MULTIPLE BRAINSTEM AUDITORY STEADY-STATE RESPONSE
INTERACTIONS FOR DIFFERENT STIMULI

by

Lori Laraine Wood

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Abstract

Auditory steady-state responses (ASSRs) have been shown to be accurate in predicting thresholds of individuals with hearing loss. Although new stimuli are being proposed and clinically implemented, there are no data to indicate whether response interactions would be adversely affected by their use. This study investigated the effects of three different stimuli (AM, AM/FM and AM^2) at two different intensities (60 dB HL and 80 dB HL) on response amplitudes and interactions in normal-hearing adults. Stimuli were generated by the Rotman MultiMASTER research system and presented via air conduction through EAR-3A insert earphones. Carrier frequencies of 0.5, 1, 2, and 4 kHz were 80-Hz modulated in three conditions: individually (monotic single; MS), simultaneously in one ear (monotic multiple; MM), and simultaneously in both ears (dichotic multiple; DM). It was predicted that stimuli with broader spectra would result in greater amplitudes. This was demonstrated in the MS condition by the AM/FM stimulus, which evoked responses significantly larger than those to both AM and AM^2 stimuli at all frequencies except 0.5 kHz at 60 and 80 dB HL. In the multiple (MM and DM) conditions, response amplitudes to AM^2 were significantly larger than AM and AM/FM response amplitudes at both intensities. It was also predicted that more interactions would be found when using stimuli with broader spectra, even at moderate intensities. This was illustrated by the drop in amplitude by the AM/FM stimulus in the multiple conditions versus in the single condition, even at 60 dB HL. Relative efficiency values in the multiple conditions were never less than that found in the single condition at 60 dB HL; at 80 dB HL, the majority (83%) of comparisons were more efficient in the multiple conditions than the single condition. Based on these results, the optimal stimulus to use appears to be dependent on the chosen condition. In the single condition, AM/FM

stimuli result in the largest response amplitudes, however, in the multiple condition, AM^2 stimuli provide the best combination of amplitude values and testing efficiency.

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List of Abbreviations

Abbreviation	Definition
ABR	Auditory brainstem response
AM	Amplitude modulation
AM/FM	Mixed modulation
ANOVA	Analysis of variance
ASSR	Auditory steady-state response
CR	Circle radius
dB	Decibel
dB HL	Decibels - hearing level
dB SL	Decibels - sensation level
dB SPL	Decibels - sound pressure level
df	Degrees of freedom
DM	Dichotic multiple
EEG	Electroencephalogram
F	Fisher's F ratio
fc	Carrier frequency
FFT	Fast Fourier transform
fm	Modulation frequency
Hz	Hertz
kHz	kiloHertz (1000 Hz)
MF	Modulation Frequency

MM	Monotic multiple
ms	millisecond
MS	Monotic single
μV	microvolt
nV	nanovolt
p	Probability
SD	Standard deviation
$\in$	Epsilon correction factor for degrees of freedom

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Chapter 1:

Literature review: Auditory Steady-State Responses

Introduction

Audiology involves the assessment, diagnosis, and treatment of hearing and balance-related issues. A key component of the assessment process is the attainment of hearing thresholds through behavioural pure-tone testing. However, as behavioural results depend on a subject's ability and willingness to participate, circumstances arise when this methodology is either not feasible (e.g., infants and other difficult-to-test populations) or desirable (e.g., adults involved in legal or compensation cases). In such instances, physiological methods of estimating hearing thresholds are both essential and invaluable.

Several auditory evoked potential (AEP) methods are available for objectively estimating hearing thresholds in children and adults through the recording of brain waves in response to auditory stimuli. The tone-evoked auditory brainstem response (ABR) is the most widely used and current AEP of choice for children (Stapells, 2000), whereas the slow cortical potential (SCP) is the current AEP of choice for adults (Stapells, 2009). Although both the ABR and SCP generate responses in an objective manner, they typically require subjective response interpretation by an experienced clinician. An alternative AEP providing objectiveness both in response generation and response detection of threshold estimations for children and adults is the auditory steady-state response (ASSR). The ASSR implements computerized statistical methods to automatically detect the presence of evoked responses.

This literature review will highlight many of the studies researching ASSRs, specifically focusing on the area of stimulus factors. This will provide the background to my research in multiple brainstem ASSR interactions.

A General Review of ASSRs

ASSRs have also been referred to as amplitude-modulated following responses (AMFRs), envelope following responses, and steady-state evoked potentials. Although steady-state auditory evoked potentials were initially recorded by Geisler in 1960 (Geisler, 1960), they were not suggested as an objective means to assess hearing thresholds for another two decades (Galambos, Makeig, & Talmachoff, 1981). A current focus of ASSR research is the clinical optimization of various recording parameters.

ASSRs provide an accurate means of objectively estimating hearing thresholds across the audiometric range (for a review, see: Picton, John, Dimitrijevic, & Purcell, 2003). The differences between ASSR thresholds and behavioural pure-tone thresholds in normal-hearing adults are generally between 5 and 15 dB (Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Perez-Abalo, et al., 2001; Rance & Rickards, 2002). Physiological thresholds are higher than behavioural thresholds due to the neural synchrony required to detect these responses (Herdman & Stapells, 2001; Lins et al., 1996; Perez-Abalo et al., 2001; Picton et al., 1998).

In order to evoke ASSRs, repeating stimuli are presented at such a rate that the response to any one stimulus overlaps the response(s) to preceding stimuli, creating a periodic waveform

(John, Lins, Boucher, & Picton, 1998b; Lins & Picton, 1995). The discrete frequency components of this periodic waveform remain constant in amplitude and phase during stimulus presentation (Regan, 1989, p.35).

Many different stimuli may be used to elicit ASSRs, such as noise bursts, beats, clicks, brief tones, sinusoidal amplitude modulation (AM), sinusoidal frequency modulation (FM), mixed modulation (MM or AM/FM), and exponential envelope modulation (AM^2). Until recently, sinusoidal AM was the most commonly used stimulus; however, there is growing interest in the use of AM/FM (a combination of sine-AM and frequency modulation) and AM^2 (AM stimuli with a steeper rise and fall slope), as these more complex stimuli have been shown to enhance response amplitudes above that generated by the sinusoidal AM stimulus (Cohen, Rickards, & Clark, 1991; John, Dimitrijevic, & Picton, 2002a). These new stimuli both have broader frequency spectra than AM (especially AM/FM), however, there are relatively few data for them.

ASSR stimuli may be presented to subjects in one of three conditions: individually (monotic single; MS), multiple stimuli to one ear (monotic multiple; MM), or multiple stimuli to in both ears (dichotic multiple; DM). Carrier frequencies (CFs) of 0.5, 1, 2, and 4 kHz are commonly utilized. In order to evoke ASSRs, CFs are modulated in the amplitude domain, the frequency domain, or both (Cone-Wesson & Dimitrijevic, 2009). A wide range of modulation frequencies (MFs) may be used, although rates between 10-200 Hz have been most often investigated. Because of the tonotopic representation of the cochlea, CFs are processed by representative regions of the cochlea; responses are initiated in these regions at their corresponding MFs (John & Purcell, 2002). In contrast to ABRs, ASSRs may be recorded to multiple simultaneous stimuli at different MFs to one or both ears, potentially speeding up testing time (Herdman & Stapells, 2001; John, Lins, Boucher, & Picton, 1998a).

Generators of the ASSR

Knowledge of intracerebral sources of steady-state responses is necessary for interpreting ASSR results (Cone-Wesson & Dimitrijevic, 2009; Herdman et al., 2002a). ASSRs have multiple generators, the contribution of each being dependant on the MF utilized (Herdman et al., 2002a). The two most widely investigated MFs include those centering around 40 and 80 Hz, as these two regions exhibit an enhancement in amplitude compared to other MFs (Cohen et al., 1991; Galambos et al., 1981; Rickards & Clark, 1984). Additional research has focused on ASSRs to lower rates (i.e., <20 Hz) where there may also be an augmentation of the response (Campbell, Atkinson, Francis, & Green, 1977; Picton, et al., 1987; Wong & Stapells, 2004).

Slow Cortical ASSR (<20 Hz MF)

Although this response may be difficult to separate from background noise, it is not impossible to record (Herdman et al., 2002a; Picton et al., 1987; Wong & Stapells, 2004). A study using brain electric source analysis (Herdman et al., 2002a) suggested responses to <20 Hz stimuli originated from the combined activation of both brainstem and auditory cortex sources.

Early Cortical ASSR (40 Hz MF)

Herdman et al. (2002a) also investigated the neural sources of ASSRs to 40 Hz, and concluded that although the response has both brainstem and cortical generators, the auditory cortex is the primary source (Herdman et al., 2002a). Electrophysiological analyses of ASSRs to 40 Hz by Johnson et al. (Johnson, Weinberg, Ribary, Cheyne, & Ancill, 1988) and Kuwada et al. (Kuwada et al., 2002) suggested they might be generated in the auditory cortices and the thalmocortical circuits. Several magnetoencephalographic studies further identified these cortical generators as originating within the supratemporal gyrus (Gutschalk et al., 1999; Hari, Hamalainen & Joutsiniemi, 1989; Mäkelä & Hari, 1987; Pantev et al., 1993; Pantev, Roberts, Elbert, Ross, & Wienbruch, 1996).

Brainstem ASSR (80 Hz MF)

Recent studies investigating human and animal neural sources of ASSRs to 80 Hz indicated they originate primarily from brainstem structures (Herdman et al., 2002a; Kuwada et al., 2002; John & Picton, 2000a; Mauer & Döring, 1999). A brain source analysis of the 88-Hz ASSR suggested a midline brainstem source, along with a minor cortical contribution (Herdman et al., 2002a). Although not yet confirmed, it is quite likely that the 80-Hz ASSRs are actually ABR waves V to rapidly presented stimuli (Lins, Picton, Picton, Champagne, & Durieux-Smith, 1995; Stapells, Herdman, Small, Dimitrijevic, & Hatton, 2005).

Subject Factors

Maturation

Although ASSR thresholds to 80-Hz air-conducted stimuli do not change significantly with age during adulthood (Boettcher, Poth, Mills, & Dubno, 2001; Johnson et al., 1988; Muchnik, Katz-Putter, Rubinstein, & Hildesheimer, 1993), they do improve with increasing age during infancy (John, Brown, Muir, & Picton, 2004; Lins et al., 1996; Savio, Cardenas, Perez-Abalo, Gonzalez, & Valdes, 2001; Suzuki & Kobayashi, 1984).

It has been found that the 40-Hz response cannot be reliably recorded in young infants (Levi, Folsom, & Dobie, 1993, 1995; Maurizi et al., 1990; Stapells, Galambos, Costello, & Makeig, 1988). Although an enhancement in the ASSR is evident in adults at 40 Hz, Stapells and colleagues (Stapells et al., 1988) found no corresponding 40-Hz augmentation in children aged 3 weeks to 29 months. It has therefore been suggested that maturational changes are responsible for the amplitude peak found near 40 Hz in adults. In contrast, ASSRs at rates near 80 Hz are readily recorded in newborns (Rickards et al., 1994; Lins et al., 1996).

Arousal State

Although ASSR amplitudes to 40-Hz stimuli are two to three times larger than those at 80 Hz in adults, they decrease in amplitude considerably during sleep and anesthesia (Galambos et al., 1981; Jerger, Chmeil, Frost, & Coker, 1986; Linden, Campbell, Hamel, & Picton, 1985). ASSRs to 80 Hz, however, are much less affected by state of arousal (Cohen et al., 1991; Levi et al., 1993; Lins et al., 1995), and for this reason much of the current clinical interest has been in the 80-Hz range. The present study also chose to investigate this modulation range, and the remainder of this literature review will focus primarily on 80-Hz ASSRs.

Measurement and Analysis of the ASSR

As mentioned above, an important feature of ASSRs is the ability to use statistical methods to objectively determine response presence/absence (Picton et al., 2003). Although several clinical ASSR systems are currently available, the following discussion pertains specifically to the multiMASTER research system (John & Picton, 2000b), the system utilized in the current study.

Steady-state responses have stable amplitudes and phases, and therefore may be recorded in either the time or frequency domain. However, because ASSRs are composed of discrete frequency components and have a repeating fundamental, they are more amenable to measurement in the frequency domain. In order to convert ASSRs to the frequency domain for response measurement, either a Fourier analyzer (Regan, 1966, 1989; Stapells, Linden, Suffield, Hamel, & Picton, 1984) or the Fast Fourier Transform (FFT; Rickards & Clark, 1984) may be employed. Most current systems (including multiMASTER) employ the FFT and measure the amplitude and phase at each MF. The spectrum generated displays vertical lines representing the ASSRs at each of the frequencies at which the CFs were modulated (John & Purcell, 2002).

An electroencephalogram (EEG) recording of brain electrical activity is recorded through scalp electrodes. The ASSR EEG includes not only the activity of interest (i.e., the signal), but also normal physiological and electrical activity (i.e., background noise). The EEG is filtered both to remove low-frequency energy and to deter aliasing, and then amplified for conversion from analog to digital (AD) form without loss of required information or addition of artifact. Because ASSR sources vary as a function of both the MF being used and the information one wishes to acquire, optimal electrode placement may also vary (Herdman et al., 2002a; John & Purcell, 2002; Van der Reijden, Mens, & Snik, 2005). If results from both ears are to be obtained, a midline channel is often necessary. To be consistent with previous research (e.g., Herdman & Stapells, 2001; John et al., 2002a; Picton et al., 1998), and to reduce the possibility of contamination from post-auricular muscle responses (Small & Stapells, 2008), this study positioned the inverting electrode at the nape, the non-inverting electrode high on the forehead at midline, and the ground electrode on the left mastoid.

ASSR detection algorithms are based primarily on the signal-to-noise ratio (SNR); that is, the ASSR signal must be significantly larger than the noise in order for the ASSR to be detected. To determine response presence/absence, amplitudes at the MFs are compared against amplitudes at adjacent frequencies (Picton et al., 2003). In the multiMASTER system, the F-test determines whether the amplitude at the MF exceeds the amplitude of noise in 120 adjacent frequency bins (i.e., 60 bins on either side of the MF), and declares significant responses with a probability of $p < .05$. The minimum SNR that indicates a response is statistically different from noise is 1.75 (John et al., 2002a).

MultiMASTER records noise in terms of circle radius, which represents the 95% confidence interval of the noise for response detection. In other words, if a response amplitude is larger than the circle radius value at that MF, there is a 95% certainty that the response is present (i.e., that the signal is significantly larger than the surrounding background noise).

As with most other evoked responses, ASSRs become more easily detected through the process of averaging. Assuming random background noise, averaging reduces the noise by the square root of the number of samples in the average (Picton, Linden, Hamel & Maru, 1983). The multiMASTER system averages recording "sweeps" together, with sweeps being composed of small segments call "epochs". Linking epochs into sweeps lengthens the data segments submitted to the FFT, thus increasing the frequency resolution of the amplitude spectra used to evaluate the ASSR (John & Purcell, 2002).

The reduction in noise due to averaging assumes constant noise. However, muscle activity due to subject movement can be very erratic. Artifact rejection discards any samples in which the voltage of an EEG exceeds a predetermined value (e.g., $\pm$ 50 μV). As artifact rejection discards the response along with the noise, longer test times may result (Cone-Wesson & Dimitrijevic, 2009); however, the fact that sweeps are divided into epochs allows for the rejection of individual epochs instead of entire sweeps.

Along with normal averaging, weighted averaging is another method used to increase the signal-to-noise ratio (Lütkenhöner, Hoke, & Pantev, 1985; John, Dimitrijevic, & Picton, 2001a).

Weighted averaging assigns more emphasis to epochs with lower noise levels compared to those with higher noise levels (John, Dimitrijevic, & Picton, 2003). Because the effects of weighted averaging are not always predictable (John et al., 2001a), it may be prudent to initially use non-weighted averaging and then subsequently re-analyze the data using weighted averaging if this was deemed desirable.

Stopping Criteria

Stopping criteria differ depending on the nature of the study. For threshold studies, recordings continue until a response is detected (p <.05). Usually a minimum of at least two consecutive sweeps at significance are required. However, Luts, Van Dun, Alaerts, and Wouters (Luts et al., 2008) recently proposed a minimum of eight sweeps be presented in order to decrease the error rate due to variable recording lengths.

In the absence of a response (p ≥.05), recordings continue until a predetermined EEG noise criterion is met. More accurate threshold estimations may be obtained with a stricter noise criterion, however testing times will also increase (John, Purcell, Dimitrijevic, & Picton, 2002b; Picton et al., 1983). The noise criterion for 80-Hz threshold studies is commonly set at ≤20 nV (CR; Dimitrijevic et al., 2002; Herdman & Stapells, 2003; Picton, Dimitrijevic, Perez-Abalo, & van Roon, 2005; Small & Stapells, 2005; Van Maanen & Stapells, 2005), and at ≤60 nV for 40-Hz studies (Fontaine, 2006; Van Maanen & Stapells, 2005).

In contrast to threshold studies, accuracy of measures in suprathreshold studies can record ASSRs until a noise criterion is reached, regardless of whether response significance has been met. The noise criterion may not be as strict as that for threshold studies (e.g., $\leq$30 nV for 80-Hz recordings), because of the larger response amplitudes obtained at suprathreshold.

For all studies, a minimum and maximum number of sweeps are typically decided upon to ensure both reliability and efficiency of results. Recording times of three minutes per stimulus are typical, however, this may increase to between 10-17 minutes at near-threshold levels (Dimitrijevic et al., 2002; Herdman & Stapells, 2001).

Stimulus Factors

Larger amplitude ASSRs are detected more rapidly and at lower intensity levels. As such, determining optimal stimulus settings which will produce increased response amplitudes is essential for efficient threshold estimations. Factors such as modulation rate, intensity, carrier frequency, and rise time all play an important role in ASSR response amplitudes.

Modulation Rate

Modulation rate refers to the frequency at which stimuli vary in amplitude, frequency, or both (Purcell & Dajani, 2008). Depending on the stimulus type, rate may refer to the MF (e.g., for AM or FM stimuli), the fluctuation in amplitude envelope (e.g., for tone pairs), or the frequency of stimulus repetition (e.g., for clicks or tone bursts). Because the majority of stimuli utilize amplitude modulation, rate is commonly referred to as MF. It is this frequency at which the response is evaluated in the EEG spectrum (Purcell & Dajani, 2008).

If all other stimulus parameters are held constant, rate has a definite effect on response amplitude in adults. ASSRs are largest at either very low rates (e.g., <10 Hz) or in the 40-Hz range (Stapells et al., 1984). Another, albeit smaller, peak is evident in the 80-100 Hz range (Lins et al., 1995). Above 100 Hz, ASSR amplitude tends to decrease towards zero and ultimately cannot be distinguished from background noise (Purcell & Dajani, 2008). Infants do not appear to have the same amplitude enhancement in the 40-Hz range, again, likely due to maturational effects (Stapells et al., 1988).

Intensity

Intensity refers to the root-mean-square level at which a stimulus is presented (Purcell & Dajani, 2008). Although great individual variability exists, increasing stimulus intensity generally increases ASSR amplitude (Campbell et al., 1977; Galambos et al., 1981; Lins, Picton, Picton, Champagne, & Durieux-Smith, 1995b; Stapells et al., 1984). This amplitude growth tends to be steeper above 60 dB SPL (Picton, van Roon, & John, 2007), and then saturates above 90 dB HL (Picton et al., 2003).

Amplitude growth may be explained by cochlear physiology. Higher stimulus intensities cause a greater spread of energy along the basilar membrane. The subsequent involvement of more hair cells leads to additional activation of afferent nerve fibres, which in turn translates into more input to ASSR generators (Purcell & Dajani, 2008). The end result is an increase in ASSR amplitudes.

Carrier Frequency

ASSR amplitudes vary depending upon the CF utilized in each of the main modulation rate ranges. In the 40-Hz modulation range, an increase in CF results in a decrease in response amplitude to AM stimuli (Galambos et al., 1981; Picton et al., 1987; Rodriguez, Picton, Linden, Hamel, & Laframboise, 1986; Ross, Draganova, Picton, & Pantev, 2003; Stapells et al., 1984), resulting in the largest ASSR responses at 0.5 kHz. This is in contrast to the pattern in the 80-Hz modulation range, where ASSR responses to AM stimuli are smallest for 0.5 kHz, largest for 1 and 2 kHz, and decrease again at 4 kHz (John, Dimitrijevic, van Roon, & Picton, 2001b; John et al., 2001b).

Rise Time

As previously mentioned, a wide array of stimuli may be used to elicit ASSRs, such as periodically repeating brief tones (John et al., 2003; Mo & Stapells, 2008; Stapells et al., 1984; Stapells, Makeig, & Galambos, 1987), clicks (Galambos et al., 1981; John et al., 2003), beats, noise bursts, and sinusoidally amplitude-modulated tones (Campbell et al., 1977; Herdman & Stapells, 2001; Lins & Picton, 1995; Lins et al., 1995; Lins et al., 1996). A key difference between these stimuli is their rise time, a feature closely linked to response amplitudes. Physiological responses vary significantly with various characteristics of the rise function (Stapells & Picton, 1981; Suzuki & Horiuchi, 1981). In general, steeper slopes or greater changes in slope over time (i.e., acceleration) produce larger and earlier responses, possibly due to greater synchronicity in neural firing (John et al., 2002a). As it is thought that AM envelopes with steeper slopes or greater accelerations will evoke larger steady-state responses, variations on the standard sinusoidal AM stimulus have been developed, such as AM^2 tones (i.e., AM tones with a more rapid or exponential envelope; John et al., 2002a, 2004).

Multiple Simultaneous Stimuli

As previously mentioned, one of the key advantages of ASSRs over ABRs is the ability of ASSRs to be recorded to multiple stimuli simultaneously presented to one or both ears, thus potentially speeding up testing times (Herdman & Stapells, 2001; John et al., 1998b; Lins & Picton, 1995; Lins et al., 1996). The responses to up to four separate tones per ear can be separated and independently assessed according to their corresponding MFs (Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; John et al., 1998b, 2002b; Lins & Picton, 1995; Perez-Abalo et al., 2001; Stapells et al., 2005). Monotic multiple (MM) refers to the simultaneous presentation of four stimuli to one ear, and dichotic multiple (DM) refers to the simultaneous presentation of four stimuli to both ears (i.e., 8 stimuli total).

The multiple-ASSR technique potentially results in faster threshold estimation times compared to the single-stimulus ASSR technique because the amount of available information for a given recording time is increased regardless of whether one or multiple stimuli are being presented (John et al., 2002b; Picton et al., 1983). However, the multiple technique may not prove significantly faster and/or more efficient than the single technique if “interactions” resulting in reduced response amplitudes occur (see below).

Relative Efficiency

Recording multiple responses simultaneously in one session may result in a significant reduction in recording time, as many responses can be recorded in the same time that it takes to record one. However, due to “interactions”, or decreases in response amplitudes when stimuli are presented simultaneously as compared to when they are presented alone, testing times may not be reduced as significantly as first thought. If amplitudes do not decrease, the multiple method is faster by a factor of the number of stimuli presented. But even if there is a decrease in amplitude when presenting stimuli simultaneously, testing multiple stimuli may still be more efficient than testing each individually. The “relative efficiency” measure estimates whether faster testing times arise from using multiple versus single stimulus presentation (Herdman & Stapells, 2001; John et al., 1998a).

As previously mentioned, background noise in an EEG recording decreases at the rate of the root number of sweeps averaged (John et al., 2002b), and the decrease in noise is consistent regardless of the number of stimuli being presented. Therefore, for multiple stimuli recordings to be more efficient than testing single stimuli independently, any decrease in ASSR amplitude when simultaneously presenting multiple frequencies must not be more than $1/\sqrt{N}$, where N is the number of stimuli (John et al., 1998a). For example, in order for four simultaneous stimuli to be more efficient than when each is presented alone, amplitude reductions of the multiple responses cannot exceed 50% of the amplitudes in the single condition. Likewise, the amplitude cannot decrease more than 65% of the single condition amplitude to declare an eight-stimulus multiple condition more efficient than single-stimulus presentation.

The separation between modulation rates of adjacent carrier frequencies may have an effect on the responses to multiply presented tones. It has been ascertained that the presentation of MFs separated by at least 1.3 Hz in adjacent carrier frequencies will not attenuate responses to multiple stimuli in the 80-Hz range (John et al., 1998a). Modulation rate separations of 7 to 9 Hz have commonly been used in 80-Hz threshold studies with no adverse amplitude effects (Armstong, 2006; Herdman & Stapells, 2001; Lins & Picton, 1995; Van Maanen and Stapells, 2005)

ASSRs to 80-Hz multiple simultaneous stimuli were first investigated by Lins and Picton in 1995. No significant decrease in response amplitude was found at 60 dB SPL when four AM tones (0.5, 1, 2, 4 kHz) were presented simultaneously in one or both ears versus when they were presented alone, as long as the CFs were separated by at least one octave (Lins & Picton, 1995). John et al. (1998a) also found no significant change in amplitude when four 80-Hz AM stimuli in one ear were separated by at least one octave at 60 dB SPL.

Herdman and Stapells (2001) studied the effects of multiple ASSR stimuli when presented at different intensities. Their study confirmed that, for 30 and 60 dB SPL, the amplitude of responses to multiple AM stimuli presented simultaneously are not significantly different from those when the stimuli are presented alone, provided all carrier frequencies are at least one octave apart (Herdman & Stapells, 2001). Attenuated responses were found when stimuli were presented simultaneously at higher intensities (e.g., 75 dB SPL) by John et al. (1998b). This was thought to be due to destructive interference of responses resulting in attenuation of the response amplitude, especially to lower carrier frequencies (John et al., 1998b).

The effect of intensity on RE is shown by Armstrong's 2006 study. At high intensities (i.e., 80 dB SPL), ASSRs to multiple AM tones were not more efficient than ASSRs to single AM tones for ASSRs to 14-, 40-, and 80-Hz modulation rate ranges (Armstrong, 2006). John et al. (2002b) used previous data (Dimitrijevic et al., 2002; Herdman & Stapells, 2001; John et al., 2001, 2002a) of multiply-presented AM, AM/FM, and AM^2 tones ($\leq$60 dB SPL) in order to estimate the multiple-stimulus technique (DM) to be two to three times faster than testing each frequency and ear separately (John et al., 2002b). Most recently, Jenny Hatton's MSc thesis (Hatton, 2008) found that infants show significant interactions at even 60 dB SPL. Despite these interactions in infants, the multiple stimulus ASSR remained the most efficient technique at this intensity.

It should be noted that all of the previously mentioned studies investigated response interactions using only AM stimuli. Hence, we have no idea if the broader spectra of AM/FM and AM2 stimuli result in greater interactions and thus less efficiency.

Physiology Underlying Interactions Between ASSRs to Multiple Simultaneous Stimuli

As alluded to above, interactions refer to changes in the amplitude of one or more response(s) when multiple stimuli are presented simultaneously versus singly (John et al., 1998a). While most interactions between responses to different stimuli are inhibitory, it is also possible for one stimulus to enhance or sensitize the response to another (Dolphin & Mountain, 1993).

The most common interactions result in an attenuation of the responses to lower-frequency stimuli when presented with stimuli of higher frequency, and an enhancement of the responses to higher-frequency stimuli when presented with lower-frequency stimuli. These changes in amplitude indicate physiologic interactions occurring in the cochlea and/or auditory nervous system (John et al., 2002b). Below is an explanation behind interactions at each of these locations.

Cochlear Interactions

Components of an input signal composed of multiple stimuli often interact in the cochlea, and almost always in a suppressive manner (Geisler, 1998). Although there is no limit to the number of stimulus components that can interact within the cochlea, this phenomenon has become known as "two-tone" suppression because the majority of studies investigating it have used two tones. Two-tone suppression has been proven to be a cochlear phenomenon because it persists even after sectioning the auditory nerve (Kiang, Watanabe, Thomas, & Clark, 1965).

The basic characteristics of two-tone suppression can be accounted for by the compressive nature of the outer hair cells (OHCs). The active process of the cochlea, generated by the OHCs, is called the cochlear amplifier. The cochlear amplifier serves to refine the sensitivity and frequency selectivity of the mechanical vibrations of the cochlea. Because of the non-linear processing in the cochlea, responses to simultaneously-presented stimuli can physically interact on the basilar membrane, resulting in constructive and/or destructive interference (John et al., 1998a). Destructive interference occurs when a suppressor tone "jams" the cochlear amplifier. The frequency separation of the stimulus tones is crucial: only if a suppressor's response peak lies within the amplification zone of the probe tone along the basilar membrane is the suppressor able to affect the probe tone's amplification process (Geisler, 1998).

Two-tone suppression may be classified as either "low-side" or "high-side" (Ruggero, Robles, & Rich, 1992; Sachs & Kiang, 1968). If the suppressor tone has a frequency below that of the probe tone CF, low-side suppression is said to occur, and, accordingly, if the suppressor has a frequency greater than the probe tone CF, high-side suppression is said to occur. It takes less intensity to cause high-side suppression (Sachs & Kiang, 1968). Two-tone suppression is not the same phenomenon as masking, whereby low-frequency tones attenuate high-frequency tones, and not vice versa (Moore, 1985).

The fact that no interactions were present when simultaneous multiple stimuli were presented to adults at $\leq$60 dB SPL (Herdman & Stapells, 2001; Lins & Picton, 1995) suggests no overlap of excitation patterns occurs at or below this intensity, at least not to the extent that OHC suppression occurs. In contrast, the findings of interactions between responses to simultaneously presented stimuli at intensities >60 dB SPL and/or at half-octave separations (John et al., 1998a; Lins & Picton, 1995) suggests an overlap of excitation patterns along the basilar membrane resulting in destructive interference. This is not surprising, as the bandwidth of the cochlear filter increases with increasing sound pressure levels (Moore, 1993). Therefore, more intense stimuli should interact even when their carrier frequencies are largely separated due to the wider cochlear filters.

It is speculated that the presentation of stimuli with broader spectra (e.g., AM/FM and AM^2) may also increase cochlear interactions. Stimuli with an inherently broader spread of acoustic energy may cause greater interference between responses to simultaneous stimuli such that the multiple-stimulus technique becomes less efficient than the single-stimulus technique.

Neural Interactions

Responses to multiple ASSR stimuli may also interact subsequent to the cochlea in more neural locations such as the brainstem and/or cortex. John et al. (1998a) assessed neural interactions by to comparing ASSRs at different modulation rates. At 40 Hz, a decrease was seen in response amplitudes when going from single to multiple stimuli at 60 dB SPL; in contrast, no amplitude reduction was evidenced for 80-Hz multiple ASSRs. As this pattern of decreases cannot be accounted for solely by cochlear processes, it was concluded that a neural component exists when presenting multiple stimuli simultaneously at 40 Hz (John et al., 1998a).

Neural interactions may also be assessed through binaural stimulation. John et al. (1998b) presented tones in the MM (four tones to one ear) and the DM (four tones to both ears) conditions to adult subjects and found greater reductions in amplitude in the DM condition (John et al., 1998b). Such a result can only be due to binaural interactions at the level of the brainstem or higher in the auditory pathway.

Magnetoencephalography has also been employed to assess neural mechanisms at 40 Hz (Ross et al., 2003). Significant interactions were found between two simultaneously-presented tones at 80 dB SPL. The greatest decrease in ASSR amplitude occurred when the carrier frequency of the interfering tone was higher than that of the test tone.

The effects of either cochlear or neural interactions were illustrated in the Mo and Stapells (2008) study investigating the effects of interfering brief-tone stimuli on response amplitudes. The largest amplitude decrease for 0.5-kHz stimuli resulted from 1-kHz interfering stimuli. The 4-kHz interfering stimuli had the greatest negative effect on the 2-kHz stimulus, but there was also a small inhibitory effect from the 1-kHz interfering stimuli (Mo & Stapells, 2008).

In Picton et al.'s 2009 study, responses at 53 dB SPL were largest for 1 and 2 kHz, but responses at 73 dB SPL were largest for 0.5 and 4 kHz (Picton, van Roon, & John, 2009). The relative sparing of the 4 kHz response at 73 dB SPL may have been due to a form of high-side suppression of either cochlear or central origin (Picton et al., 2009).

In contrast to adults, infants display significantly reduced amplitudes in the multiple versus the single stimulus condition at 60 dB SPL (Hatton, 2008). Although the exact mechanisms are not fully understood, infant reductions in amplitudes in the multiple condition may be explained by cochlear and/or neural factors such as broader tuning filters and decreased brainstem processing time (Hatton, 2008).

Frequency Specificity of Stimuli

A compromise must be reached between stimuli that have sufficiently rapid onsets to evoke easily recognizable responses and stimuli that are sufficiently frequency-specific to estimate pure-tone thresholds. More rapid onsets lead to larger responses but also decrease the frequency specificity of stimuli (Cobb, Skinner, & Burns, 1978; Hecox, Squires, & Galambos, 1976; Kodera, Yamane, Yamada, & Suzuki, 1977). The frequency specificity of a stimulus may be looked at in terms of its acoustic specificity, cochlear place specificity, or the frequency specificity of the central auditory neurons.

Acoustic Specificity

The acoustic specificity of a stimulus depends on the amount of spectral splatter around the nominal frequency (Durrant, 1983). A large amount of spectral splatter causes activation of cochlear regions other than the frequency of interest, possibly resulting in an underestimation of the threshold for the target frequency (Herdman, Picton, & Stapells, 2002b). An increase in stimulus intensity also causes greater spread of activation as acoustic side lobes become more intense and exceed the thresholds at their respective frequencies. Besides rise/fall time, other factors determining frequency specificity include stimulus duration, gating, the transfer function of the transducer, and the resonant properties of the acoustic coupler (Burkard, 1984; Durrant, 1983; Harris, 1978; Nuttal, 1981).

Clicks are broad-band stimuli which elicit relatively large ASSRs and ABRs (John et al., 2003; Stürzebecher, Cebulla, & Neumann, 2003). However, because they contain energy across a wide-frequency spectrum, they are not very frequency-specific, and usually show more energy at the harmonics of the stimulus rate (Mo & Stapells, 2008; Picton et al., 2005). Beats, although quite frequency-specific (i.e., they contain acoustic energy at only two points in the spectrum), produce response amplitudes of only 70% of those to sinusoidal AM (Picton et al., 2005).

Cochlear Place Specificity

Cochlear place specificity refers to the ability of a stimulus to activate only discrete regions of the cochlea along the basilar membrane. This is both facilitated and countered by the upward and downward spread of activation present in the cochlear basilar membrane. Upward spread of excitation results in displacement of basal cochlear regions which have characteristic frequencies above the stimulus' spectral components (Dallos, 1996), causing the possible underestimation of hearing thresholds; conversely, stimulation of high frequency sidelobes may result in overestimation of hearing thresholds. It is important to note that few, if any, studies have investigated place specificity of AM/FM and AM^2 stimuli for moderate-to-high (i.e., >60 dB SPL) stimuli (Herdman et al., 2002b).

AM tones demonstrate both high acoustic frequency specificity and reasonable place specificity (Hartmann, 1977; Herdman et al, 2002b; Herdman & Stapells, 2003; John et al., 2002a; Stapells et al., 2005). Derived-response analysis has shown that ASSRs to sinusoidally amplitude-modulated tones have place specificity similar to that of brief tones (Herdman et al., 2002b). Using AM/FM or AM^2 rather than AM decreases the frequency specificity of the response because the spectra for the AM/FM and AM^2 stimuli spread more widely than the spectrum of the AM tone. A spectral comparison of these three stimuli can be seen in Figure 1.1, where the -20 dB bandwidth for 2-kHz stimuli are 174, 653, and 370 for AM, AM/FM, and AM^2, respectively.

Specificity of Central Auditory Neurons

The frequency specificity of central auditory neurons is tied to the activation patterns of the basilar membrane through the tuning of cochlear filters (Pickles, 1988). Central neurons primarily activated by fibres emanating from the same primary cochlear filter have good frequency specificity; however, central neurons activated by converging fibres emanating from a range of cochlear filters have broader tuning curves (Rhode & Greenberg, 1992). Herdman et al., (2002b) found that ASSRs to stimuli with MFs near 80 Hz have broader frequency specificity than primary auditory neurons.

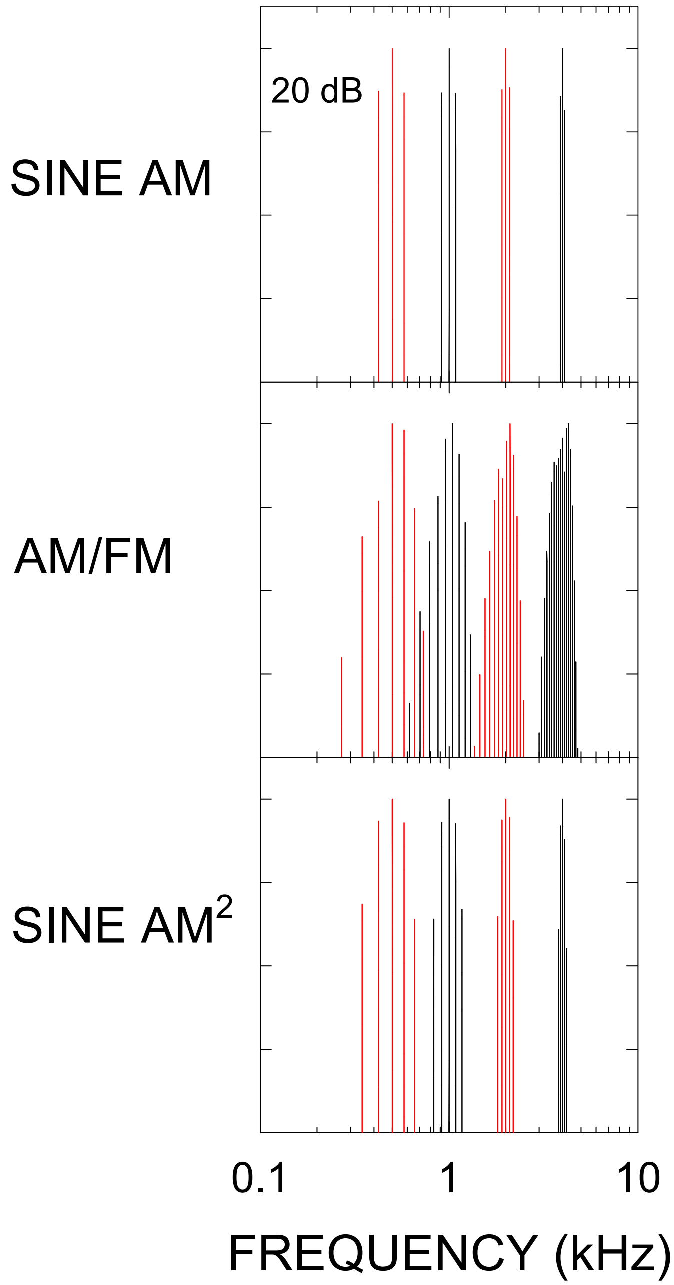

Figure 1.1. Acoustic spectra of stimuli used in this study (AM, AM/FM, and AM^2) for carrier frequencies of 0.5, 1, 2, and 4 kHz. Y axis ticks represent 20 dB intervals.

Stimuli Used in Current Study

As previously mentioned, threshold estimation can be improved if the amplitude of a response is increased without significantly affecting its frequency specificity. Currently, the two most common approaches to achieving this goal are the use of “mixed modulation” and “exponential” envelopes. As such, this study compared amplitudes obtained from AM, AM/FM and AM^2 stimuli.

Sinusoidal AM

The most common stimulus used to date has been continuous sinusoidally amplitude-modulated (AM) tones. Sinusoidally AM stimuli are created by multiplying or adding two sine waves together; the sine wave with the higher frequency becomes the carrier (f_c), and the sine wave with the lower frequency becomes the modulating envelope (f_m; John et al., 1998b). The high acoustic frequency specificity of this stimulus is due to the presence of spectral energy only at $f_c \pm f_m$. The modulation depth for AM tones is usually set to 100%, which results in the amplitude envelope decreasing to zero for every cycle, and the amplitude of the sidebands to be 50% of the carrier (John & Purcell, 2002).

Several studies have investigated ASSRs to AM tones in the 80-Hz modulation range in addition to those previously outlined (see *Relative Efficiency* section). John et al. (2002b) investigated ASSRs to AM stimuli modulated at 80 Hz in the MM condition at intensities less than 50 dB SPL. They found responses to low-frequency stimuli to be attenuated by the presence of higher frequency stimuli (John et al., 2002b). This corresponds to an earlier finding stating that responses to CFs between 1 and 3 kHz were generally larger than those outside this range for AM stimuli (John et al., 2001b).

Picton et al. (2009) found that amplitudes for 1 and 2 kHz decreased in the DM condition as compared to the MS condition, but there were no differences in amplitudes between the DM and MM conditions. At 53 dB SPL, the largest responses were present at 1 and 2 kHz; at 73 dB SPL, the largest responses were at 0.5 kHz, and MM and DM responses were significantly smaller than MS responses, especially at 1 and 2 kHz (Picton et al., 2009).

Mixed Modulation (AM/FM)

Stimuli created through mixed modulation have both amplitude and frequency modulation occurring at the same modulation rate. Sidebands for the AM component are at $f_c \pm f_m$, and for the FM component are at $f_c \pm$ integer multiples of the f_m (John et al., 2001b). Modulation depths are commonly set to 100% for amplitude and 20-25% for frequency (Cohen et al., 1991; John et al., 2003). John et al. (2001b) used 25% FM to determine the optimal FM phase setting to obtain the largest percent of responses detected (John et al., 2001b). A setting of 25% FM indicates stimulus fluctuation of ±12.5% from the CF (John & Picton, 2000b).

It has been proposed that an AM/FM stimulus may produce larger amplitudes due to two possible mechanisms: (1) the increased spread of spectra energy present with AM/FM stimuli (see Figure 1.1) may cause more neurons to be activated (Cohen et al., 1991); and/or (2) the AM and FM components may evoke independent responses, the addition of which would result in a larger combined response (John et al., 2001b, 2004). Psychophysical and neuromagnetic studies have indicated that certain systems in the auditory neural pathways are selectively sensitive to frequency change, rather than amplitude modulation (Kay & Matthews, 1972; Tansley & Regan, 1979; Tansley, Regan, & Suffield, 1982; Tansley & Suffield, 1983; Rees & Kay, 1985; Mäkelä, Hari, & Linnankivi, 1987).

Because the maximum amplitude of the FM response occurs slightly earlier than that of the AM response, the phase of the FM modulation envelope is adjusted to ensure the maximum combined response is obtained (Cohen et al., 1991; John et al., 2001b). However, it must be noted that the optimal relative phase between AM and FM may vary with each subject and carrier frequency, and will have to be adjusted accordingly. In addition to this phase adjustment, a frequency adjustment is also necessary because peaks do not occur exactly at desired CF values (see asymmetrical AM/FM spectra in Figure 1). In order for the maximum energy of the spectra to occur at 0.5, 1, 2, and 4 kHz, Dimitrijevic et al. (2002) shifted CF values to 0.5, 0.92, 1.85, and 3.81 kHz (Dimitrijevic et al., 2002). Because stimulus parameters for the current study differed slightly from Dimitrijevic et al.'s, our CF values were adjusted to 0.5, 0.96, 1.92, and 3.9 kHz for 0.5, 1, 2 and 4 kHz, respectively.

Cohen, Rickards, and Clark (1991) originally showed that the use of simultaneous amplitude and frequency modulation produced larger responses in adults than when presenting AM stimuli alone. Their 80-Hz data indicated that responses to AM/FM stimuli were significantly larger than responses to AM stimuli at 2 and 4 kHz for intensities less than 55 dB HL (Cohen et al., 1991).

John and Picton (2000a) confirmed Cohen et al.'s findings, reporting that AM/FM stimuli with 25% FM at 50 dB SPL evoked responses that reached significance almost twice as fast as AM stimuli (John & Picton, 2000). When John et al. (2001b) compared responses to AM and AM/FM tones in the MM condition at 50, 40, and 30 dB SPL, they found an enhancement in AM/FM at the middle CFs over the lower and higher frequencies. The average AM/FM responses were 27, 40, and 24% larger than the AM responses at 50, 40, and 30 dB SPL, respectively (John et al., 2001b). John and colleagues later demonstrated 20% larger responses for both adults (at CFs of 0.5, 1, and 2 kHz) and infants (at CFs of 1 and 2 kHz) when using AM/FM versus AM stimuli in the DM condition (John et al., 2004).

Dimitrijevic et al. (2002) estimated the audiogram using multiple (DM) ASSRs to AM/FM stimuli modulated in the 80 Hz range. Similar to other studies comparing results to behavioural thresholds, Dimitrijevic et al. found the largest discrepancy for the 0.5 kHz stimulus (Aoyagi et al., 1994; Rance, Rickards, Cohen, DeVidi, & Clark, 1995; Lins et al., 1996; Herdman & Stapells, 2001; Perez-Abalo et al., 2001). The decrease at 0.5 kHz may be related to issues of neural synchrony. The broader region of activation on the basilar membrane at this frequency versus at higher frequencies (due to the tonotopic distribution of the cochlea) may result in more latency jitter in the responding neurons, which would decrease the time-locked summation of responses (Dimitrijevic et al., 2002). This effect is compounded by the greater spectral spread resulting from using AM/FM stimuli.

Exponential Envelope Modulation (AM^2)

An exponential envelope modulated stimulus consists of a sine wave envelope raised to a power of N (i.e., $\sin^N$; John et al., 2002a). Increasing the value of N results in a decrease in tone duration, and a corresponding decrease in rise time. Because response amplitudes do not increase appreciably beyond N=2, AM^2 has been chosen as the optimal exponential envelope (John et al., 2002a). AM^2 stimuli are easier to setup than AM/FM stimuli because there does not need to be any adjustment of the relative phase or frequency and there is no concern that in certain subjects the optimum relative phases of the AM and FM components may differ from normal values (John et al., 2004).

Altering the envelope of a stimulus has the following effects: (i) it increases the maximum slope and the maximum acceleration of the stimulus, (ii) it decreases the durations at which the slope and the acceleration are near their maximum value, (iii) it changes the timing of these maxima so that they occur later within the cycle, and (iv) it increases the duration when the stimulus is below half its maximum amplitude (John et al., 2002). The increased periods of low level sound between successive peaks of the modulation envelope (see Figure 1.1) increase the likelihood that refractory periods (i.e., periods of neuronal response to each stimulus presentation) will end before the start of the next stimulus presentation (John et al., 2002a).

John, Dimitrijevic, and Picton (2003) used noise and tones with exponential envelopes to obtain ASSRs. In all cases, the ASSRs for the exponential modulations were larger than those for either AM or AM/FM tones. John et al. (2004) compared infant ASSRs to 80-Hz modulated AM, AM/FM and AM^2 stimuli in the DM condition at 50 dB SPL. They found that AM/FM and AM^2 stimuli produced responses 15% larger than AM stimuli in newborns, and 17% larger than AM stimuli in older infants.

The amplitude enhancement by this stimulus is likely caused by the steeper slopes of AM^2 envelopes, which increase the synchrony of the neural responses (John et al., 2002a, 2004). John and colleagues (John et al., 2002a) demonstrated that the AM^2 stimulus increased response amplitudes over those from the AM stimulus by 39% at 35 dB pSPL and by 18% at 55 dB pSPL in the DM condition (CFs: 0.5-6 kHz). Contrary to what is found with AM/FM stimuli, AM^2 stimuli tend to produce larger responses at lower (e.g., 0.5 kHz) and higher (e.g., 4 kHz) CFs in both adults and infants (John et al., 2002a, 2004). This increase at lower CFs (i.e., <1 kHz) might be due to individual waves of the stimulus activating responses more quickly to exponential envelopes. The response enhancement at higher CFs (e.g., >2 kHz) may be the result of responses following the overall shape of the stimulus envelope (John et al., 2002a).

A decrease in stimulus duration may affect response amplitude in the following ways: (1) it causes a wider acoustic frequency spread which stimulates a greater number of neural elements; (2) it causes an increase in the rise time, resulting in greater neural synchrony; and (3) it results in longer silent periods between stimuli, allowing for more response recovery and thus larger amplitudes (John et al., 2002a).Mo and Stapells (2008) used brief tones to investigate the effect of stimulus duration on ASSR amplitudes. When brief tone durations were set under three or four cycles, a significant amplitude increase was evident for 0.5 and 2 kHz tones presented alone. When presented simultaneously with other stimuli, the 2 kHz response still increased with decreasing duration; however, the 0.5 kHz stimulus displayed no change as duration decreased (Mo & Stapells, 2008).

No study has directly compared ASSRs to AM/FM and AM^2 stimuli in adults. It is also important to note that previous AM/FM and AM^2 studies have not made direct comparisons of single versus multiple responses for all CFs (i.e., 0.5, 1, 2, and 4 kHz). Nor have AM/FM or AM^2 ASSRs been fully investigated at higher intensities (e.g., 60-80 dB SPL). The current study addressed all of these previous shortcomings.

Summary and Rationale for the Study

The clinical application of ASSRs, especially for threshold estimation in infants and young children, has increased tremendously in recent years. This is evidenced by the existence of several commercially available systems for recording ASSRs (as reviewed in Cone-Wesson & Dimitrijevic, 2009). An emerging concern is the lack of standardization among the different systems. Some of these systems are fairly closely based on the equipment and techniques used in much of the foundational ASSR research; however, many are not (Stapells et al., 2005; D'haenens et al., 2007). As researchers, clinicians, and equipment companies begin to use various multiple stimuli to elicit ASSRs, it is important to better understand the effects of stimulus factors on subsequent responses. Most current ASSR systems use AM or AM/FM stimuli. Even though new stimuli (e.g., AM^2) are being implemented, there are no data to indicate their effects on response interactions and/or testing efficiency.

The effects of stimulus rise time, intensity, and single versus multiple presentation all need to be investigated. Increases in intensity result in greater activation of the basilar membrane, possibly increasing response interactions. Rise time affects frequency specificity, and may contribute to response interactions even at lower intensities. The presentation of simultaneous stimuli may produce such interactions that the multiple-stimulus technique might become less efficient than the single-stimulus technique with new stimuli. Very few studies have obtained single- versus multiple-stimuli data, especially for new stimuli.

Chapter 2:

Multiple brainstem auditory steady-state response interactions for different stimuli

Introduction

Auditory steady-state responses (ASSRs) are an objective, efficient, and frequency-specific means by which to test hearing thresholds (Picton, John, Dimitrijevic, & Purcell, 2003). As such, ASSRs may be useful in the assessment of individuals who are unable to respond behaviourally (e.g., infants) or those who choose not to cooperate (e.g., medical-legal cases). ASSRs employ statistical techniques to objectively determine if a response is present, as opposed to subjective analyses of waveforms by clinicians (John & Picton, 2000b; Stapells, Herdman, Small, Dimitrijevic, & Hatton, 2005).

ASSRs provide an accurate means of objectively estimating hearing thresholds across the audiometric range (for a review, see: Picton et al., 2003). The differences between ASSR thresholds and behavioural pure-tone thresholds in adults are generally between 5 and 15 dB (e.g., Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; Perez-Abalo et al., 2001; Rance & Rickards, 2002).

In order to evoke ASSRs, repeating stimuli are presented at such a rate that the response to any one stimulus overlaps the responses to preceding stimuli, creating a periodic waveform (John, Lins, Boucher, & Picton, 1998b; Lins & Picton, 1995). The discrete frequency components of this periodic waveform remain constant in amplitude and phase during stimulus presentation (Regan, 1989, p.35).

A wide array of stimuli may be used to evoke ASSR responses, such as clicks, beats, noise bursts, tone pips, sinusoidally amplitude-modulated tones (AM), frequency-modulated tones (FM), mixed-modulation tones (AM/FM), and exponentially modulated tones (AM^2). ASSR stimuli may be presented to subjects in one of three conditions: individual stimuli in one ear (monotic single; MS), multiple stimuli simultaneously in one ear (monotic multiple; MM), or multiple stimuli simultaneously in both ears (dichotic multiple; DM). Carrier frequencies (CFs) of 0.5, 1, 2, and 4 kHz are commonly utilized.

In order to evoke ASSRs, CFs are modulated in either the amplitude or frequency domain, or both (Cone-Wesson & Dimitrijevic, 2009). A wide range of modulation frequencies (MFs) may be used (e.g., 10-200 Hz), but the two most studied regions are 40 and 80 Hz. Research into intracranial sources has shown that ASSRs to MFs in the 40-Hz range correspond primarily to activity in the auditory cortical areas of the brain, whereas ASSRs to MFs in the 70-110 Hz range correspond primarily to brainstem activity (Herdman et al., 2002a; Mauer & Döring, 1999; Wong & Stapells, 2004). Although the 40-Hz ASSR cannot be reliably recorded in young infants (Levi, Folsom, & Dobie, 1993, 1995; Maurizi et al., 1990; Stapells, Galambos, Costello, & Makeig, 1988), ASSRs to rates near 80 Hz are readily recorded in newborns (Rickards et al., 1994; Lins et al., 1996).

An important feature of ASSRs is the ability to use statistical methods to objectively determine response presence/absence (Picton et al., 2003). Because ASSRs are composed of discrete frequency components and have a repeating fundamental, they are amenable to measurement in the frequency domain. Either a Fourier analyzer (Regan, 1966, 1989; Stapells, Linden, Suffield, Hamel, & Picton, 1984) or the Fast Fourier Transform (FFT; Rickards & Clark, 1984) may be employed to convert ASSRs to the frequency domain. The multiMASTER research system (John & Picton, 2000b) employs the FFT to measure the amplitude and phase at each MF. The spectrum generated displays vertical lines representing the ASSRs at each of the frequencies at which the CFs were modulated (John & Purcell, 2002).

ASSR detection algorithms are based primarily on the signal-to-noise ratio; that is, the ASSR signal must be significantly larger than the noise in order for the ASSR to be detected. To determine response presence/absence, amplitudes at the MFs are compared against amplitudes at adjacent frequencies (Picton et al., 2003). In the multiMASTER system, the F-test determines whether the amplitude at the MF exceeds the amplitude of noise in 120 adjacent frequency bins (i.e., 60 bins on either side of the MF), and declares significant responses with a probability of $p < .05$.

As with most other evoked responses, ASSRs become more easily detected through the process of averaging. Assuming random background noise, averaging reduces the noise by the square root of the number of samples in the average (Picton, Linden, Hamel & Maru, 1983). The multiMASTER system averages recording “sweeps” together, sweeps being composed of smaller segments called “epochs”. Linking epochs into sweeps lengthens the data segments submitted to the FFT, thus increasing the frequency resolution of the amplitude spectra used to evaluate the ASSR (John & Purcell, 2002).

One of the key advantages of ASSRs is the ability of responses to be recorded to simultaneously presented (i.e., multiple) stimuli. Indeed, ASSRs may be evoked by simultaneously presenting at least four separate tones per ear (Herdman & Stapells, 2001; John, Lins, Boucher, & Picton, 1998b; Lins, Picton, Picton, Champagne, & Durieux-Smith, 1995; Lins et al., 1996), and the responses to these multiple stimuli can be separated and independently assessed according to their corresponding MFs (Dimitrijevic et al., 2002; Herdman & Stapells, 2001, 2003; John et al., 1998b, John, Purcell, Dimitrijevic, & Picton, 2002b; Lins & Picton, 1995; Perez-Abalo et al., 2001; Stapells et al., 2005).

Recording multiple responses simultaneously in one session may result in a significant reduction in recording time as many responses can be recorded in the same time that it takes to record one. However, due to interactions between responses, recording ASSRs to simultaneous stimuli often results in decreased response amplitudes compared to amplitudes when stimuli are presented alone. The "Relative Efficiency" (RE) measure takes both of these factors into consideration when determining whether faster testing times arise from using single versus multiple stimulus presentation (Herdman & Stapells, 2001; John, Lins, Boucher, & Picton, 1998a).

The most common interactions result in attenuation of the responses to lower-frequency stimuli when presented with stimuli of higher frequency, and an enhancement of the responses to higher-frequency stimuli when presented with lower-frequency stimuli. These changes in amplitude indicate physiologic interactions in the cochlea and/or auditory nervous system (John et al., 2002b). Because the bandwidth of the cochlear filter enlarges with increasing sound pressure levels (Moore, 1993), very intense stimuli may interact even when their carrier frequencies are well separated. It is possible that the presentation of stimuli with broader spectra (e.g., AM/FM or AM^2) may also increase cochlear interactions.

As previously mentioned, a wide array of stimuli may be used to elicit ASSR responses. A key difference between these stimuli is their rise time, a feature closely linked to response amplitudes. In general, steeper slopes or greater changes in slope over time (i.e., acceleration) produce larger and earlier responses, possibly due to greater synchronicity in neural firing (John, Dimitrijevic, & Picton, 2002a). Larger responses are desired as they are recognized as significant more rapidly and at lower intensities than smaller responses (John, Brown, Muir, & Picton, 2004). Current research and clinical interest has focused on the use of AM/FM and AM^2 stimuli.

Using AM/FM stimuli produces significantly larger responses in adults compared to presenting AM stimuli alone (Cohen, Rickards, & Clark, 1991; John, Dimitrijevic, van Roon, & Picton, 2001b). John et al. (2001b) compared responses to AM and AM/FM tones in the monotic multiple (MM) condition at 50, 40, and 30 dB SPL and found an enhancement in AM/FM at the middle CFs over the lower and higher frequencies. The larger amplitudes produced by AM/FM stimuli may be due to two possible mechanisms: (1) the wider frequency spectra may cause more neurons to be activated (Cohen et al., 1991); and/or (2) the AM and FM components may evoke independent responses, the addition of which would result in a larger combined response (John et al., 2001b, 2004).

The amplitude enhancement of AM^2 stimuli over AM stimuli is likely caused by the steeper slopes of AM^2 envelopes, which increase the synchrony of the neural responses (John et al., 2002a, 2004). John et al. (2002a) demonstrated that the AM^2 stimulus increased response amplitudes over those from the AM stimulus by 39% at 35 dB pSPL and by 18% at 55 dB pSPL in the dichotic multiple (DM) condition. Contrary to what is found with AM/FM stimuli, AM^2 stimuli produce larger responses at lower (e.g., 0.5 kHz) and higher (e.g., 4 kHz) CFs in both adults and infants (John et al., 2002a, 2004).

A tradeoff must often be made between stimuli with faster rise times, producing larger and earlier responses, and those with better frequency specificity (Cobb, Skinner, & Burns, 1978; Hecox, Squires, & Galambos, 1976; Kodera, Yamane, Yamada, & Suzuki, 1977; John et al., 2002a; Mo & Stapells, 2008; Stapells & Picton, 1981). Sinusoidally amplitude-modulated (AM) tones demonstrate high acoustic frequency specificity (Herdman, Picton, & Stapells, 2002b; Herdman & Stapells, 2003) because their spectral power occurs only at the carrier frequency (f_c) and at two side bands ($f_c \pm f_m$; John et al., 2004). In contrast, the spectra for AM/FM and AM^2 stimuli spread more widely than sinusoidal AM, causing them to have reduced frequency specificity. Spectral bandwidths for 2-kHz stimuli at -20 dB, as calculated from Figure 2.1, are 174, 653, and 370 Hz for AM, AM/FM, and AM^2, respectively.

Stimuli with increased rise times may pose some issues when presented simultaneously and/or at higher intensities. In a recent study conducted by Mo and Stapells (2008), shorter duration stimuli (i.e., brief tones of <12 ms) displayed increased interactions when presented simultaneously at 75 dB SPL. No study has directly compared ASSRs to AM/FM and AM^2 stimuli in adults. It is also important to note that previous AM/FM and AM^2 studies have not made direct comparisons of single versus multiple responses for all CFs (i.e., 0.5, 1, 2, and 4 kHz). Nor have AM/FM or AM^2 ASSRs been fully investigated at higher intensities (e.g., 60-80 dB SPL).

It is predicted that stimuli with broader spectra, while providing increased response amplitudes, will also result in greater response interactions. These interactions may be such that testing individual stimuli will be more efficient than multiple presentation, even at reduced intensities. The purpose of my thesis research was twofold: (1) to compare amplitudes of ASSRs to three stimuli (AM, AM/FM, AM^2) in the single and multiple conditions at moderate and high intensities to determine which stimuli elicits the largest amplitudes and whether interactions are greater for stimuli with broader frequency spectra (e.g., AM/FM) and/or faster rise times (e.g., AM^2); and (2) to assess whether any reductions in amplitude(s) result in the multiple technique becoming less efficient to the extent that it is actually faster to use single stimuli for the different stimuli investigated.

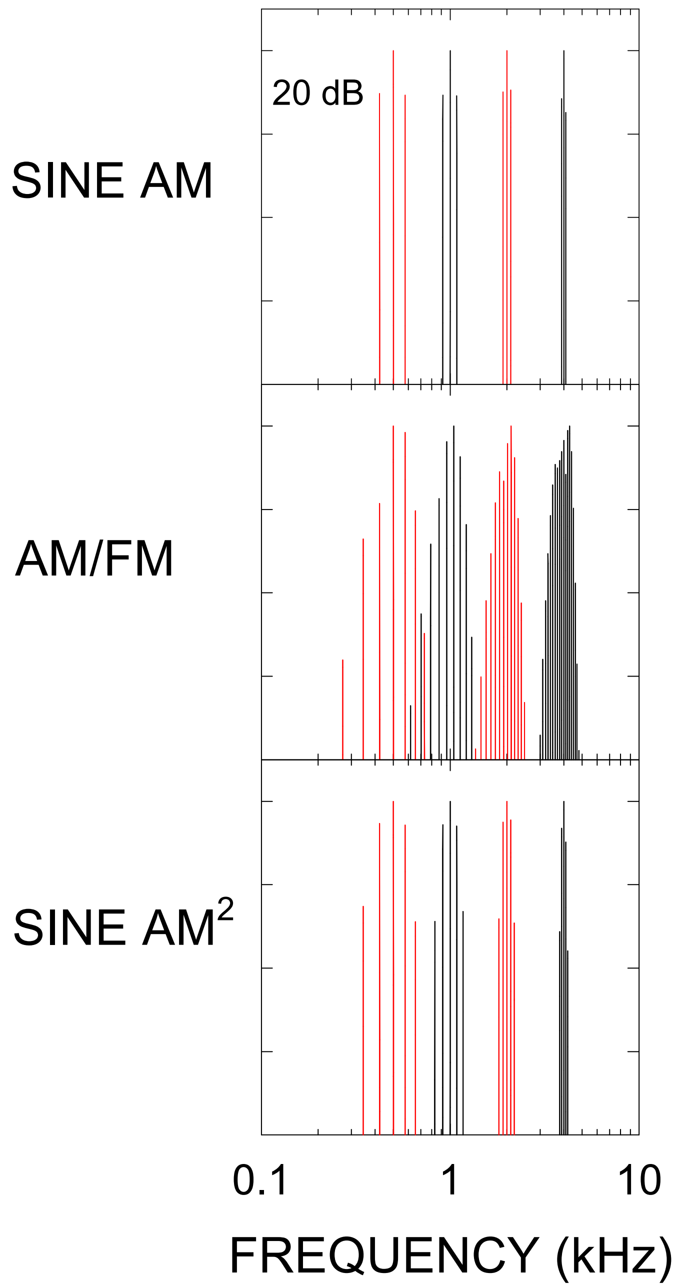

Figure 2.1. Acoustic spectra of stimuli used in this study (AM, AM/FM, and AM^2) for carrier frequencies of 0.5, 1, 2, and 4 kHz. Y axis ticks represent 20 dB intervals.

Methods

Subjects

Data for 15 subjects (10 females) between the ages of 19 and 40 years (mean = 25 years) were included in this study. Twelve additional participants were excluded due to excessive EEG "noise" (i.e., circle radius noise values exceeded 30 nV after 60 sweeps for three consecutive stimulus presentations). All subjects had pure-tone behavioural thresholds equal to or better than 15 dB HL (re: ANSI S3.6-1996) at 0.5, 1, 2, and 4 kHz for both ears.

Auditory Stimuli

For all stimuli, CFs of 0.5, 1, 2, and 4 kHz were used, and modulation rates in the 70-110 Hz range were used, with rates of 77.15, 84.96, 92.77, 100.59 (left ear) and 81.06, 88.87, 96.68, 105.47 (right ear) for 0.5, 1, 2, and 4 kHz, respectively. The modulation rates were chosen to ensure each EEG recording contained an integer number of MF cycles and each recording sweep contained an integer number of CFs (John & Picton, 2000b). Both monotic single (MS) and monotic multiple (MM) stimuli were presented to the left (test) ear only, and dichotic multiple (DM) stimuli were presented to both ears (but results were only considered for the left ear).

Stimuli consisted of: (i) 100% sinusoidally amplitude-modulated tones (AM); (ii)100% sinusoidally amplitude-modulated and 25% frequency-modulated (AM/FM) tones; and (iii) 100% amplitude-modulated tones with exponential (sine^2) envelopes (AM^2). All stimuli were generated by the Rotman MultiMASTER research system (John & Picton, 2000b), attenuated through Tucker-Davis Technologies (TDT) PA5 attenuators, then routed to a TDT HB7 module and ER-3A insert earphones.

AM/FM stimuli were created with AM of 100% and FM of 25% (John et al., 2001b; John & Picton, 2000b). The FM modulation depth of 25% (i.e., stimulus fluctuation of ±12.5% from CF; John & Picton, 2000b) was chosen because John et al. (2001b) determined it to be optimal for obtaining the largest percent of responses detected (John et al., 2001b). Because of the spectral asymmetry in AM/FM stimuli, CF values were adjusted from 0.5, 1, 2, and 4 kHz to 0.5, 0.96, 1.92, and 3.9 kHz so that the spectral peaks occurred at or close to the octave CF values (see Figure 1), similar to those used by Dimitrijevic et al. (2002). The same values were used for both ears.

The exponential component of the AM^2 stimulus was formed by taking only the square of the modulation function prior to its multiplication with the CF (John et al., 2002a). The modulation envelope was based on a function using $\sin^N$ where N was 2. Figure 1 shows the spectra of AM, AM/FM and AM^2 stimuli used in this study. Notice the AM spectra only contains energy at the carrier frequency plus two side-bands, whereas both the AM/FM and AM^2 stimuli have broader spectral widths. The asymmetry of the AM/FM stimuli is also evident.

Stimuli were measured in dB peak SPL, converted to dB SPL by subtracting 3 dB, and subsequently calibrated in dB HL (re: ANSI S3.6-1996). A Larson Davis System 824 sound level meter and a G.R.A.S. Sound & Vibration RA0113 2-cc coupler were used in the calibration procedure. All tones were calibrated individually for each carrier frequency.

Stimulus intensities were 60 and 80 dB HL. Although several prior research studies presented stimuli at "equal SPL", this study used equivalent dB HL levels in order to be consistent with current clinical practices. The differences between dB HL and dB SPL are fairly small: 5.5, 0, 3, and 5.5 dB at 0.5, 1, 2, and 4 kHz, respectively.

Recordings

ASSRs were recorded using a single EEG channel. Three gold-cup electrodes were placed on the scalp: the non-inverting electrode was placed high on the forehead at midline, the inverting electrode was placed at the midline of the nape (just below the hairline), and the ground electrode was placed on the left mastoid. All electrode impedances were kept below 3 kΩ at 10 Hz. The EEG signal was band-pass filtered from 30-250 Hz (12 dB/octave) and amplified with a gain of 80,000 (Herdman & Stapells, 2001). Analog-to-digital (A/D) conversion of the EEG recording was performed at 1250 Hz (Small & Stapells, 2004). Sixteen consecutive data epochs of 0.8192 seconds each were linked together to form sweeps of 13.072 seconds. An artifact rejection level of ±60 μV was set to minimize the effect of muscle artifacts due to movement.

Responses were averaged in the time domain and converted on-line to the frequency domain by the MultiMASTER system using a Fast Fourier Transform. Non-weighted averaging in the multiMASTER system was used. Recording continued until EEG noise (circle radius; CR) was reduced to 30 nV or less. In addition to this noise level criterion, a minimum of 12 and a maximum of 60 sweeps were recorded. If the CR did not reach 30 nV after 60 sweeps, the condition was repeated and/or excluded from subsequent data analyses. Although not a stopping criterion, response significance (i.e., $p < .05$) was also noted.

Procedure

After informed written consent was obtained, a standard behavioural hearing threshold test was administered to confirm normal hearing status. EEG electrodes were applied to the scalp. Each subject was asked to relax and/or sleep in a double-walled sound-attenuated booth throughout the recordings. Subjects were given ample opportunity to take breaks between test blocks. A total of 36 test blocks were presented to each subject.

The test blocks were broken up as follows: (1) 24 blocks in MS condition (all four carrier frequencies presented individually to the test ear for all three stimuli at both intensities); (2) six blocks in MM condition (all four carrier frequencies presented simultaneously to the test ear for all three stimuli at both intensities); and (3) six blocks in the DM condition (eight stimuli presented simultaneously -- four carrier frequencies per ear -- for all three stimuli at both intensities). The order of all 36 blocks was randomized across subjects (see below for details). The total testing time was spread across two test sessions, and did not exceed 2.5 hours per session.

Stimuli were presented via air conduction through EAR-3A insert earphones. The left ear was the "test ear" for all conditions; right ear results were not considered in the DM condition. All test parameters were randomized across subjects; first the session intensity was chosen (i.e., 60 versus 80 dB HL), then the order of stimulus type (i.e., AM, AM/FM, AM^2), and finally the order of conditions within each stimulus (i.e., DM, MM, MS). The second session followed the same randomization procedure for the remaining intensity.

Data Analyses

Amplitude

Response amplitudes were averaged across subjects for each test block, and analyzed within and between the three test stimuli. Analyses were performed using two- (i.e., stimulus x frequency) and three-way (i.e., stimulus x condition x frequency) repeated-measures ANOVAs (intensities were kept separate to facilitate interpretation of results). Huynh-Feldt kf correction factors for degrees of freedom were used as appropriate for all repeated-measures ANOVAs. Differences in amplitudes were considered significant at the $p < .05$ level and a trend at the $p < .1$ level. Newman-Keuls post-hoc analyses ($p < .05$) were performed for significant main effects and interactions. Because initial analyses revealed few differences between response amplitudes for MM and DM conditions at both 60 and 80 dB HL, we also combined the MM and DM data (i.e., "MULT") at each intensity.

Relative Efficiency

Recording multiple responses simultaneously in one session may result in a significant reduction in recording time as many responses can be recorded in the same time that it takes to record one. However, due to interactions, recording ASSRs to simultaneous stimuli often results in decreased response amplitudes compared to amplitudes when stimuli are presented alone. The "Relative Efficiency" (RE) measurement takes both of these factors into consideration when determining whether faster testing times arise from using single versus multiple stimulus presentation (Herdman & Stapells, 2001; John et al., 1998a). RE was calculated for both the MM and DM conditions (note: the RE of the MS condition is always "1"). If the RE is greater than 1 in the MM or DM condition, the multiple-stimulus technique is more efficient than the single-stimulus technique. The RE formula was: (multiple condition amplitude / single condition amplitude) * $\sqrt{N}$, where N = the number of simultaneously presented frequencies (i.e., 4 or 8; Herdman & Stapells, 2001; John et al., 2002b; John et al., 1998a). *T*-tests were performed to determine the significance of each of the 48 MM and DM blocks (i.e., 2 intensities x 3 stimuli x 2 conditions x 4 frequencies) relative to the MS value of 1. The Bonferroni correction for $p < .05$ was used to determine whether MM and DM were significantly greater than 1 (the value of MS); thus $p < .001$ (i.e., .05/48) for significance and $p < .002$ (i.e., .1/48) for a trend.

Results

ASSR Amplitudes

Figure 2.2 shows the average amplitudes for each stimulus (AM, AM/FM, and AM^2) grouped by carrier frequency at intensities of 60 and 80 dB HL for all conditions (MS, MM, and

DM). In order to simplify the presentation of results, the effect of stimulus type in the MS condition will first be presented.

Monotic Single Condition

MS condition amplitudes in response to 60 dB HL stimuli were analyzed using a two-way repeated measures ANOVA (3 stimuli x 4 frequencies). A significant main effect for stimulus was present (F=29.0; df =2, 28; ϵ=.92; $p < .001$), with Newman Keuls *post-hoc* analysis revealing response amplitudes were greatest to the AM/FM stimulus compared to the AM (p = .001) and AM^2 (p = .001) stimuli. However, a stimulus x frequency interaction (F=6.3; df=6, 84; ϵ=.58; $p < .001$) was also present, with *post-hoc* analyses showing AM/FM amplitudes significantly larger than AM and AM^2 amplitudes at 1, 2, & 4 kHz, but no significant difference in amplitudes between stimuli at 0.5 kHz. Individual stimuli also showed amplitude differences according to frequency: AM responses at 0.5 kHz were significantly larger than 2 (p = .03) and 4 kHz (p = .05); AM/FM responses at 1 and 2 kHz were significantly (p = .020-.023) larger than 0.5 and 4 kHz; and AM^2 responses at 4 kHz were significantly smaller than 2 kHz (p = .02). There was no significant main effect for frequency (F=1.97; df=3, 42; ϵ=.70; p = .155). A two-way repeated measures ANOVA (3 stimuli x 4 frequencies) was performed on the 80 dB HL results for the MS condition, revealing a main effect for stimulus (F=58.0; df=2, 28; ϵ=1.0; $p <$ .001). The *post-hoc* analysis of this effect revealed that responses to AM/FM stimuli were larger than those to AM (p = .0001) and AM^2 (p = .0001) stimuli. No stimulus x frequency interaction was found (F=2.3; df=6, 84; ϵ=.67; p = .068), but there was a non-significant trend suggesting

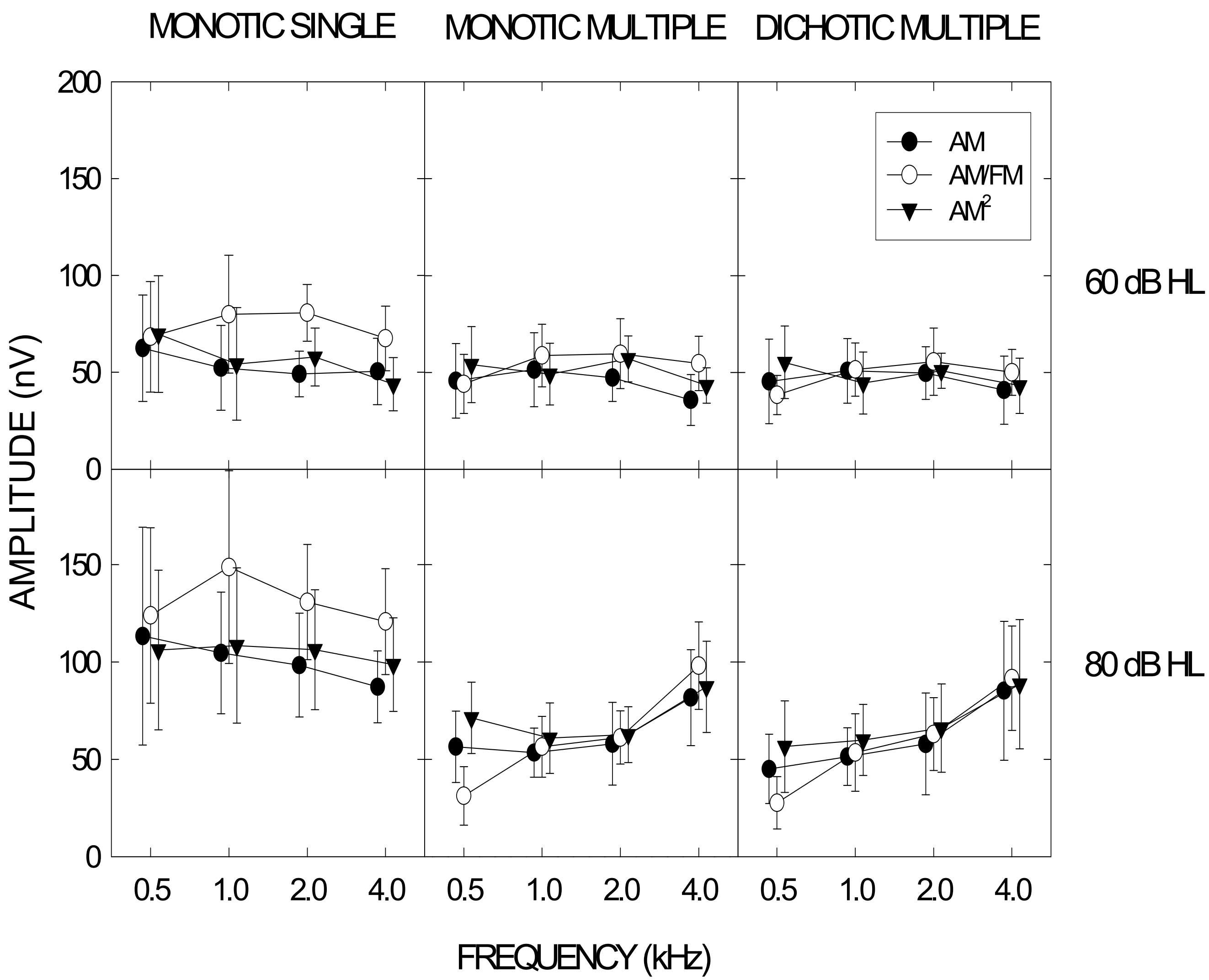

Figure 2.2. Mean amplitudes (±1 SD) for all stimuli (AM, AM/FM, and AM^2) in all conditions (MS, MM, and DM) at both intensities (60 and 80 dB HL).

that the responses to the AM/FM stimuli were greater to the responses to the other stimuli at all frequencies except 0.5 kHz.

Monotic Multiple Condition

A two-way repeated-measures (3 stimuli x 4 frequencies) ANOVA performed for the MM condition at 60 dB HL revealed significant main effects for stimuli ($F = 6.2$; df=2, 28; $\epsilon = 1.0$; $p = .006$) and frequency ($F = 3.2$; df=3, 42; $\epsilon = .91$; $p = .039$), and a significant stimulus x frequency interaction ($F = 4.72$; df=6, 84; $\epsilon = 1.00$; $p < .001$). The *post-hoc* analysis of the stimulus main effect showed that response amplitudes to AM stimuli were significantly smaller than those to both AM/FM ($p = .005$) and AM^2 ($p = .037$), with no significant difference between amplitudes to AM/FM and AM^2. The *post-hoc* analysis for the main effect of frequency revealed that response amplitudes at 4 kHz were significantly smaller than those at 2 kHz ($p = .044$). *Post-hoc* analyses of the stimulus x frequency interaction revealed that response amplitudes to AM stimuli were significantly smaller than those to AM/FM stimuli at 2 kHz ($p = .029$), and significantly smaller than both AM/FM ($p = .0002$) and AM^2 ($p = .05$) stimuli at 4 kHz. There were no significant differences between amplitudes for stimuli at 0.5 ($p = .09$-$.67$) or 1 kHz ($p = .11$-$.54$).

A two-way repeated-measures ANOVA (3 stimuli x 4 frequencies) for the MM condition at 80 dB HL revealed a significant main effect for stimuli ($F = 5.6$; df=2, 28; $\epsilon = .99$; $p = .009$). The *post-hoc* analysis for this effect showed that AM^2 response amplitudes were significantly larger than both AM ($p = .009$) and AM/FM ($p = .015$) response amplitudes. A significant main effect for frequency (F=39.3; df=3, 42; ϵ=.64; $p < .05$) was also present, with a *post-hoc* analysis revealing significantly larger amplitudes to 4 kHz ($p = .0001$). *Post-hoc* analyses of a significant stimulus x frequency interaction (F=14.5; df=6, 84; ϵ=1.0; $p < .001$) revealed significant differences between all responses at 0.5 kHz (i.e., AM^2 > AM > AM/FM) and significantly larger amplitudes to AM/FM stimuli compared to AM ($p = .0009$) and AM^2 ($p = .014$) at 4 kHz. The *post-hoc* analysis of this interaction also revealed that: (i) the responses to AM stimuli were significantly (p = .00012-.00013) larger at 4 kHz than at all other frequencies; (ii) responses to AM/FM stimuli were significantly (p = .00012-.00015) smaller at 0.5 kHz, and significantly (p = .00012-.00013) larger at 4 kHz than at all other frequencies; and (iii) responses to AM^2 stimuli were significantly (p = .0012-.0001) larger at 4 kHz than at all other frequencies, and those at 0.5 kHz were significantly ($p = .049$) larger than those at 2 kHz.

Dichotic Multiple Condition

A two-way (3 stimuli x 4 frequencies) repeated measures ANOVA performed for the DM condition at 60 dB HL indicated no main effects for stimulus (F=.69; df=2, 28; ϵ=.98; $p = .51$) or frequency (F=1.3; df=3, 42; ϵ=.93; $p = .29$). A significant stimulus x frequency interaction (F=4.5, df=6, 84; ϵ=1.0; $p < .001$) was present, with *post-hoc* analyses revealing AM^2 amplitudes to be larger than AM/FM amplitudes at 0.5 kHz ($p = .004$), but not different at other frequencies (p = .44-.67). As well, response amplitudes to AM/FM stimuli at 2 kHz were significantly larger than those at 0.5 kHz ($p = .004$).

At 80 dB HL, main effects were found for both stimulus (F=4.6; df=2, 28; ϵ=1.0; *p* = .019) and frequency (F=18.0; df=3, 42; ϵ=.54; *p* < .001). *Post-hoc* analyses revealed AM^2 amplitudes were slightly but significantly larger than both AM (*p* = .021) and AM/FM (*p* = .027) amplitudes, and 4 kHz amplitudes were significantly (*p* = .00013-.00031) larger than those at all other frequencies. A significant stimulus x frequency interaction was also present (F=3.9; df=6, 84; ϵ=.85; *p* = .003), with *post-hoc* analyses revealing that AM/FM response amplitudes were significantly smaller than both AM (*p* = .002) and AM^2 (*p* = .0001) response amplitudes at 0.5 kHz. Individual stimuli also showed differences according to frequency: (i) AM response amplitudes were significantly (*p* = .00012-.00013) larger at 4 kHz than at all other frequencies; (ii) AM/FM response amplitudes at 0.5 kHz were significantly (*p* = .00012-.00017) smaller than at other frequencies, and those at 4 kHz were significantly (*p* = .00012-.00013) larger than at other frequencies; and (iii) AM^2 response amplitudes at 4 kHz were significantly (*p* = .00012-.00027) larger than amplitudes at all other frequencies.

Monotic Multiple versus Dichotic Multiple Conditions

At 60 dB HL, a three-way repeated measures ANOVA (3 stimuli x 2 conditions x 4 frequencies) was performed comparing the MM and DM conditions. No main condition effect was found (*p* =.07), but there was a non-significant trend suggesting amplitudes were larger in the MM condition. A stimulus x condition significant interaction (F=3.34; df=2, 28; ϵ=1.0; *p* = .049) was present, with *post-hoc* analyses indicating responses amplitudes to AM/FM stimuli were significantly larger in the MM condition (*p* = .02), and response amplitudes to AM stimuli were significantly smaller than those to AM/FM (p = .0008) and AM^2 (p = .04) in the MM condition.

At 80 dB HL, a three-way repeated measures ANOVA (3 stimuli x 2 conditions x 4 frequencies) revealed no main effect for condition (p = .19) and no significant interactions involving condition (p = .19-.99). Because of the lack of significant condition effects at 80 dB HL and the presence of only one significant interaction at 60 dB HL, the MM and DM data were combined into a "MULT" condition for each intensity. To determine significant differences between amplitudes in the MS condition versus those in the multiple conditions, a three-way repeated measures ANOVA (3 stimuli x 2 conditions x 4 frequencies) was performed at each intensity (see below).

Single vs Multiple Condition

At 60 dB HL, a three-way repeated measures ANOVA revealed main effects for stimulus (F=21.9; df=2, 28; ϵ=1.0; p < .001) and condition (F=13.1; df=1, 14; ϵ=1.0; p = .003). The *post-hoc* analysis of the stimulus main effect revealed AM/FM response amplitudes to be significantly larger than both AM (p = .0001) and AM^2 (p = .0002) response amplitudes. *Post-hoc* analysis of the condition main effect revealed amplitudes in the MS condition to be significantly larger than those in the MULT condition (p = .003) for all stimuli. A significant stimulus x condition interaction was also present (F=21.3; df=2, 28; ϵ=.91; p < .001), with *post-hoc* analyses revealing that the single-condition amplitudes to AM/FM stimuli were significantly (p = .00013-.00014) larger than those to other stimuli, and for the multiple condition, amplitudes to AM/FM stimuli were significantly (p = .016) larger than amplitudes to AM stimuli, but not significantly (p = .321) different from amplitudes to AM^2 stimuli. *Post-hoc* analyses of the significant stimulus x frequency interaction (F=9.7; df=6, 84; ϵ=.62; $p < .001$) revealed the following: (i) AM/FM response amplitudes were significantly (p = .00012-.00021) larger than those for other stimuli at 1, 2, and 4 kHz; (ii) responses to AM^2 stimuli were significantly (p = .038) larger than responses to AM stimuli at 0.5 kHz; and (iii) responses to AM^2 stimuli were almost significantly (p = .051) larger than those to AM/FM stimuli at 0.5 kHz.

A significant stimulus x frequency x condition interaction was also present at 60 dB HL (F=2.6; df=6, 84; ϵ=.80; p = .034). *Post-hoc* analyses for this complicated interaction revealed that, in the MS condition, there were no significant (p = .13-.67) differences between responses to different stimuli at 0.5 kHz, but in the MULT condition, responses to AM^2 stimuli were significantly (p = .008) larger than those to AM/FM stimuli at 0.5 kHz. As well, responses to AM/FM stimuli were significantly (p = .00012-.00020) larger than those to AM and AM^2 stimuli at 1, 2 and 4 kHz in the MS condition, but responses to AM/FM stimuli were only significantly (p = .002) larger than those to AM stimuli at 4 kHz in the MULT condition.

At 80 dB HL, a three-way repeated measures ANOVA indicated main effects for both stimulus (F=19.8; df=2, 28; ϵ=1.0; $p < .001$) and condition (F=90.2; df=1, 14; ϵ=1.0; $p < .001$). *Post-hoc* analyses revealed significantly (p = .0001-.001) larger response amplitudes to AM/FM stimuli than to either AM or AM^2 stimuli (stimulus main effect), and significantly (p = .0002) larger response amplitudes in the MS condition compared to the MULT condition (condition main effect). There was no main effect for frequency (F=3.3; df=3, 42; ϵ=.68; p = .052), but a trend was evident such that response amplitudes were larger at 4 kHz compared to other frequencies. *Post-hoc* analysis of a significant stimulus x condition interaction (F=66.0; df=2, 28; ϵ=1.0; p < .001) revealed AM/FM response amplitudes to be significantly (p = .0001) larger than AM and AM^2 response amplitudes in the single condition, and AM^2 response amplitudes to be significantly (p = .002) larger than AM and AM/FM response amplitudes in the multiple condition. A significant stimulus x frequency interaction was present (F=6.5; df=6, 84; ϵ=.77; p < .001), with *post-hoc* analyses indicating responses to AM/FM stimuli were significantly (p = .0001-.039) larger than those to AM and AM^2 stimuli at 1, 2 and 4 kHz, and responses to AM/FM stimuli were significantly (p = .00012-.00037) smaller at 0.5 kHz than at all other frequencies.

Post-hoc analyses of a significant condition x frequency interaction (F=15.5; df=3, 42; ϵ=.63; p < .001) at 80 dB HL showed that in the MS condition, amplitudes decreased significantly (p = .026) as frequency increased from 1 to 4 kHz, but in the MULT condition, amplitudes increased significantly (p = .00013) as frequency increased from 1 to 4 kHz. Although the stimulus x condition x frequency interaction did not quite reach significance, there was a trend evident (F=2.6; df=6, 84; ϵ=.60; p = 0.055) such that there was no difference between stimuli at 0.5 kHz in the MS condition, but a near significant difference (i.e., AM^2 > AM > AM/FM) between stimuli at this frequency in the MULT condition.

Relative Efficiency

Significant reductions in amplitude do not necessarily mean the multiple condition is less efficient than the single condition. Recall that as long as the amplitudes are at least 50% that of the single amplitudes in the monotic multiple condition and at least 35% for the dichotic multiple condition, multiple stimuli are more efficient than single.

Figure 2.3 displays the mean RE results for each stimulus at 60 and 80 dB HL. As previously mentioned, the RE value of all stimuli in the MS condition is, by default, "1"; *t*-tests were used to determine whether RE values in the MM and DM conditions were significantly different from 1.

All RE values obtained for the multiple stimulus conditions and frequencies at 60 dB HL were greater than "1", indicating that, for 60 dB HL stimuli, the multiple conditions (MM, DM) were never less efficient than the single condition. In fact, 18 out of 24 comparisons (i.e., 75%) showed mean RE values that were significantly (or approaching significance) larger than the MS value of 1 at 60 dB HL. Only the MM RE values for the AM and AM/FM stimuli at 0.5 kHz did not reach or approach significance at this intensity.

At 80 dB HL, most (83%) multiple conditions were larger than 1, however fewer comparisons were significantly so (33%). At 4 kHz, all stimuli showed significantly better efficiency in the multiple conditions than in the single condition. As well, the AM^2 stimulus in the DM condition was significantly more efficient than the MS condition at 1 and 2 kHz. It is

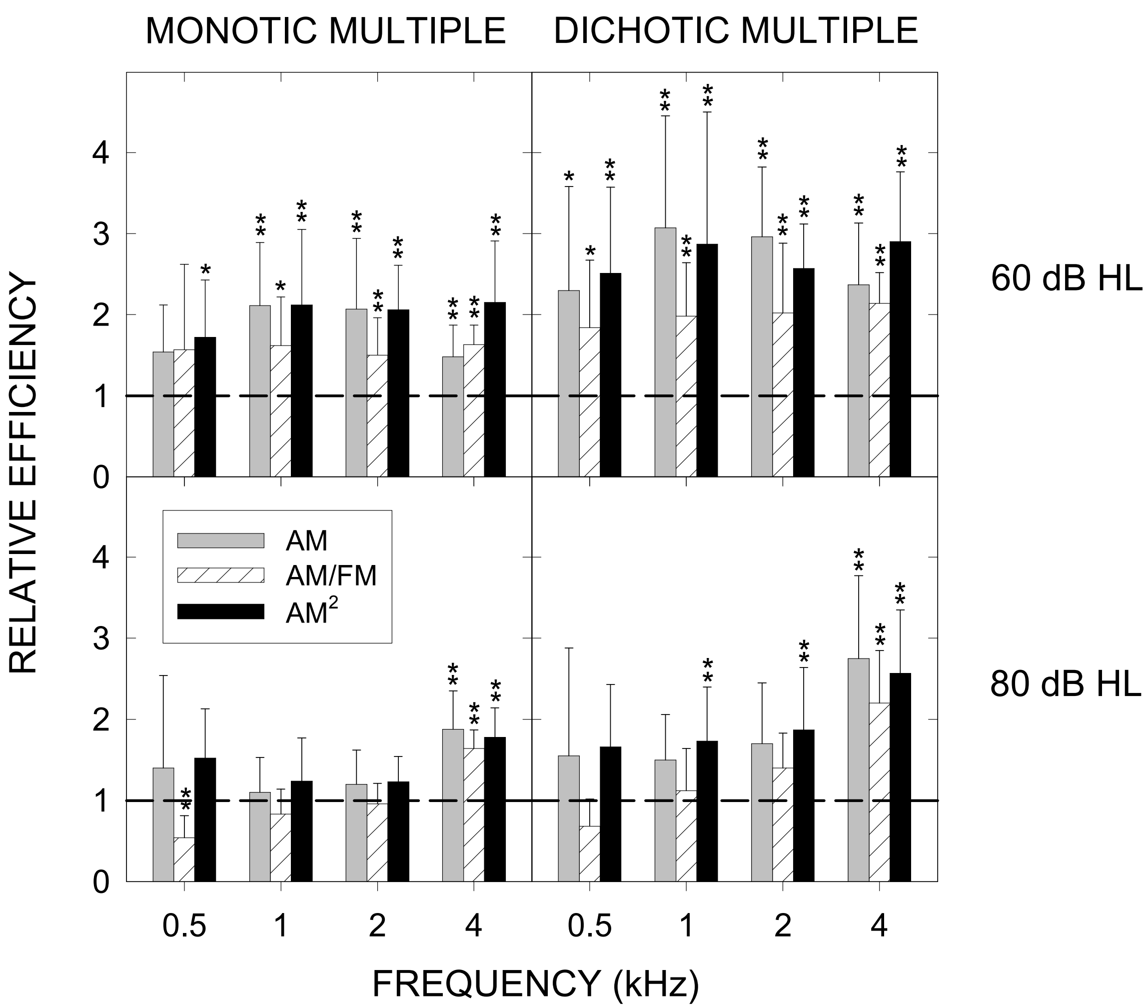

Figure 2.3. Mean (±1 SD) relative efficiency (RE) values for all stimuli in MM and DM conditions at both intensities. Double asterisks over individual bars indicate values are significantly higher or lower than 1; single asterisks indicate nearly significant trends. Dashed line represents RE of MS condition (i.e., 1).

worth noting that four of the RE values for the AM/FM stimuli at 80 dB HL were less than 1 (i.e., worse than the RE in the MS condition) when presented simultaneously; significantly so for 0.5 kHz in the MM condition.

Discussion

Amplitudes

This study revealed a number of interesting and new findings. In terms of response amplitudes, when stimuli were presented in the single condition, responses were largest to AM/FM stimuli at all frequencies except 0.5 kHz. However, when stimuli were presented in either of the multiple conditions at both intensities, responses to AM/FM were no longer the largest. Responses to AM and AM^2 stimuli also showed this interaction, but only at the higher intensity.

Other less obvious yet significant findings included the significantly smaller responses to AM/FM stimuli at 0.5 kHz in both multiple conditions, and the larger responses at 4 kHz versus all other frequencies at 80 dB HL in the multiple conditions but not in the single condition. Overall, it appears that when moving from the single condition to either multiple condition, differences between responses for the different stimuli (when they exist) are much smaller.

To date, no other study has shown responses to be larger for AM/FM stimuli compared to other stimuli at 1, 2, and 4 kHz in the single condition for both 60 and 80 dB HL. However, in the multiple condition (MM and DM), John et al. (2001) revealed that AM/FM stimuli evoke responses one-third larger than AM stimuli at intensities of 30-50 dB SPL for CFs between 0.5 to 5 kHz.

The 4 kHz rise in amplitude with increasing stimuli evidenced in the multiple conditions for all stimuli at 80 dB HL and not at 60 dB HL was similar to what Picton and colleagues (Picton, van Roon, & John, 2009) found with AM stimuli at 73 dB SPL. They postulated it originated from processes which become more apparent at higher intensities. The attenuation of the responses to lower-frequency stimuli when presented with stimuli of higher frequency explain the relative drops in amplitude for 0.5, 1 and 2 kHz. The lack of higher frequency suppression in turn explains the relative sparing of the amplitude to 4 kHz stimuli (John et al., 1998a; Ross, Draganova, Picton,& Pantev, 2003).

In addition to 73 dB SPL, Picton et al. (2009) tested AM stimuli at a lower intensity (53 dB SPL) and found the largest responses in the multiple condition to be at 1 and 2 kHz. Although Picton et al. (2009) showed responses at 0.5 kHz to be larger than those at 1 and 2 kHz in the multiple condition at 73 dB SPL, the present study's results did not replicate this. We did, however, show an increase at 0.5 kHz for AM in the single condition at 60 and 80 dB HL. This discrepancy between studies in the multiple condition may be due to differences in methodology.

Previous studies in adults have only investigated AM^2 in the multiple (DM) condition. Picton et al. (2005) used AM^2 stimuli to estimate audiometric thresholds. They showed response amplitudes to AM^2 stimuli presented in the multiple condition at 70 dB SPL to be highest at 0.5

kHz and lowest at 2 kHz. In contrast, the present study's results showed lowest response amplitudes at 0.5 kHz and largest amplitudes at 4 kHz.

John et al. (2002a) compared responses to AM^2 stimuli with, among others, responses to AM stimuli at 35 and 55 SPL. They showed that using AM^2 stimuli increased response amplitudes by 39% at 35 dB SPL and 18% at 55 dB SPL compared to AM stimuli. Their pattern of responses for the DM condition at 55 dB SPL was similar to that found in the present study at 60 dB HL.

It was hypothesized that stimuli with faster rise times would result in greater amplitudes due to their increased synchronicity of neural responses. This was demonstrated by AM^2 stimuli in the multiple conditions, which produced slightly but significantly higher response amplitudes than AM and AM/FM stimuli, in particular at 0.5 kHz.

Similarly, it was predicted that stimuli with broader spectra would result in greater amplitudes due to their increased spread of spectral energy activating more neurons. This was demonstrated in by the AM/FM stimulus in the MS condition, which evoked responses significantly larger than those to both AM and AM^2 stimuli at all frequencies except 0.5 kHz. However, it was also predicted that more interactions would be found when using stimuli with broader spectra, even at moderate intensities. This was illustrated by the drop in amplitude by the AM/FM stimulus in the multiple conditions versus in the single conditions, even at 60 dB HL.

Relative Efficiency

Relative efficiency is an important factor to consider when selecting optimal clinical stimuli. The ability to present multiple ASSR stimuli simultaneously allows for a potential decrease in testing times. However, due to response interactions occurring at cochlear and/or neural levels, response amplitudes may be reduced to the extent that single stimuli presentation proves more efficient than multiple. Clinically, a stimulus that provides a large response and does not decrease significantly when presented simultaneously with other stimuli is desirable.

The RE values calculated from this study's amplitude data showed the multiple conditions were never less efficient than the single condition at 60 dB HL, and at 80 dB HL, the multiple conditions were primarily (83%) just as efficient as the single condition. Four of the AM/FM RE values were worse in the multiple conditions than in the single condition at 80 dB HL; significantly so for 0.5 kHz in the MM condition. The problematic frequency when looking at RE seems to be 0.5 kHz. As such, it is predicted 0.5 kHz will be the limiting factor ultimately determining testing time.

Only a handful of previous ASSR studies have calculated relative efficiency; the majority of which investigated AM stimuli (Armstrong, 2006; Fontaine, 2006; Hatton, 2008). John et al. (1998b) recorded responses to AM stimuli at 35, 60, and 75 dB SPL in MS and MM conditions at 1 and 2 kHz. For 75 dB SPL stimuli, their responses in the MM condition decreased from those in the MS condition by a similar amount to what was found in the current study. For example, at 75 dB SPL, their MM values were 56 and 49% of MS values at 1 and 2 kHz, respectively, and this study's 80 dB HL MM values were 50 and 59% of MS values at 1 and 2 kHz, respectively.

Unfortunately, previous studies examining AM/FM and AM^2 stimuli did not test both single and multiple conditions, thus preventing the subsequent calculation of their RE values. Amstrong (2006) revealed the MM condition was not significantly more efficient than the MS condition for AM stimuli at 80 dB SPL. Fontaine (2006) investigated ASSRs to 40 Hz at 80 dB SPL and found that MM and DM conditions were significantly more efficient than the MS condition, but not significantly different from each other.

Examination of raw amplitude data from Herdman and Stapells (2001) reveals their relative efficiency values for AM stimuli at 60 dB SPL to be quite similar to what was found in the current study at 60 dB HL. John et al (1998b) recorded ASSRs to AM stimuli at 60 and 75 dB SPL in MS and MM conditions at 1 and 2 kHz only. Their 60 dB SPL results are similar to ours at 60 dB HL, but at 75 dB SPL their RE value for 2 kHz is below that in the MS condition, a finding not duplicated in the current study.

Clinical Implications

In choosing optimal clinical testing parameters, both stimulus choice and presentation condition must be considered. The results of this study indicate that multiple-stimulus conditions are more efficient than the single condition for AM and AM^2 stimuli at 60 dB HL, and at least as efficient at 80 dB HL. If one were to choose the single-stimulus condition, AM/FM stimuli are best; however, use of AM/FM stimuli in multiple test presentations is not recommended due to the significant decrease in response amplitudes at 0.5 kHz (compared to other frequencies and stimuli).

Perhaps response interactions would be lessened if stimuli with broader spectral widths were only combined with one or two other frequencies per ear. For example, 1, 2, and 4 kHz could be combined into a multiple condition and 0.5 kHz could be tested separately in a single condition for AM/FM and AM^2 stimuli. Likewise, stimuli could be grouped to maximize frequency separation (i.e., 0.5 and 2 kHz versus 1 and 4 kHz). By exploring similar combinations, the most efficient methodology by which to attain response amplitudes may be determined.

Future Directions

Future research is required to investigate interactions in individuals with sensorineural hearing loss. Hearing-impaired individuals may have more interactions due to their broader cochlear filters (Moore, 1993) causing a given stimulus to activate a broader region along the basilar membrane. This may cause even a stimulus with a relatively narrow acoustic spectra (e.g., AM) to evoke more response interactions than what is seen in normal-hearing individuals. However, the effects of stimulus intensity on normal cochlear physiology must also be remembered, as cochlear filters may be wider just due to increased intensity. As well, individuals with SNHL often have unequal thresholds across the frequency range, both intra and interaurally. Such differences may significantly decrease the efficiency of testing multiple stimuli simultaneously, resulting in monotic testing being more efficient than dichotic testing.

Infants comprise another important population to investigate. Possible cochlear and/or neural auditory pathway immaturities may increase response interactions, negatively affecting response amplitudes (Hatton, 2008) and thus testing efficiency. Research is needed to investigate response amplitudes to (and efficiency of) various stimuli in infants. Such research should be extended to hearing-impaired infants, as this is ultimately the population of most interest.

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Appendix A: Corrected amplitude (nV) data

Appendix A1: Corrected amplitude (nV) data for AM stimuli at 80 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	187	144	164	102	40	51	80	76	62	66	89	66
2	70	107	118	78	60	40	62	66	62	50	41	68
3	44	51	77	91	60	49	63	61	31	51	47	62
4	169	134	111	104	88	62	78	118	40	52	74	133
5	138	108	107	90	48	48	42	83	33	79	45	96
6	27	68	73	83	61	77	37	76	52	41	54	61
7	106	93	100	90	70	48	65	90	67	50	52	67
8	189	158	92	75	75	68	107	122	41	40	127	150
9	171	141	126	119	51	74	56	87	31	39	78	139
10	44	66	81	68	32	41	37	57	49	46	71	78
11	153	128	121	111	70	66	74	108	56	77	52	123
12	139	98	83	58	60	51	54	58	78	70	40	54
13	88	86	63	66	22	43	37	58	19	34	43	57
14	53	87	72	106	75	40	54	117	**17**	37	27	93
15	122	102	88	68	36	44	25	49	38	39	29	32

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Amplitudes have been corrected for residual noise (Picton et al., 2003).

Bold values indicate amplitudes that met noise criterion but did not differ significantly from the background EEG noise.

Appendix A2: Corrected amplitude (nV) data for AM/FM stimuli at 80 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	183	225	194	126	34	60	80	101	36	88	74	75
2	123	139	144	86	38	34	57	86	31	61	72	79
3	81	94	118	129	18	65	57	93	31	29	54	80
4	169	151	87	167	58	100	71	123	32	68	73	154
5	159	152	154	135	**18**	72	74	124	**24**	91	91	121
6	56	97	123	138	32	42	58	75	**20**	51	69	75
7	47	129	146	129	**6**	59	56	91	**9**	41	34	83
8	91	232	163	90	**42**	59	51	81	**21**	48	53	111
9	168	204	118	145	39	47	35	126	**9**	27	40	106
10	85	84	134	75	35	45	71	72	45	65	86	91
11	173	204	163	155	59	63	86	141	56	41	92	113
12	159	153	113	101	31	57	65	83	42	67	66	53
13	118	121	98	98	19	47	46	79	13	30	53	82
14	101	162	103	136	**26**	47	63	119	**26**	41	39	101
15	146	85	104	102	**15**	51	48	78	20	55	49	51

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Amplitudes have been corrected for residual noise (Picton et al., 2003).

Bold values indicate amplitudes that met noise criterion but did not differ significantly from the background EEG noise.

Appendix A3: Corrected amplitude (nV) data for AM^2 stimuli at 80 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	167	159	159	111	84	71	77	93	69	81	80	102
2	84	89	107	77	66	57	54	72	56	48	39	70
3	31	43	59	85	46	55	47	74	**18**	54	68	66
4	127	174	125	113	90	91	77	102	48	36	124	191
5	153	130	138	112	89	64	67	104	47	83	68	93
6	66	86	91	103	56	67	70	75	57	54	77	56
7	98	95	87	84	95	40	61	97	100	63	78	85
8	160	131	159	97	73	65	84	123	59	60	65	97
9	115	140	113	137	49	47	45	107	37	57	63	104
10	57	56	83	75	73	64	42	40	65	50	92	94
11	146	139	135	126	90	86	71	114	69	97	54	92
12	132	145	85	76	93	87	85	58	103	84	51	53
13	102	99	72	73	40	44	47	69	22	46	48	63
14	79	64	86	142	64	29	56	109	49	36	51	96
15	76	77	96	69	62	47	58	72	50	51	34	67

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Amplitudes have been corrected for residual noise (Picton et al., 2003).

Bold values indicate amplitudes that met noise criterion but did not differ significantly from the background EEG noise.

Appendix A4: Corrected amplitude (nV) data for AM stimuli at 60 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	37	41	65	55	15	41	38	27	**19**	51	49	37
2	83	35	54	27	53	63	42	27	42	33	32	40
3	23	23	27	71	**21**	31	47	51	40	57	41	34
4	83	83	63	80	42	46	37	30	33	56	69	68
5	63	63	57	68	47	75	65	64	36	44	60	74
6	53	27	53	52	37	26	61	39	34	33	46	29
7	66	59	44	48	66	59	46	21	90	44	38	30
8	111	56	42	35	81	66	36	26	77	32	65	32
9	118	102	64	61	64	57	52	34	42	63	52	37
10	30	60	47	37	42	38	27	32	38	52	50	32
11	74	55	58	67	50	83	67	60	59	74	77	79
12	51	70	29	40	53	69	60	29	78	92	35	36
13	44	35	49	26	17	15	37	24	**13**	33	37	23
14	53	47	46	58	65	59	39	43	48	52	37	33
15	48	30	39	32	32	43	55	30	31	46	57	29

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Amplitudes have been corrected for residual noise (Picton et al., 2003).

Bold values indicate amplitudes that met noise criterion but did not differ significantly from the background EEG noise.

Appendix A5: Corrected amplitude (nV) data for AM/FM stimuli at 60 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	93	97	94	70	36	55	46	42	32	40	39	43
2	52	79	83	45	38	37	59	35	41	40	48	47
3	27	50	77	79	33	63	56	57	**28**	55	29	62
4	110	124	71	76	40	84	42	65	32	67	43	53
5	54	68	93	72	56	77	90	69	39	73	65	49
6	60	51	102	80	32	49	95	64	44	52	70	51
7	45	84	77	54	56	55	33	41	32	52	32	35
8	95	92	64	36	41	49	50	36	52	57	51	36
9	98	104	96	74	39	47	44	75	35	52	42	69
10	31	51	55	54	70	52	74	48	38	29	87	41
11	68	65	99	97	60	83	76	71	46	51	78	70
12	51	89	93	63	53	72	71	45	55	72	67	42
13	61	34	67	57	18	29	46	53	20	30	53	43
14	121	148	70	92	65	59	58	74	53	62	55	68
15	59	64	70	64	**24**	70	55	45	29	40	74	42

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Amplitudes have been corrected for residual noise (Picton et al., 2003).

Bold values indicate amplitudes that met noise criterion but did not differ significantly from the background EEG noise.

Appendix A6: Corrected amplitude (nV) data for AM^2 stimuli at 60 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	85	67	76	48	44	54	54	42	53	25	63	53
2	53	36	58	26	66	30	39	37	64	27	39	40
3	38	26	36	60	**23**	46	45	44	**24**	42	43	48
4	127	105	96	64	63	62	76	37	60	37	66	34
5	53	48	66	37	59	56	51	52	45	42	53	49
6	51	26	54	47	42	28	64	36	51	54	50	48
7	70	56	56	45	78	56	53	24	86	40	51	26
8	107	57	51	34	33	40	53	47	89	34	43	33
9	105	116	62	65	81	45	44	55	53	50	53	73
10	38	31	59	30	51	68	73	44	58	31	48	37
11	79	30	69	64	45	36	62	56	62	65	58	67
12	51	71	48	36	77	85	68	43	72	76	55	39
13	43	27	42	27	27	27	41	41	27	25	36	27
14	108	83	51	34	80	54	67	57	34	67	43	49
15	38	36	44	41	41	49	66	34	50	53	62	24

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Amplitudes have been corrected for residual noise (Picton et al., 2003).

Bold values indicate amplitudes that met noise criterion but did not differ significantly from the background EEG noise.

Appendix B: Circle radius noise (CR)

Appendix B1: EEG noise (nV) for AM stimuli at 80 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	30	11	22	16	29	29	27	26	28	29	27	30
2	28	14	11	25	25	23	22	20	29	28	26	25
3	24	18	15	16	26	24	22	19	25	26	23	22
4	29	27	28	27	30	28	23	23	30	28	26	25
5	30	24	18	30	22	19	18	18	29	26	25	24
6	22	20	16	16	29	27	27	24	28	29	23	23
7	18	20	20	13	30	27	28	25	24	23	20	19
8	24	21	23	20	28	27	28	28	29	28	28	29
9	30	30	30	29	29	28	27	24	30	27	27	26
10	19	29	22	19	29	25	25	24	29	25	27	27
11	21	29	21	17	25	23	20	21	29	25	23	22
12	17	16	14	27	25	25	24	23	29	29	27	26
13	29	29	29	28	14	14	12	11	15	12	12	12
14	30	23	30	20	22	20	17	16	30	27	25	23
15	16	16	14	16	19	17	15	13	21	19	17	16

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix B2: EEG noise (nV) for AM/FM stimuli at 80 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	16	24	11	21	21	22	18	18	22	22	21	21
2	20	21	17	18	28	29	28	27	26	24	25	22
3	21	21	18	30	20	18	19	15	27	24	23	22
4	27	20	29	29	30	25	24	23	30	26	25	24
5	29	29	29	28	19	18	17	17	30	28	27	25
6	22	19	16	30	28	29	26	24	28	29	29	28
7	29	30	29	30	30	28	27	24	29	30	29	26
8	30	30	29	28	24	22	23	23	30	26	28	29
9	30	30	29	27	29	27	27	25	15	15	13	14
10	18	29	20	24	25	25	25	24	29	28	26	27
11	30	29	28	18	30	29	27	24	29	28	25	24
12	19	21	14	24	23	21	19	17	26	23	21	19
13	15	20	13	12	14	13	12	12	17	15	13	13
14	26	17	18	14	30	26	23	23	27	26	23	22
15	19	30	14	13	19	17	17	15	19	16	16	15

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix B3: EEG noise (nV) for AM^2 stimuli at 80 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	12	13	10	9	21	17	18	19	16	13	12	11
2	21	30	14	15	13	11	12	12	28	25	24	25
3	23	19	29	15	22	20	19	19	22	23	20	19
4	29	30	26	19	30	29	27	28	21	22	19	18
5	29	27	26	24	29	29	24	24	30	30	27	22
6	18	25	16	16	18	17	16	14	24	21	23	20
7	18	29	30	30	30	26	28	26	30	30	29	28
8	25	30	30	19	30	30	28	26	30	28	26	29
9	24	19	18	26	28	25	22	21	17	15	14	12
10	17	22	29	20	28	27	26	24	26	27	29	27
11	19	18	18	22	29	27	28	27	27	29	27	25
12	29	18	15	30	19	18	16	14	29	27	24	27
13	14	12	12	11	13	11	12	12	17	17	17	16
14	30	26	20	19	23	20	18	16	23	20	20	20
15	30	21	14	14	24	23	24	22	23	20	20	17

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix B4: EEG noise (nV) for AM stimuli at 60 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	20	12	13	15	14	14	13	12	29	27	26	25
2	28	19	19	27	29	25	25	24	23	19	19	17
3	22	20	26	16	24	24	19	18	28	25	24	24
4	18	18	29	29	21	19	18	17	28	27	29	26
5	29	30	28	27	29	27	24	25	30	26	25	22
6	19	17	17	12	21	21	19	19	22	22	19	20
7	30	29	17	19	18	17	17	17	30	28	27	28
8	19	16	20	19	22	22	20	19	22	24	22	23
9	25	27	30	25	29	25	22	21	29	27	26	26
10	27	26	16	21	16	16	16	16	22	20	21	19
11	22	29	30	23	30	29	27	25	30	29	28	27
12	18	30	23	13	17	17	15	12	29	30	29	28
13	29	26	14	17	15	15	14	13	15	14	13	12
14	16	29	21	15	18	17	15	14	27	23	21	19
15	29	16	13	29	17	14	14	12	24	17	17	15

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix B5: EEG noise (nV) for AM/FM stimuli at 60 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	24	21	19	14	29	28	28	27	29	29	28	26
2	15	15	23	22	24	24	23	22	22	22	20	20
3	16	16	18	27	30	25	25	24	28	26	24	22
4	24	21	26	20	30	25	22	21	29	29	25	26
5	30	20	29	29	28	28	30	28	30	28	25	27
6	26	20	25	16	18	18	16	13	26	25	20	22
7	29	30	30	23	30	29	26	25	30	26	27	23
8	16	16	15	18	19	16	15	13	21	20	17	18
9	29	29	30	15	30	27	23	23	30	27	26	26
10	28	30	29	29	30	28	27	23	28	27	25	27
11	30	21	30	24	30	28	28	27	29	30	28	28
12	30	18	26	12	20	17	15	14	20	19	15	14
13	30	13	14	29	15	14	13	12	17	15	15	15
14	30	30	29	22	25	23	20	19	20	20	16	16
15	22	17	14	12	29	24	22	23	28	25	26	24

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix B6: EEG noise (nV) for AM^2 stimuli at 60 dB HL by condition and subject

	MS				MM				DM			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	30	20	11	19	18	17	16	17	24	23	21	20
2	25	28	18	26	19	19	19	19	22	21	21	20
3	17	16	29	20	28	25	27	21	21	19	17	15
4	30	28	25	29	22	20	20	19	27	29	26	25
5	18	29	22	30	30	24	21	19	30	29	25	23
6	17	21	14	29	19	18	17	16	26	23	22	20
7	30	29	30	30	29	26	25	23	29	26	26	24
8	21	16	29	14	30	27	25	24	26	23	22	22
9	30	24	22	30	30	26	27	25	29	27	26	23
10	27	26	30	23	29	27	23	22	27	25	26	24
11	24	28	29	20	25	23	21	23	30	26	25	23
12	21	16	14	13	19	17	14	12	30	28	29	24
13	16	16	12	15	24	24	20	20	22	23	22	22
14	29	17	16	30	27	29	23	23	22	19	17	15
15	30	12	11	29	27	25	22	21	19	17	16	15

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix C: Phase (degrees)

Appendix C1: Phase (degrees) of AM stimuli at 80 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	265.039	230.432	215.764	185.913	179.095	218.801	208.029	188.262	225.046	217.770	219.546	202.185
2	199.664	164.771	138.931	110.798	125.294	105.986	125.122	103.808	136.066	127.873	149.473	104.324
3	209.805	183.793	188.434	164.714	99.798	126.440	184.825	169.756	159.557	127.758	190.955	154.802
4	264.867	223.155	210.092	176.574	210.493	176.287	178.293	175.256	238.167	183.449	261.372	253.923
5	231.234	183.621	185.856	173.709	147.296	123.461	154.286	192.216	172.678	148.614	187.346	238.396
6	161.620	70.176	121.685	145.348	113.090	128.274	143.629	157.552	125.008	114.236	135.149	148.900
7	245.214	200.065	188.434	160.073	218.572	175.142	180.126	161.906	234.672	175.485	215.993	153.656
8	232.609	193.877	183.220	146.837	197.601	165.802	157.781	110.856	235.646	198.690	162.250	121.627
9	240.058	232.896	197.029	174.225	164.485	209.404	192.846	178.694	190.783	200.008	202.071	202.185
10	191.986	186.257	184.366	160.989	139.790	158.067	162.995	160.015	128.216	137.269	173.709	181.387
11	212.613	172.907	172.506	140.879	175.256	166.031	153.598	136.925	182.361	140.478	171.818	137.498
12	228.541	173.423	155.718	163.281	143.285	148.957	137.212	154.171	178.923	142.483	162.365	179.954
13	247.735	197.945	183.621	163.682	156.463	160.989	179.042	161.677	182.762	156.578	171.360	152.281
14	267.502	212.670	231.406	191.471	198.805	163.797	187.804	186.658	-35.019	175.944	194.622	191.012
15	226.708	189.351	171.818	166.547	134.920	138.873	143.285	156.864	131.826	120.711	176.689	169.584

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix C2: Phase (degrees) of AM/FM stimuli at 80 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	-80.226	218.400	208.545	203.560	234.385	214.275	192.330	203.102	224.702	198.003	205.394	209.290
2	231.692	145.462	136.696	145.233	186.372	125.753	148.671	143.056	198.633	115.726	147.640	125.982
3	242.407	155.432	159.729	194.221	90.573	115.955	175.485	164.026	96.245	103.178	172.678	184.710
4	-79.366	195.883	244.240	180.871	210.837	165.057	176.517	200.638	254.267	190.268	-79.939	-85.669
5	237.823	163.682	169.928	173.537	158.526	109.595	147.869	173.079	165.172	113.549	150.963	176.058
6	211.238	84.099	122.372	155.203	132.399	99.855	137.212	170.157	177.548	123.461	128.617	182.017
7	-20.695	190.726	199.836	169.584	97.563	164.198	196.570	158.354	168.954	168.323	188.835	159.786
8	-75.699	201.097	174.339	172.105	184.653	173.595	178.006	147.869	244.011	177.720	159.213	157.151
9	264.752	200.237	194.794	193.533	225.562	165.860	203.789	170.042	186.658	178.980	183.908	178.866
10	233.812	145.233	169.297	169.240	128.560	129.534	165.573	159.156	116.700	123.633	176.975	165.000
11	-88.534	179.152	153.598	150.332	188.320	147.353	167.578	151.650	180.585	110.569	161.276	134.977
12	256.903	155.432	145.405	161.448	136.581	122.315	144.145	177.605	153.656	130.279	149.645	171.303
13	244.641	175.371	160.703	171.818	205.451	150.848	149.072	175.199	159.328	133.602	142.196	183.736
14	-85.382	187.804	189.236	196.513	150.447	149.874	185.283	199.148	-69.397	202.013	203.904	212.899
15	244.412	169.183	170.157	169.469	217.254	115.096	158.526	174.225	161.906	120.309	184.080	178.923

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix C3: Phase (degrees) of AM^2 stimuli at 80 dB HL by condition and subject

	MS				MM				DM			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	245.100	220.061	199.378	187.632	193.132	206.826	199.836	179.897	194.393	192.903	201.097	190.955
2	185.340	148.556	119.794	109.366	109.423	99.912	124.091	113.262	149.473	100.657	115.153	112.231
3	143.743	160.359	191.127	159.442	82.265	119.565	170.787	150.734	119.393	114.465	170.042	146.150
4	243.324	197.945	183.220	176.918	186.944	164.427	192.903	213.530	190.955	168.266	-77.705	268.018
5	213.358	156.005	175.371	153.140	143.686	130.909	151.478	162.021	178.236	120.882	136.696	157.437
6	97.563	69.603	103.751	142.827	79.629	102.834	117.330	139.618	127.586	106.788	120.768	148.098
7	208.087	202.644	191.929	172.334	186.085	173.251	170.902	140.306	210.780	167.980	184.194	154.916
8	215.363	217.369	212.384	153.255	171.990	150.390	167.177	131.253	195.482	193.877	177.090	121.742
9	226.765	201.154	177.949	157.437	160.989	188.721	138.816	159.099	161.505	160.359	174.912	168.667
10	139.675	163.568	172.621	175.772	113.147	132.112	177.777	150.161	107.131	147.754	162.135	167.006
11	196.226	165.688	159.729	140.363	146.093	149.301	142.139	132.342	169.698	138.873	145.119	136.009
12	205.336	149.645	153.369	165.630	156.291	147.525	146.494	147.238	146.952	152.452	162.135	150.161
13	216.394	174.912	158.698	152.395	145.577	146.952	154.744	147.067	151.135	148.499	172.048	173.537
14	240.745	189.408	193.419	171.704	177.376	188.778	170.959	176.058	227.510	173.423	175.543	163.625
15	232.265	191.471	152.452	156.177	109.882	106.100	129.419	154.171	134.576	127.987	171.016	158.812

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix C4: Phase (degrees) of AM stimuli at 60 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	252.090	203.216	200.867	183.220	188.721	194.794	193.018	176.116	269.737	196.857	207.456	197.029
2	142.311	99.110	110.856	113.434	137.384	122.601	182.246	128.675	146.551	115.669	166.891	103.694
3	158.010	127.013	189.236	154.687	142.027	101.370	155.360	162.977	175.256	136.238	172.391	153.426
4	242.636	177.777	206.024	178.006	192.731	169.469	190.440	201.841	193.705	168.667	257.590	225.676
5	208.087	136.639	133.946	151.135	166.203	133.258	128.847	128.388	215.993	136.811	151.822	142.483
6	157.666	49.836	82.838	125.695	138.014	93.667	98.537	145.749	142.483	103.178	89.141	132.743
7	211.524	156.807	170.787	120.424	179.840	154.171	179.381	132.399	206.139	168.209	228.770	169.698
8	195.596	170.099	145.691	114.752	164.771	165.860	133.774	118.304	196.112	194.851	166.834	111.486
9	222.984	177.777	151.192	166.318	167.407	187.460	166.031	164.599	183.736	175.428	200.237	176.631
10	120.367	132.513	151.536	159.271	125.351	133.430	158.067	149.989	135.894	124.377	167.865	148.327
11	216.738	152.968	149.301	137.040	192.388	140.363	160.932	152.911	233.469	152.395	172.964	150.332
12	165.115	160.417	136.753	141.795	157.724	152.796	149.015	125.237	171.933	149.301	142.368	150.103
13	208.946	161.849	132.972	136.983	197.315	153.770	145.290	141.108	194.450	148.785	138.014	138.472
14	247.907	201.899	196.742	159.557	199.435	195.825	197.601	168.209	-84.007	209.118	220.119	177.892
15	169.584	95.730	136.925	136.868	149.072	102.605	143.514	146.666	152.682	105.470	148.270	145.462

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix C5: Phase (degrees) of AM/FM stimuli at 60 dB HL by condition and subject

	MS				**MM**				**DM**			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	265.440	180.012	168.782	179.897	223.098	148.213	169.125	169.240	244.298	164.141	171.417	186.658
2	184.481	92.693	127.070	149.358	139.504	109.824	127.013	114.293	173.251	112.173	136.696	120.481
3	158.698	79.801	129.935	167.349	149.072	88.396	210.436	206.654	150.275	91.146	135.264	170.271
4	-84.236	153.942	173.308	152.281	198.060	136.066	182.533	183.564	204.248	147.983	161.161	166.948
5	235.302	116.413	115.325	126.497	151.536	82.953	119.565	165.630	148.270	84.671	116.127	189.179
6	159.958	61.352	93.724	133.316	149.645	83.755	102.089	138.243	134.232	64.389	85.073	135.149
7	246.360	130.966	181.845	142.941	196.971	125.867	143.056	175.428	190.268	144.889	154.802	176.689
8	201.555	143.113	143.915	136.123	163.453	145.004	146.150	111.085	170.386	147.468	161.906	162.651
9	252.720	179.095	157.265	155.833	190.611	119.908	159.442	152.911	213.530	156.578	178.293	179.782
10	159.213	120.711	155.088	158.526	148.098	90.229	145.749	153.656	133.373	72.639	156.349	144.259
11	221.379	100.199	134.175	130.222	155.890	80.374	112.632	121.112	125.180	71.837	137.785	125.638
12	181.043	121.742	138.300	140.478	163.740	107.590	145.863	144.488	178.465	104.152	138.071	136.410
13	219.947	122.028	130.107	163.797	172.621	130.394	126.154	161.391	174.970	79.057	114.179	164.943
14	-57.537	179.038	195.252	177.720	238.110	184.309	175.944	169.355	-67.048	185.627	184.080	175.886
15	204.821	65.535	130.336	142.368	133.029	85.531	144.145	140.821	142.483	77.968	151.765	132.170

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix C6: Phase (degrees) of AM^2 stimuli at 60 dB HL by condition and subject

	MS				MM				DM			
Subject	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**	**0.5 kHz**	**1 kHz**	**2 kHz**	**4 kHz**
1	269.336	179.954	167.808	160.760	168.209	162.193	174.053	190.210	213.186	183.048	163.682	143.342
2	128.216	116.528	94.584	83.927	97.563	88.281	122.429	87.479	122.028	112.575	103.694	100.256
3	115.038	128.331	162.938	140.363	138.169	97.118	140.275	164.587	132.988	84.895	157.730	151.227
4	243.553	148.213	162.880	134.060	166.433	157.895	169.813	167.808	178.694	196.971	181.731	165.229
5	171.646	129.591	131.138	148.957	126.326	112.002	121.799	119.278	105.355	80.088	153.083	140.535
6	119.737	59.977	56.253	121.570	117.559	74.874	72.124	125.982	115.382	71.493	72.697	135.837
7	193.304	147.353	167.177	133.029	173.079	178.579	168.724	150.218	193.075	153.598	154.802	167.063
8	180.699	139.618	167.865	118.934	191.986	154.286	191.242	125.810	166.490	159.901	149.473	107.131
9	205.279	168.667	158.297	156.463	154.802	195.539	168.896	138.701	172.735	171.188	176.631	156.177
10	132.170	116.012	125.237	140.535	122.143	128.732	134.633	141.108	99.855	102.089	133.545	135.321
11	177.376	94.469	107.819	131.425	163.740	107.819	146.837	108.105	181.158	106.329	130.107	117.445
12	142.196	127.586	129.419	126.612	145.119	114.351	120.080	134.232	140.649	120.481	125.294	150.390
13	203.675	170.386	127.242	106.444	194.106	118.304	125.982	125.122	214.446	130.107	116.184	119.106
14	256.215	177.376	169.698	188.148	199.951	179.210	182.017	165.516	246.188	196.627	182.361	156.234
15	134.633	67.139	123.690	140.191	125.523	96.245	129.821	139.618	129.706	102.204	120.596	108.507

Conditions: monotic single (MS), monotic multiple (MM), dichotic multiple (DM).

Appendix D: Relative efficiency data

Appendix D1: Relative efficiency data of AM stimuli at 80 dB HL by condition and subject

	MM				**DM**			
Subject	**0.5**	**1**	**2**	**4**	**0.5**	**1**	**2**	**4**
1	0.43	0.71	0.98	1.49	0.94	1.30	1.53	1.83
2	1.71	0.75	1.05	1.69	2.51	1.32	0.98	2.47
3	2.73	1.92	1.64	1.34	1.99	2.83	1.73	1.93
4	1.04	0.93	1.41	2.27	0.67	1.10	1.89	3.62
5	0.70	0.89	0.79	1.84	0.68	2.07	1.19	3.02
6	4.52	2.26	1.01	1.83	5.45	1.71	2.09	2.08
7	1.32	1.03	1.30	2.00	1.79	1.52	1.47	2.11
8	0.79	0.86	2.33	3.25	0.61	0.72	3.90	5.66
9	0.60	1.05	0.89	1.46	0.51	0.78	1.75	3.30
10	1.45	1.24	0.91	1.68	3.15	1.97	2.48	3.24
11	0.92	1.03	1.22	1.95	1.04	1.70	1.22	3.13
12	0.86	1.04	1.30	2.00	1.59	2.02	1.36	2.63
13	0.50	1.00	1.17	1.76	0.61	1.12	1.93	2.44
14	2.83	0.92	1.50	2.21	0.91	1.20	1.06	2.48
15	0.59	0.86	0.57	1.44	0.88	1.08	0.93	1.33

Conditions: monotic multiple (MM) and dichotic multiple (DM).

Note: Relative efficiency values for monotic single (MS) condition all equal "1".

Appendix D2: Relative efficiency data of AM/FM stimuli at 80 dB HL by condition and subject

	MM				DM			
Subject	**0.5**	**1**	**2**	**4**	**0.5**	**1**	**2**	**4**
1	0.37	0.53	0.82	1.60	0.56	1.11	1.08	1.68
2	0.62	0.49	0.79	2.00	0.71	1.24	1.41	2.60
3	0.44	1.38	0.97	1.44	1.08	0.87	1.29	1.75
4	0.69	1.32	1.63	1.47	0.54	1.27	2.37	2.61
5	0.23	0.95	0.96	1.84	0.43	1.69	1.67	2.54
6	1.14	0.87	0.94	1.09	1.01	1.49	1.59	1.54
7	0.26	0.91	0.77	1.41	0.54	0.90	0.66	1.82
8	0.92	0.51	0.63	1.80	0.65	0.59	0.92	3.49
9	0.46	0.46	0.59	1.74	0.15	0.37	0.96	2.07
10	0.82	1.07	1.06	1.92	1.50	2.19	1.82	3.43
11	0.68	0.62	1.06	1.82	0.92	0.57	1.60	2.06
12	0.39	0.75	1.15	1.64	0.75	1.24	1.65	1.48
13	0.32	0.78	0.94	1.61	0.31	0.70	1.53	2.37
14	0.51	0.58	1.22	1.75	0.73	0.72	1.07	2.10
15	0.21	1.20	0.92	1.53	0.39	1.83	1.33	1.41

Conditions: monotic multiple (MM) and dichotic multiple (DM).

Note: Relative efficiency values for monotic single (MS) condition all equal "1".

Appendix D3: Relative efficiency data of AM^2 stimuli at 80 dB HL by condition and subject

	MM				DM			
Subject	**0.5**	**1**	**2**	**4**	**0.5**	**1**	**2**	**4**
1	1.01	0.89	0.97	1.68	1.17	1.44	1.42	2.60
2	1.57	1.28	1.01	1.87	1.89	1.53	1.03	2.57
3	2.97	2.56	1.59	1.74	1.64	3.55	3.26	2.20
4	1.42	1.05	1.23	1.81	1.07	0.59	2.81	4.78
5	1.16	0.98	0.97	1.86	0.87	1.81	1.39	2.35
6	1.70	1.56	1.54	1.46	2.44	1.78	2.39	1.54
7	1.94	0.84	1.40	2.31	2.89	1.88	2.54	2.86
8	0.91	0.99	1.06	2.54	1.04	1.30	1.16	2.83
9	0.85	0.67	0.80	1.56	0.91	1.15	1.58	2.15
10	2.56	2.29	1.01	1.07	3.23	2.53	3.14	3.54
11	1.23	1.24	1.05	1.81	1.34	1.97	1.13	2.07
12	1.41	1.20	2.00	1.53	2.21	1.64	1.70	1.97
13	0.78	0.89	1.31	1.89	0.61	1.31	1.89	2.44
14	1.62	0.91	1.30	1.54	1.75	1.59	1.68	1.91
15	1.63	1.22	1.21	2.09	1.86	1.87	1.00	2.75

Conditions: monotic multiple (MM) and dichotic multiple (DM).

Note: Relative efficiency values for monotic single (MS) condition all equal "1".

Appendix D4: Relative efficiency data of AM stimuli at 60 dB HL by condition and subject

	MM				**DM**			
Subject	**0.5**	**1**	**2**	**4**	**0.5**	**1**	**2**	**4**
1	0.81	2.00	1.17	0.98	1.45	3.52	2.13	1.90
2	1.28	3.60	1.56	2.00	1.43	2.67	1.68	4.19
3	1.83	2.70	3.48	1.44	4.92	7.01	4.30	1.35
4	1.01	1.11	1.17	0.75	1.12	1.91	3.10	2.40
5	1.49	2.38	2.28	1.88	1.62	1.98	2.98	3.08
6	1.40	1.93	2.30	1.50	1.81	3.46	2.45	1.58
7	2.00	2.00	2.09	0.88	3.86	2.11	2.44	1.77
8	1.46	2.36	1.71	1.49	1.96	1.62	4.38	2.59
9	1.08	1.12	1.63	1.11	1.01	1.75	2.30	1.72
10	2.80	1.27	1.15	1.73	3.58	2.45	3.01	2.45
11	1.35	3.02	2.31	1.79	2.26	3.81	3.75	3.34
12	2.08	1.97	4.14	1.45	4.33	3.72	3.41	2.55
13	0.77	0.86	1.51	1.85	0.84	2.67	2.14	2.50
14	2.45	2.51	1.70	1.48	2.56	3.13	2.28	1.61
15	1.33	2.87	2.82	1.88	1.83	4.34	4.13	2.56

Conditions: monotic multiple (MM) and dichotic multiple (DM).

Note: Relative efficiency values for monotic single (MS) condition all equal "1".

Appendix D5: Relative efficiency data of AM/FM stimuli at 60 dB HL by condition and subject

	MM				**DM**			
Subject	**0.5**	**1**	**2**	**4**	**0.5**	**1**	**2**	**4**
1	0.77	1.13	0.98	1.20	0.97	1.17	1.17	1.74
2	1.46	0.94	1.42	1.56	2.23	1.43	1.64	2.95
3	2.44	2.52	1.45	1.44	2.93	3.11	1.07	2.22
4	0.73	1.35	1.18	1.71	0.82	1.53	1.71	1.97
5	2.07	2.26	1.94	1.92	2.04	3.04	1.98	1.92
6	1.07	1.92	1.86	1.60	2.07	2.88	1.94	1.80
7	2.49	1.31	0.86	1.52	2.01	1.75	1.18	1.83
8	0.86	1.07	1.56	2.00	1.55	1.75	2.25	2.83
9	0.80	0.90	0.92	2.03	1.01	1.41	1.24	2.64
10	4.52	2.04	2.69	1.78	3.47	1.61	4.47	2.15
11	1.76	2.55	1.54	1.46	1.91	2.22	2.23	2.04
12	2.08	1.62	1.53	1.43	3.05	2.29	2.04	1.89
13	0.59	1.71	1.37	1.86	0.93	2.50	2.24	2.13
14	1.07	0.80	1.66	1.61	1.24	1.18	2.22	2.09
15	0.81	2.19	1.57	1.41	1.39	1.77	2.99	1.86

Conditions: monotic multiple (MM) and dichotic multiple (DM).

Note: Relative efficiency values for monotic single (MS) condition all equal "1".

Appendix D6: Relative efficiency data of AM^2 stimuli at 60 dB HL by condition and subject

	MM				**DM**			
Subject	**0.5**	**1**	**2**	**4**	**0.5**	**1**	**2**	**4**
1	1.04	1.61	1.42	1.75	1.76	1.06	2.34	3.12
2	2.49	1.67	1.34	2.85	3.42	2.12	1.90	4.35
3	1.21	3.54	2.50	1.47	1.79	4.57	3.38	2.26
4	0.99	1.18	1.58	1.16	1.34	1.00	1.94	1.50
5	2.23	2.33	1.55	2.81	2.40	2.47	2.27	3.75
6	1.65	2.15	2.37	1.53	2.83	5.87	2.62	2.89
7	2.23	2.00	1.89	1.07	3.47	2.02	2.58	1.63
8	0.62	1.40	2.08	2.76	2.35	1.69	2.38	2.75
9	1.54	0.78	1.42	1.69	1.43	1.22	2.42	3.18
10	2.68	4.39	2.47	2.93	4.32	2.83	2.30	3.49
11	1.14	2.40	1.80	1.75	2.22	6.13	2.38	2.96
12	3.02	2.39	2.83	2.39	3.99	3.03	3.24	3.06
13	1.26	2.00	1.95	3.04	1.78	2.62	2.42	2.83
14	1.48	1.30	2.63	3.35	0.89	2.28	2.38	4.08
15	2.16	2.72	3.00	1.66	3.72	4.16	3.99	1.66

Conditions: monotic multiple (MM) and dichotic multiple (DM).

Note: Relative efficiency values for monotic single (MS) condition all equal "1".

Appendix E: Behavioural research ethics board (BREB) approval

The University of British Columbia
Office of Research Services
Behavioural Research Ethics Board
Suite 102, 6190 Agronomy Road, Vancouver, B.C. V6T 1Z3

CERTIFICATE OF APPROVAL - MINIMAL RISK

PRINCIPAL INVESTIGATOR:	INSTITUTION / DEPARTMENT:	UBC BREB NUMBER:
David R. Stapells	UBC/Medicine, Faculty of/Audiology & Speech Sciences	H08-00874

INSTITUTION(S) WHERE RESEARCH WILL BE CARRIED OUT:

Institution	Site
UBC	Vancouver (excludes UBC Hospital)

Other locations where the research will be conducted:
WorkSafe BC, Richmond (Audiology division) Western Institute for the Deaf and Hard of Hearing, Vancouver

CO-INVESTIGATOR(S):

Grace S Shyng
Lori Wood

SPONSORING AGENCIES:

Natural Sciences and Engineering Research Council of Canada (NSERC)

PROJECT TITLE:
Efficiency of multiple ASSRs in adults with hearing loss

CERTIFICATE EXPIRY DATE: June 23, 2009

DOCUMENTS INCLUDED IN THIS APPROVAL:	DATE APPROVED:
	June 23, 2008

Document Name	Version	Date
Consent Forms:		
Consent form	N/A	May 28, 2008
Advertisements:		
Recruitment flyer	N/A	May 28, 2008
Letter of Initial Contact:		
Invitation_ASSRefficiency_May27_2008	N/A	May 27, 2008

The application for ethical review and the document(s) listed above have been reviewed and the procedures were found to be acceptable on ethical grounds for research involving human subjects.

Approval is issued on behalf of the Behavioural Research Ethics Board
and signed electronically by one of the following:

Dr. M. Judith Lynam, Chair
Dr. Ken Craig, Chair
Dr. Jim Rupert, Associate Chair
Dr. Laurie Ford, Associate Chair
Dr. Daniel Salhani, Associate Chair
Dr. Anita Ho, Associate Chair