Efficient Stimuli for Evoking Auditory Steady-State Responses

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Objective: **To compare the magnitudes of the steady-state responses evoked by several types of stimuli, and the times required to recognize these responses as significant.**

Design: **In the first two experiments, we examined auditory steady-state responses to pure tones, broadband noise and band-limited noise. The stimuli were amplitude modulated in the 75 to 100 Hz range with sinusoidal or exponential envelopes. A third experiment investigated the effects of exponential envelopes on the responses to broadband noise. The final experiment examined auditory steady-state responses evoked by rapidly presented transient stimuli, such as clicks, brief tones and brief noise-bursts. All stimuli were presented dichotically at intensities 30 to 50 dB above behavioral thresholds. The subjects were adults, who drowsed or slept during the recording sessions.**

Results: **The responses to the noise were larger than the responses to the tones. At an intensity of 32 dB nHL, the average amount of time needed to obtain significant responses for the amplitude-modulated noise was 43 sec and the maximum time was 2 minutes. The average time for pure tone stimuli was approximately 2 minutes but 25% of the responses remained undetected after 5 minutes. Combining the responses to all the frequency-specific stimuli showed results similar to using noise stimuli. Using exponential envelopes did not increase response amplitudes for noise stimuli. At 45 dB nHL, the steady-state responses to clicks and other transient stimuli were larger than responses to the broadband noise. The average time to detect steady-state responses to transient stimuli was approximately 20 sec, which was a little faster than for amplitude modulated noise.**

Conclusions: **Auditory steady-state potentials evoked by amplitude modulated noise or transient stimuli might be useful in providing rapid and objective tests of hearing during screening procedures. Another approach might be to record responses to multiple frequency-specific stimuli and to evaluate the combined responses for a rapid indication that some hearing is present.**

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Auditory steady-state potentials are attractive for objective audiometry because multiple responses can be simultaneously recorded (Lins & Picton, 1995; John, Lins, Boucher, & Picton, 1998) and objectively evaluated (Cohen, Rickards, & Clark, 1991; Dobie & Wilson, 1996; Lins, Picton, Boucher, Durieux-Smith, Champagne, Moran, Perez-Abalo, Martin, & Savio, 1996). Most studies of the auditory steady-state responses have used modulated tones, because these have good frequency-specificity (Herdman, Picton & Stapells, 2002). In some contexts, however, it might be advantageous to trade frequency-specificity for increased amplitude. Obtaining steady-state responses as quickly as possible would be useful for hearing screening (Picton, John, & Dimitrijevic, 2002; Stürzebecher, Cebulla & Neumann, 2003) and for measuring responses at many different modulation frequencies to estimate temporal modulation transfer functions (Grant, Summers, & Leek, 1998; Viemeister, 1979).

Several studies have explored methods of increasing the size of the response compared to that evoked by a simple amplitude-modulated carrier. Mixed modulation (MM) combines amplitude-modulation (AM) and frequency-modulation (FM) and evokes a response that is almost as large as the sum of these two responses evoked separately (Cohen et al., 1991; John, Dimitrijevic, van Roon, & Picton, 2001). Modulating the carrier with a sinusoidal function raised to a power greater than 1 increases the response amplitudes for low and high carrier frequencies (John, Dimitrijevic, & Picton, 2002). Using multiple AM carriers separated from each other by the modulation frequency also produces larger responses (Stürzebecher, Cebulla & Pschirrer, 2001). Responses are also larger when noise rather than a tone is used as the carrier (Picton, John, Dimitrijevic & Purcell, 2003). At 60 dB SPL, amplitude modulated broadband noise (200 to 8000 Hz) produced a response that was twice as large as a 1000-Hz pure tone (John et al., 1998). Periodic transient stimuli, rather than amplitude-modulated stimuli, also can evoke large steady-state responses. Stürzebecher et al. (2003) have shown that rapidly presented 125 μsec rarefaction clicks can elicit a large steady-state response. Auditory steady-state responses evoked by noise stimuli, or by rapidly presented transient

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stimuli, might be useful in neonatal hearing screening.

We evaluated several different stimuli to see which might evoke larger steady-state responses and be more rapidly recognized. We first compared the responses to amplitude modulated broadband noise (BBN) to frequency-specific responses evoked using the typical **M**ultiple **A**uditory **STE**ady-State **R**esponse (MASTER) technique. We also evaluated the responses to four tonal carriers all modulated at the same modulation-frequency (SMF). This synchronous modulation was also used with mixed-modulation tones and with exponential envelopes. A second experiment compared the BBN to amplitude modulated low-pass noise (LPN) and high-pass noise (HPN) presented alone or simultaneously. Simultaneously presenting LPN, modulated at one rate, and HPN, modulated at another rate, might provide information about low- and high-frequency hearing in roughly the same time as the BBN stimulus. A third experiment compared the auditory steady-state responses evoked by BBN stimuli modulated with exponential envelopes using powers of 1, 2, and 10. Because exponential envelopes increased the size of the responses to tonal stimuli (John, Dimitrijevic, & Picton, 2002), they might also enhance the responses to BBN stimuli. The fourth experiment compared the auditory steady-state responses obtained using BBN with those evoked by various types of transient stimuli: clicks, brief noise-bursts and brief tone-bursts, presented at rates equal to the modulation frequencies of the BBN.

METHODS

Subjects

Twelve adult volunteers (5 female, age 21 to 33 yr) participated in Experiments 1 and 2. Ten adult volunteers (6 female, age 18 to 40 yr) participated in Experiment 3. Ten adult volunteers (7 female, age 22 to 47 yr) participated in Experiment 4. All subjects had hearing thresholds below 30 dB SPL for tones of 500, 1000, 2000 and 4000 Hz.

Stimuli

All stimuli were created within the LabVIEW™ based MASTER data collection software (John & Picton, 2000a; see also www.hearing.cjb.net). The modulation rates and carrier frequencies were set to provide integer numbers of cycles within the 1.024 s data epoch. For example, a modulation frequency of 80 Hz was modified to 80.078 Hz. For simplicity, these frequencies will henceforth be reported to the nearest integer value.

Sound Calibration

Stimuli underwent D/A conversion at 32 kHz (34,560 Hz for Experiment 4) and were then sent to a Grason Stadler (GSI 16) audiometer where they were adjusted to a calibration intensity before being transmitted to a pair of Etymotic 3A insert earphones for transduction of the signals into sound. Intensities were calibrated using linear-weighting with a Brüel and Kjaer 2230 sound level meter with a 2 cc DB 0138 coupler and were accurate to within 3 dB across different calibration sessions.

Behavioral Thresholds

Behavioral thresholds were obtained using a 10 dB down and 5 dB up procedure, with threshold chosen at the level in which 2 of 3 responses were detected. This produced thresholds estimates within 5 dB of true threshold.

Experiment 1: Comparison Between Broad-Band Noise and Tones

Figure 1 shows examples of the different dichotic stimuli investigated in Experiment 1. These stimuli were presented at a moderate intensity of 50 dB SPL (for nHL levels, see Table 1). This experiment first examined the difference between the responses obtained using amplitude modulated broadband noise (BBN) and the traditional MASTER stimuli (see top row of Figure 1). BBN stimuli were created by multiplying a uniform white noise time-series (i.e., having a rectangular probability distribution between its limits, rather than the bell-shaped distribution of Gaussian white noise), that ranged from +1 to -1, with an offset sine function that ranged between 0 and +1. The noise subroutine was fed with a different random seed to make a unique noise stimulus for each recording. The stimulus was then amplified to obtain the desired stimulus intensity. Bandpass noise was created by passing the noise through a digital 8th order Butterworth band-pass filter, before multiplication by the modulation function. In our experiments, the BBN stimuli were created with a band-pass of 1 to 8 kHz and modulation frequencies of 80 Hz (left ear) and 83 Hz (right ear). However, because the ER3A transducers only pass energy up to approximately 4.5 kHz (in which the energy is −3 dB), energy at higher frequencies, which exists within the electrical stimulus, will be greatly reduced in the ear of the subjects. The MASTER stimuli were created by multiplying each of 4 carriers by a unique modulation function and then adding the four modulated waveforms together to produce a stimulus that was presented to the left or right ear. Comparing the magnitude of the responses evoked by the amplitude modulated BBN

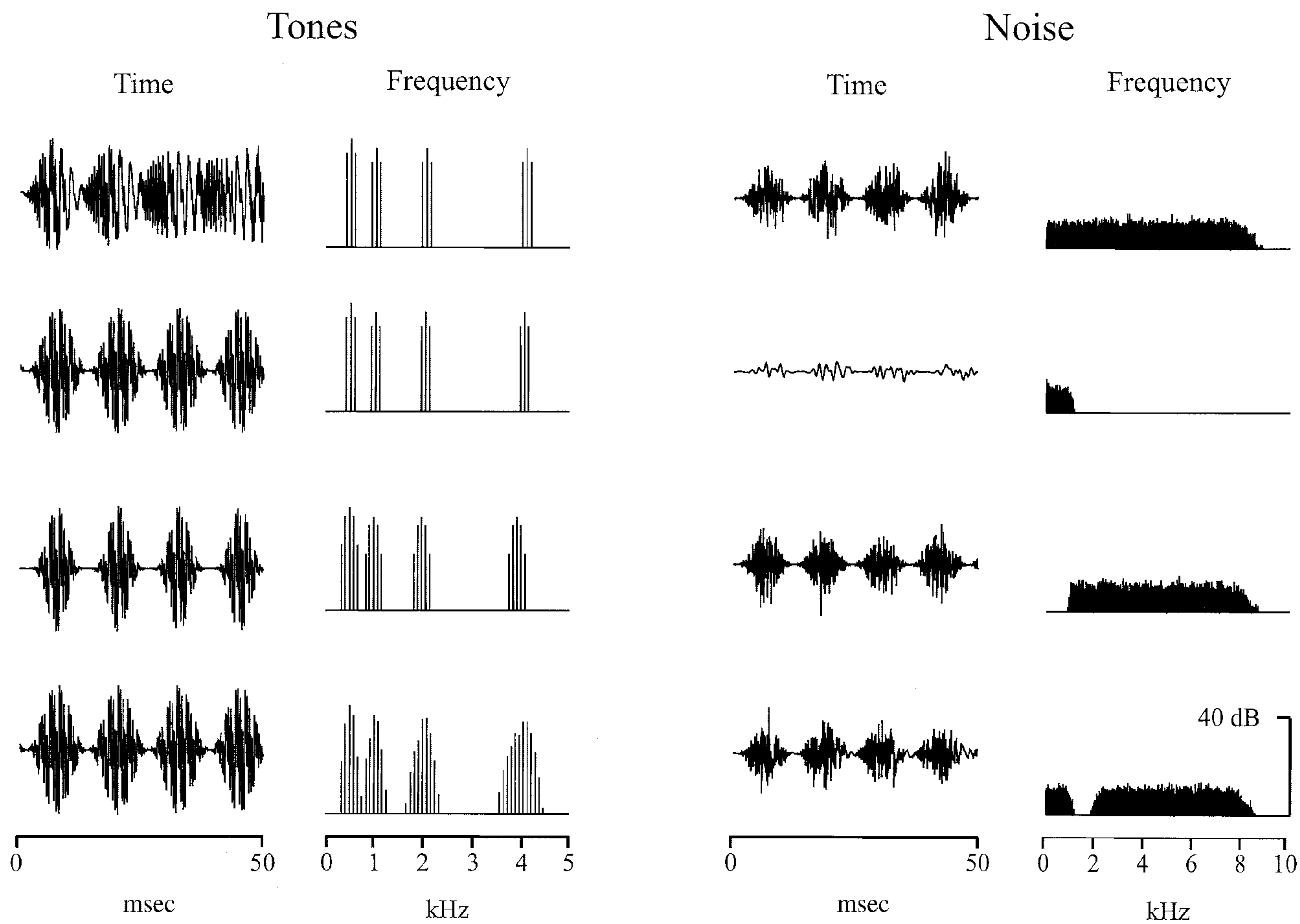

Figure 1. Tones and noise. The top row shows the traditional MASTER stimulus and its associated amplitude spectra. There are four carriers each modulated at a different modulation rate. The spectrum of the 0.5 kHz carrier is slightly larger than the other carriers to adjust for the lower transfer of the acoustic transducer at this frequency. The top row (right side) shows an amplitude modulated broadband noise (BBN) stimulus and its associated spectrum with energy from 1 to 8 kHz. SMF stimuli are shown in Rows 2 (SMF-AM), 3 (SMF-AM^2), and 4 (SMF-MM) of the left side of the figure. The waveforms show that each of four carrier frequencies (i.e., 0.5, 1, 2, and 4 kHz) has been modulated at a single modulation frequency (SMF-AM). Rows 2, 3, and 4 of the noise stimuli show, respectively, a low-pass noise (LPN) stimulus with energy from 1 to 1000 Hz, a high-pass noise (HPN) stimulus with energy from 1 to 8 kHz, and a compound stimulus consisting of both low-pass noise (Combined-LPN2) stimulus with energy from 1 Hz to 1 kHz and high-pass noise (Combined-HPN2) stimulus with energy from 2 to 8 kHz. In this last stimulus, the low-pass and high-pass energy is modulated at two different rates.

stimuli to the frequency specific responses, obtained using the typical MASTER technique, provided an estimate of how much larger the response to the BBN stimulus would be compared to the frequency-specific responses usually obtained.

Normally we use a unique modulation frequency for each carrier so that we can independently evaluate hearing at each carrier frequency. However, the individual responses can be combined into a single large response when all the carrier frequencies are modulated at a single modulation frequency (SMF-AM). The SMF was 80 Hz for the left ear and 85 Hz for the right ear. This stimulus can be seen in the second row of the left column of Figure 1. The next two rows of the column show stimuli that were also SMF but created using an exponential envelope (with a power of 2) for the modulation, or using MM instead of simple AM. The amount of FM was 20% (i.e., 10% above and below the center frequency) and the phase of the FM function was adjusted to be at −135° relative to the amplitude modulation (sine onset, see John & Picton, 2000b).

The calibration of the MASTER stimuli and the SMF stimuli were performed for each individual carrier. In order for all of the 4 stimuli to be presented at the approximately the same intensity (i.e., to compensate for the transfer function of the acoustic transducer), the amplitudes of the 500 Hz and 6000 Hz carriers were set larger than the other carriers so that all stimuli were approximately 50

TABLE 1. Stimulus intensities

Stimulus Type	Stimulus Intensity nHL	Behavioral Threshold		
		pSPL	RMS SPL	SD
Tonal stimuli				
1000-Hz (50 dB SPL)	**39**	33	**11**	**5**
SMF-AM	**33**	35	**23**	**4**
SMF-MM	**31**	37	**23**	**5**
SMF-AM^2	**29**	38	**26**	**5**
Noise stimuli				
BBN (50 dB SPL)	**32**	33	**18**	**4**
LPN	**24**	29	**16**	**4**
HPN	**33**	31	**16**	**4**
Combined LPN-HPN-1	**33**	30	**16**	**4**
Combined LPN2-HPN2	**32**	31	**17**	**4**
Exponential envelope noise				
BBN (40 dB SPL)	**23**	33	**19**	**4**
BBN^2	**23**	32	**18**	**3**
BBN^{10}	**20**	33	**17**	**3**
Transient stimuli				
BBN (65 dB SPL)	**47**	30	**16**	**4**
Click (+)	**44**	**32**	14	**4**
Click (−)	**44**	**32**	14	**3**
BBN-Burst	**46**	**35**	14	**4**
HPN-Burst	**44**	**36**	15	**5**
1.4 kHz-Burst	**54**	**25**	11	**4**

The intensities for the key stimuli in the first column were those used to set up the stimuli for the different experiments. The intensities in the other columns were those measured during the calibration after the experiments and, due to the random structure of the noise stimuli, are occasionally up to 3 dB different.

dB SPL. Although the individual frequency specific stimuli were each calibrated to 50 dB SPL, combining the 4 stimuli in each ear increased the compound stimulus by 5 to 6 dB (Lins et al., 1996). However, because the independent carrier frequencies are processed in separate regions of the cochlea, the "functional" intensity of the individual carriers is still 50 dB. The intensity of the four stimuli presented together was 55 dB SPL, for both the MASTER and SMF stimuli. The noise stimuli (right side of figure) were presented at an intensity of 50 dB SPL.

Experiment 2: Comparison between Broad-Band Noise and Filtered Noise

Because previous studies had led us to believe that the BBN stimuli would evoke larger responses than those traditionally obtained using MASTER, we examined whether it would be possible to use noise, rather than tonal stimuli, to evaluate both low-frequency and high-frequency regions of the cochlea in a quick manner. The BBN stimulus was divided into a low-pass noise (LPN) stimulus and high-pass noise (HPN) stimulus. The LPN stimulus contained energy from 1 Hz to 1 kHz and was modulated at 80 Hz and 83 Hz for left and right ears, respectively. The HPN stimulus contained energy from 1 kHz to 8 kHz and was modulated at 85 Hz and 87 Hz for the left and right ears, respectively. Although the LPN has a smaller amplitude than BBN or HPN (see right column of Figure 1), the amplitude spectrum shows a constant level across the different frequencies. Because there is a 3 dB increase in RMS SPL for a doubling of the bandwidth (Hartmann, 1997), one would expect the intensity of the LPN to be 9 dB lower than the HPN.

To determine whether it would be possible to measure simultaneous responses to the LPN and HPN, a compound stimulus was created by adding the low-pass noise stimulus (combined-LPN) to the high-pass noise stimulus (combined-HPN). It should be apparent, from Figure 1, that by adding the spectra of the LPN stimulus to the spectra of the HPN stimulus, the spectra of the BBN stimulus would be obtained. Because interactions between stimuli occur when simultaneously presented stimuli are separated by less than 1 octave (Dolphin, 1997; John et al., 1998), we created a second compound stimulus consisting of both low-pass noise stimulus (combined-LPN2) with energy from 1 Hz to 1 kHz and high-pass noise stimulus (combined-HPN2) with energy from 2 kHz to 8 kHz. The BBN, HPN, combined-HPN, and combined-HPN2 stimuli were all presented at 50 dB SPL (within a range of +/- 3 dB). The intensity of the LPN was 40 dB SPL.

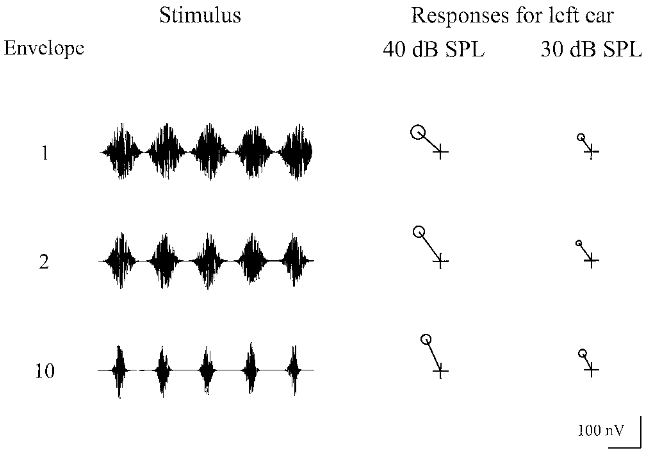

Figure 2. Exponential noise envelopes. The left side of the figure shows the time waveforms of the noise stimuli when the exponent of the envelope function was 1, 2, or 10. The right side of the figure shows the averaged responses to these stimuli as polar plots. The phase of the responses demonstrated a significant change with increasing the power of the exponent and a much smaller effect of intensity.

Experiment 3: Noise Stimuli with Exponential Envelopes

Because noise appeared to be a promising stimulus, we examined the effects of increasing the exponent of the modulation envelopes of the BBN stimuli. To see how these stimuli might perform in screening procedures we used an intensity of 40 dB SPL, which is approximately 20 dB nHL. This level in adults might be considered equivalent to the 30 to 40 dB nHL levels used for clicks in infants. We also used an intensity of 30 dB SPL to examine the effect that a decrease of 10 dB may have on the size of the response to BBN stimuli (for nHL levels see Table 1) We had previously enhanced the responses to tonal stimuli by using higher exponential terms in the modulation function (John, Dimitrijevic, & Picton, 2002). In all conditions the stimuli were modulated at 85 Hz for the left ear, and 95 Hz for the right. The BBN modulation envelopes were based on $\sin^N$ functions (John, Dimitrijevic, & Picton, 2002) with N set to 1, 2 or 10 (Figure 2). The exponential envelopes made with powers of 2 and 10 have an equivalent peak SPL level to when the power is 1, but they are theoretically decreased in RMS SPL by −2 and −6 dB, respectively. Although the change in the RMS level can be compensated by dividing the signal by the RMS value of the envelope, we did not choose to do this. Using correction factors to maintain RMS would have increased the slope at higher values of N even more than the effect of N, because increasing stimulus amplitude also increases slope. To investigate the effect of the various envelope functions more directly, we therefore did not incorporate a correction factor (John, Dimitrijevic, & Picton, 2002). In future clinical applications of exponentially modulated BBN stimuli, this could be done. Further, because the noise stimuli are created from random numbers, the RMS SPL will change by +/- 1 to 2 dB SPL during independent measurements. The measured SPL levels were 42.0, 40.8, 37.4 dB SPL for the 3 types of stimuli, respectively. Accordingly, the BBN stimuli were presented at an RMS SPL of approximately 40 dB and 30 dB, with the exponential BBN having less energy as just indicated.

Experiment 4: Transient Stimuli

Experiment 4 evaluated six different stimuli, some of which are shown in Figure 3, along with their associated spectra. These stimuli were presented at a higher intensity level than in the other experiments to ensure that electrical artifact was not contributing to the generation of the recorded responses. The intensity was 65 dB RMS SPL for BBN stimuli, and 75 to 80 dB pSPL for the transient stimuli (which is equivalent to 60 to 65 dB SPL). For nHL levels see Table 1. The clicks were adjusted to have approximately the same intensity in dB nHL as the BBN, and the other transient stimuli had the same maximum amplitude (in the electrical signal) as the clicks. The first stimulus was the BBN stimulus. The next two stimuli were condensation clicks (CC) and rarefaction clicks (RC), lasting 125 μsec. The remaining stimuli were 1 msec bursts with instantaneous rise and fall times. These bursts contained BBN, HPN or a 1400 Hz tone. As is clear from the figure, the BBN burst consisted of frequencies from 1 Hz to 8 kHz. The HPN burst consisted of frequencies from 2 kHz to 8 kHz. The 1.4 kHz burst contained energy at 1.4 kHz, with spectral splatter due to the rectangular gating window. In a control recording, a condensation click was presented to the subject with the ear-tube of the ER-3A transducer occluded, to rule out electrical artifacts.

In order for the Fourier analysis to work accurately, the transient stimuli had to occur at intervals that were equal to integer sub-multiples of the DA and AD buffers. The stimuli in one ear also had to occur at a different rate than in the other ear. Accordingly, the number of points in the DA buffer was made equal to the product of the integer numbers of cycles of the two stimuli within a single epoch multiplied by a power of 2 (giving approximately 32,000 data points). A further proviso that the AD buffer was exactly 1⁄32 of the DA buffer was ensured by choosing the two rates so that the final number of DA-buffer points was divisible by 32. We chose the two modulation rates to be 90 and 96 cycles per epoch, which resulted in a product of 8640. This

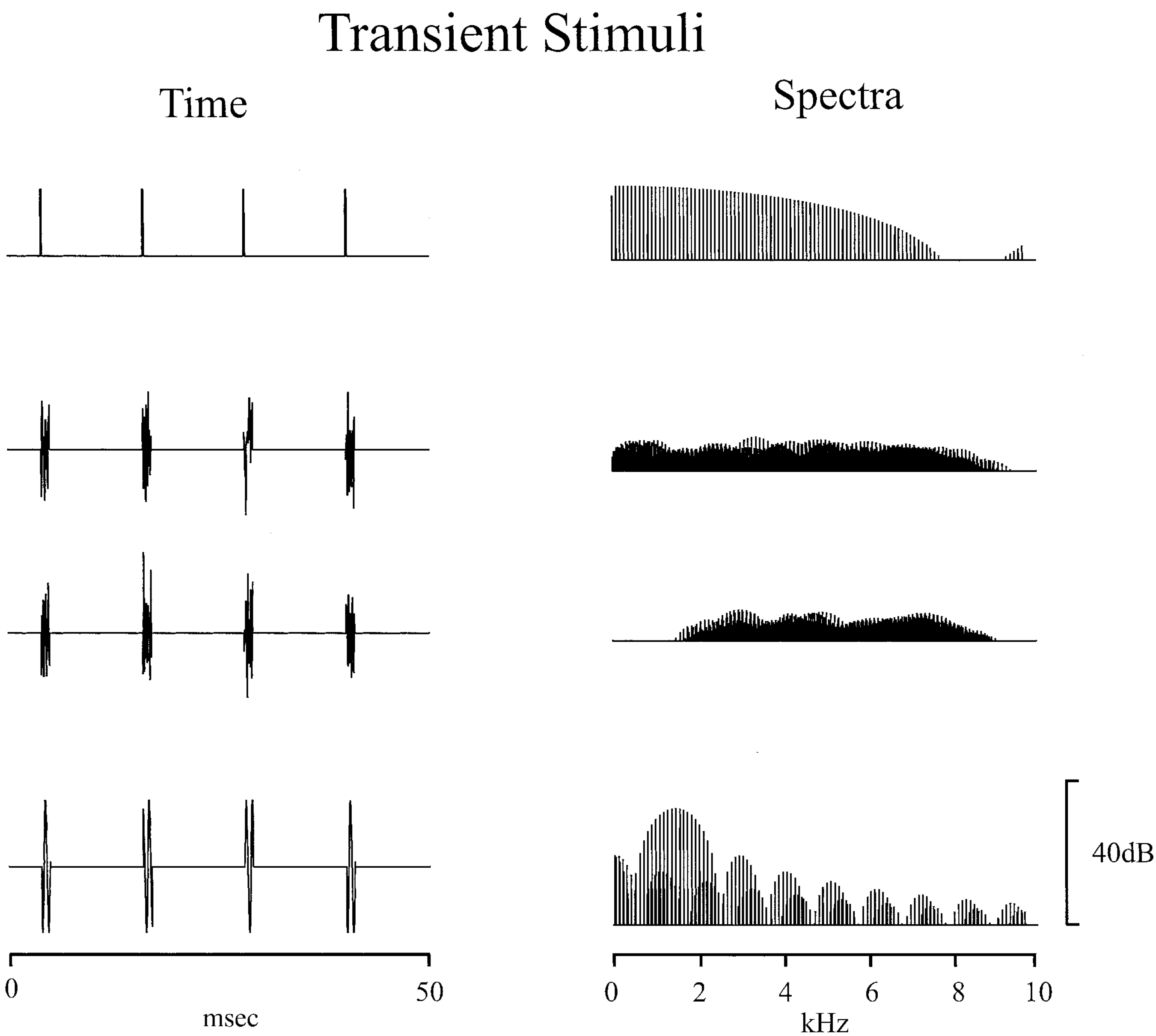

Figure 3. Transient stimuli. Time waveforms are plotted on the left and spectra (of the electrical waveform) are plotted on the right. The top stimulus is a 125 μsec condensation click (CC) stimulus. The spectrum of the click stimulus is broadband with a null occurring at the inverse of the click duration. The energy in the electrical stimulus continues into higher frequencies, but these do not pass through the transfer function of the ER3A inserts. The second row shows a 1-msec burst of 1 to 8 kHz noise. The third row shows a HPN click with energy from 2kHz to 8 kHz. The bottom row shows a 1.4 kHz burst. The spectrum has the main lobe of energy at 1.4 kHz with spectral spread to both lower and higher frequencies caused by the rectangular windowing function.

value was then multiplied by 4 to give 34,560 points. This result was then divided by 32 to obtain the number of points (1080) that were in each AD buffer. Because the A/D rate was set at 1000 Hz and the A/D buffer was 1080, the epoch duration was 1080 msec and the actual frequencies for the two stimuli were 83.33 Hz [i.e., 90*(1000/1080)] and 88.89 Hz, respectively. Both the A/D rate of 1000 Hz and the D/A rate of 32,000 Hz were acceptable, because these are both integer submultiples of the 20 MHz clock used by the MASTER system.

Recording and Measuring the Steady-State Responses

Stimuli were presented and steady-state responses were collected using the MASTER data collection system (John et al., 2000a). The EEG was recorded from an electrode placed at Cz using an electrode on the posterior neck as reference, and an electrode on the clavicle as ground. The EEG was obtained using a Grass P55 pre-amplifier with a gain of 10,000, a low-pass filter setting of 300 Hz and a high-pass filter set at 0.3 Hz. There was an additional gain of 5 on the data acquisition board making the final amplification 50,000. All data were collected at an A/D conversion rate of 1000 Hz.

In each recording, 16 individual data epochs of 1024 points each were collected and linked together into sweeps lasting 16.384 sec each. After each sweep was completed it was added to a running average sweep, which was then submitted to an FFT routine. The data in these experiments were recorded without artifact rejection limits. On-line weighted averaging of the individual epochs was carried out to reduce the effects of brief periods of increased noise that occurred during data collection (John, Dimitrijevic, & Picton, 2001). The average amplitude spectrum allows the measurement of the steady-state evoked potentials at frequencies equal to the modulation rates of the stimuli and the estimation of background noise levels at frequencies adjacent to the stimulus frequencies. The amplitude at each frequency of modulation is compared to the background noise level at 60 frequency bins above and below the frequency at which the signal was present, using an F-ratio which is evaluated at 2 and 240 degrees of freedom (John et al. 2000a; Zurek, 1992). Accordingly, the noise estimate is drawn from 3.66 Hz (60 bins $\times$ 0.061 Hz frequency resolution) above and below the frequency being examined. In the experiment that evaluated transient stimuli, the EEG epochs contained 1080 time-points, creating a sweep length of 17,280, rather than 16,384 points. In this case the MASTER software utilized the LabVIEW discrete Fourier Transform (DFT), rather than the FFT, because the data array is not a power of 2. The software automatically re-scaled the results into meaningful units.

At 50 dB SPL or higher, responses to frequency-specific stimuli may reach significance within the first minute of testing, whereas at near threshold intensities up to 20 minutes may be required. Because the responses presented here are much larger than those obtained by frequency specific stimuli, many of our recordings should have lasted only about 2 minutes. However, to obtain more stable and accurate estimates of the response amplitudes, and to decrease the amount of background noise that may have been present in the frequency bins of interest, recordings lasted longer. For Experiments 1 and 2 recordings lasted 5.2 minutes each. For Experiment 3, recordings lasted 5 and 12 minutes when stimuli were presented at 40 dB SPL and 30 dB SPL, respectively. For Experiment 4, the recordings lasted 5.5 minutes each.

All recordings were obtained during experimental sessions that lasted approximately 2 hr, including behavioral tests and EEG setup time. Subjects were tested in a sound and light attenuated chamber and were asked to sleep for the duration of the recording session. Most subjects were able to sleep for the entire session. The conditions within each of the experiments were randomized between subjects. Because it required approximately 2 or 3 minutes for the subjects to relax after the recording session began, the first condition was halted and restarted after the subject's EEG demonstrated that the subject had attained a stable, relaxed state.

As well as amplitudes, we also evaluated the phases and estimated latencies. The phases were converted into latency using the preceding cycles technique, assuming one full cycle of the stimulus occurred before the partial cycle of the measured phase (John et al., 2000b). This procedure allowed us to compare the latencies between the ears, which had different phases because of the different modulation frequencies. The latencies for the responses to the transient stimuli were calculated similarly with the proviso that the transient stimulus began at the same time as the beginning of the rise of the modulated stimulus (a quarter cycle difference, because we were using a sine modulation function for the BBN). The 0.9-msec latency delay in the ear tube was subtracted from the measurements. Apparent latencies (John et al., 2000b) were also calculated from the vector-averaged mean phases, using the values from each ear to calculate the slope of phase versus stimulus frequency.

Combining Responses Across Stimuli

The use of the SMF to combine all four responses in one ear gives a large response that is more rapidly recognized than any of the single responses. However, it is impossible subsequently to determine the individual responses to each carrier frequency. Instead of combining the responses physiologically, as occurs when a single modulation rate is used for all carriers, separate responses can be obtained for each frequency using the traditional MASTER technique, and these responses might be combined mathematically. We therefore considered the possibility of "virtually" combining the responses to the four carrier frequencies when each was recorded at its own modulation frequency. Two different statistics were used to assess the signal-to-noise ratio.

In the typical MASTER technique, a single response to each modulated carrier is assessed using the statistic

$$\frac{\frac{1}{2}(x_s^2 + y_s^2)}{\frac{1}{2N}\sum_1^N (x_n^2 + y_n^2)}$$

in which x_s and y_s are the real and imaginary components of the spectrum at the signal frequency, and x_n and y_n are the real and imaginary components at the N frequencies used to estimate the noise. The statistic is distributed as F with 2 and 2N degrees of freedom.

If we were to use K signal frequencies, we could evaluate a similar statistic

$$\frac{\frac{1}{2K}\sum_1^K (x_s^2 + y_s^2)}{\frac{1}{2N}\sum_1^N (x_n^2 + y_n^2)}$$

which would be distributed as F with 2K and 2N degrees of freedom. In terms of amplitude, this is comparing the "root-mean-square" (RMS) amplitude of the K signals to the root-mean-square amplitude of the noise. Our measurements with the 4-frequency combined stimulus would thus use an F-value with 8 and 2N degrees of freedom. N would be determined by the number of points used to provide the noise estimate, which would have to span the frequency range of the stimuli (discussed below).

Alternatively, we could average the K responses. This requires paying attention to the phase of the responses (using "vector-averaging"). This raises the problem that the different responses have different phases. One approach to this problem is to project each of the responses to the phase that is expected for each particular carrier frequency and modulation frequency (using the expected phase to determine the x and y values in the equation below). For the purpose of testing this method, we used the mean phase for all the subjects to estimate the expected phases. (Given the relatively small effects of the carrier frequency and the modulation frequency on the phase of the responses, we could have merely vector-averaged the responses without compensating for the expected phase). Averaging gives a single vector measurement in the numerator of the ratio. The denominator that estimates the noise must be divided by K to compensate for the fact that the signal has been averaged over K responses (this is simpler than averaging K different noise estimates). The statistic becomes:

$$\frac{\frac{1}{2}(\bar{x}_s^2 + \bar{y}_s^2)}{\frac{1}{2NK}\sum_1^N (x_n^2 + y_n^2)}$$

where $\bar{x}_s^2$ is the square of the mean of the real components of the K signals and $\bar{y}_s^2$ is the square of the mean of the imaginary components. This ratio is distributed (in the same way as the single measurement ratio) as F with 2 and 2N degrees of freedom.

For these combined measurements, we used a range of frequencies from 70 to 100 Hz for our noise estimate, so that this estimate reliably reflected the noise that existed across the range of all the separate responses. This gave a total of 483 bins, given that the signal frequencies were excluded. Although the number of noise bins is much larger than the 120 used to evaluate the single responses, any increase in statistical power (from the greater degrees of freedom) would have been countered by the greater range of the EEG noise level, which decreases from low to high frequencies (and there fore increases the over all amplitude of the noise estimates).

Measurement of Time to Significance

The amount of time to reach significance was measured for the responses by multiplying the number of sweeps required by 16.384 sec. If a response was not significant by the end of a sweep it was not evaluated again until the next sweep had been fully recorded. A shorter sweep length would have increased the precision of this timing measurement, but we wanted to use the recording parameters that we had used for many of our previous studies. Response times were calculated for both the traditional MASTER stimuli and the new types of stimuli. However, some MASTER stimuli evoke responses that are bigger (and more efficiently recorded) than others. Accordingly, the responses to the 1000 Hz tone were examined separately because of the frequency-specific stimuli, these responses, on average, became significant most quickly.

Statistical Analyses

The effects of the different stimuli on the amplitude of the response were assessed using repeated measures ANOVAs. Greenhouse-Geisser corrections for the probability levels were used when appropriate. Post-hoc comparisons relied on the Fisher Least Significant Difference (LSD) test. Degrees of freedom had to be reduced when some data were missing (e.g., one of the subjects did not complete all of the conditions in the first experiment). Differences were considered significant at the $p < 0.01$ level for

TABLE 2. Stimulus parameters and response amplitudes

Stimulus	Ear	Carrier (kHz)	Modulation (Hz)	Response (nV)	SD
BBN	L	1Hz-8kHz	80	77	26.8
	R	1Hz-8kHz	83		
MASTER	L	750	80	36	45
		1500	85	42	20
		3000	90	36	17
		6000	95	25	12
	R	500	78	43	52
		1000	83	50	30
		2000	87	33	18
		4000	92	37	22
SMF-AM	L	500, 1000, 2000, 4000	80	81	49
	R	500, 1000, 2000, 4000	83		
SMF-MM	L	500, 1000, 2000, 4000	80	87	51
	R	500, 1000, 2000, 4000	83		
SMF-AM^2	L	500, 1000, 2000, 4000	80	83	53
	R	500, 1000, 2000, 4000	83		
LPN	L	1Hz-1kHz	80	34	31
	R	1Hz-1kHz	83		
HPN	L	1kHz-8kHz	85	89	33
	R	1kHz-8kHz	87		
Combined HPN-LPN	L	1Hz-1kHz	80	24	25
	R	1Hz-1kHz	83		
	L	1kHz-8kHz	85	94	32
	R	1kHz-8kHz	87		
Combined HPN2-LPN2	L	1Hz-1kHz	80	32	24
	R	1Hz-1kHz	83		
	L	2kHz-8kHz	85	77	30
	R	2kHz-8kHz	87		

The amplitudes of the responses to the left and right ears were averaged arithmetically in order to obtain the values in the "Response" column. The standard deviations (SD) were computed upon the raw values for both the left and right ears.

the ANOVAs and then <0.05 for the post-hoc tests (provided the ANOVA effects were significant).

RESULTS

Behavioral Thresholds

The behavioral thresholds for each of the stimuli used in the different experiments are shown in Table 1. The tonal and noise stimuli are best considered in terms of the RMS SPL whereas the transient stimuli are more appropriately considered in terms of the pSPL (as is suggested by the bold print in the table).

Auditory Steady-State Responses

Experiment 1: Broadband Noise, MASTER Responses, and SMF Tones • The average amplitudes of the responses recorded in the first experiment are shown in Table 2. Although the amplitudes of the responses to individual tones are shown in the table, the average of all 4 amplitudes, for each ear, in each ear were used as an estimate of the frequency-specific response amplitude. An ANOVA (ear x stimulus type) of the response data for the first 5 stimuli of Table 2 showed a significant effect of stimulus type ($F = 8.36$; d.f.=4,40; $p < 0.01$), but no effect for ear and no significant interactions. Post-hoc tests indicated that BBN, SMF-AM, SMF-MM, and SMF-AM^2 were all larger than the average amplitude of the frequency specific responses, but were not significantly different from each other. Although the average amplitude for all the frequency specific responses was 38 nV, the 1000 Hz response was the largest of these responses. A t-test indicated that the response to the BBN stimulus was still significantly larger ($p < 0.01$) than the 1000 Hz response. A comparison of the responses to the MASTER stimuli and the BBN stimuli can be seen for a single subject in Figure 4.

Experiment 2: Comparisons of Broadband Noise and Filtered Noise Stimuli • The amplitudes for responses evoked by the different steady-state noise stimuli are also shown in Table 2. An ANOVA (ear x stimulus type) of the responses to these noise stimuli showed a significant effect of stimulus type ($F = 35.73$; d.f.=6,60; $p < 0.01$), but no effect for ear and no significant interactions. Post-hoc tests indicated that the response to BBN was larger than each of the LPN responses ($p <$

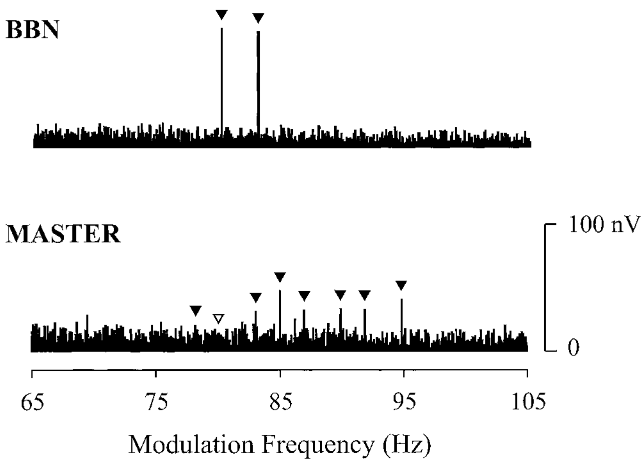

Figure 4. Responses to BBN and MASTER. Responses for a single subject are plotted in the frequency domain. The filled triangles represent responses that are recognized as significant and the open triangle one that is not significant. The BBN responses are more than twice as big as the MASTER stimuli and are easily significant. For this particular subject, the largest response to the MASTER stimuli occurs at 85 Hz, in which the carrier is 1500 Hz.

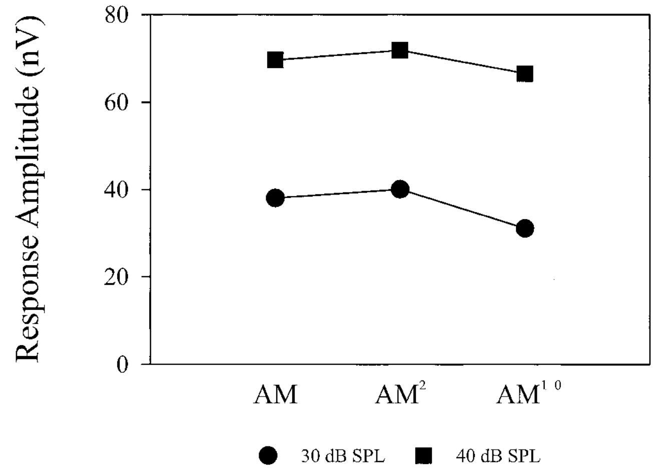

Figure 5. Noise modulated with exponential envelopes. This graph plots the average amplitudes in the different experimental conditions. The amplitudes of responses evoked by noise stimuli modulated with envelopes raised to powers greater than 1 were not larger than when the power was set to 1. The decrease in intensity of 10 dB produced a decrease of approximately 25 nV.

0.001). The response to LPN, when presented alone, was significantly larger than the combined-LPN response ($p < 0.01$), which was not separated by 1 octave, but was not larger than the combined-LPN2 response. The response to combined-HPN was larger than the response obtained to BBN stimuli ($p < 0.01$). Although the response to HPN presented alone was larger than the response to BBN, this did not reach significance.

The average phase delays of the responses to the BBN stimulus were 218° and 225° for the left and right ears, respectively. These phases could be converted to latencies equal to 19.2 and 18.7 msec with the assumption of one preceding cycle. The average phase delays for the HPN (236° and 238°) were similar to those for the BBN, but the phase delays for the LPN were much longer (314° and 313°). For the eight tones in the MASTER stimulus the estimated latencies varied regularly from 16.5 msec at 6000 Hz to 21.8 msec at 500 Hz.

An ANOVA that examined the responses to stimuli from both Experiments 1 and 2 (which used the same subjects) allowed us to compare the response amplitudes for the HPN, combined-HPN, combined-HPN2, SMF stimuli and the 1000 Hz stimulus. This showed an effect of stimulus ($F = 3.74$; df = 6,60; $p < 0.01$), with post-hoc tests indicating that the all of the responses were bigger than the responses to 1000 Hz. None of the other post-hoc tests reached significance.

Experiment 3: Noise Stimuli with Exponential Envelopes • The results of Experiment 3 are shown in Figure 5. An ANOVA (ear x envelope x intensity) of these data showed a significant effect of stimulus type ($F = 103.6$; d.f.=1,10; $p < 0.001$), and intensity ($F = 11.9$; d.f.=2,20; $p < 0.001$) with no effect for ear. The responses at the higher intensity produced larger responses. Post-hoc tests indicated that the responses when the exponent was set to 1 or 2

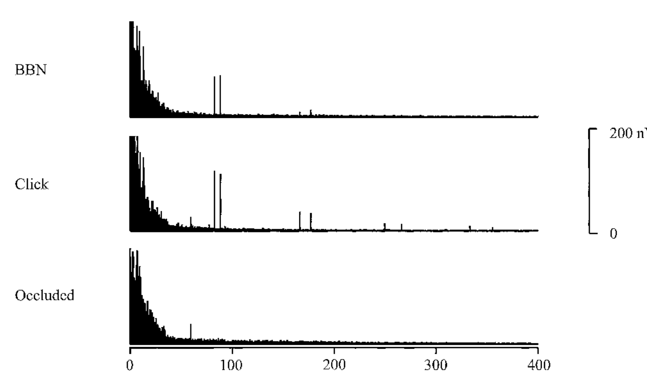

Figure 6. Responses to clicks and amplitude-modulated broadband noise. Grand averaged amplitude spectra across 10 subjects. The top of the figure shows the amplitude spectrum for the response to the amplitude modulated BBN stimulus. The response shows up at the first harmonics, with the second harmonics having a small response. The middle amplitude spectrum shows the response to the rarefaction click. The response is evident at the first harmonics and also at the second, third, and fourth harmonics. The lower spectrum is for the rarefaction click when the insert earphone was occluded. There are no significant responses in this spectrum. The peaks at 60 Hz in the middle and lower rows are caused by line noise.

TABLE 3. Transient stimuli and responses

Stimulus	Ear	Carrier (kHz)	Modulation (Hz)	Response (nV)	SD
BBN	L	1Hz-8kHz	83	90	26
	R		89		
CLICK (+)	L	Broadband	83	129	39
	R		89		
CLICK (−)	L	Broadband	83	137	42
	R		89		
BBN-BURST	L	1Hz-8kHz	83	126	39
	R		89		
HPN-BURST	L	1kHz-8kHz	83	106	28
	R		89		
1400 Hz BURST	L	1400 Hz	83	149	44
	R		89		

evoked responses that were significantly larger than when the exponent was set to 10 ($p < 0.05$).

The phases from Experiment 3 were converted into latencies using the preceding cycles technique (John et al., 2000b). Only responses whose amplitudes were large enough that the responses were evaluated by the software as present (106 out of 120 total responses) were evaluated. The mean latency increased with the increasing exponent from 17.9 msec ($N = 1$) to 18.6 msec ($N = 10$). There was also a slight increase in latency with the 10 dB decrease in intensity from 17.9 msec to 18.3, but this only occurred for $N = 1$. Neither of these effects was significant. Apparent latencies calculated for the mean phases were a little smaller than those calculated with the preceding cycles technique, varying between 13 and 16 msec.

Experiment 4: Comparisons of Noise and Transient Stimuli • The mean responses for some of the conditions in this experiment are shown in Figure 6. The mean amplitudes are shown in Table 3. An ANOVA of this data showed a significant effect of stimulus type ($F = 72.35$; d.f.=6,54; $p < 0.001$) with no effect for ear and no significant interactions. Post-hoc t-tests indicated that the response to the clicks, the BBN-burst, and the 1.4 kHz burst were all significantly larger than the BBN amplitude modulated stimulus ($p < 0.001$). The average response to the HPN-burst was also larger than the BBN amplitude modulated stimulus ($p < 0.05$), but was smaller than the responses to the other burst stimuli and the click stimuli ($p < 0.01$). The response to the 1.4 kHz burst was significantly larger than the responses obtained by all other stimuli.

TABLE 4. Response latencies for BBN and transient stimuli

Stimulus	Left Ear		Right Ear	
	Latency (msec)	SD	Latency (msec)	SD
BBN	17.9	0.4	17.6	0.6
Click (+)	13.2	0.7	13.3	0.6
Click (−)	13.2	0.8	13.4	0.6
BBN-Burst	13.2	0.9	13.2	0.6
HPN-Burst	13.1	0.4	12.9	0.5
1.4 kHz Burst	13.6	0.7	13.7	0.7

TABLE 5. Time needed to obtain a significant response

Stimulus	Stimulus Intensity nHL	Average Time seconds (SD)	Maximum Time (sec)	MISSES (%)
MASTER stimuli				
All 8 TONES	*	110 (102)	320	25
1000 Hz	39	72 (30)	256	17
Steady-state stimuli				
BBN	32	43 (35)	128	0
SMF-AM	33	50 (53)	256	0
SMF-AM^2	31	39 (24)	88	0
SMF-MM	29	70 (79)	304	0
HPN	33	37 (27)	128	0
Combined-HPN	33	37 (22)	96	0
Exponential stimuli				
BNN	23	54 (52)	252	0
BNN^2	23	50 (68)	252	10
BNN^{10}	20	44 (58)	240	0
Transient stimuli				
BBN	47	42 (35)	160	0
CLICK (CC)	44	24 (17)	80	0
CLICK (RC)	44	22 (14)	64	0
BURST-BBN	46	23 (16)	64	0
BURST-HPN	44	28 (20)	80	0
BURST (1400 Hz)	54	18 (4)	32	0

** nHL levels for each carrier are different, only the 1000 Hz was assessed as reported in the cell below.*

The phases for the responses to the transient stimuli presented at each rate were all very similar. For example, the average phase delays of the rarefaction and condensation clicks were 181° and 180° in the left ear and 212° and 215° in the right. The phases were converted into latency using the preceding cycles technique (John et al., 2000b). An ANOVA (ear x stimulus type) of the latency data indicated a significant effect for stimulus type, but no effect for ear and no significant interactions. Post-hoc testing indicated that the latency of the BBN was longer than the latency of all the other stimuli ($p < 0.01$).

In the "occluded" condition, there was no evidence for any response. The amplitudes did not reach significance and the standard deviation for the latencies were more than 3 times any of the other conditions.

Time Required to Detect Responses

Table 5 shows the time required to reach significance (at $p < 0.05$) for selected stimuli from the four experiments. The first two rows show the responses obtained using the MASTER technique. The eight tones required an average of approximately 2 minutes to become significant, whereas one-quarter of the tones did not reach significance by the end of the 5-minute recording period. Because the largest average response was found for the 1000 Hz tone it was evaluated separately. At approximately 30 dB nHL, the BBN stimulus requires approximately ⅔ the time of the 1000 Hz tone. At approximately 45 dB nHL, the transient stimuli required approximately ⅔ the time needed by the BBN stimuli.

An ANOVA (ear x stimulus type) compared the responses for the potentially efficient steady-state stimuli from Experiments 1 and 2 (BBN, SMF, 1000 Hz, HPN, and combined-HPN). A significant effect was found for stimulus but not for ear. The SMF-AM[2], HPN, and combined-HPN were all found to become significant faster than the 1000 Hz response ($p < 0.05$). The BBN response did not become significant faster than the 1000 Hz response. The SMF-MM took longer than the SMF-AM. Although the SMF-MM is one of the largest average responses, in 2 ears the responses took quite some time to reach significance (hence the larger standard deviation).

An ANOVA (ear x stimulus type) compared the responses to the 3 types of exponential envelope stimuli listed in Table 5. No main effects or interactions were found to be significant.

An ANOVA (ear x stimulus type) compared the responses to the five types of transient stimuli and the BBN. Although the BBN response was slower in reaching significance than the responses to any of the transient stimuli, this difference did not reach significance. It is likely that this difference was not significant because most subjects had significant responses by the end of the first sweep for almost all the stimuli.

Combining the 4 MASTER responses in one ear using the RMS or vector-averaging techniques gave a time course to significance for the combined data that was similar to the time-course of the SMF-AM response, and a little slower than that of the BBN. These results are illustrated in Figures 7 and 8. Because the average onset phases of all the MASTER responses were very similar (varying between 116° for the 1000 Hz carrier and 148° for the 3000 Hz carrier), simply vector-averaging the data was not significantly different from vector averaging after compensating for the expected phase (considered as the mean phase across subjects for each carrier). We used only the phase-compensated data for the Figures and for the statistics. To evaluate the time course for recognizing a response to a single tone, we used the 1000 Hz (right ear) and 1500 Hz (left ear) responses from the MASTER recording (termed "Single" technique in Fig. 8). We compared the time to reach $p < 0.01$ across five different techniques (BBN, SMF-AM, RMS, Vector-averaging, Single) and two ears for eleven subjects (data for one subject were incomplete). There was a significant effect of technique ($F = 4.6$; df 4,40; $p < 0.01$) and no effect of ear or interaction. Post-hoc testing showed that the Single technique (average time 8.2 sweeps) was slower than all the others, which showed no significant differences among themselves (varying between 3.1 and 3.9 sweeps). Using broadband noise as a stimulus or combining the responses across the different components of a multi-stimulus response (either by modulating all stimuli with the same frequency, or mathematically combining the responses to the stimuli when they were modulated separately) led to faster response-recognition than when the responses to only one tone was evaluated.

DISCUSSION

Behavioral Thresholds

The thresholds for the stimuli are similar to those reported in the literature, given the 5-dB accuracy of threshold estimation. The 11-dB SPL threshold, which we obtained for the 1000-Hz AM tone stimulus, is similar to the threshold of 9 dB SPL reported by Herdman et al. (2001). Our 32 dB pSPL threshold for the 125 μsec clicks at 83 and 89 Hz is similar to the normal threshold for 100 μsec clicks at 80/s, which is also approximately 32 dB pSPL (Stapells, Picton, & Smith, 1982). The threshold for the BBN is likely based on the thresholds at the frequencies near 1000 to 2000 Hz, where human hearing is most acute. The actual measured intensity of the stimulus is, however, elevated because of the total energy (i.e., larger bandwidth) of the stimulus, which makes the intensity higher but does not change the audibility of the stimulus. Assuming the overall bandwidth of the BBN stimulus (1 to 8 kHz) is approximately 8 times the bandwidth that is determining the threshold, one would estimate the threshold stimulus at approximately 9 dB greater than the threshold level for the 1000 Hz tone. Because the MASTER stimuli and the SMF stimuli are approximately 6 dB higher in intensity than any single stimulus, one would expect the SMF stimuli to have a threshold level approximately 6 dB greater than the threshold for a single modulated tone. The fact that the actual thresholds were 12 to 15 dB higher may be because of the variability in the measurements or to some inter-stimulus perceptual inhibition. This type of inhibition may occur at the level of the cochlea (Ruggero, Robles, & Rich, 1992). For example, two-tone suppression may cause the 2000 Hz response to be suppressed by the 4000 Hz stimulus (Dolphin & Mountain, 1993). The 1400 Hz

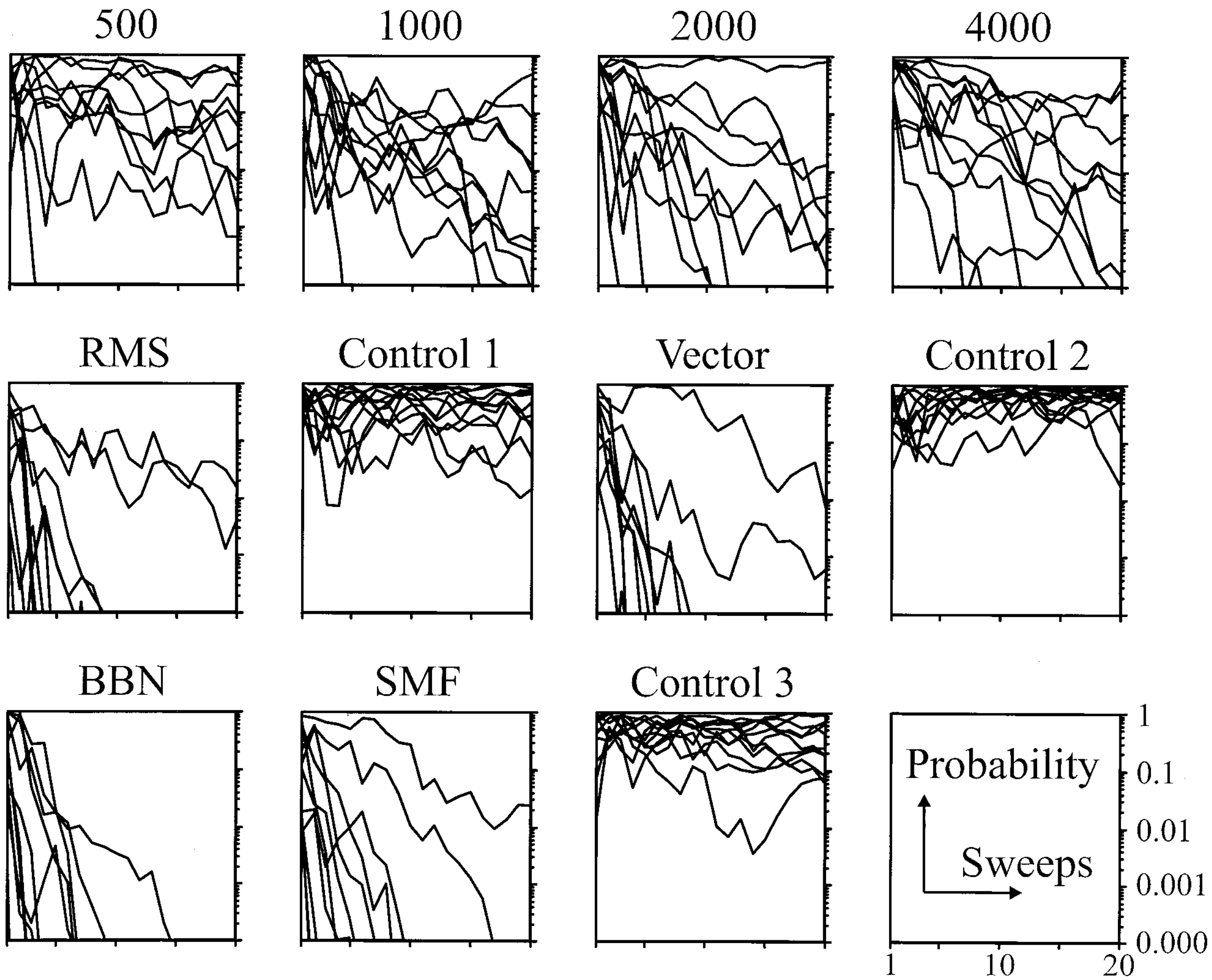

Figure 7. Time course to significance: individual data. This figure plots the probability of the F-ratio for the different statistical tests as the number of sweeps increases from 1 to 20. The probabilities are plotted separately for each of 11 subjects. Only the results from the right ear are shown. The upper row of graphs shows the probabilities for each of the four stimuli presented to the right ear with the MASTER technique. In some of the subjects, the responses do not reach accepted levels of significance ($p < 0.05$ or $p < 0.01$) even after 20 sweeps. This is particularly true for the 500 Hz carrier. The middle row shows the same data analyzed after combining the four responses with the RMS technique or vector-averaging (with phase compensation). Control 1 shows what happens with the RMS technique when 4 signal frequencies were chosen in which there were no stimuli. Because many tests were performed, the probabilities occasionally reached levels of significance by chance alone. Control 2 is the control for the vector averaging technique. The bottom line of graphs shows the responses to BBN and SMF-AM as well as a control (3) for checking a single response (appropriate for the top line of graphs as well).

tone-burst has a large amount of spectral splatter because of the instantaneous rise and fall times. This stimulus is basically a click with some accentuation of its energy in the 1000 to 2000 Hz range. As such, it fits the human threshold curve and has the lowest threshold of the transient stimuli.

Noise and Tones

Experiments 1 and 2 demonstrated that the SMF and BBN stimulus (and the various HPN stimuli) evoked responses that were significantly larger than the responses to the AM tones of the MASTER stimuli. Because the dB nHL values for all these stimuli were similar (except, in the case of the LPN), the differences in response amplitude are not caused by a difference in the intensity of the stimulus relative to threshold. The SMF and noise responses also reached significance more rapidly than any of the individual tones in the MASTER stimuli. Using such stimuli may therefore be appropriate if one wishes to record a response from the ear as quickly as possible and is not overly concerned about hearing at specific frequencies.

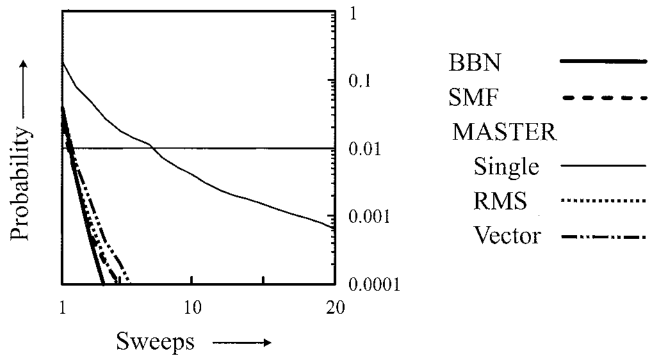

Figure 8. Time course to significance: mean data. This graph shows the mean probabilities across both ears for three different stimuli (BBN, SMF-AM, and MASTER). The responses to the MASTER stimulus were evaluated as Single responses and using the RMS or Vector techniques. The tracing for the Single stimuli is the average across all of the MASTER stimuli. For this figure the probabilities have been averaged after logarithmic conversion.

Interactions within the BBN

The BBN response is evoked through a wide range of the cochlea. The HPN and the combined-HPN evoked responses were significantly larger than the BBN response. Because the BBN stimulus is effectively a combination of HPN and LPN, the lower amplitude of the BBN than predicted from the arithmetic sum of the two components might in part be caused by the phase differences between the responses to HPN and LPN. However, even the vector sum of the two components cannot fully explain the results, because this sum is larger than what we obtained empirically. One must conclude that the activation of many different regions of the cochlea by the BBN may result in complex interactions (cf. John et al., 1998). Two-tone suppression at the level of the cochlea or lateral inhibition at later stages in the auditory pathway are examples of such interactions. Our results with the combined HPN and LPN stimuli support the idea of some interactions between the stimuli. The HPN response was smaller when presented alone compared to when it was presented with the LPN, and the opposite effect occurred for the LPN. These results indicate the tendencies of low-frequency tones to enhance the responses to high-frequency tones and of high-frequency tones to suppress the responses to low-frequency tones. Similar interactions between the responses to tones of different frequencies have been reported previously (Dolphin, 1997; John et al., 1998; John, Purcell, Dimitrijevic, & Picton, 2002). The attenuation of the combined-LPN due to masking, when it was presented with combined-HPN, did not occur in the case of the combined-HPN2, which was separated by 1 octave. The interactions between stimuli are minimal when stimuli are separated by an octave or more (John et al., 1998).

Single-Modulation Frequency (SMF) for Multiple Tones

We evaluated the SMF stimuli in addition to modulated BBN because, as just mentioned, there might be less interaction between the frequency components of a stimulus when they are separated by an octave from each other. The responses to the SMF stimuli were indeed larger than the responses to BBN, but not by much. To determine whether the amplitudes of the SMF responses may have been caused by the simple addition of the responses to the four tones, we modeled this process using the amplitudes of the tonal responses in the MASTER stimuli and the phases that would be predicted for these responses at the 80 and 83 Hz rates (John et al., 2000a). The amplitude of the modeled response was less than the arithmetic sum (non-vector) of the amplitudes of the responses to the individual MASTER responses because the phases of each of these responses were different. However, the size of the "virtual" response was still approximately 25% greater than the actual SMF-AM responses. This difference indicates some interaction between the tones that make up the SMF stimulus. This decrement in the size of the observed SMF response is unlikely caused by interaction between the carrier-frequencies, because it does not occur when the modulation frequencies are different: when carrier frequencies of the MASTER stimuli are each modulated at a different rate, and they are an separated by an octave, there is no significant interaction between the stimuli. It is therefore likely caused by interactions within those neurons that respond to particular modulation frequencies, that are distributed across multiple carrier frequencies (Biebel & Langner, 2002) or to destructive interference derived from non-optimum alignment of the dipole sources which correspond to the multiple frequency-specific areas that are simultaneously activated by the carriers of the SMF.

Combining the MASTER Responses

Using multiple carriers all modulated at the same frequency gives a large combined response, but does not allow the individual responses to be separately evaluated. We therefore considered two ways to combine the responses to the MASTER stimuli. We examined both root mean square and vector averaging. Both techniques worked very well, and produced "virtual" responses that were detected in approximately the same time as the BBN or the SMF stimuli. These techniques let one both have one's cake immediately and keep it for later. One can use the technique in a screening situation to show quickly that there is some response from the ear. If there is sufficient time one can continue the recording to demonstrate responses at specific frequencies. At intensity levels 30 to 40 dB above threshold in adult subjects it generally takes less than two minutes to demonstrate that a combined response is present (see RMS, Vector, BBN and SMF in Figs. 7 and 8), between two and three minutes to recognize a single response to one of the frequencies (usually 1000 or 1500 Hz, see upper row of Fig. 7) and five or more minutes to show that all four responses are present (data not shown in figures). These data are similar to those obtained by averaging the times to significance for the different subjects (Table 5).

The graphs in Figure 7 each contain responses (for 12 subjects) assessed at each sweep over 20 sweeps (approximately 5.5 minutes). In the top of the figure, the responses to frequency specific stimuli, show that a considerable portion of the subjects responses fail to reach significance in the allotted timeframe. Using this same frequency specific data to test general hearing ability using a "virtual SMF" response (RMS or Vector in Figure 7), all but 2 of the subjects become significant at $p < 0.0001$(the lower boundary of the graphs) within 20 sweeps. This result approximated what occurred when using an actual SMF response (bottom row), although 1 of the 2 subjects reached significance by approximately 15 sweeps. The BBN stimuli clearly provided a faster (within 5 sweeps or <3 minutes), yet non-frequency specific, indication of hearing status for all subjects tested. Even when Bonferroni-correcting the probability criteria from .05 to .0025 to account for the multiple comparisons (i.e. checking the probability after each of the 20 sweeps), the BBN stimulus still would become significant very rapidly. The data for Figure 8, which represent the average of the data plotted in Figure 7, clearly show the overall effects. The responses of a typical subject are significant at $p < 0.01$ after 2 sweeps (33 sec) for the combined techniques and after 7.5 sweeps (2 minutes) when looking for a response to either a 1000 Hz or a 1500 Hz tone ("Single").

Exponential Envelopes for the BBN

Experiment 3 showed no advantage to using exponential envelopes with the BBN stimuli. This differs from the results with tonal stimuli (John, Dimitrijevic, & Picton, 2002). Because the peak SPL of the stimuli was constant across conditions, the RMS SPL decreased with increasing envelope power. However, there was little change in the behavioral threshold (which must therefore have been determined mainly by the peak SPL). Exponential envelopes were tested because rapid rise times can increase the amplitude of both transient (Gorga & Thornton, 1989; Suzuki et al., 1981) and amplitude-modulated tonal stimuli (John, Dimitrijevic, & Picton, 2002). For tonal stimuli, the faster slope of the exponential envelope likely increases the synchrony of activation within the local region of the basilar membrane activated by the tone. In the case of noise, the greater dispersal of the activation over the basilar membrane causes responses with many different latencies. Increasing the slope of the rise function, for both tonal and noise carriers, will increase the strength of the responses in single units of the auditory system (Heil, 1997a, 1997b; Phillips, Hall, Guo, & Burkard, 2001). However, increasing the slope of the rise function will not necessarily act to increase synchrony of firing, with respect to the summation that leads to the far field response, and may therefore not lead to increased amplitudes in the case of ASSRs evoked by noise stimuli.

Transient Responses

Transient stimuli such as clicks cause large responses. At the moderate intensities examined here, the responses to click stimuli were significantly larger than those evoked by the steady-state BBN stimulus. As pointed out by Stürzebecher et al. (2003), recording steady-state responses to rapidly presented click stimuli might allow rapid and objective screening for hearing in newborn infants. One advantage of the steady-state responses over the transient responses currently used in screening is that the statistical demonstration of the responses is simple (F tests or the like) one does not need to change the detection protocols to account for different latencies at different ages (because the basic F-test is phase insensitive). If age-appropriate phases of the steady-state response are to be incorporated into the statistical procedure then one merely adjusts for the age-related changes in phase by inserting a single number for each expected phase value. Additionally, presenting stimuli at faster rates enables more stimuli to be presented per unit time, without worrying about superimposition of residual responses to previous stimuli (in fact, this is expected). Although these advantages exist, in order for steady-state based techniques to be used clinically (e.g., for a screening test) they will, of course, have to be evaluated with respect to specificity and sensitivity.

One of the advantages of tonal steady-state stimuli is that no energy occurs at the modulation rate in the original stimulus. Rectification occurring in the cochlea results in energy at the modulation frequency. Accordingly, unless there is some sort of non-linear process in the recording system, the steady-state responses that are recorded are biologic in origin and are not caused by stimulus artifact. This is not the case with the transient stimuli (or modulated broadband noise), which contain energy at the modulation frequency. This increases the danger that stimulus artifact is entering into the recorded response. At the levels that we used in the fourth experiment (approximately 45 dB nHL/76 dB pSPL) we demonstrated no recognizable artifact when the ear canals were occluded (Figure 6). Other parts of our data also suggest that stimulus artifact is not a problem. The best argument that the steady-state response to the click is not an artifact is that the condensation and rarefaction responses were almost identical in phase. Electrical artifact would be 180° out of phase. Although stimulus artifact does not seem to be a problem at the intensities we evaluated, which are higher than would be appropriate in screening, caution must nevertheless be exercised when using these stimuli at higher intensities.

Phases and Latencies

The latencies we estimated for the noise responses are similar to the 17 to 23 msec latencies previously estimated for tones (John et al., 2000b). The latencies for the transient stimuli were shorter, but it was difficult to relate these to the latencies of the auditory brain stem response. Unfortunately, phase is an ambiguous measurement because it circles back on itself. The preceding cycles technique (John et al., 2000b) attempts to determine how many cycles have occurred before the cycle being measured in the response. However, this cannot handle non-linear filtering effects in the generation of the response. A related problem occurs with the transient response: where does one set the zero point? One could argue that the click should occur at the lowest or highest values of cosine used to measure the phase. Apparent latency or "group delay" gets around some of these problems. However, both apparent latency and the preceding-cycles technique run into a further problem of what happens when multiple generators (each activated at different times) contribute to the response. For example, the 80 Hz responses might be generated both in the brain stem and the auditory cortex. Differences in phase are likely more meaningfully related to timing, between responses evoked by different stimuli, than trying to assess absolute latencies. Thus one can understand the increase in phase delay with decreasing carrier frequency, but the absolute latencies of the different responses may not be that meaningful.

Time Needed to Recognize Responses

Table 5 shows that the response to BBN and to transient stimuli became significant faster than the responses to tones. Although the responses to transient stimuli did not statistically differ from the BBN in the speed with which they were recognized, they are larger, and would likely have been statistically faster if we used greater resolution in tracking the responses (shorter sweeps) or if we used stimuli with lower intensity. For rapid screening purposes either clicks or BBN might be more appropriate than the usual MASTER stimuli. However, one might also consider using the MASTER stimuli and calculating the statistics for all four stimuli after they have been "virtually" combined. This technique will have to be evaluated further.

The current analysis did not use phase-weighted statistics, which may improve detection efficiency even more. We have shown previously (Picton, Dimitrijevic, John, & van Roon, 2001) that biasing the statistical test according to an expected phase can increase the detection of the steady-state response. The response to the BBN stimulus does not change its phase with intensity, as much as was seen with tones. Accordingly, the expected phases for the responses to this stimulus would not have to be adapted individually for each intensity being tested. Further, the phases for the responses to the different types of transient stimuli, which were examined here, had a very small range. Accordingly, screening techniques that utilized transient stimuli would be likely to benefit from incorporating expected phase values into the statistical assessment of the response.

Stimulus Intensity

In the first two experiments, stimuli were presented at approximately 30 dB nHL (50 dB SPL range), which is close to the 35 dB nHL often used for universal newborn hearing screening procedures. We chose this intensity range to gather initial data with which we could make an informal comparison between the two techniques. At this intensity the stimuli investigated here seemed to perform comparably to what one might expect from a conventional ABR test. In the third experiment we decreased the intensity to approximately 20 dB nHL to see if the moderate decrease in intensity would result in significantly longer times-to-significance, with respect to the BBN stimulus. In the fourth experiment we increased stimulus intensity to approximately 50 dB nHL to see if a moderate increase in intensity would result in shorter times-to-significance, with respect to the BBN stimulus. The results from these three intensity ranges, suggested that regardless of the 30-dB range of the BBN stimulus, its magnitude was consistently sufficient enough to become significant in approximately 40 sec. In the fourth experiment, we also increased the intensity of the stimuli to increase the chance that artifactual responses could occur in response to the transient stimuli. Even at 10 dB above the level that might be used by a screening test, no response artifacts were produced by the instrumentation.

In this initial study, it would have been difficult to make the intensity levels of the stimuli exactly identical, with respect to dB nHL levels. When only 10 to 12 subjects are used, a test-retest difference of 5 dB in only 1 or 2 subjects will create a small difference in the nHL levels. Accordingly, we attempted to set the intensities of our stimuli so that they would be roughly similar in dB RMS SPL or dB pSPL. Within each of the four experimental conditions, the stimuli were within 3 dB of each other except for 3 exceptions. The first exception occurred in Experiment 1, in which the 1000 Hz tone was presented at 4 to 6 dB below the SMF stimuli. Within the SMF stimuli, the 1000 Hz tone was presented at the same intensity as the 1000 Hz tone presented alone. Because each of the carrier frequencies are processed relatively independently in the cochlea, we wanted the 1000 Hz energy to be the same whether presented alone or simultaneously with other stimuli. Equivalating for dB nHL rather than dB SPL would have made the SMF responses slightly smaller. In any case, relative to the transient stimuli, the SMF showed only moderate increases over the BBN stimulus (Tables 2 and 3). The second exception occurred in the case of the LPN stimulus of Experiment 2. We evaluated HPN and LPN with the intent of seeing whether we could get some idea of the ear's responsiveness to high and low frequencies while still getting larger responses than tones. This was true for the HPN, but not for the LPN. The LPN had a lower intensity than the other stimuli by approximately 8 dB, because the LPN intensity was set to be the same as that which occurred in the LPN frequency region of the BBN stimulus. This was done in order enable a comparison between the BBN amplitude with the sum of the LPN and HPN responses. Increasing the LPN stimulus intensity by 8 to 10 dB, so that it was the same intensity as the other stimuli of that condition, may have increased its amplitude. However, even if this was done, the amplitude of the LPN response would probably not have been larger (i.e., more efficient) than those obtained using amplitude modulated pure tone stimuli below 1000 Hz (see Table 2). The last exception was the stimulus in Experiment 4, in which the 1.4 kHz tone was used. Although the pSPL levels were within 5 dB of the BBN stimulus and the other transient stimuli, within the individuals tested, the subjective thresholds for this stimulus was lower than for the other stimuli, and therefore it was presented at a 10 dB nHL above the other stimuli. Future studies, which comprehensively examine this stimulus over many subjects, may choose to decrease the intensity of this stimulus accordingly.

The intensities of the stimuli investigated here are presented in several units. It is appropriate to use pSPL when describing transient stimuli. However, steady-state stimuli are usually measured in RMS dB SPL. Both of these measures can be made more sensible by converting to nHL, which is what is used in Table 1, to present the results obtained across the different experiments.

Overview

Rather than obtaining frequency specific steady-state responses, the experiments presented here were concerned with getting a response as quickly as possible. Because the 1000-Hz frequency specific response is the largest of the frequency specific responses, the responses obtained here should be compared to it. Compared to the 50 nV amplitude of the 1000-Hz response, the BBN, HPN, and combined HPN, separated by 1 octave, were 56%, 80%, and 90% larger. These stimuli reliably reached significance within approximately 33 sec at 50 dB SPL, suggesting that ASSRs can be used to provide a rapid and objective tests of hearing. The fourth experiment suggested that clicks might the most efficient stimuli for screening purposes. We did not formally compare the combined MASTER statistics to the transient responses, but it would appear that the combined techniques work with approximately the same speed as, or a little slower than, the BBN. Studies in newborn infants which compared BBN, clicks and combined MASTER (SMF or "virtual" SMF) would allow us to decide which is indeed the best stimulus both in terms of speed as well as with respect to sensitivity and specificity. In other tests that require rapid responses such as estimating the modulation transfer function of the auditory system, the BBN stimulus may be the best, because it is not clear how to relate the transient responses to modulation detection.

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