to these specific frequencies, as shown on the right side of this figure. The corresponding modulation frequencies assigned to these CF tones are 76 Hz (500), 82 Hz (1000), 95 Hz (2000), and 101 Hz (4000). These unique modulation frequencies are necessary for the processing of the stimuli to remain independent through the auditory system and up to the brain. The four CF tones in turn activate the four regions of the basilar membrane that are best tuned to these specific frequencies, as shown on the right side of this figure. The brain’s response to these four unique MFs is seen in the FFT results (as shown in the panel on the right side of this figure). The strategies for analyzing the ASSR will be discussed in the next section.

With the multifrequency stimulation technique, it is also possible to record the ASSR binaurally. In this binaural mode, eight CF tones are presented simultaneously (four per ear). Each CF tone is assigned a unique MF, which can range from approximately 75 to 110 Hz. The possible advantage of using binaural stimulation with the multifrequency technique is that hearing sensitivity could be assessed at 500–4000 Hz in both ears.
in approximately the same amount of time it would take to test one stimulus frequency in one ear using the single frequency stimulation technique (Lins et al, 1996).

An important issue that needs to be considered when employing the multifrequency stimulation technique with either normal hearing or hearing-impaired listeners is the potential of interactions that occur in the cochlea and/or brain among these stimuli at each of the carrier frequencies. When tonal stimuli occur together, several types of interactions can occur including masking effects, suppression, and/or facilitation (see Picton, 2011, for a more in-depth discussion of this issue). Despite these concerns, several investigators have shown that ASSR amplitudes in normal hearing adults to the simultaneous presentation of four AM tones with MFs ranging between 70 and 110 Hz to one and/or both ears at stimulus intensities ≤60 dB SPL are not significantly different from ASSR amplitudes when each AM tone is presented alone (Lins and Picton, 1995; John et al, 1998; Herdman and Stapells, 2001; Mo and Stapells, 2008). In addition, Herdman and Stapells (2001) reported that there were no significant differences in ASSR thresholds for normal hearing adults when single AM tones were presented to one ear or when multiple (four) AM tones were presented unilaterally or bilaterally.

A few investigators have raised concern whether the inclusion of lower frequency stimuli (e.g., 500 or 1000 Hz tones) in the multifrequency stimulation technique would cause masking of ASSRs to higher frequency stimuli (e.g., 2000 or 4000 Hz) for individuals with moderate to severe SNHLs (Picton et al, 1998; Dimitrijevic et al, 2002). Specifically, Dimitrijevic and colleagues (2002) reported that a few (n = 5) of their hearing-impaired subjects had more accurate ASSR threshold estimations for 2000 and 4000 Hz using the single frequency versus the multifrequency stimulation methods, thus suggesting that a possible masking effect was occurring in the MF test condition. In a more recent study, Herdman and Stapells (2003) addressed this issue by comparing ASSR thresholds for 2000 and 4000 Hz obtained using the single frequency versus the multifrequency stimulation techniques in ten adults with severe SNHLs. These investigators reported there were no significant differences in the mean ASSR thresholds as a function of stimulation technique (single frequency = 63 ± 9 dB nHL; multifrequency = 64 ± 14 dB nHL) for these higher CFs. Therefore, Herdman and Stapells (2003) concluded that there is no masking of high-frequency ASSRs by concomitant presentation of lower frequency stimuli in the multifrequency ASSR technique.

John et al (1998) provided several recommendations to avoid significant interactions effects in adults when using the multifrequency stimulation technique. These recommendations include (1) MFs for the CF tones should be between 70 and 110 Hz, (2) CF tones need to be at least one octave apart in order to simultaneously present up to four tonal stimuli to one ear without significant loss in the amplitude of the ASSR, and (3) stimulus intensities of the CF tones need to be 60 dB SPL or less.

Recently, Hatton and Stapells (2011) addressed the issue of possible interaction effects in the cochlea and/or brain to the simultaneous presentation of multifrequency stimuli at 60 dB SPL in ASSRs recorded in normal hearing infants. In this study, the response amplitudes of ASSRs recorded to four CF tones (500–4000 Hz) in 15 normal-hearing infants, ages ~6-38 weeks, were compared across

**Figure 5.** Displays how the four carrier tones are presented simultaneously and thus stimulate the frequency regions of the basilar membrane best tuned to these frequencies. The energy present at the MF can be seen in the FFT results. (Modified and adapted from John and Purcell, 2008).
three different stimulus conditions: monaural single frequency, monaural multifrequency, and binaural multifrequency. The stimuli were presented at 60 dB SPL for all test conditions. All infants had passed DPOAE screenings bilaterally on the day of testing. Hatton and Stapells (2011) reported that the mean ASSR amplitudes for the monaural single frequency test condition were significantly larger than the response amplitudes for the two multifrequency test conditions. The infants’ mean response amplitudes decreased as the number of simultaneous stimuli increased. These findings suggest that interactions in the cochlea and/or brain do occur in response to the presentation of multiple stimuli at 60 dB SPL in the infants’ ears. These results differ substantially from those seen in adults, where no significant interactions to the presentation of multifrequency stimuli were seen at stimulus intensities ≥60 dB SPL (John et al, 1998; Herdman and Stapells, 2001). Hatton and Stapells (2011) suggest that the reductions in amplitude seen in the infants’ multifrequency test conditions are likely the result of the immaturity of neural development within the auditory brainstem region as well as possible immaturity in more peripheral structures, such as the ear canal, middle ear, and/or cochlea.

METHODS OF ANALYZING RESPONSES

The ASSR is unlike many other AEPs in the way that the responses are analyzed. Traditionally, for most AEPs, latency and amplitude measurements are taken on the various components present in the response. This peak-picking task requires some degree of subjective interpretation on the part of the examiner. In contrast, the analysis of the ASSR is objective and relies on statistical methods, such as the F test, to predict the presence or absence of a response with a certain degree of statistical accuracy (p < 0.05). Two primary techniques are used to analyze the ASSR, and both methods initially require that the temporal waveform of the ASSR be converted into the frequency domain using FFT analysis.

One technique used to analyze the ASSR relies on phase-coherence values. "Phase coherence (PC) is related to the signal (response)-to-noise (background EEG and myogenic) ratio" (Cone and Dimitrijevic, 2009, p. 333). Phase coherence uses a measure called the phase coherence squared (PC²) value. These PC² values range from 0.0 to 1.0 and are measured on a normalized scale. The closer the value is to 1.0, the higher the coherence value is, indicating that the amplitude of the response is significant and is distinguishable from the amplitude of the background noise. In this technique, the amplitude and phase information, provided by the FFT results, is used to form a plot displayed in polar coordinates, commonly called a polar plot (see Fig. 6A). The magnitude or amplitude of the response corresponds to the length of the vector, whereas the phase or time delay is indicated by vector angle (see Fig. 6A).

If the vectors in the resultant polar plot are located primarily in one quadrant (see Fig. 6B), they form a cluster of responses. The pattern is referred to as phase locked, and the phase coherence value is close to 1.0. This situation only occurs when the brain is accurately responding or firing in response to the temporal information present in the stimulus. Figure 6B shows an example of a phase-locked response. The vectors are clustered in one quadrant indicating synchronous firing to the stimulus presentation. The PC² value is 0.9, indicating a response is present, distinguishable from the EEG noise, and the brain is synchronously firing to the stimulus. In contrast, if the polar plot contains vectors at random phase angles (see Fig. 6C) this means that the pattern is not phase locked and the phase coherence value would be closer to 0.0. Figure 6C displays an example of a random response. In this polar plot, the vectors are present in all four quadrants indicating dysynchrony in the neural firing pattern. The PC² value in this example is 0.1, indicating a response was not detected. The ASSR is judged to be a random response and not a true neural response to the stimulus being presented.

Another method of analyzing the ASSR uses a combination of the FFT results and the F-test, to statistically evaluate the presence or absence of a response to a certain CF tone presented at one stimulus intensity. The FFT results provide a spectral view of the energy occurring at the modulation frequency(ies) in comparison to the energy present at the
surrounding frequencies. If the amplitude of the response at
the MF is significantly larger than the EEG energy at fre-
quencies above and below the MF, then a response has been
detected for the CF tone presented at that stimulus intensity.

Figure 7 displays examples of this type of response
analysis being applied to an ASSR recorded using a single
frequency stimulation technique (top panel) and using a
multifrequency stimulation technique (lower panel). The
FFT results in the top panel clearly demonstrate that
energy present at the MF (85 Hz) is considerably larger
than the amplitude of the EEG activity in the neighbor-
ing bins. The F-test is then used to objectively determine
the strength of the energy present at the MF relative to
the energy present in the surrounding bins (usually 60
bins both above and below the MF). Clinically, each ASSR
system sets an alpha level (typically $p < 0.05$) as the cri-
teria for determining if the energy present at that MF is
significantly greater in amplitude in comparison to the
ongoing EEG energy present in the surrounding bins.
In this example, the ASSR would be judged to be present
for the 1000 CF tone at this stimulus intensity.

In contrast, the multifrequency analysis begins with a
MM stimulus, which consists of four CF tones (500, 1000,
2000, and 4000 Hz) being presented at four unique MFs
(77, 85, 93, and 101 Hz) to the right ear (seen in lower
panel of Fig. 7). The results of the FFT show that the
energy present at the four MFs is significantly larger than
that of the surrounding EEG activity. Therefore, in this
example, the ASSR would be judged to be present at
500, 1000, 2000, and 4000 Hz for this stimulus intensity.

Regardless of which analysis technique is used to deter-
mine if a response is present in an ASSR recording, the
results are usually very similar (Dobie and Wilson, 1996).
While the two methods above are the most commonly
used methods of analysis, there are also variations and
combinations of these methods used (Picton et al, 2003).

A concern with the use of the F-test statistic for ASSR
response detection arises with repeated measures. As
sweeps are collected, the F-test is applied to each sub-
sequent ensemble average. The repeated use of the
F-test results in diminishing the statistical strength
of the test. The probability of multiple repeated mea-
sures being significant is higher than a single measure.
Several methods have been proposed to overcome this
issue. One approach is to compensate for the repeated
measure by increasing the response statistical criteria
for each subsequent measure. This may be accomplished
using a Bonferroni correction (Benjamini and Hochberg,
1995). Another approach is to monitor the response level
over multiple measures in order to assure that the re-
response remains at a statistically significant level over a
specific time period and therefore reduce the probability
of false response detection (Luts et al, 2008). Still another
approach is to modify the response criteria depending on
other response quality measures (Sankoh et al, 1997;
John and Purcell, 2008).

**TECHNICAL PARAMETERS**

Recording the ASSR requires the use of specific tech-
nical parameters in order to maximize the amplitude
of the response and to reduce the background noise. Four
technical factors that play an important role in recording
the ASSR are the analog EEG band pass filter settings, the
electrode montage, the number of recording channels, and
automatic stopping rules and residual noise criteria that
can be used to determine the number of sweeps needed to
successfully meet that criteria for each test condition.

**Analog EEG Band Pass Filter Setting**

The appropriate analog EEG band pass filter settings for
recording any AEP are determined by knowledge of the
spectral energy that is present in the response. The energy
present in the ASSR is determined by the modulation fre-
quencies used to record the response. These MFs generally
range from 77 to 101 Hz (Small and Stapells, 2008b). In
order to successfully capture the energy present at these
modulation frequencies and to help prevent electrical arti-
fact at the rate of modulation, a commonly used and rec-
commended analog EEG band pass filter for recording
either the single frequency and/or multifrequency ASSR
to air and/or bone conducted stimuli is 30–300 Hz (Lins
et al, 1996; Bohorquez and Ozdamar, 2008).

![Figure 7](image_url)

**Figure 7.** This figure shows a comparison of the single frequency and monaural multifrequency stimulation techniques in the temporal
and frequency domains. (Modified and adapted from Lins et al, 1996.)
Electrode Montage

The electrode montage used in recording an ASSR is similar to that used in recording an ABR. The ground electrode is typically placed on the forehead at Fpz. The non-inverting electrode is placed at the vertex or Cz location. The inverting electrodes are placed on the earlobes of both the test ear and the non–test ear, referred to as A1 and A2 locations. This configuration of electrodes allows for a two channel (ipsilateral and contralateral) recording, and it also permits the ability to switch test ears without changing the positions of the electrodes. A single channel midline recording technique is also possible; this electrode montage is useful for newborn hearing screening applications.

Number of Recording Channels

To date, only three research groups have investigated whether ipsilateral and/or contralateral recording channels would yield larger ASSR amplitudes, lower ASSR thresholds, and higher SNRs for air-conducted or bone-conducted stimuli in adults and infants (van der Reijden et al, 2001, 2005; Small and Stapells, 2008b; Van Maanen and Stapells, 2009). Small and Stapells (2008b) reported that in normal-hearing adults, there were no large differences (within 1 dB) in the mean ASSR thresholds recorded in the ipsilateral versus contralateral channels for both air- and bone-conduction testing. These investigators also reported the largest difference in ASSR thresholds between recording channels was 10 dB, and this occurred in only 28% of their adult subjects.

In contrast, all three research groups reported that air-conducted ASSRs recorded in infants using the multifrequency stimulation technique were either significantly smaller in amplitude or often absent in the contralateral channel when the responses were judged to be present in the ipsilateral channel. Specifically, Van Maanen and Stapells (2009) recorded multifrequency air-conduction ASSRs in 54 normal hearing infants (aged 0.7 to 66 mo) and reported that the amplitudes of the contralateral ASSRs to 500, 1000, and 2000 Hz stimuli were less than 50% of the amplitudes of the ipsilateral responses for all stimulus intensities. These authors also reported that the contralateral ASSRs were only present for 31% of their infants across all test frequencies. Based on these findings, Van Maanen and Stapells (2009) concluded that when considering infants’ ASSR to AC stimuli, absent contralateral ASSRs cannot be used to indicate an elevated AC threshold, and only the results from the ipsilateral recording channel should be considered.

Small and Stapells (2008a) reported a similar pattern of findings for bone-conducted ASSRs in 14 normal hearing infants (aged 8–44 wk). Specifically, infants had significantly smaller mean ASSR amplitudes in the contralateral versus ipsilateral channel, and the mean bone-conduction ASSR thresholds, collapsed across test frequencies, were 13 to 15 dB poorer for ASSRs recorded in the contralateral versus ipsilateral channels. These authors also reported that 34% of the infants did not have significant bone conduction ASSRs (BC-ASSRs) in the contralateral channel when the responses were judged to be present in the ipsilateral channel.

Lastly, van der Reijden et al (2005) investigated whether certain EEG recording channels would yield high SNRs in ASSRs recorded in infants aged 0 to 5 mo. These investigators simultaneously recorded the ASSR on 10 different channels, with various electrodes located on the frontal lobe, parietal lobe, right/left mastoids/earlobes, the inion, and the nape of the neck, all referenced to Cz. van der Reijden and colleagues (2005) reported that the highest SNR was obtained when the inverting electrode was ipsilateral to the stimulated ear, with the noninverting electrode located at the vertex (Cz).

In general, the use of two recording channels (ipsilateral and contralateral) is recommended for ASSR testing, especially with infants. If differences in ASSR threshold estimations between channels are seen during testing and testing errors have been eliminated, then audiologists should rely on the responses obtained in the ipsilateral channel.

Automatic Stopping Rules and Criteria

Stopping rules include rules or algorithms that will terminate a test when a response is detected and when there is no reasonable possibility of detecting a response. Typically, a relatively large number of sweeps is needed to obtain high SNRs and accurate estimates of behavioral thresholds (John and Picton, 2000; Tlumak et al, 2007). As the number of sweeps increases, so does the testing time, which can be clinically undesirable. In order to shorten test duration, but still maintain an adequate SNR, automatic stopping rules have been developed. Most ASSR response detection algorithms rely on the SNR of the response to determine if a true neural response has occurred (Cone and Dimitrijevic, 2009). As discussed previously, an F-test is used to determine the statistical strength of the SNR measure. If the SNR is found to be statistically significant and stable over multiple sweeps, the ASSR system will determine that a response has been detected and will automatically stop the test. In cases where multifrequency ASSRs are being acquired, the system may continue to test all frequencies until all frequencies have met the required SNR criteria or may stop testing specific frequencies as each one meets the SNR criteria. If the SNR criterion is not met, most systems will continue to acquire data until a prespecified number of maximum sweeps is reached.

Response detection is an important component in ASSR testing and automated data acquisition; however, stopping rules when “no response” is present are also important. The use of a residual noise (RN) measure has been previously used in the acquisition of auditory evoked potentials (AEPs). The RN measure can be used both to determine
the quality of a response and to stop recording when no response is present (Ozdamar and Delgado, 1996). A commonly used method for evaluating RN is to use a split-sweep buffer technique, in which the even and odd sweep presentations are averaged into different acquisition buffers. The sum of the two buffers provides the signal estimate while the difference provides the noise estimate. The RN can be calculated from the noise estimate in both the time and frequency domains. The RN measure provides an efficient method for automatically stopping the acquisition of ASSR recordings when these have reached an adequate noise level. This technique is currently used in some commercial ASSR systems.

**SUBJECT VARIABLES**

ASSRs may be affected by various subject factors including age, subject state (awake versus asleep), and the listener's attention to the task. The impact of each of these factors will be briefly discussed.

**Age**

The effect of age on the ASSR was one of the original limitations for the 40 Hz response. Specifically, a robust 40 Hz response could be recorded from adults with normal hearing sensitivity; however, this response was absent in infants and young children. Possible explanations for the discrepancy in the presence/absence of this response between these clinical populations included these: (1) children have immature auditory cortices compared to adults, making it potentially more difficult for them to process fast stimulation rates, and (2) the absent 40 Hz responses in infants was likely due to these young children being asleep during the recordings (Picton et al, 2003). It was later discovered that the ASSR could be reliably recorded in infants and children but at significantly higher modulation rates of 80 Hz or higher (Aoyagi et al, 1993; Levi et al, 1993; Rickards et al, 1994).

**Sleep**

The patient's sleep state, both natural and sedated, can affect the amplitude and detectability of the response due to the changes that sleep causes in the physical-electrical activity that occurs in the brain. Several investigators have reported that the response amplitudes of the ASSRs were considerably smaller when patients were in natural and/or sedated sleep compared to when they were in an alert state (Galambos et al, 1981; Linden et al, 1985; Plourde and Picton, 1990; Dobie and Wilson, 1998; Picton et al, 2003). For example, Plourde and Picton (1990) reported that the mean amplitude of the ASSR was 0.41 µV for their patients prior to undergoing general anesthesia and then significantly decreased to 0.17 µV during late induction of the anesthetic agent.

**Attention**

A subject's attention to the listening task often plays an important role in the responses obtained to various auditory evoked testing; however, the relationship between attention and the ASSR is less defined. Early studies showed that the role of attention was negligible on the 40 Hz response, but more recent studies have shown that the general amplitude of the ASSR increases when the subjects were attending to the stimulus (Linden et al, 1987; Ross et al, 2004). Linden et al (1987) reported no significant difference in the amplitude of the ASSR in eight adults, regardless of whether the subject was attending to or ignoring the stimuli. In contrast, Ross et al (2004) reported that the grand-mean amplitude of ASSR increased by 60% when subjects (n = 12) were attending to the stimuli compared to when they were not. One main reason for the discrepancy in the results of these two studies is likely due to the type of attention task used. Linden and colleagues (1987) used intensity and frequency discrimination tasks in which the subjects counted the number of intensity or frequency changes they heard in the “Attend” condition. In contrast, Ross and colleagues (2004) used an AM discrimination task in which the listeners were required to discriminate changes in the rhythm of the stimulus in the “Attend” condition. Picton et al (2003) commented that the relationship between attention and the ASSR is still unclear and further investigation of this topic is needed.

**ACCURACY OF BEHAVIORAL THRESHOLD PREDICTION**

One of the primary roles of the ASSR is to estimate the pure tone audiogram in difficult to test populations. Two issues that are integral in determining the accuracy of behavioral threshold predictions are the frequency specificity of the ASSR as well as the cochlear place specificity of this response. Each of these two concepts will be briefly defined below.

The frequency specificity of the ASSR is clearly dependent upon the type of stimuli used to record the response and the frequency or acoustic specificity of these stimuli. As previously mentioned, the stimuli commonly used to clinically record the ASSR (i.e., AM, FM, MM, and RSG tones) all have good acoustic specificity, as their main energy is located at the CF with small side lobes of energy present both above and below the CF (CF + MF and CF−MF) as shown in Figure 4. The frequency specificity of the response is a term generally applied to threshold estimations, and it “refers to how independent a threshold at one stimulus frequency is of contributions from surrounding frequencies” (Oates and Stapells, 1998, p. 61). Cochlear place specificity, in contrast, refers to the specific point along the basilar membrane that has been maximally activated by the stimulus (Herdman et al, 2002).
Herdman and colleagues (2002) investigated the cochlear place specificity of the ASSR using a noise masking technique known as the high pass noise derived response (HP/DR) technique. Results from this study demonstrated that the maximum amplitude of the derived bands occurred within a half octave of the CF tone at each stimulus frequency and that there were no significant differences in the place specificity of the ASSR for the single frequency versus multifrequency technique. Thus, these investigators concluded that “ASSRs to moderately intense tonal stimuli (60 dB SPL) reflects activation of a reasonably narrow cochlear region surrounding the CF tone, regardless of whether the AM tones are presented simultaneously or separately” (Herdman et al., 2002, p. 1569). They also concluded that the place specificity of the ASSR is as good or slightly better as that obtained with the ABR and/or MLR elicited by brief tones.

One way to assess the frequency specificity of the ASSR is to see how well the ASSR thresholds estimate behavioral pure tone thresholds, especially in individuals with sensorineural hearing loss (SNHL). The next sections of this manuscript will review how well the ASSR estimates behavioral thresholds in certain clinical populations (i.e., normal hearing sensitivity and SNHL). In these sections of the manuscript, the findings from the air conduction (AC) ASSR studies will be presented first followed by the findings from the bone conduction (BC) ASSR studies. Within the AC and BC sections, the results of adult ASSR studies will precede the results of ASSR studies conducted on the pediatric population.

**AIR CONDUCTION**

**Adults with Normal Hearing Sensitivity**

Several studies have investigated the accuracy of using AC ASSR thresholds to predict behavioral pure tone thresholds in adults with normal hearing sensitivity by calculating **mean difference scores (MDSs)** (Lins et al., 1996; Cone-Wesson, Dowell, et al., 2002; Dimitrijevic et al., 2002; Herdman and Stapells, 2003). These MDSs are calculated by subtracting the ASSR threshold from the behavioral pure tone threshold at the CF of interest, typically 500–4000 Hz.

As shown in Table 1, the MDS across studies ranged from ~3.72 to 14 dB for the single frequency stimulation technique (see row A) and from 4 to 17 dB for the multifrequency stimulation technique (see row B) across the four CFs. The variability present in these studies, reflected in the SD values, was similar for both the single frequency and multifrequency stimulation techniques. In general, there were minimal differences in these MDS as a function of carrier frequency. Collectively, the results of these studies suggest that both the single frequency and the multifrequency ASSR techniques can be used to reliably estimate AC behavioral pure tone thresholds from 500 through 4000 Hz in adults with normal hearing sensitivity.

Recently, D’Haenens et al. (2008) demonstrated that ASSR thresholds have excellent test-retest reliability for all four CF tones as evidenced by little or no changes in MDS from trial 1 to trial 2 (as seen in Table 1, row C). Lastly, Herdman and Stapells (2003) demonstrated minimal differences (1–3 dB) in the MDS across CFs for the monaural versus dichotic/binaural ASSR test conditions (see row D). Therefore these investigators concluded that the use of the binaural multifrequency technique has the potential to significantly reduce testing time for individuals with normal hearing, without sacrificing the accuracy of threshold prediction.

**Adults with SNHL**

Much research has been conducted on the accuracy of the ASSR in estimating AC behavioral thresholds in adults with SNHL. The issues addressed in the literature include the overall accuracy of threshold

<p>| Table 1. Summary of the Mean Difference Scores (and their SD values) for the Four Carrier Frequency Tones Reported across Studies for Adults with Normal Hearing Sensitivity |</p>
<table>
<thead>
<tr>
<th>Description</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong> Single Frequency</td>
<td>Cone-Wesson, Dowell, et al (2002)</td>
<td>SF, Monotic</td>
<td>-3.72 (15.0)</td>
<td>-0.45 (14.7)</td>
</tr>
<tr>
<td></td>
<td>Herdman and Stapells (2003)</td>
<td>SF, Monotic</td>
<td>7 (13)</td>
<td>10 (12)</td>
</tr>
<tr>
<td></td>
<td>Herdman and Stapells (2003)</td>
<td>MF, Monotic</td>
<td>11 (11)</td>
<td>10 (11)</td>
</tr>
<tr>
<td><strong>C</strong> Test-Retest Reliability</td>
<td>D’Haenens et al (2008)</td>
<td>MF, Monotic Trial 1</td>
<td>19 (13)</td>
<td>14 (10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF, Monotic Trial 2</td>
<td>19 (11)</td>
<td>13 (10)</td>
</tr>
<tr>
<td><strong>D</strong> Monotic vs. Dicotic</td>
<td>Herdman and Stapells (2001)</td>
<td>MF, Monotic</td>
<td>11 (11)</td>
<td>10 (11)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MF, Dicotrich/Binaural</td>
<td>14 (10)</td>
<td>8 (7)</td>
</tr>
</tbody>
</table>

*Note: SF = single frequency stimulation technique; MF = multifrequency stimulation technique.*
Studies have compared the accuracy of ASSR threshold estimations using the single frequency versus multifrequency techniques in individuals with SNHL (e.g., Luts and Wouters, 2005). These investigators reported there were no significant differences between ASSR threshold predictions obtained using the single frequency versus multifrequency stimulation technique as shown by similar MDS for these two stimulation techniques (see Table 2, row D).

Collectively, the results of these studies suggest that the accuracy of AC threshold prediction in adults is not influenced by either the degree of the SNHL or by the configuration of the hearing loss. Both single frequency and multifrequency ASSR techniques are accurate predictors of AC behavioral thresholds (within ~8–13 dB) in adults with SNHL.

INFANTS AND YOUNG CHILDREN WITH NORMAL HEARING SENSITIVITY

In the pediatric population, the early detection and treatment of hearing loss are critical steps in preventing the delay of speech and language development in an infant and/or young child (Yoshinaga-Itano et al, 1998; Moeller, 2000). To achieve these goals, many countries worldwide have mandated newborn hearing screening programs, which rely on objective tests, such as click-evoked ABRs and/or OAEs, as the screening instruments (Joint Committee on Infant Hearing [JCIH], 2007). For infants <6 mo of age, electrophysiological evaluation procedures have been recommended to quantify the degree and configuration of the hearing loss. Currently, recording the ABR to AC and/or BC tonal stimuli is the clinical gold standard for estimating behavioral thresholds in this neonate population (JCIH, 2007). More recently, the ASSR has emerged as a possible alternative electrophysiological technique to the ABR for estimating behavioral thresholds in this clinical population. The next section of this manuscript will discuss how factors, such as the type of test environment, the length of the recording time per stimulus

<table>
<thead>
<tr>
<th>Description</th>
<th>Mean Difference Scores (MDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500 Hz</td>
</tr>
<tr>
<td>A Accuracy</td>
<td></td>
</tr>
<tr>
<td>Lins et al (1996)</td>
<td>MF, Moderate SNHL</td>
</tr>
<tr>
<td>Dimitrijevic et al (2002)</td>
<td>MF, Mild-severe SNHL</td>
</tr>
<tr>
<td>B Degree</td>
<td></td>
</tr>
<tr>
<td>SF, Degree of loss: 60+ dB HL</td>
<td>7.9</td>
</tr>
<tr>
<td>C Configuration</td>
<td></td>
</tr>
<tr>
<td>Herdman and Stapells (2003)</td>
<td>MF, Group A: Steeply sloping (≥30 dB/octave)</td>
</tr>
<tr>
<td>MF, Group B: Flat/shallow (≤30 dB/octave)</td>
<td>15 (13)</td>
</tr>
<tr>
<td>D SF vs. MF</td>
<td></td>
</tr>
<tr>
<td>Luts and Wouters (2005)</td>
<td>SF, AUDERA</td>
</tr>
<tr>
<td>MF, MASTER</td>
<td>17 (12)</td>
</tr>
</tbody>
</table>

Note: SF = single frequency stimulation technique; MF = multifrequency stimulation technique.
intensity, the SNR of the response, and the gestational age of the infant can influence ASSR thresholds. Lastly, there is a brief review of the effects of SNHL on ASSRs recorded in infants and young children.

The data in Table 3 clearly demonstrate that the type of test environment and the level of the ambient noise present in this environment can have a negative effect on ASSR thresholds in infants. In a study by Lins and colleagues (1996) the ASSR infant thresholds were reported from two different sites (Ottawa and Havana). The Ottawa data were recorded in a sound-attenuated room, and the ambient noise levels measured ranged from 26 to 47 dB SPL, while the data collected in Havana was recorded in a room with no sound attenuation and the ambient noise levels ranged from 36 to 53 dB SPL (Lins et al, 1996). As can be seen in Table 3, the ASSR thresholds from Ottawa are significantly lower (better) for all four CF tones in comparison to the ASSR thresholds recorded in Havana. These researchers hypothesized that this difference in ASSR thresholds between these two sites is most likely due to the difference in ambient background noise present in each of these test environments (Lins et al, 1996). The impact of high ambient noise levels is also evident in the Savio et al (2001) data. In this study the ambient noise levels ranged from 62 to 65 dB SPL. The ASSR thresholds in the Savio et al study were approximately 5 to 20 dB higher (poorer) than the ASSR thresholds recorded in several infant ASSR studies, which utilized sound-attenuated chambers for their recordings (e.g., Levi et al, 1995; Lins et al, 1996 [Ottawa data]; Swanepoel and Steyn, 2005; Stroebel et al, 2007; Van Maanen and Stapells, 2009). Savio and colleagues (2001) hypothesized that their ASSR thresholds may have been elevated due to the level and spectral composition of the ambient noise present during their testing.

A second factor that may influence the ASSR thresholds in infants is the length of the recording time. In several of the single frequency studies (e.g., Levi et al, 1995; Rance et al, 2006), the recording time per intensity is fairly brief, ranging from ~20 to 100 sec. In contrast, the mean recording times per intensity for the multifrequency studies were considerably longer (e.g., 3–13 min for the Ottawa data in Lins et al [1996] and 6.3 ± 3.1 min for the Van Maanen and Stapells [2009] data). Picton and colleagues (2005) have stated that when the duration of the recording is longer, the residual noise in the EEG is less, making small amplitude responses close to threshold easier to recognize.

A related concept that influences the detectability of small amplitude responses in infants at near threshold levels is the SNR of the response. SNR is calculated by dividing the response amplitude of the ASSR by the amplitude of the background EEG noise. Both of these amplitude units are typically expressed in nanovolts (nV). Several investigators have demonstrated that infants have considerably smaller ASSR response amplitudes in comparison to adults (e.g., John et al, 2004; Luts et al, 2006). Specifically, John et al (2004) reported that the mean ASSR amplitude to a 50 dB SPL exponentially modulated AM tone (AM²) tone is ~35 nV in normal hearing adults, while the mean amplitude to the same tone in a newborn is only 17 nV. Therefore, one way to enhance the SNR of the ASSR in infants is to employ a stringent noise criterion (the lower the nV value, the more stringent the criteria). For example, Luts et al (2006) reported that the mean ASSR amplitude for a 2000 Hz CF tone presented at 30 dB SPL in infants was 6 nV. If a strict 5 nV noise criterion is employed, then the SNR = 1.20 (6/5), which is double the SNR value that would occur if a less strict noise criterion, such as 10 nV, were employed (SNR = 0.6 [6/10]).

### Table 3. Summary of the Mean Threshold Levels in dB HL (and their SD values) for the Four Carrier Frequency Tones Reported across Studies for Infants with Normal Hearing Sensitivity

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Participants</th>
<th>Test Environment/Avg.</th>
<th>Recording Time</th>
<th>dBA (0.5–3.5 min)</th>
<th>dB SPL (100 sec)</th>
<th>dBA (3–13 min)</th>
<th>dB SPL (3–13 min)</th>
<th>dBA (3–8 wk)</th>
<th>dB SPL (3–8 wk)</th>
<th>dBA (6 mo)</th>
<th>dB SPL (6 mo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Single</td>
<td>Rickards et al, 1994</td>
<td>1–7 day</td>
<td>245</td>
<td>Quiet Room/~30 dBA</td>
<td>0.5–3.5 min</td>
<td>41.3</td>
<td>36</td>
<td>34.1</td>
<td>34.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Levi et al, 1995</td>
<td>1 mo</td>
<td>55</td>
<td>SA</td>
<td>100 sec</td>
<td>42</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Rance and Tomlin, 2006</td>
<td>0 wk</td>
<td>20</td>
<td>NSA/~46.1 dB SPL</td>
<td>22.4–89.6/6sec</td>
<td>46.0</td>
<td>39.7</td>
<td>32.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Swanepoel and Steyn, 2005</td>
<td>6 wk</td>
<td>20</td>
<td>NSA/~45.6–46.1 dB SPL</td>
<td>22.4–89.6/6sec</td>
<td>39.7</td>
<td>32.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B Multifrequency</td>
<td>Lins et al, 1996</td>
<td>1–10 mo (Ottawa)</td>
<td>21</td>
<td>SA/26–47 dB SPL</td>
<td>3–13 min</td>
<td>33</td>
<td>30</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>3–11 mo (Havana)</td>
<td>30</td>
<td>NSA/36–53 dB SPL</td>
<td>3–13 min</td>
<td>36</td>
<td>30</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Savio et al, 2001</td>
<td>0–1 mo</td>
<td>25</td>
<td>NSA/62–65 dBA</td>
<td>3–8 min</td>
<td>57</td>
<td>46</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>7–12 mo</td>
<td>13</td>
<td>NSA/62–65 dBA</td>
<td>3–8 min</td>
<td>57</td>
<td>46</td>
<td>33</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Swanepoel and Steyn, 2005</td>
<td>3–8 wk</td>
<td>5</td>
<td>SA</td>
<td>37</td>
<td>34</td>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Van Maanen and Stapells, 2009</td>
<td>Younger (≤6 mo)</td>
<td>10</td>
<td>SA</td>
<td>7.03 min</td>
<td>39.0</td>
<td>34.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>6 mo</td>
<td>19</td>
<td>SA</td>
<td>5.80 min</td>
<td>41.3</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Older (≥6 mo)</td>
<td>10</td>
<td>SA</td>
<td>7.03 min</td>
<td>39.0</td>
<td>34.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>All</td>
<td>29</td>
<td>SA</td>
<td>6.3 min</td>
<td>35.8</td>
<td>31.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: SA = sound attenuated chamber; NSA = no sound attenuation.


†All data from Lins et al (1996) study was reported in dB SPL values. Ottawa data subsequently converted into dB HL values and reported in John et al (2004). Current authors converted Havana data into dB HL values using the same conversion factors.
In the Van Maanen and Stapells (2009) study, these investigators continued recording at each stimulus intensity until the mean noise level in the side bins surrounding the modulation frequencies was ≤5 nV. They demonstrated that the detectability of the ASSR in infants was substantially enhanced for all four CF tones when the noise criterion was reduced from 10 to 5 nV due to improvements in the SNRs (Van Maanen and Stapells, 2009).

A fourth factor that influences ASSR thresholds in infants is the gestational age (GA) of the infant. Two primary approaches to studying the effects of age on infant ASSRs have been (1) to compare ASSR thresholds in infants versus adults and (2) to compare ASSR thresholds in newborns versus older infants. Lins et al. (1996) measured ASSR thresholds to 500–4000 Hz CF tones in a group of normal hearing infants (1–10 mo) and in a group of normal hearing adults and reported that ASSR thresholds were ~10–15 dB higher (poorer) in the infants across all frequencies. Similarly, Rance and Rickards (2002) compared ASSR thresholds of adults versus older infants (mean age of 3 mo) and reported that older children and adults had approximately 10 dB lower (better) thresholds in comparison to infants. Lastly, Van Maanen and Stapells (2009) reported that the ASSR thresholds for their normal-hearing infants were considerably higher (poorer) at 500–2000 Hz in comparison to their ASSR data reported for normal hearing adults in Herdman and Stapells (2001).

Several investigators were interested in comparing ASSRs in younger babies versus older babies (Savio et al., 2001; Cone-Wesson, Parker, et al., 2002; John et al., 2004; Luts et al., 2006; Rance and Tomlin, 2006; Ribeiro et al., 2010). In general, the collective results of these studies demonstrate that ASSR thresholds improve as the infant matures. For example, Savio et al. (2001) compared results for a group of neonates (0–1 mo) and a group of older babies (7–12 mo) and found that the older babies had ASSR thresholds that were ~10–15 dB lower (better) than their younger counterparts (see Table 3). Similarly, John et al. (2004) reported that their group of older babies (tested between 3 and 15 wk following birth) had ASSR thresholds ~10 dB lower (better) than their group of younger babies (GA = 37–42 wk, tested within 2–3 days of birth).

Based on the age-related effects seen in the ASSR thresholds, Rance and Tomlin (2006) conducted a longitudinal study on 20 full-term infants (post-conceptual age [PCA] = 39–41 wk) to systematically study the maturational changes that occur in ASSR thresholds in normal developing infants. Normal hearing status was suggested by ABR and OAE results. Single frequency ASSR data were recorded to 500 and 4000 Hz CF tones and was collected at 4 discrete points in time (i.e., week 0 (3–6 days following birth) and weeks 2, 4, and 6). Their results demonstrated that ASSR thresholds improved by ~5–6 dB at both test frequencies during the first 6 weeks of life (as seen in Table 3). These investigators hypothesized that the ASSR threshold changes seen in the neonatal/early infancy period are the result of neural development in the auditory brainstem. Rance and Tomlin (2006) also reported that the variability in these threshold measures, reflected in the SD values, tended to decrease as the infants matured, and thus concluded that clinical ASSR assessment may be better left until normal full-term infants are at least 2 weeks of age.

**EFFECTS OF PREMATURITY ON THE ASSR**

Given the relatively high incidence of premature births, a couple of important questions arise regarding the potential clinical application of ASSR testing in premature infants. These questions are as follows: (1) Can ASSR thresholds be reliably recorded in premature infants? and (2) Is there an optimal age at which ASSR testing should be used with these infants? Several researchers have addressed these concerns by comparing response properties of ASSRs recorded in full-term neonates versus those recorded in premature neonates (Cone-Wesson, Parker, et al., 2002; John et al., 2004; Luts et al., 2006; Ribeiro et al., 2010). John et al. (2004) compared ASSRs recorded in 23 premature infants (GAs = 37–42 weeks) to ASSRs recorded in 20 full-term infants (tested between 3 and 15 wk following birth). ASSRs in both age groups were recorded to AM, MM, and AM2 stimuli using a monaural multifrequency stimulation technique. John and colleagues (2004) reported that full-term infants had significantly larger response amplitudes at 1000, 2000, and 4000 Hz in comparison to premature infants. This finding was true regardless of stimulus type. John et al. (2004) also reported that infants in both age groups had significantly larger response amplitudes for the MM and AM2 stimuli versus the AM stimuli and thus recommended that these types of stimuli should be the stimuli of choice in this clinical population.

Luts et al. (2006) was interested in determining if there was difference in the SNR of the binaural multifrequency ASSR in premature infants (n = 14 ears with PCA <41 wk) versus full-term infants (n = 16 ears with PCA ≥41 wk). These investigators reported that the SNR of the ASSR increases significantly with age. For example, at 50 dB SPL, the SNR of the full-term infants was 41% larger/better than the SNR of the premature infants. Based on this finding, Luts and colleagues concluded that the optimal age for ASSR testing (corrected for prematurity) is between 1 wk and 3 mo due to the better SNRs obtained at this later age.

Ribeiro et al. (2010) also compared ASSR thresholds obtained in 27 full-term infants (GA >38 wk) versus 21 premature infants (GA <37 wk). These investigators reported that the full-term infants had larger response amplitudes in comparison to the premature infants, similar to the findings of John et al. (2004). However, in the current study, these age-related threshold differences only reached statistical significance at 500 and 4000.
Ribiero et al also reported that there were no significant differences in the ASSR amplitudes, background EEG noise levels, and SNR for these two age groups. Based on these findings, Ribeiro and colleagues (2010) concluded that a significant maturational effect occurs during gestation at the level of structures involved in the formation of the ASSR at 500 and 4000 Hz. They caution that further studies in this area are needed and “should include the measurement of in situ thresholds during the preterm period to ensure that the maturational component of the threshold can be properly quantified and controlled to obtain an accurate diagnosis and appropriate therapy” (Ribeiro et al, 2010, p. 108.).

**EFFECTS OF SNHL ON INFANT ASSRs**

Both the single frequency and the multifrequency stimulation techniques have been used to study the relationship between ASSR thresholds and behavioral thresholds in infants and young children with SNHLs. A series of studies from the University of Melbourne, in Australia, have used the monaural single frequency stimulation technique to record the ASSR and have relied on phase coherence analysis techniques to determine the presence/absence of a response at a particular CF and stimulus intensity (Rance et al, 1995; Rance and Briggs, 2002; Cone-Wesson, Dowell, et al, 2002). In general, these studies have reported that a strong positive relationship exists between ASSR thresholds and behavioral hearing thresholds (BHTs) in hearing-impaired infants and young children. For example, Rance et al (1995) recorded ASSRs in 60 subjects, 25 children (mean age = 29 mo) with moderate to severe SNHLs and 35 adults (mean age = 55.7 yr) with BHTs ranging from normal to profound and reported that the correlations between ASSR thresholds and BHTs were ≥0.96 at 250–4000 Hz. Rance and Briggs (2002) extended these initial findings to include 184 infants (aged 1–8 mo), with moderate to profound SNHLs and also reported that strong positive correlations (r = 0.81–0.93) exist across frequencies between ASSR thresholds and BHTs in this clinical population. Lastly, Cone-Wesson, Dowell, et al (2002) investigated the relationship between ASSR and BHTs in 51 cases with near normal/mild to severe/profound hearing losses. Similarly, these investigators reported high correlation values (r = 0.77–0.88) for these two measures at 500–4000 Hz. Collectively, these three research groups concluded that the single frequency ASSR technique can be used to make frequency specific estimates of behavioral audiometric thresholds in young children with SNHLs, and are accurate enough to form a basis for hearing aid fittings and early intervention.

In contrast, several research groups have focused their investigations on the potential use of the multifrequency ASSR stimulation technique to estimate frequency specific behavioral thresholds in hearing impaired infants (Luts et al, 2004; Han et al, 2006; Rodrigues and Lewis, 2010; Van Maanen and Stapells, 2010). Luts et al (2004) recorded binaural multifrequency ASSRs in 10 infants (mean age = 7 mo) who were suspected of having a hearing loss. They compared ASSR thresholds to both click-evoked ABR thresholds and to BHTs. Luts et al reported that a significant positive correlation (r = 0.77) exists between click-evoked ABR thresholds and ASSR thresholds at 2 kHz. Similarly, they also reported that significant positive correlations (r = 0.91–0.93) exist between ASSR thresholds and BHTs at all four CFs. In 2006, Han et al also compared the relationship between binaural multifrequency ASSR thresholds and BHTs in 40 young children, aged 6 mo to 5 yr, with varying degrees of SNHL. These investigators reported these two measures were highly correlated (r = 0.79–0.89) at 500 through 4000 Hz (Han et al 2006).

Recently two studies have looked at the relationship between ASSR thresholds and tone-evoked ABR thresholds in this pediatric hearing impaired population (Rodrigues and Lewis, 2010; Van Maanen and Stapells, 2010). These investigators were interested in using tone-evoked ABR thresholds as opposed to click-evoked ABR thresholds, as the former are currently the “clinical gold standard” for predicting the pure tone audiogram in the pediatric population. Rodrigues and Lewis (2010) recorded ASSR in 17 infants, aged 2–36 mo, using the binaural multifrequency stimulation technique. In this study, the ASSR and ABR testing were not conducted on the same day. Rodrigues and Lewis (2010) reported that the correlation values between these two measures were all ≥0.76, indicating that a strong relationship exists between tone-evoked ABR thresholds and ASSR thresholds at 500–4000 Hz. These investigators also compared the infants’ BHTs to both their tone-evoked ABR thresholds and their ASSR thresholds. Rodrigues and Lewis (2010) reported that strong positive correlations exist between both tone-evoked ABR thresholds and BHTs (r = 0.81–0.94) and between ASSR thresholds and BHTs (r = 0.94–0.97) at 500–4000 Hz. In 2010, Van Maanen and Stapells also compared binaural multifrequency ASSR thresholds to tone-evoked ABRs in 141 ears with SNHL, 29 ears with conductive hearing loss, and four ears with loss of unknown origin as well as in a group (n = 34) of young children with normal hearing sensitivity (Van Maanen and Stapells, 2010). A unique aspect of this study was that the tone-evoked ABR thresholds and the ASSR thresholds were measured in the same test session for >93% of the participants, to ensure that the infants’ hearing status had not changed between test sessions. Van Maanen and Stapells (2010) reported that the multifrequency ASSR thresholds were strongly correlated (r = 0.97) with the tone-evoked ABR thresholds for all four CFs, similar to that reported by Rodrigues and Lewis (2010). Van Maanen and Stapells also reported that the multifrequency ASSR thresholds (in dB nHL) were ~6–11 dB higher than the tone ABR thresholds (in dB nHL).
Collectively, the results of these four studies suggest that the binaural multifrequency ASSR technique can be used to reliably estimate frequency-specific hearing thresholds in young infants with SNHL. However, both Rodrigues and Lewis (2010) and Van Maanen and Stapells (2010) caution audiologists that although the ASSR looks like a promising clinical tool for the assessment of hearing status in infants and young children, the data on the use of the binaural multifrequency ASSR technique with infants and young children who have SNHLs is still very limited, and further studies with a larger number of infants and more homogenous samples are needed.

**SCREENING FOR HEARING LOSS IN THE PEDIATRIC POPULATION**

In two recent studies, Van Maanen and Stapells (2009, 2010) have addressed the question of whether the multifrequency ASSR technique can be used to distinguish “normal” versus “elevated” thresholds in the pediatric population. In their 2009 study, these investigators developed recommended AC screening levels based on their own data in conjunction with data from other infant ASSR studies. Van Maanen and Stapells (2009) recommended the use of 50 dB HL at 500 Hz, 45 dB HL at 1000 Hz, and 40 dB HL at 2000 and 4000 Hz as “normal” screening levels. In their preliminary data on a small (n = 23) group of children with diverse hearing losses, the recommended ASSR screening levels did not pass any infant with a hearing loss. In 91.2% of the tests, the ASSR and tone ABR results classified the infant’s hearing status in the same category (“normal” versus “elevated”). There was only 1/80 tests (i.e., 1.3%) where the ASSR results were categorized as “normal” when the tone ABR results were classified as “elevated.” In 2010, Van Maanen and Stapells investigated whether the normal screening ASSR levels they had proposed in 2009 could now be accurately applied to hearing impaired infants. These investigators reported that in 94% of the comparisons, the multifrequency ASSR thresholds categorized hearing in a similar fashion to the tone ABR thresholds for this hearing-impaired population (Van Maanen and Stapells, 2010). Although these data are preliminary, it lends support to the use of the multifrequency ASSR to quickly confirm whether the infant has normal or elevated AC thresholds for 500–4000 Hz in both ears.

**BONE CONDUCTION**

Accurate estimation of pure tone bone conduction thresholds is important to distinguish the type of hearing loss that may exist, and this issue is particularly relevant for infants and young children with unilateral or bilateral otitis media or malformations of the outer or middle ear (Small and Stapells, 2006, 2008a; Brooke et al, 2009). One of the primary sources of information on BC-ASSRs in the literature is a series of studies conducted by Small and Stapells (Small and Stapells, 2005, 2006, 2008a, b; Small et al, 2007). Several clinically relevant questions were addressed in these studies including (1) Do BC-ASSR thresholds accurately predict behavioral thresholds in normal hearing adults? (2) Does the accuracy of the ASSR threshold prediction vary as a function of age? (3) Does the coupling method and placement of a bone oscillator affect accuracy of threshold prediction? and (4) Does the recording channel (ipsilateral versus contralateral) employed affect the accuracy of ASSR threshold prediction? These issues will be briefly addressed in this section of the manuscript.

Small and Stapells (2006) investigated the accuracy of multifrequency BC-ASSR thresholds in predicting behavioral thresholds in normal hearing adults and reported that their mean thresholds ranged from 16 to 25 dB nHL at CFs of 500–4000 Hz (as shown in lower portion of Table 4, row A). The BC-ASSR thresholds reported in this study were approximately 6 dB lower at the higher versus lower frequencies. The variability in these measures, reflected in the SD values, was similar across all four CFs.

Small and Stapells (2006) demonstrated that age related differences occurred when BC-ASSR thresholds in infants with normal hearing were compared to adults with normal hearing, such that infants’ mean BC-ASSR thresholds were considerably better (lower) at the lower frequencies (500 and 1000 Hz) in comparison to the adults’ thresholds (see Table 4, row A). Based on these findings, Small and Stapells (2008a) were interested in determining the time course of maturation of BC hearing sensitivity in these infants. In this subsequent study, BC-ASSRs were recorded in three clinical groups: young infants (0–11 mo), older infants (12–24 mo), and adults (19–48 yr). These investigators reported that low frequency BC-ASSR thresholds increase with age/maturation, while high frequency ASSR thresholds are essentially unaffected by age. Specifically, the young infants had mean ASSR thresholds that were approximately 15 to 20 dB lower at 500 and 1000 Hz in comparison to the adults’ thresholds (Table 4, row B). These threshold differences persist until at least 2 yr of age. In light of these findings, Small and Stapells stressed the importance of establishing normal BC hearing levels for a range of test frequencies when conducting ASSRs on infants of different ages.

Small et al (2007) looked at the role of both the coupling method (elastic head band versus handheld) and the location of the bone oscillator on the skull (temporal bone versus mastoid versus forehead) on the accuracy of BC behavioral threshold predictions via BC-ASSR. These investigators reported that mean ASSR thresholds obtained using an elastic head band and the handheld coupling methods were similar at 500–4000 Hz in normal hearing adults (as shown in lower portion of Table 4, row C). Overall, the mean elastic band minus handheld threshold difference, collapsed across frequency, was only
–1.4 dB. A similar pattern of findings was seen for the infants. There were no significant differences in the mean ASSR thresholds obtained at 500–4000 Hz using these two coupling methods for the infants (as shown in the upper portion of Table 4, row C). There was a trend for the BC-ASSR threshold at 4000 Hz to be slightly higher (i.e., 9 dB) for the handheld versus elastic band coupling method; however, this difference did not reach statistical significance. Small and colleagues (2007) also reported the mean BC-ASSR thresholds recorded from the temporal bone and the mastoid placement in infants were similar at 500–4000 Hz (Table 4, row D), and these two locations yielded considerably better (lower) thresholds than did the forehead placement.

Lastly, Small and Stapells (2008b) investigated possible asymmetries between mean BC-ASSR thresholds obtained from ipsilateral versus contralateral recording channels in infants and adults with normal hearing. Their results revealed similar mean thresholds obtained from ipsilateral and contralateral channel recordings in adults, as shown in the lower portion of Table 4, row E. The same pattern, however, was not true for infants, who had substantially better (lower) BC-ASSR thresholds for the ipsilateral versus contralateral recordings. This finding was true for all CF tones.

One potential limitation that can occur when recording BC multifrequency ASSRs to sinusoidally amplitude modulated (SAM) stimuli presented at intensities ≥40 dB HL are electromagnetic artifacts, which can contaminate the ASSR. Recently, Picton and John (2004) and Small and Stapells (2004) reported that the artifact BC responses that were seen for the low CF tones (i.e., 500 Hz) may have been influenced by physiologic, nonauditory (likely vestibular responses) activity that was not related to the stimulus artifact. Picton and John (2004) as well as Small and Stapells (2004) reported that there are several ways to successfully prevent these spurious ASSRs. One is to use anti-aliasing filters with steep filter slopes and/or procedures that deflect the artifact to regions of the spectrum that are distant from the frequency of the steady state response. A second way is to ensure that the analog to digital (AD) conversion rate is not an integer submultiple of the CF tones. Thirdly, audiologists/hearing scientists can use stimuli with frequency spectra that do not alias back to the response frequency, such as alternating SAM tones or beats. Lastly, alternating the polarity of the stimulus can help to reduce artifactual responses arising from stimulus artifact. Picton and John (2004) and Small and Stapells (2004) reported that the artifact BC responses that were seen for the low CF tones (i.e., 500 Hz) may have been influenced by physiologic, nonauditory (likely vestibular responses) activity that was not related to the stimulus artifact.

**SUMMARY OF THE ACCURACY OF AIR AND BONE CONDUCTION ASSR TESTING IN ESTIMATING BEHAVIORAL PURE TONE THRESHOLDS**

Collectively the results of the ASSR threshold studies, discussed above, reveal several patterns of
interest for estimating air and bone conduction pure tone thresholds in individuals with normal hearing sensitivity as well as those with SNHL. These patterns are summarized below:

**Air Conduction**

- The overall accuracy of ASSR thresholds in estimating behavioral thresholds, as reflected in the MDS, was within ~0–17 dB for adults with normal hearing sensitivity and within ~5–13 dB for adults with SNHL ranging from mild to severe.
- Degree and configuration of the SNHL does not impact the accuracy of behavioral threshold prediction for adults.
- Accuracy of threshold prediction is similar across CFs.
- ASSR thresholds have good test-retest reliability in normal hearing adults.
- Infants have considerably smaller ASSR response amplitudes in comparison to adults and thus have ASSR thresholds that are approximately 10–15 dB higher (poorer) than adults.
- There are considerable differences in the response amplitudes, ASSR thresholds, and SNR of the responses for premature infants versus older infants due to the maturational changes that occur in the auditory system in the first few months of life.
- If audiologists are using the results of the multifrequency ASSR to distinguish between normal versus elevated thresholds in infants and young children, it is recommended that they use 50 dB HL at 500 Hz, 45 dB HL at 1000 Hz, and 40 dB HL at 2000 and 4000 Hz as the normal screening levels (Van Maanen and Stapells, 2009, 2010).

**Bone Conduction**

- BC-ASSR thresholds are fairly good predictors of behavioral BC thresholds at 1000 through 4000 Hz in normal hearing adults.
- Low frequency BC-ASSR thresholds increase with age, and thus different normal BC hearing levels must be established for each frequency when conducting infant ASSRs.
- There is no significant effect of BC coupling method (handheld versus elastic head band) on ASSR thresholds in adults or infants.
- Placement of the BC oscillator on either the temporal bone or mastoid yields the best (lowest) BC-ASSR threshold in infants.
- The ipsilateral recording channel yielded significantly better (lower) BC-ASSR thresholds in infants.
- In conclusion of this threshold estimation section, it is crucial for audiologists to realize that “it is premature

to rely on the ASSR as the primary electrophysiological measure of thresholds in infants, except possibly as the first step in a diagnostic protocol to quickly differentiate normal versus elevated thresholds” (Van Maanen and Stapells, 2010, p. 544). These investigators recommend that audiologists switch to tone ABR when ASSR thresholds are elevated to confirm the degree and type of hearing loss. This is necessary due to the lack of sufficient air- and bone-conduction ASSR data in infants with various types and degrees of hearing loss. Recent data by both Rodrigues and Lewis (2010) and Van Maanen and Stapells (2010) suggest that ASSR thresholds would provide an excellent cross-check of the AC tone-evoked ABR thresholds.

**EFFECTS OF TEST DURATION ON THE ACCURACY OF ASSR THRESHOLDS AND THE RELATIVE EFFICIENCY OF RECORDING SINGLE FREQUENCY VERSUS MULTIFREQUENCY ASSRS**

An important concern that audiologists need to consider when establishing ASSR clinical test protocols is the influence of test duration on the accuracy of the ASSR thresholds. Luts and Wouters (2004) explain that both the accurate estimation of ASSR thresholds as well as establishing a reasonable testing time are crucial elements for the clinical applicability of an ASSR technique. These investigators reported that several factors can influence test duration. These factors include the length of the individual recording sweeps, the number of sweeps recorded per intensity level, and the number of intensity steps that are needed to define threshold. In a series of studies, Stapells and colleagues have looked at the time efficiency of the single frequency versus the multifrequency ASSR techniques for both adults and infants, and their results are outlined below.

In 2001, Herdman and Stapells compared mean recording times (RTs) needed to establish ASSR thresholds for the single frequency versus the multifrequency stimulation techniques in adults with normal hearing sensitivity. In this study, ASSRs were recorded using the MASTER software, and a “no response” could only be determined after a total of 48 sweeps had been collected at each stimulus intensity for each CF tone. These same recording parameters were applied in their subsequent studies. These investigators reported that the mean RT needed to obtain ASSR thresholds for the four CF tones tested in the single frequency condition was 164 ± 22 min. This mean RT was almost twice as long as that required to obtain thresholds for the four CF tones tested in the two multifrequency test conditions. Therefore, Herdman and Stapells (2001) concluded that the RTs for either the monaural or binaural multifrequency test conditions have the potential of being up to four to eight times more time efficient, respectively, than the monaural single frequency test condition, without
sacrificing the accuracy of behavioral threshold estimations.

In a subsequent study, Herdman and Stapells (2003) were interested in determining what mean RTs were needed to obtain accurate ASSR thresholds using the monotic multifrequency technique in adults with varying degrees of SNHL. They reported that accurate ASSR thresholds for the four CF tones could be obtained within 60 min for 78% (18/23) of their subjects. The mean RTs needed to determine accurate ASSR thresholds in adults with steeply sloping SNHLs were 49 ± 13 min, and 49 ± 14 min for adults with flat or mildly sloping SNHLs. Herdman and Stapells (2003) concluded that the monotic multifrequency ASSR technique is useful in accurately estimating behavioral thresholds in individuals with SNHL in a reasonable amount of time.

Recently, Hatton and Stapells (2011) were interested in determining whether the single frequency technique or the multifrequency technique was more time efficient for recording ASSRs in normal hearing infants. They employed a measure known as "relative efficiency" to address this issue. "Relative efficiency is a measure which considers the increase in information relative to the decrease in response amplitudes that occurs when going from the single frequency to multifrequency ASSR test conditions" (Hatton and Stapells, 2011, p. 352). These investigators calculated relative efficiency (RE) values using the following formula: RE = (AMPi/AMPg) × √K. In this formula, AMPi = individual subject’s response amplitude for a specific CF tone and test condition; AMPg = mean group amplitude for a specific CF tone in the monaural single frequency test condition; and K = number of simultaneous stimuli being presented. Hatton and Stapells (2011) explained that in practical terms, if a binaural multifrequency test condition (i.e., eight stimuli are being presented simultaneously, four to each ear) had an RE value of 2, this would predict that audiologists could obtain results for these eight stimuli in this binaural multifrequency condition in half the time it would take to achieve the same SNR for the eight stimuli presented separately in the single frequency test condition.

Hatton and Stapells (2011) demonstrated that the two multifrequency test conditions (monaural and binaural) had significantly higher RE values in comparison to the monaural single frequency test condition in these normal hearing infants. The mean RE values (collapsed across carrier frequency) were 1.0, 1.7, and 2.0 for the monaural single frequency, monaural multifrequency, and binaural multifrequency conditions, respectively. Given these findings, Hatton and Stapells (2011) concluded that despite the finding that the ASSR response amplitudes decreased when going from single frequency to multifrequency stimuli (as discussed earlier in the section on interaction effects), the multifrequency technique is still more time efficient than the single frequency technique when testing at a supra-threshold level (e.g., 60 dB SPL) in normal-hearing infants. Additional research is needed to determine whether these RE findings hold true for normal-hearing infants at near-threshold levels and/or for infants with varying degrees of SNHL.

**Calibration**

An often overlooked yet important area that can directly affect the accuracy of behavioral threshold estimations is the calibration of the ASSR stimuli. At present there is some variation in the physical units of measurement that investigators use to calibrate ASSR stimuli. Researchers tend to calibrate the stimuli in either dB HL (e.g., Rance et al, 2006) or in dB SPL (e.g., Herdman and Stapells, 2003) units. The reason for the discrepancy is in the nature of the stimuli used for ASSR. The AM and MM stimuli used in ASSR are similar to the long duration pure tone stimuli audiologists use in behavioral audiology and, therefore, the reference equivalent threshold sound pressure level (RETSPL) used for pure tones should be the same (Gorga et al, 2004; Stapells et al, 2005). This has led many researchers and ASSR system manufacturers to calibrate ASSR stimuli in dB HL according to various national or international standards such as American National Standards Institute (ANSI) (1996) standards (Gorga et al, 2004; Stapells et al, 2005). Other researchers and ASSR system manufacturers calibrate ASSR stimuli in the same measurement units (dB peak SPL, dB peak-to-peak equivalent SPL, and dB nHL) in which ABR stimuli are calibrated (Stapells et al, 2005). Recently, the International Electrotechnical Commission (IEC) published a new standard (IEC 60645-7) for measuring dB peak SPL and dB peak-to-peak SPL for these AEP stimuli (IEC, 2009). Stapells and colleagues (2005) reported that when ASSR thresholds obtained with stimuli calibrated in dB HL were compared to pure tone behavioral thresholds, they were found to be elevated. In contrast, when ASSR thresholds were obtained with stimuli calibrated in dB peak-to-peak equivalent SPL units they were similar to ABR thresholds evoked with tones in infants (Stapells et al, 2005). Stapells and colleagues (2005) theorized that the response seen in ASSR thresholds is likely a result of a brief portion of the stimulus, unlike responses found in ABR testing. The issue of calibration has not been widely discussed in the literature and is an area in need of future research.

**Potential Clinical Applications of the ASSR**

As can be appreciated, ASSR testing has evolved greatly since it was first described by Galambos et al in 1981. There has been a wide range of ASSR stimuli proposed, including
AM, FM, MM, and RSG tones. Each of these has contributed to our understanding of ASSR generation and provides different testing advantages. The introduction of multifrequency stimulation further expanded the complexity and possibilities of ASSR testing by allowing the evaluation of several test frequencies simultaneously. Objective response detection techniques provide ASSR testing with the capability to offer unbiased estimates of behavioral hearing thresholds. Unlike the ABR, which requires human expert interpretation of time domain data; ASSR response detection is by nature objective due to its frequency domain statistical analysis approach. A multitude of studies described earlier have documented the accuracy of these behavioral hearing estimates. All these capabilities and improvements have made the ASSR into a valuable clinical tool with a wide range of applications. In this tutorial, the authors have chosen to concentrate on three clinically relevant applications of ASSR; these are the use of the ASSR to assess the functional benefit that individuals with SNHL derive from their amplification; use of ASSR with cochlear implant (CI) patients; and use of ASSR with difficult to test patients, such as infants with perinatal brain injury and individuals with auditory neuropathy spectrum disorder (ANSD).

Picton et al (1998) conducted a preliminary investigation to determine whether the multifrequency ASSR technique could be used to objectively estimate aided sound field behavioral thresholds. Thirty-five children (mean age = 15 yr) with moderate SNHLs participated in the study. Picton et al reported that the average differences between the physiological and behavioral thresholds were 17, 13, 13, and 16 dB for CFs of 500, 1000, 2000, and 4000 Hz, respectively. More recently, Stroebel et al (2007) compared aided versus unaided ASSR thresholds and subsequent behavioral thresholds in six infants with moderate to profound SNHLs. Single frequency ASSRs were recorded at 500–4000 Hz. Stroebel and colleagues reported that aided ASSR thresholds were obtained for 83% of the frequencies where aided behavioral thresholds were subsequently measured. The average difference between the aided ASSR threshold and the behavioral threshold was 13 dB (±13). Collectively the results of these studies suggest that the ASSR shows promise in objectively assessing aided thresholds in subjects who cannot be reliably tested with behavioral techniques.

During the last decade several investigators have also looked at the efficacy of recording electrically evoked auditory steady state responses (EASSRs) in CI recipients. Some of these have been animal studies (Jeng et al, 2007, 2008), while others have been human studies (Ménard et al, 2004; Yang et al, 2008; Hofmann and Wouters, 2010). One consistent problem that has occurred in recording EASSRs across studies has been electrical artifact contamination produced by stimulus pulses and radio frequency (RF) transmission, especially at high stimulus intensities. Jeng et al (2007) demonstrated that EASSRs could be successfully recorded from adult guinea pigs by separating the stimulus artifact from the evoked neural response using the sum of alternate polarity waveforms and spectral analysis techniques. Similarly, Hofmann and Wouters (2010) reported they were able to successfully record and interpret EASSRs to low pulse trains in six adult users of the Cochlear Nucleus cochlear implant. These investigators also employed a variety of artifact rejection methods to compensate for the electrical artifacts. Overall these investigators suggest that additional research is needed in this area to close the gap between exploratory studies of these issues and clinical practice.

Santiago-Rodriguez et al (2005) investigated the accuracy of the ASSR in correctly identifying hearing loss in 53 infants with confirmed perinatal brain injuries in comparison to their click-evoked ABR results. For 63% of the infants, ABR results were consistent with normal hearing; however, ASSR results revealed only 32% of those same infants had normal hearing. Santiago-Rodriguez et al (2005) reported that the multifrequency ASSR had a 100% sensitivity rate but only a 48.5% specificity rate. Moreno-Aguirre et al (2010) also evaluated the utility of the ASSR compared to the ABR for detecting hearing loss in 299 infants with perinatal brain injury. They reported that the ASSR had a high sensitivity (92%) and moderate specificity (68%) for identifying hearing loss in this population. Collectively these findings suggest the ASSR can be used in conjunction with the ABR to diagnose hearing loss in infants with perinatal brain injury.

Attias et al (2006) investigated how well the multifrequency ASSR predicted BHTs in individuals with moderate SNHLs, ANSI, and/or CI candidates. They reported that the ASSR and BHTs were similar in the SNHL group. In contrast, the ANSI group had significantly higher ASSR thresholds (1000–4000 Hz) compared to their BHTs while the CI candidates had exactly the opposite pattern. Attias et al (2006) concluded that the multifrequency ASSR technique should be used in conjunction with other subjective and objective measures to ensure the accuracy of threshold prediction for patients who are CI candidates or have ANSI.

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REFERENCES


Appendix A. 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

Modulation frequency The frequency at which electroencephalography (EEG) activity is synchronized to fire and can be derived by calculating the period of the modulation frequency.

Types of Stimuli Used in ASSR

Amplitude modulated (AM) tone A pure tone that changes in amplitude over time.

Blackman-gated tone Commonly used type of RSG (repeating sequence gated tone) 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.

Chirp A type of stimulus that covers a broader range of frequencies than traditional modulated pure tones, activating more hair cells.

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 (Hall, 2007).

Frequency modulated (FM) tone A pure tone that changes in frequency over time.

Mixed modulated (MM) tone A pure tone that changes in both frequency and amplitude over time.

Repeating sequence gated (RSG) tone A series of gated tones that can be combined to form either a single frequency tone or a multiple frequency tone.

Tone burst A brief (<1 sec) tonal stimulus that is frequency specific.

Stimulation Techniques

Multiple frequency A method of stimulation that presents multiple carrier frequency tones (up to four in each ear) simultaneously. These carrier frequency tones are presented either to one ear (monaural test condition) or to both ears (binaural test condition).

Single frequency A method of stimulation that presents one carrier frequency tone at one modulation frequency to one ear at a time.

Analyses Techniques

Fast-Fourier transform (FFT) analysis A computerized technique for separating a complex waveform consisting of multiple frequencies into its individual frequency components (Hall, 2007).

F-test (or F-ratio) A statistical method that is applied in auditory steady state response (ASSR) testing to estimate the probability that the amplitude of an ASSR found at a particular modulation frequency is statistically different from the energy found at the surrounding frequencies that are attributed to the ongoing electroencephalography (EEG) noise.

Phase coherence Phase coherence “is related to the signal (response)-to-noise (background EEG and myogenic) ratio” (Cone and Dimitrijevic, 2009, p. 333).

Neuro-Imaging Techniques

Brain Electrical Source Analysis (BESA) Software for source analysis and dipole localization that is used in electroencephalography (EEG) and magnetoencephalography (MEG) research.

Functional magnetic resonance imaging (fMRI) A type of magnetic resonance imaging (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.

Terms Associated with Threshold

Frequency specificity of the response “How independent a threshold at one stimulus frequency is of contributions from surrounding frequencies” (Oates and Stapells, 1998, p. 61). This refers to behavioral threshold estimations.

Mean difference score (MDS) The behavioral pure tone threshold minus the ASSR threshold equals the difference score. This is calculated separately for each carrier frequency.

Place specificity Place specificity of the response refers to the specific point along the basilar membrane that has been maximally activated by the stimulus (Herdman et al., 2002).