CHAPTER FIVE

Possible Roles for the Auditory Steady-State Responses in Fitting Hearing Aids

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Introduction

The advent of universal newborn hearing screening will ensure that infants born with a significant hearing-impairment will be fitted with hearing aids within the first few months of age. Unfortunately, accurate individual real-ear acoustic measurements are not always possible at this age, and infants cannot provide reliable behavioral responses to either aided or unaided sounds. The fitting of young infants with hearing aids is therefore much more uncertain than in older children or adults. Electrophysiological tests can assist those who provide aids since these tests can measure auditory function objectively. This paper considers the possible roles that one particular electrophysiological test – the auditory steady-state responses – might play in the fitting of hearing aids.

Hearing aid fitting follows three main steps – assessing the hearing loss, prescribing an aid to compensate for this hearing loss, and verifying that this aid provides adequate hearing (Stelmachowicz 2000; Scollie and Seewald 2001). Each step provides its own set of data. Assessment evaluates the hearing thresholds, maximum comfort levels and loudness discomfort levels at different frequencies. Prescription sets the gain of a selected aid so that the average spectrum of speech sounds (Cornelisse, Gagné and Seewald 1991; Stelmachowicz, Mace, Kopun and Carney 1993) is amplified to levels within the range of the unaided thresholds and the loudness discomfort levels (Byrne and Dillon 1986; Cornelisse, Seewald and Jamieson 1995). The data at this step concern the real ear insertion gain of the hearing aid at the different frequencies, a measurement that combines the amplifier gain functions with the resonance characteristics of the individual external ear. Verification provides some measurement of how well sounds are heard when the aid is used at its prescribed settings (Stelmachowicz, Kopun, Mace, Lewis and Nittrouer 1995).

Some measurements required during these fitting procedures are objective and some are subjective. Insertion gain and its related measurements, obtained using electro-acoustical procedures, are objective in the sense that they do not require any active response on the part of the subject. However, the infant must agree not to move or cry during the measurement procedure. Average normative values from other infants can be used, but these do not consider individual variability. Conventional audiometric measurements of threshold, loudness discomfort and speech perception are all subjective measurements, and are not possible in young infants. Objective versions of these tests would be very helpful.

Subjective measurements assess the audibility, discriminability and intelligibility of sounds. These three terms overlap in their usage (Stach 1997; Mendel, Danhauer and Singh 1999), but for the purposes of this paper we shall try to distinguish between them. A sound is "audible" if it occurs at an intensity greater than hearing threshold. For a speech sound to be fully audible, all frequency-regions of the sound should be above threshold (Stelmachowicz et al. 1995; Stelmachowicz, Kopun, Mace and Lewis 1996). Often this means that the sound is then discriminible from a different speech sound, but this is not necessarily so if distortion occurs in either the amplification of the sound or its neural processing. Sounds are "discriminible" if the subject can reliably distinguish between them. This term is often used in the context of differentiating between different speech sounds but

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we prefer a more generic meaning. Thresholds for differentiating between different sounds on the basis of their frequency or intensity are often termed "limens" in order to distinguish them from hearing threshold. A sound is "intelligible" if it can be meaningfully understood. This involves both discriminating the sound from similar sounds and recognizing that it is equivalent to some stored template of a sound that has a meaning. These three different abilities are mainly related to three levels of processing in the auditory system: the ear (audibility), the brainstem (discriminability) and the cortex (intelligibility).

These different hearing abilities can be considered from two directions. The bottom-up view assesses whether the sound is presented to the ear at a high enough level and with a sufficient lack of distortion so that it is capable of being heard, distinguished or recognized. The top-down perspective assesses the ability of the individual to recognize the meaning of a sound on the basis of discriminating what has been heard from other meaningful sounds. In a sense, there are two approaches to fitting aids – to make the sound optimally audible and to make the perception maximally intelligible.

Auditory steady-state responses may provide us with some estimates of both the audibility and the discriminibility of sounds. The great advantages of these measurements are that they are objective and can be recorded in infants. The information they provide can be combined with electro-acoustical measurements to decrease the uncertainties inherent in fitting hearing aids to hearing-impaired infants. We envision three steps, with a role for the steady-state responses in the first and third. First, the auditory steady-state responses can estimate hearing thresholds at different frequencies. Second, electro-acoustical measurements can take these thresholds and prescribe the necessary gain for a hearing aid. Third, the auditory steady-state responses can verify that the aid is working and that the brain is both receiving sounds and discriminating them.

This paper first reviews how the auditory steady-state responses can estimate the pure-tone audiogram, and then considers some preliminary data about how these responses might estimate the brain's ability to discriminate sounds. The first of these roles is established in adults and already tested in infants, whereas the second is in its initial studies. At present one can justifiably employ the auditory steady-state responses in the first role, but one can only entertain the possibilities of these responses in the second role.

Estimating the Pure-Tone Audiogram Using Auditory Steady-State Responses

The procedures of newborn hearing screening provide techniques to detect whether a hearing loss is present, to confirm that this is not transient, and to assess the severity of the loss. Auditory brainstem responses to clicks can be used at each of these steps; otoacoustic emissions can be used instead of the auditory brainstem response at the first step. Once identified, the hearing-impaired infant is referred for hearing aids. However, fitting aids requires some knowledge of the hearing thresholds at different frequencies. How best to obtain this information is not known. In the field of detecting and treating infant hearing loss, this is presently what we understand the least.

Auditory brainstem responses can measure frequency-specific thresholds using two main approaches (Stapells, Picton and Durieux-Smith 1994). The first presents a click and isolates responses from different regions of the cochlea using high-pass masking (Ponton, Eggermont, Coupland and Winkelaar 1992). The second and more widely used approach presents brief tones with or without masking noise in order to limit the spectral splatter caused by the brevity of the stimulus. Stapells (2000a, 2000b) has reviewed the use of tone-evoked brainstem responses to assess hearing thresholds in infants and young children. Some of these data are given in table 1 for later comparison with the auditory steady-state responses.

Estimating the audiogram using the tone-evoked auditory brainstem responses has limitations. First, recognizing the responses is not always an easy task. The latency and morphology of the responses vary with the type of brief tone used as a stimulus, the intensity of the stimulus, the frequency-bandpass of the amplifiers and the age of the infant. Second, the threshold is not precisely estimated. Although on average the thresholds for the tone-evoked brainstem response are about 10 dB above behavioral threshold, the differences between physiological and behavioral thresholds have a standard deviation of about 10 dB. This means that in about one in twenty subjects behavioral thresholds are under- or over-estimated by 20 dB. Third, the procedure takes a long time. If the infant condescends to sleep through the entire testing procedure, it might require two hours to obtain

Table 1. Frequency-Specific Thresholds Using Physiological Tests. Mean thresholds ± standard deviations. The data from the Stapells study are taken from tables 5 and 6 with the standard deviations calculated from the standard errors (by multiplying by the square root of the number of subjects). The data for the normal babies are estimated in dB nHL using the adult behavioral thresholds of Herdman and Stapells (2001) for a sound-attenuated chamber: 11, 9, 8 and 7 dB for 500, 1000, 2000 and 4000 Hz respectively. The data for tone-ABRs and for MASTER are generally comparable for the different groups of subjects except that the normal children tested with ABRs were generally much older than the babies tested with MASTER.

Response	Paper	Subjects	Physiological-Behavioral Differences (dB)			
Tone-ABR	Stapells (2000b)	Normal Adults	20±13	16±10	13±7	12±8
		Normal Children	20±10	17±6	14±7	16±10
		Hearing-Impaired Children	6±15	5±14	1±12	–8±12
MASTER	Lins et al. (1996)	Normal Adults	14±11	12±11	11±8	13±11
		Normal Babies	34±13	20±10	18±8	24±10
		Hearing-Impaired Children	9±9	13±12	11±10	12±13
	Picton et al (1998)	Aided Children	17±8	13±8	14±8	17±13

reliable thresholds at three or four frequencies in each ear. More often than not, the infant wakes up prior to the end of the testing period, and one is left with only a partial audiogram.

In recent years the auditory steady-state responses have given us a different approach to measuring the brain's responses to sound. Rather than reflecting the transient effects of a single stimulus, the steady-state responses represent the unchanging effects of a regularly repeated stimulus. Steady-state responses are usually evoked by rapidly recurring stimuli or by the regular modulation of a continuous tone. Auditory steady-state responses were initially recorded at stimulus rates between 30 and 50 Hz (Galambos, Makeig and Talmachoff 1981), and these 40-Hz responses provide excellent audiometric information in adults and older children. However, these responses are attenuated by sleep and are difficult to record in infants (Stapells, Galambos, Costello and Makeig 1988). Attention has therefore shifted to responses evoked by stimulus rates of over 70 Hz, which can be reliably recorded down to near-threshold levels in newborn infants and young children (Rickards et al. 1994; Aoyagi et al. 1994; Lins et al. 1996; Perez-Abalo et al. 2001; Savio, Cárdenas, Pérez-Abalo, González and Valdés 2001; Cone-Wesson, Parker, Swiderski and Rickards 2002).

Auditory steady-state responses are most easily measured in the frequency domain – as peaks in a spectrum rather than peaks in a time-waveform (John and Picton 2000; Picton, Dimitrijevic and John in press). Figure 1 shows how these responses are measured. First, one records a sweep of electroencephalographic activity during which an integer number of cycles of stimulation occurs. In this example, the stimulus was an amplitude-modulated tone with 80 cycles of modulation occurring within a sweep lasting 1.024 seconds. Here, two hundred sweeps have been averaged together. Within the averaged sweep, one can just see the response riding on the slower background activity. The response has been made easier to observe by using spline-techniques to collapse the sweep down to two cycles. However, one still has to pick out the peaks and decide whether they are occurring at the correct latency. If one converts the average sweep into the frequency domain using a Fast Fourier Transform, the response easily is seen in the spectrum at the frequency of stimulation (80/1.024 or 78.125 Hz). Statistics can compare this response to the noise levels at adjacent frequencies in the spectrum and provide the probability that the response is significantly larger than these noise levels. For visual simplicity, the figure presents data recorded using a brief 1.024-second sweep. Our current procedures use much longer sweeps to provide a better resolution of the frequencies (John and Picton 2000).

In the context of objective audiometry, the auditory steady-state responses offer some advantages over transient responses. First, the response is easy to recognize, since the statistical techniques that distinguish the response from the background noise in which it is recorded (Dobie and Wilson 1993, 1996; John and Picton 2000) need not vary with the latency or morphology of the response. Second, thresholds can be estimated with about the same accuracy (table 1) and the same frequency-specificity (Herdman, Picton and Stapells in review) as when using tone-evoked

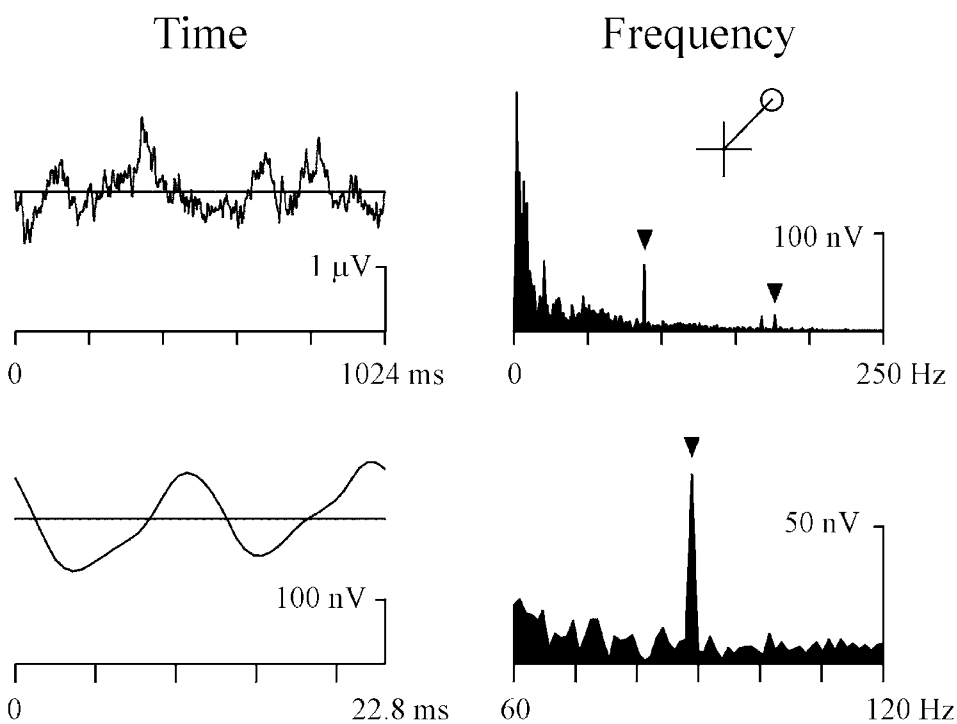

Figure 1. Recording auditory steady-state responses. This figure shows how the auditory steady-state responses are recorded and measured. The upper left tracing shows the average of 200 sweeps each lasting 1.024s, recorded from the vertex in response to a 70-dB SPL AM tone with exactly 80 cycles within the sweep. The lower left tracing shows the response collapsed down to 2 cycles of the stimulus (averaging together each of the forty 2-cycle periods in the full sweep). The upper right of the figure shows the response transferred into the frequency domain by means of a Fast Fourier Transform. The spectrum shows the amplitudes of the response out to 250 Hz. A clear response can be identified (arrowheads) at the exact frequency of stimulation (78.125 Hz) and at double this frequency. The diagram plotted above the spectrum represents the amplitude and phase of the response at 78.125 Hz. The cross shows the axes of this polar plot. The length of the line leading upward and toward the right from the origin of the axes shows the amplitude of the response (equal to the height of the spectrum at 78.125 Hz) and the angle this makes with the horizontal axis represents the phase of the response. The circle around the distal end of the line represents the confidence limits of the noise (at adjacent frequencies in the spectrum). Since the origin of the plot is not included within this circle, the response is significantly different from noise at $p<0.05$. The lower right of the figure shows an enlargement of the amplitude spectrum between 60 and 120 Hz.

auditory brainstem responses. Third, multiple responses can be recorded at the same time (Lins and Picton 1995). We have been using a system for recording Multiple Auditory STEady-state Responses (MASTER; John, Lins, Boucher and Picton 1998; John and Picton 2000), which can simultaneously present 8 stimuli (4 in each ear). Although this does not necessarily mean that eight thresholds can be estimated in the same time that it would take to estimate one, the technique does provide threshold information in significantly less time than the single-stimulus technique (John, Purcell, Dimitrijevic and Picton in press). Fourth, the typical stimuli used to evoke the steady-state responses are much more suited for evaluating hearing aids than brief tones. The fact that the stimuli are much more stable over time than brief transients means that they are more reliably transferred through free field speakers and hearing aids (even when the hearing aids are nonlinear).

The thresholds for recognizing the auditory steady-state responses are higher than the behavioral thresholds for pure tones. In normal adults these physiological-behavioral differences vary on average between 10 and 20 dB (Rance, Rickards, Cohen, De Vidi and Clark 1995; Lins et al. 1996; Herdman and Stapells 2001; Dimitrijevic et al. in press). In hearing-impaired individuals the difference is often less. This might be attributable to recruitment, since the response may increase in amplitude more rapidly as the intensity exceeds threshold in hearing-impaired individuals compared to an individual with normal hearing. Although the mean differences are small, individual differences may occasionally reach 40 dB (Dimitrijevic et al. in press). These results are similar to those obtained with adults using tone-evoked auditory brainstem responses (Stapells 2000b).

The auditory steady state responses in infants are smaller than in adults and the thresholds for recognizing the responses are higher (Lins et al. 1996). Figure 2 presents some data from this Lins et al. study showing the incidence of recognizable responses in adults and young infants. These results were obtained using the multiple auditory steady-state response technique with recording times lasting between 3 and 13 minutes. Superimposed on these data are the results obtained by Cone-Wesson et al. (in press) using single-stimulus recording of the steady-state responses using a much shorter time of 95 seconds (in the context of a brief screening test). The data are compatible if one makes the reasonable assumption that more responses would have been recognized if the Cone-Wesson recordings had continued for a longer period.

Thresholds for recognizing the auditory steady state responses babies are usually reported in the literature in terms of dB SPL since the babies are unable to provide behavioral thresholds. Unfortunately, many of these thresholds have been estimated in noisy environments (Rickards et al. 1994; Lins et al. 1996; Savio et al. 2001), and it is difficult to know how they relate to adult thresholds recorded in much quieter conditions. Some of the data reported in Lins et al. (1996) were recorded in a sound-attenuated audiometric chamber and these are presented in table 1 for comparison to results with adult steady state responses, and with adult and infant tone-evoked ABRs.

The following conclusions are warranted. First, the two techniques – tone-evoked auditory brainstem responses and auditory steady-state responses – give

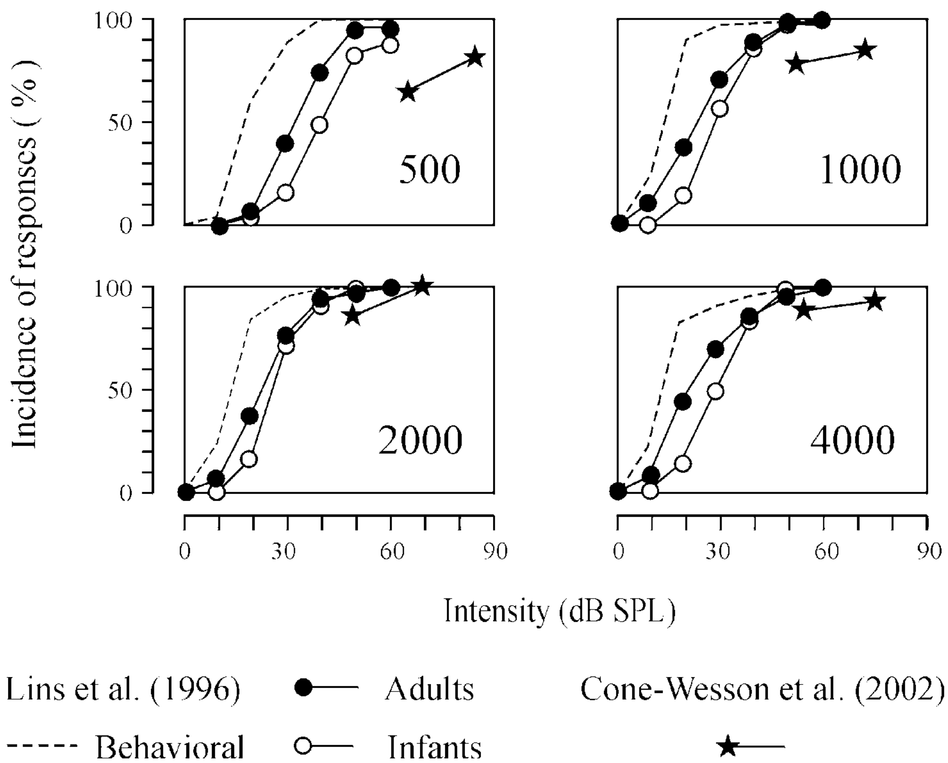

Figure 2. Auditory steady-state responses in infants. These data plot the incidence of responses significantly different from noise at different intensities (in dB SPL) and at different frequencies (in Hz). Most of the data are derived from Lins et al (1996). These data compare the auditory steady-state responses (circles) to behavioral responses (dashed lines). The steady state response curves are shifted between 5–20 dB to the right of the behavioral curves, with the shift being greater for the infants than for the adults and greater at 500 Hz than at other carrier frequencies. Data from Cone-Wesson et al. (in press) have also been added to the graphs (stars). These data were obtained from premature and newborn infants using a much shorter recording period than in the Lins et al. study.

approximately similar thresholds in similar groups of subjects. The major difference in table 1 occurs when comparing the tone-ABRs in children to the steady state response thresholds in much younger babies. Second, the accuracy of estimating threshold is more dependent on the standard deviation than on the actual mean differences between physiological and behavioral thresholds. In this respect, both tests show similar standard deviations. Third, proper comparison of the two techniques must consider the duration of the testing procedures. A formal comparison would evaluate the tests using recording and response-recognition procedures that are optimized for each technique. The comparison would then evaluate the information obtained within a set amount of time. Our intuition is that using the multiple-stimulus protocols for steady-state responses would be more information-efficient. However, techniques to record auditory brainstem responses using sequences of multiple tones are possible (Fausti et al. 1995) and might be further investigated. Fourth, much more research is needed to evaluate the use of tone-evoked auditory brainstem responses and auditory steady-state responses in babies in the first few months of age. This is crucial. Fitting hearing aids in young infants needs better data on the accuracy and reliability of threshold-estimation procedures in the first few months of age.

Evaluating Supra-Threshold Discrimination using Auditory Steady-State Responses

The auditory steady state responses can be recorded using free-field stimuli presented to subjects using hearing aids (Picton et al. 1998). This study showed that aided thresholds could be reasonably well estimated from the thresholds for steady-state responses in a group of children using aids (table 1). One obvious difficulty with using aided thresholds to assess how well a hearing aid is working is that the assessment is occurring at levels that are not relevant to the perception of amplified speech. One does not fit a hearing aid to allow the patient to listen to faint sounds. Furthermore, given the nonlinear amplification functions of modern hearing aids, it is difficult to extrapolate from threshold levels to the levels at which normal speech occurs. Aided thresholds are not uninformative – if the aided thresholds are below the intensities at which speech normally occurs, the aid cannot improve speech perception. Nevertheless, some measurement of supra-threshold discrimination would be much more helpful in terms of adjusting a hearing aid or monitoring its performance.

Auditory steady state responses can be used to evaluate supra-threshold hearing abilities as well as estimating the hearing thresholds. Three types of testing are readily available. First, a physiological intensity-discrimination limen can be estimated by recording responses to amplitude-modulated tones with different depths of modulation. Second, frequency-discrimination can be similarly studied using frequency-modulated tones of different depths of modulation. Third, the temporal resolution of the auditory system can be estimated by measuring the steady-state responses to tones that are modulated at different modulation-rates. This might provide us with a physiological measurement of the temporal modulation transfer function. We are currently conducting some studies to examine the temporal resolution of the auditory system in this way, but we shall confine our comments in this paper to measurements of intensity- and frequency-discrimination.

John, Dimitrijevic, van Roon and Picton (2001) measured the physiological thresholds for amplitude and frequency modulation using tones of 1000 Hz modulated at a rate of 82 Hz. For amplitude modulation, the theshold or limen was 20% for the physiological responses and 6% for behavioral responses. For frequency modulation, the limens were 5% and 1.4%. It is therefore possible to assess how well a subject can discriminate between intensities or frequencies by measuring these limens. However, measuring these limens would take time, since we would have to demonstrate both the presence of responses at modulation depths above threshold and the absence of responses at depths below threshold. Furthermore, we might again be chasing irrelevant information. The perception of speech involves discriminating intensities and frequencies that are much greater than these threshold levels and there is no necessity that the limens will predict perceptual performance with these larger changes.

We therefore decided to construct a stimulus that contains many different amplitude and frequency changes at many different frequencies. In a sense we wished to construct an artificial speech stimulus. John et al. (2001) showed that the steady-state responses to amplitude-modulation (AM) and frequency-modulation (FM) are largely independent at modulation rates of 80–100 Hz. The response to a carrier that was modulated in both amplitude and frequency using the same modulation frequency (mixed modulation or MM) varied in amplitude with the phase differences between the AM response and the FM response. When the response phases coincided, the MM response attained its maximum amplitude which was only 10–20% less than the sum of the amplitudes of the AM and FM responses. This means that the responses are largely independent of each other, and justifies the use of mixed modulation when assessing hearing thresholds (Cohen, Rickards and Clark 1991) since the combined response is larger than the simple response to amplitude modulation. However we reasoned that, if the responses are indeed independent, we could present a single carrier frequency with AM at one rate and FM at another rate ("independent amplitude and frequency modulation" or IAFM) and obtain two responses for each carrier frequency. Figure 3 illustrates this type of stimulus. Multiple IAFM stimuli at different carrier frequencies might then be used to assess intensity and frequency-discrimination over the range of frequencies heard in speech.

We initially evaluated this idea using IAFM stimuli (four carrrier frequencies each modulated at 50% in amplitude and 20% in frequency) at different stimulus intensities in normal subjects (Dimitrijevic, John, van Roon and Picton 2001). Our logic was that as we decreased the intensity of this eight-stimulus combination the modulations would become less discriminable in the same way that speech sounds became less intelligible at lower intensity. The number of responses recognized as significantly different from the residual background electrical noise should represent the amount of information in the stimulus that has been discriminated by the auditory nervous system. We therefore correlated the number (out of eight) of significant IAFM responses with the percentage of words recognized in a phonetically balanced word list presented at the same root-mean-square intensity as the IAFM stimuli. The correlation coefficient was 0.74. This finding was highly significant but was not strong enough to suggest that the word recognition score could be accurately predicted from the number of significant responses obtained in response to an IAFM stimulus.

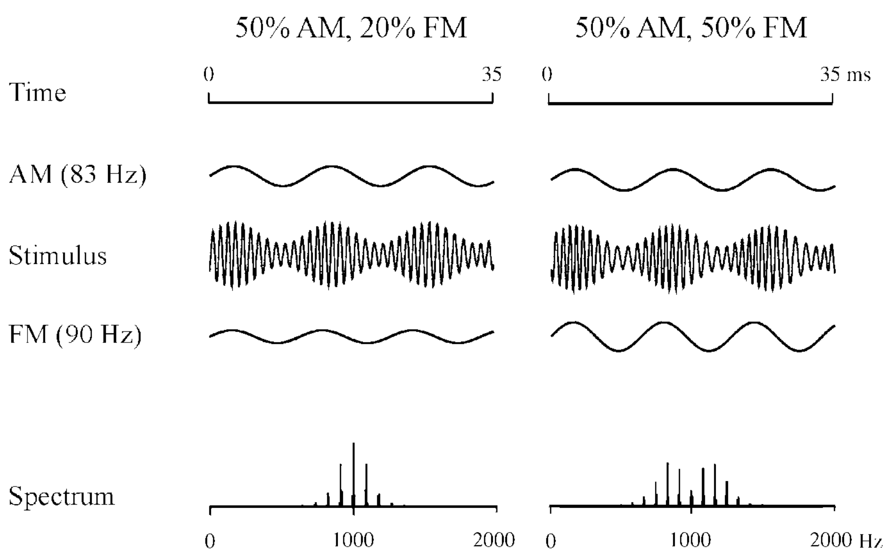

Figure 3. Independent amplitude and frequency modulation (IAFM). The graph shows IAFM stimuli in the time domain (waveforms in the middle of the figure) and in the frequency domain (lower spectra). The amplitude of the 1000-Hz stimulus is modulated at a frequency of 83 Hz (AM) and its frequency is modulated at a frequency of 90 Hz (FM). The graphs on the left show the stimulus when the amount of FM is 20% (as was used in the recordings). Since it is difficult to see the frequency-changes at this level, we have shown in the right half of the figure the stimulus with the amount of FM increased to 50%. The maximum frequency at the beginning of the sweep occurs at about the same time as the maximum amplitude, but by the end of the sweep the maximum frequency is occurring before the maximum amplitude.

In the study reported in this paper we evaluated the responses to IAFM stimuli in normal subjects and in hearing-impaired subjects wearing hearing aids. The stimuli were presented in free field rather than through insert phones. Each of four carrier frequencies (500, 1000, 2000 and 4000 Hz) was amplitude modulated at a depth of 50% and frequency modulated at a depth of 20%. The modulation frequencies were 78, 83, 88, and 93 Hz for AM and 85, 90, 95 and 100 Hz for FM at carrier frequencies of 500, 1000, 2000 and 4000 Hz, respectively. The ten normal subjects were between 21 and 35 years old and the fourteen hearing-impaired subjects were between 62 and 90 years old. This is a far cry from hearing-impaired newborn infants, but these elderly subjects were more readily available, and the general principles of fitting aids

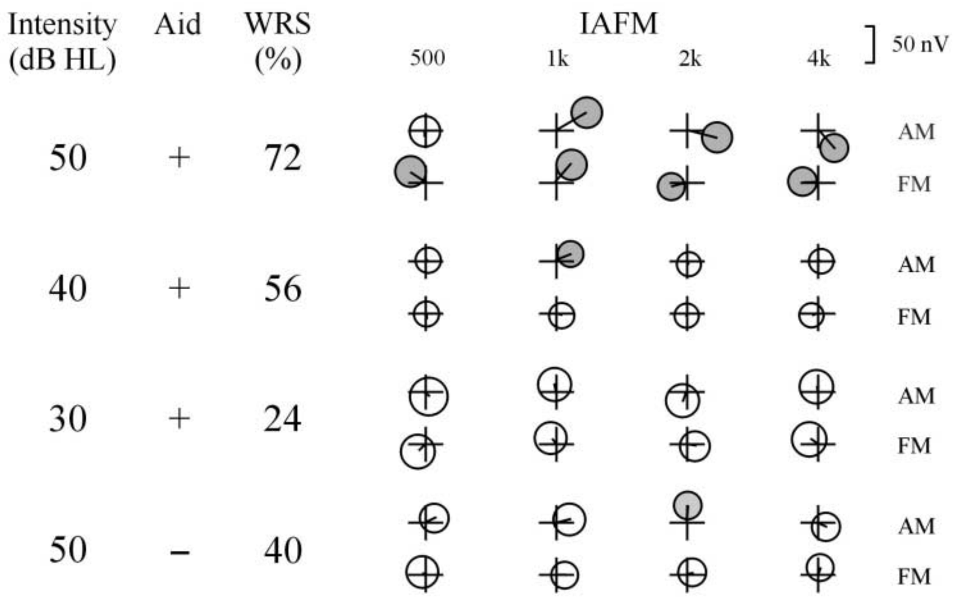

Figure 4. IAFM responses in a subject with a hearing aid. This figure shows the responses to an IAFM stimulus presented in free field to a subject either wearing his aid (upper 3 sets of data) or not (bottom set of data). The subject was 87 years old and used a hearing aid in his left ear, which showed unaided thresholds of 15, 20, 40 and 55 dB HL at 500, 1000, 2000 and 4000 Hz, respectively. Responses with the aid were obtained at the maximum comfort level, which in this subject was 50 dB HL, and at intensities 10 and 20 dB lower. The unaided response was recorded using stimuli presented at an intensity (50 dB HL) that was the maximum comfort level with the aid. The responses are shown in polar-plot format with the circle indicating the confidence limits of the response. The shaded circles indicate responses that are significantly different from the electrical noise. At each intensity, four AM responses and four FM responses were recorded. At 50 dB HL with the aid, the subject showed a word recognition score of 72% and seven out of eight of the IAFM responses were significant. At the same intensity without the aid, the word recognition score was 40 % and only one IAFM response was significant.

are the same at all ages (although actual techniques are adjusted to what is possible). The hearing-impaired subjects had mild or moderate hearing impairments with unaided pure tone averages between 28 and 58 dB HL. We asked the subjects to set their hearing aids at the level they normally used and to adjust the sound levels for the word-recognition measurements to a maximum comfort level (MCL). We then tested both the word recognition scores and the IAFM responses at MCL and at intensities 10 and 20 dB below MCL. The average MCL was 50 (range 40–70) dB HL in the normal subjects and 56 (range 40–65) dB HL in the aided subjects. In the hearing impaired subjects we also measured the IAFM responses and the word recognition score at the aided MCL level when the subject was not wearing an aid. Sample results in one hearing-impaired subject are shown in figure 4.

As in the initial study, we correlated the number of significant responses to the word recognition scores obtained at the same SPL. The results are shown in figure 5. The correlation coefficient between the word-recognition scores and the number of significant responses to the IAFM stimulus over all subjects was 0.55. This was highly significant ($p<0.001$), but the coefficient was lower than we had noted in the initial study. It was also lower for normal subjects (0.31) than for hearing-impaired subjects (0.52). The slope of the regression line (a 7.5% increase in word recognition score per recognized IAFM response) was a little lower than the slope of 9.9 obtained in the preceding study (Dimitrijevic et al. 2001).

One obstacle in interpreting these results was that our normal subjects set their MCL higher than the subjects with hearing aids in relation to their speech reception threshold (SRT, the level at which the subject detected 50% of spondee words). MCL was set on average 43 dB above SRT for normal subjects and 22 dB above their aided SRT for the hearing impaired subjects. This difference is likely related to recruitment, which would bring the SRT and the MCL closer together in the aided subjects. (This

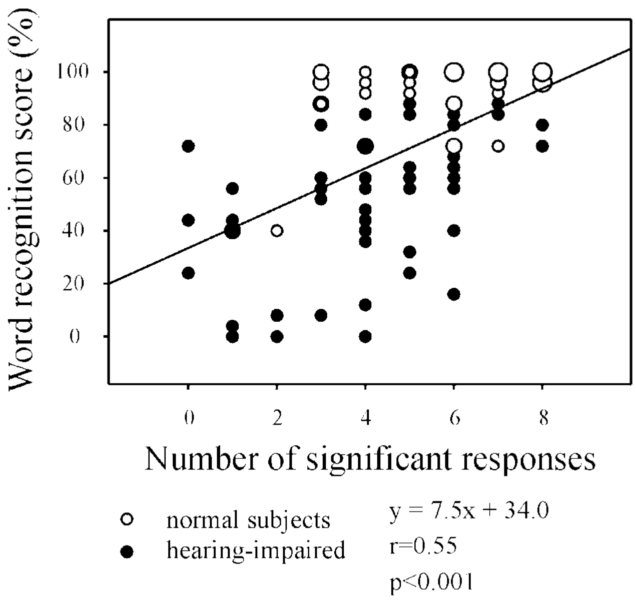

Figure 5. Relations between word recognition score and IAFM responses. This figure plots data from 10 normal subjects and 14 hearing-impaired individuals using hearing aids. (The data from one of these hearing-impaired subjects are shown in figure 4.) The numbers of IAFM responses out of 8 that were significantly different from noise are plotted against the word recognition score (for phonetically balanced monosyllables) obtained at the same SPL. The larger circles represent two superimposed data points. Higher word recognition scores are associated with a significantly greater number of IAFM responses, although there is a large amount of variability among the subjects. The parameters of the regression line are shown below the figure.

effect would itself be partially counteracted by the compression of the aids). Nevertheless, the high intensity levels used by the normal subjects may have obscured any correlation in this group since these subjects had very high word recognition scores at the MCL-10 and MCL-20 levels.

The data reported in this paper were obtained without paying much attention to the settings of the hearing aids. Our subjects used a variety of aids, both analog and digital, with a variety of compression functions. The study was designed to see whether there was any relation between speech intelligibility and the supra-threshold auditory steady-state responses. There is a significant relationship. We now need to pay much more attention to the hearing aid settings and how they might affect our IAFM stimulus differentially from speech. We must also pay more attention to recording more noise-free responses. It is essential to know whether a response is absent because the modulation is not being recognized in the nervous system or because the residual background electrical noise in the recording is too high.

We are left with a tantalizing idea that is still far from clinical application. We shall need to design a better stimulus. The optimal stimulus would be one that better represents the intensity- and frequency-differences in speech and presents them at intensities that are representative of typical speech. The long term acoustic spectrum of speech could be used to set the stimulus levels, but we shall need more work to select representative modulation depths. We may also consider using slower modulation-frequencies, since the typical changes in intensity and frequency in speech occur at slower rates than 80 Hz (Shannon, Zeng, Kamath, Wygonski and Ekelid 1995). Time-varying sounds have been developed to assess how effectively speech-like sounds are amplified by compression hearing aids (Cole and Sinclair 1998), and we shall have to consider these sounds when developing stimuli to evoke aided steady-state responses. Finally, it is essential to see how well infants respond to FM stimuli, and to AM stimuli when the depth of modulation is less than 100%. There is much to do before we can put together an objective test of how well the brain might discriminate those parameters of a speech sound that allow it to be recognized and understood. However, the idea is good and the preliminary data promising.

Summary

Steady-state responses are evoked potentials that maintain a stable frequency-content over time. In the frequency domain, these responses show a spectrum with peaks at the rate of stimulation and its harmonics. Auditory steady-state responses can be reliably evoked by tones that have been amplitude-modulated at rates between 75 and 110 Hz. These responses show great promise for objective audiometry since they can be readily recorded in infants and are unaffected by sleep. Responses to multiple tones presented simultaneously can be independently assessed if each tone is modulated at a different modulation-frequency. This makes it possible to estimate thresholds at several audiometric frequencies in both ears at the same time. Since tones that have been sinusoidally modulated are not significantly distorted by free-field speakers and microphones, they might also be used to evaluate the performance of hearing aids. Furthermore, these continuous tones are more

consistently handled by nonlinear aids than brief transient stimuli. Thus responses to amplitude- and frequency-modulation may become helpful in assessing the supra-threshold auditory processes necessary for aided speech perception. These supra-threshold responses may help determine how well hearing aids improve the discriminability as well as the audibility of sounds. Much research is needed, particularly in the use of these responses in the first few months of age.

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