Human temporal auditory acuity as assessed by envelope following responses[a)]

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Temporal auditory acuity, the ability to discriminate rapid changes in the envelope of a sound, is essential for speech comprehension. Human envelope following responses (EFRs) recorded from scalp electrodes were evaluated as an objective measurement of temporal processing in the auditory nervous system. The temporal auditory acuity of older and younger participants was measured behaviorally using both gap and modulation detection tasks. These findings were then related to EFRs evoked by white noise that was amplitude modulated (25% modulation depth) with a sweep of modulation frequencies from 20 to 600 Hz. The frequency at which the EFR was no longer detectable was significantly correlated with behavioral measurements of gap detection ($r = -0.43$), and with the maximum perceptible modulation frequency ($r = 0.72$). The EFR techniques investigated here might be developed into a clinically useful objective estimate of temporal auditory acuity for subjects who cannot provide reliable behavioral responses. © *2004 Acoustical Society of America.* [DOI: 10.1121/1.1798354]

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I. INTRODUCTION

Prosody (rhythmic and stress variations in the amplitude envelope of a speech signal) is crucial to speech intelligibility. The envelopes of speech signals contain enough information, even without their spectral content, to permit a listener to identify tokens (Van Tasell *et al.*, 1987; Rosen, 1992). Shannon *et al.* (1995) showed that a listener can recognize words, phrases, and sentences using amplitude envelopes of the speech signal in each of four frequency regions to modulate corresponding bandlimited noises. They found that speech intelligibility remained high when they recombined these four bands of amplitude-modulated noise. The envelopes of the speech signal in different spectral regions therefore play an important role in speech understanding.

Anything that reduces a listener's sensitivity to these amplitude modulations (auditory temporal acuity) is likely to lead to problems in speech understanding. Temporal acuity deteriorates in old age (Schneider *et al.*, 1998; Snell and Frisina, 2000; Gordon-Salant and Fitzgibbons, 1999), and this deficit may explain many age-related hearing problems (Schneider, 1997; Schneider *et al.*, 2002; Snell *et al.*, 2002). Certain disease processes can also result in decreased temporal acuity. For example, patients with auditory neuropathy (Zeng *et al.*, 1999, 2001) or multiple sclerosis (Rappaport *et al.*, 1994) have difficulty perceiving rapid changes in auditory input. Temporal auditory acuity can be abnormal in sensorineural hearing loss (e.g., Fitzgibbons and Wightman, 1982; Formby, 1987), although if one adjusts the intensity and bandwidth of the sounds to compensate for a subject's hearing loss, there is no impairment (Moore, 1995; Grose *et al.*, 2001). Decreased sensitivity to amplitude fluctuations may also contribute to developmental language disorders (Benasich and Tallal, 2002), but the nature of this relationship is not clear (Bishop *et al.*, 1999; Amitay *et al.*, 2002). Given the importance of envelope cues to speech intelligibility, tests to evaluate temporal acuity are essential.

The two most prevalent subjective ways to measure a listener's sensitivity to envelope fluctuations are to determine how sensitive they are to sinusoidal modulations in the amplitude of a sound (the temporal modulation transfer function, TMTF), or how sensitive they are to a gap in an otherwise continuous sound or between two sounds (gap detection). In the first procedure, a sound (often a band of noise) is sinusoidally modulated at a given frequency, with the depth of modulation (the ratio of the difference between the peak and trough of the modulated wave and their sum) systematically adjusted until the listener can no longer detect the modulation. Intensity adjustments are typically made to the modulated stimulus to control for intensity differences between modulated and unmodulated stimuli (Viemeister, 1979). The frequency of modulation is then changed and the procedure repeated (Viemeister and Plack, 1993).

In young, normal-hearing human listeners, the behavioral TMTF for white noise can be modeled as a single-pole low-pass filter with a 3-dB cutoff near 55 Hz (Viemeister,

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1979). This means that sensitivity to sinusoidal variations in the amplitude envelope remains roughly constant so long as the frequency of modulation is less than approximately 55 Hz, and then begins to decline steadily. However, the rate of decline is slow enough that listeners can normally detect a 25% amplitude modulation up to frequencies of about 500 Hz. The highest frequency at which a subject can discriminate 100% amplitude modulation is approximately 2.5 kHz, if the stimulus is designed to minimize high-frequency intensity effects (Viemeister and Plack, 1993).

Gap detection tests measure the shortest perceptible duration of a gap in an ongoing sound, or between two sounds. In young, normal-hearing human listeners, gap detection thresholds are about 1 ms for white noise. For pure tones the gap threshold increases with decreasing frequency from 2.3 ms at 8000 Hz to 22.5 ms at 200 Hz (Shailer and Moore, 1983). Since two cycles of a 100% modulated sound roughly resemble a gap between two short sounds (sound off, sound on, gap, sound on, sound off), it might be expected that the two tasks engage somewhat similar mechanisms. Note, however, that 100% modulation of a sound is similar to a continuous string of gaps between adjacent, identical, short-duration sounds. Hence, the modulation detection task allows for integration of information about periodic level changes over a time period that is much longer than that involved in detecting a gap between two short sounds. Accordingly, a reduced correspondence would be expected between modulation detection and detection of a gap in an otherwise continuous stimulus, or detection of a gap between two spectrally different sounds. Indeed, in the latter case, gap detection thresholds can be as much as ten times longer than when the markers are the same on both sides of the gap (Phillips *et al.*, 1997). In the former case, auditory processes (such as neural adaptation to the first marker) are likely to affect gap duration thresholds.

These two measures of temporal acuity are also likely to be related to different aspects of speech recognition. Phonemic contrasts can be cued by differences in the size of gaps between bursts that signal the presence or absence of a stop consonant (e.g., *slit* versus *split*). Hence, gap detection acuity is likely to be most relevant at the segmental or phonemic level. The TMTF, on the other hand, limits the processing of amplitude modulations at the syllabic or suprasegmental level, and is therefore likely to be more directly relevant to speech prosody. However, to the extent that the detection of a gap between two identical short-duration sounds can be conceived of as two cycles of an amplitude modulated envelope, knowledge of the TMTF could also be informative about the ability of a listener to detect a gap.

Most of the information that is known about temporal acuity has been collected using behavioral paradigms. An objective electrophysiological measure of human temporal auditory acuity would be very helpful in testing subjects who are unable to give accurate behavioral responses (e.g., young children, individuals with language impairment, or patients with cognitive difficulties). The present study addresses this need. In the research reported here, auditory steady-state response methods (Picton *et al.*, 2003a) were adapted to objectively estimate the TMTF. The results from this electrophysiological method were compared to behavioral measures of the TMTF.

The spectrum of the electrophysiological response to an amplitude-modulated signal contains energy at the modulation frequency. Thus, if a 1-kHz tone is modulated at a rate of 80 Hz, the spectrum of the response will reveal energy at 80 Hz and at overtones of 80 Hz (due to nonlinearities in the auditory system), even though there is no energy in the stimulus at the modulating frequency. The strength of the 80-Hz component can be taken as an index of the brain's sensitivity to an 80-Hz modulation of the stimulus, and the modulation depth at which the 80-Hz component is first detected can be considered as a measure of the modulation threshold at that frequency.

Auditory steady-state responses must be recorded across a wide band of modulation frequencies in order to obtain an electrophysiological representation of the TMTF. While multiple separate responses can be sequentially recorded at selected modulation frequencies (Stapells *et al.*, 1984; Rees *et al.*, 1986; Sapsford *et al.*, 1996), a more efficient approach might be to use a continuous sweep of modulation frequency through the band of interest. Sweep techniques were originally employed for the measurement of visual evoked potentials (Regan, 1966, 1989; Norcia *et al.*, 1989). They have also been used for auditory stimuli, where both intensity (Picton *et al.*, 1984; Linden *et al.*, 1985; Rodriguez *et al.*, 1986), and modulation rate (Linden *et al.*, 1985) have been varied. In the sweep technique, some aspect of the stimulus is continuously changed or "swept" across a specified range. Since the stimulus changes over time, the instantaneous amplitude and phase of the response is continuously changing. Referring to these as "auditory steady-state responses" is therefore not appropriate. However, since the modulation frequency of the stimuli used here was fast relative to the rate of change of modulation frequency, the responses examined in this paper are much more akin to auditory steady-state responses than to transient evoked responses. For simplicity, they will henceforth be referred to with the more general term of envelope following response (EFR).

This paper describes the results of a set of experiments examining how well the human EFR can be recorded by sweeping through a range of modulation frequencies. Several preliminary experiments evaluated the effects of different stimuli and subject states on the EFRs recorded using the sweep technique. The results of these experiments helped shape the experimental parameters for the main experiment, which compared objective EFR measurements of the TMTF and subjective measurements of temporal acuity in younger and older subject groups.

II. METHODS

A. Subjects

Two groups of adult subjects participated in this study. The younger group ($n=25$, 20 females) had normal thresholds of hearing (≤20 dB HL) for octave frequencies from 500 to 4000 Hz, and varied in age from 18 to 43 years. Fourteen of these subjects (11 females) participated in the main experiment comparing younger and older subjects. The older group ($n=13$, 8 females) ranged in age from 60 to 78 years. They had mildly elevated thresholds relative to those of young normal-hearing adults, but did not use hearing aids. On average, their thresholds were 20.8 dB HL (over the range from 500 to 4000 Hz) with standard deviation (SD) 12.6 dB. Only three individuals had any thresholds >35 dB HL. For the preliminary experiments, individuals from the younger group were employed. The main experiment, involving both EFRs and behavioral measurements, used both subject groups.

During the main experiment, it was found that the background noise in the older group's electroencephalogram (EEG) was approximately 1.5 times that in the younger group (probably due to increased muscle activity associated with wakefulness; older subjects tended to have more difficulty sleeping for the duration of the experiment). In order to approximately equalize the background EEG-noise levels to which the averaged EFRs are compared, the younger group attended one measurement session, whereas the older group attended two. Therefore, the older group had twice as many repetitions in the averaged EEG data (and the noise levels were reduced by $\sqrt{2}$).

B. Auditory stimuli

Acoustic stimuli were generated using a MASTER research system (John and Picton, 2000; see www.mastersystem.ca) running the SWEEP_V1 software module which permits using external sound files. Amplitude modulation was applied to either a uniform white-noise carrier or a 1-kHz tone. The depth of modulation was 100%, 50%, or 25% in the preliminary experiments, and 25% in the main experiment. Each sound file consisted of a single stimulus "sweep" containing 30 1.024-s epochs. For the first 15 epochs, the modulation rate increased linearly from the minimum to the maximum instantaneous frequency. In the second half of the sweep, the modulation rate decreased from maximum to minimum in symmetry with the first half. In some test conditions, the modulation rate was fixed in frequency throughout the 30.72-s sweep. The sweeps were repeated without any pause between them, since the sounds were designed so that there was no discontinuity at the transition between the end of one sweep and the beginning of the next.

Digital-to-analog conversion was performed using a National Instruments 6052E input/output board at 32 kHz with 16-bit precision. The electrical stimulus amplitude was adjusted using a Grason-Stadler model 16 audiometer prior to transduction by a pair of Etymotic ER-2 transducers with a flat frequency response at the eardrum up to 10 kHz. Generally, a single channel was used to present the stimulus monaurally using a foam ear insert. A Knowles DB-100 Zwislocki coupler and Brüel & Kjær sound-level meter were used to calibrate the stimulus.

C. Recordings

Measurements were performed in an Industrial Acoustics Company (IAC) sound-insulated room. During the experiments, the participants sat in a comfortable chair and watched a silent subtitled movie. The chair could be reclined for protocols wherein the subjects slept. The experiments generally took between 1 and 2 h. Gold-plated Grass electrodes were used to record the EEG from the vertex (Cz), and just below the hairline at the posterior midline of the neck (reference), with a ground on the collarbone. All electrode impedances were below 8 kOhm at 10 Hz. Responses were amplified with gain 10 000 and bandpass filtered 1–300 Hz or 1–1000 Hz using a Grass P50 battery-powered amplifier. The acquisition board applied a further gain of 5, and data were digitized at 16-bit resolution, and stored on disk at a rate of 1 (preliminary studies) or 2 (main experiment) kHz.

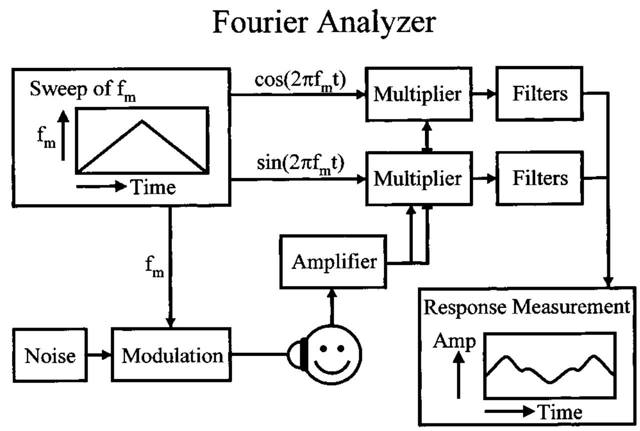

FIG. 1. Fourier analyzer schematic. Diagram showing how modulation rate, f_m, is swept over time, and how the instantaneous frequency is used to modulate the stimulus and extract the response in a Fourier analyzer.

D. EFR analysis

Data analysis was performed offline after the experimental recordings were completed. Data from each sweep were synchronously averaged in the time domain. The number of sweeps averaged was between 50 and 100. A noise rejection algorithm was employed to exclude 1.024-s epochs of data if a threshold noise level was exceeded in a broad frequency band containing the response frequency. Prior to averaging, the mean and SD of the noise in all epochs were estimated. The noise rejection threshold for any given epoch was then set as 1.5 SDs above the mean noise. Given that a sweep was divided into 30 1.024-s epochs, each "epoch slot" could contain a different number of epochs in the average. Typically, fewer than five epochs would be rejected from each slot when 50 sweeps were averaged.

The EFR was extracted from the average EEG sweep using a Fourier analyzer (FA) with orthogonal reference sinusoids that matched the instantaneous frequency of the stimulus (Regan, 1989). The complex outputs of the analyzer were filtered using simple 1.024-s boxcar filters (applied twice per multiplier) as shown in Fig. 1. The second half of the analyzed sweep was subsequently vector averaged with the first half of the sweep. This "fold-and-average" operation was justified since the modulation frequency was reversed between the two halves of the sweep. Given the 30.72-s sweep length, and the filter windows of 1.024 s, anticipated physiological delays (which could have been up to 60 ms) were neglected during the averaging operation.

The instantaneous response amplitude at each frequency of interest was compared to a noise estimate, derived from the discrete Fourier transform (DFT) of the average sweep folded in the time domain, in order to determine whether a given response signal was statistically different from the background EEG-noise level estimate. This noise estimate was calculated using ± 60 DFT frequency bins (± 3.9 Hz) surrounding the instantaneous modulation rate of the swept stimulus. Since the FA passes more noise than the DFT (due to its wider bandwidth), a scaling factor was determined using simulated noise. The EEG noise in FA estimates effectively had an amplitude 3.24 times greater than in the DFT estimates. An F ratio was then employed to test whether the FA response amplitude was significantly different from the scaled DFT EEG-noise estimate (John and Picton, 2000).

In the main experiment, the highest frequency at which the EFR could be reliably measured was estimated for comparison with the behavioral thresholds. The measured EFR amplitude never reaches zero due to noise passing through the FA. The EFR amplitude was therefore phase weighted using an expected phase. This phase-weighted amplitude can reach zero, and a threshold can therefore be determined.

The phase-weighted EFR amplitude was calculated from the projection of the complex FA output onto an expected phase (Picton *et al.*, 2001)

$$A_w = A\cos(\theta - \theta_e), \quad (1)$$

where A_w is the phase-weighted amplitude, A is the FA output amplitude, θ_e is the expected phase, and θ is the FA output phase. The analysis assumes that a single EFR source with a modulation-frequency-independent delay is dominating the measured EFR, and that the phase therefore changes linearly with the instantaneous modulation frequency. The expected phase was determined by linear regression of the phase versus frequency data for frequencies between 100 Hz and the highest frequency at which a response was judged significantly different from background EEG noise using an F ratio. For one subject the regression was based in the 40-Hz range because this subject had no significant responses at frequencies over 100 Hz. The maximum frequency at which an EFR was recognizable was then taken as the highest frequency at which the phase-weighted amplitude was significantly different from zero using a t test.

Apparent latencies were calculated using linear regression as the slope of the phase by frequency plot over a range of frequencies (Regan, 1966, 1989). No correction was made for the small acoustic delay of approximately 0.9 ms from the Etymotic ER-2 transducer to the ear canal through a short sound tube (292 mm, including foam insert).

E. Behavioral measurements

Two behavioral measurements of temporal auditory acuity were employed. A two-alternative, forced-choice paradigm was used, and thresholds were estimated using a procedure derived from PEST (Taylor and Creelman, 1967). The initial increase in difficulty was one step per correct answer, until the first error. Subsequently, the difficulty was increased one step every three correct answers, and decreased one step for every error. A complete test was composed of 105 trials, and took approximately 10 to 20 min to finish depending on the task and the individual. The behavioral threshold for a given test was determined as the average of all available reversals, excluding the first.

The threshold for detecting 25% amplitude modulation of a white-noise carrier was found by asking the participant to choose which of two randomized 1-s sounds was modulated. The nonmodulated sound was of equal duration and power (Viemeister, 1979). For most individuals, the modulation frequency started at 50 Hz and increased in equal steps of 50 Hz. Some of the participants had a relatively low threshold, and were tested beginning at 10 Hz, and increasing in equal steps of 10 Hz. Sounds were presented at 60 dB SPL, but could be increased for the comfort of listeners in the older group. This should have no effect on the detection threshold at these sensation levels (Bacon and Viemeister, 1985).

The threshold for detecting a gap between brief white-noise markers was found by asking the participant to choose which of two randomized sounds contained a gap. The gap target was created with two 5-ms markers with Gaussian-shaped rise and fall times (SD 0.167 ms) separated by a short interval. The nontarget sound was white noise of equal duration and total energy, and had similar rise and fall envelopes (Schneider and Hamstra, 1999). The gap duration started at 20 ms, and decreased in equal steps of 1 ms to a minimum of 1 ms. For training purposes, larger gap durations were available for subjects who initially had trouble with 20 ms. Sounds were presented at 75 pSPL, but could be increased if requested by listeners in the older group. Changes in sensation level should have no effect on the detection threshold at these levels (Schneider *et al.*, 1998; Schneider and Hamstra, 1999).

All participants performed training trials until it was clear that they understood how to respond. For each task, training was typically about 10 trials. The younger subject group was generally familiar with behavioral testing, and performed the modulation and gap detection tasks once (105 trials each). The older group performed both tasks twice, and thresholds were determined from the results of the second tests.

F. Statistical analyses

Repeated-measures analyses of variance (ANOVAs) were performed using Greenhouse–Geisser corrections. In the main experiment, a correlation analysis was performed between the behavioral thresholds, and values derived from the EFR measurements. This was to determine if physiological measurements could serve as useful indices of the behavioral responses. The behavioral thresholds were (a) the maximum frequency (Hz) at which 25% amplitude modulation of noise could be detected; (b) the minimum gap (ms) that could be detected between brief noise markers; (c) the reciprocal of this gap detection threshold (Hz); (d) the mean pure-tone hearing threshold (dB HL) from 500 to 4000 Hz. The EFR measurements were (a) the highest frequency (Hz) at which the phase-weighted amplitude of the EFR was statistically different from noise; (b) the apparent latency (ms) of the EFR in the frequency band used to calculate the expected phase; (c) the frequency (Hz) at which amplitude peaked between 30 and 50 Hz; (d) the amplitude (nV) of the peak frequency between 30 and 50 Hz; (e) the apparent latency (ms) between 30 and 50 Hz; (f) the mean amplitudes (nV) from 30–50 Hz, 80–100 Hz, 100–200 Hz, 200–300 Hz, 300–400 Hz, and 400–500 Hz; and (g) the optimal cutoff frequency of a first-order low-pass filter model fit to the amplitude data above 80 Hz, using a fixed gain of mean amplitude 80–100 Hz and a least-squares cost function. The correlations between all of these measures and age (in years) were also investigated. Two-tailed separate variance *t* tests were employed to assess the null hypotheses that the group means were equal for each variable above.

Similar *t* tests were also used to evaluate at what frequency the phase-weighted EFR amplitude was no longer significantly different from zero. In this implementation of the FA, the output was determined from data averaged in the time domain. Therefore, multiple signal estimates were not available at a given response frequency, and the variance of the amplitude estimate had to be calculated indirectly for use in the *t* tests. The variance across ±60 DFT EEG-noise bins near the response frequency was employed instead, after appropriate scaling. Simulations showed that the variance of multiple estimates from the FA is similar to the DFT variance across multiple noise bins, after scaling by the effective bandwidths of the two analyzers.

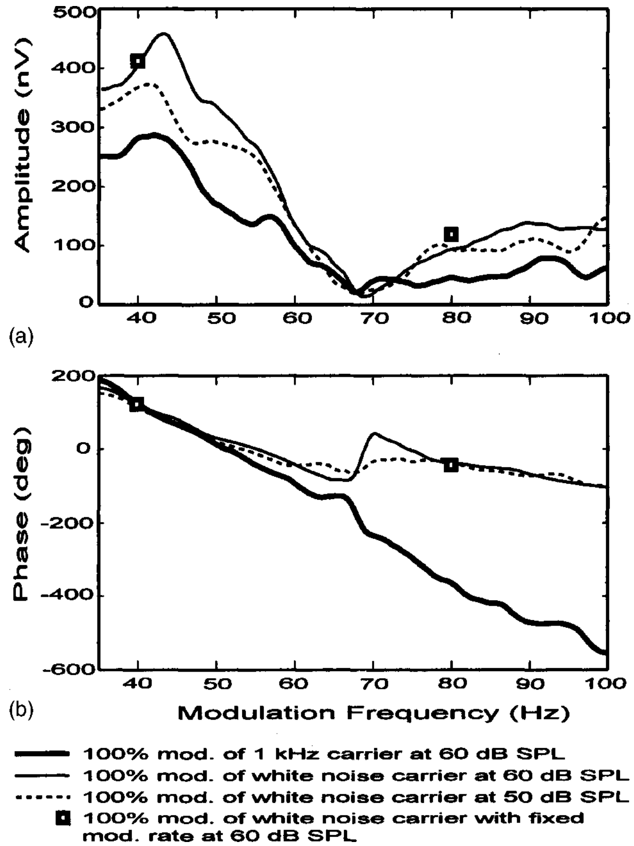

FIG. 2. Grand average of responses from five waking individuals. Panel (A) shows the response amplitude, and panel (B) the response phase as the rate was swept from 35 to 100 Hz for 100% amplitude modulation. The continuous thick line is the response to a 1-kHz pure-tone carrier presented at 60 dB SPL. The continuous thin and dashed lines are the responses to white-noise carriers presented at 60 and 50 dB SPL, respectively. The open squares show the responses to noise modulated at fixed rates of 40 and 80 Hz, and presented at 60 dB SPL.

III. RESULTS

A. Preliminary experiments

1. Effects of carrier and level

The purpose of the first experiment was to evaluate the influence of stimulus carrier and level on the response. Three different amplitude-modulated stimuli were presented in a balanced design: white noise presented at 60 and 50 dB SPL, and a 1-kHz tone presented at 60 dB SPL. Figure 2(A) plots the average amplitude of the frequency component in the evoked response corresponding to the modulation frequency in the stimulus. These average amplitudes represent the grand vector average of 58 sweeps from each of five waking individuals in response to 100% amplitude modulation at frequencies from 35 to 100 Hz. In the band 35 to 60 Hz, the modulated noise elicited a larger response than the modulated pure tone. Since these averages were determined during a sweep over the modulation frequencies employed, also shown are the responses to noise at 60 dB SPL that was modulated at fixed rates of 40 and 80 Hz (squares), and analyzed using the DFT. The amplitudes measured during the sweep are the same as those obtained using a fixed modulation frequency.

Also shown in Fig. 2(B) is the average phase of the frequency component in the evoked response corresponding to the modulation frequency. All responses in the grand average were statistically different from the background EEG noise, with the exception of the region between 65 and 75 Hz. This loss of significance corresponds to the reduced response amplitude and rapid phase changes observed near 70 Hz. Apparent latencies were calculated for the changing modulation rate stimuli. In the band 38 to 60 Hz, the latencies were 22.4, 22.7, and 29.9 ms for the 60- and 50-dB SPL noise, and the 60-dB SPL 1-kHz tone, respectively. Peak amplitudes between 35 and 50 Hz were significantly larger at 60 dB SPL for the noise than for the 1-kHz tone ($F=5.96$; $df=2, 8$; $p<0.03$; *post hoc t* test).

2. Comparing swept and fixed modulation frequencies

The purpose of the second experiment was to confirm that the sweep stimulus elicited the same response as fixed modulation rate stimuli, including at higher modulation rates. The grand vector average of 56 sweeps from each of 10 waking individuals is shown in Fig. 3. The stimulus was 60 dB SPL 100% amplitude modulated noise presented in a balanced design for the two ranges 20 to 100 Hz, and 70 to 200 Hz. Also shown are the DFT results for fixed modulation rates of 40, 80, and 160 Hz. Responses were highly significant with the exception of about a 5-Hz band centered on 27 Hz, where there was a null in the amplitude response. The apparent latency was 20.9 ms for the band 35 to 55 Hz, and 8.6 ms from 80 to 190 Hz.

A repeated-measures ANOVA of the EFR amplitude at the frequencies 40, 80, and 160 Hz with factors of frequency and modulation type (fixed or swept) showed a significant effect of modulation frequency ($F=115.385$; $df=2, 18$; p

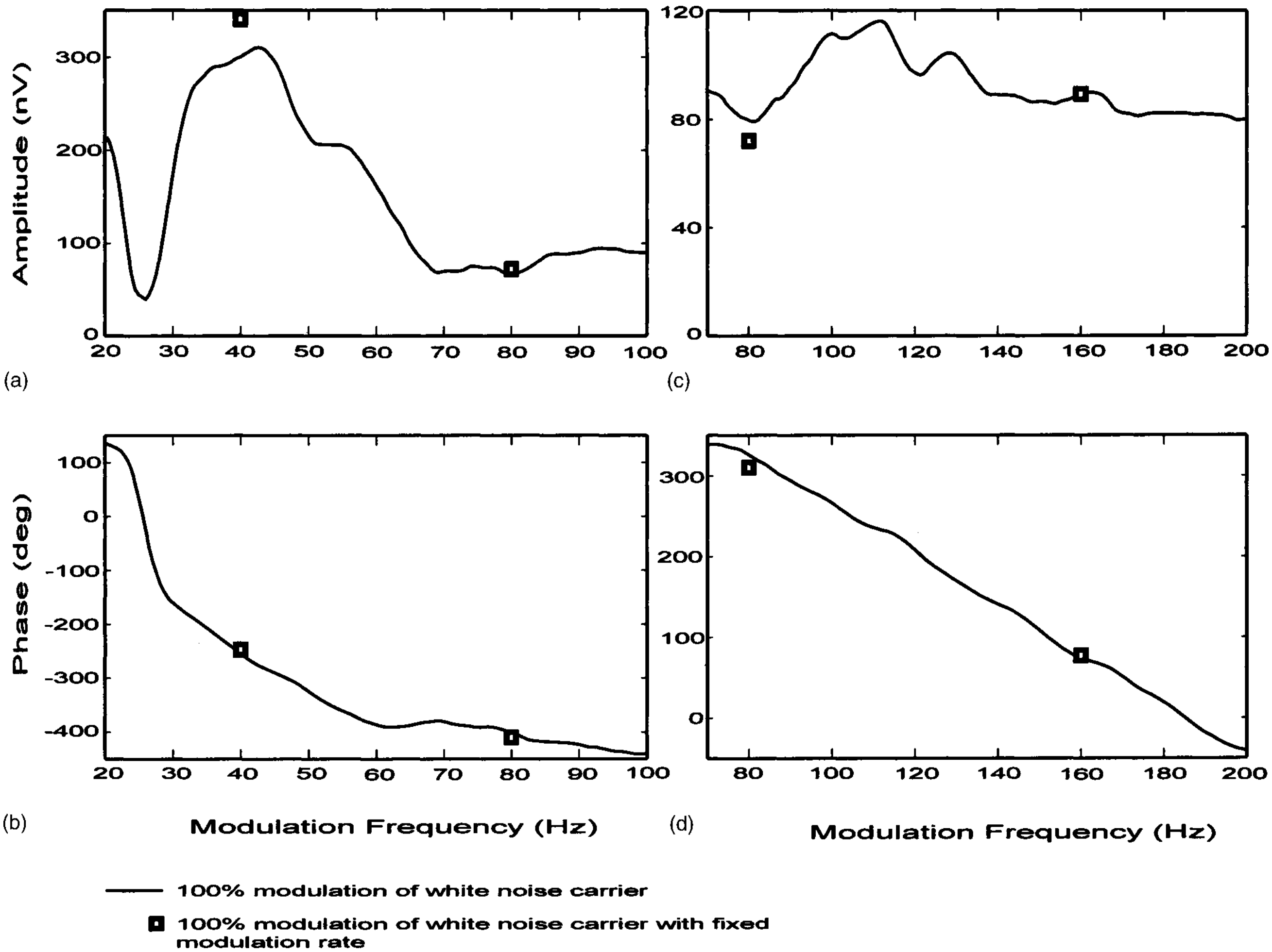

FIG. 3. Grand average of responses from 10 waking individuals. Panels (A) and (B) show the amplitude and phase responses for the range 20 to 100 Hz for 100% amplitude modulation of a white-noise carrier presented at 60 dB SPL. Similarly, panels (C) and (D) show the responses for the range 70 to 200 Hz. The open squares show the responses to noise modulated at fixed rates of 40, 80, and 160 Hz and presented at 60 dB SPL.

<0.001), but no effect of modulation type and no interaction. The fixed-rate response amplitude at 40 Hz was a little larger than the swept-rate measurement, but the difference was not significant using a *t* test.

In two subjects, responses were examined near 70 Hz, where the amplitude was low, using swept modulation frequencies. Five measurements were made with fixed modulation rates distributed within a few hertz of 70 Hz, and responses were analyzed using the DFT. There was no clear difference between swept and fixed modulation responses, indicating an amplitude minimum near 70 Hz that was independent of the recording technique.

3. Electrical artifacts

The purpose of the third experiment was to verify that there were no electrical artifacts influencing the EFR measurements. The EFR was obtained in a balanced design with amplitude-modulated noise either delivered to the ear, or delivered to a Zwislocki coupler on the subject's shoulder. Responses were recorded to a variety of sweeps (20–100 and 70–200 Hz modulated 100% at 60 dB SPL, and 100–700 Hz modulated 50% at 65 dB SPL) in four subjects. All subjects had highly significant responses when the stimulus was in the ear. When the stimulus was delivered to the Zwislocki coupler, the EFR was significant with an average incidence during the sweep across the different subjects and conditions of 5.4% (range 0%–11%). This result was expected since a statistical criterion of $p<0.05$ was used to evaluate whether a given EFR amplitude was significantly different from an estimate of the background EEG noise. When no stimulus was delivered to the ear, a false positive detection would be expected at the EFR frequency 5/100 times, which is close to the 5.4% found here.

4. Effects of sleep

The purpose of the fourth experiment was to investigate the effects of sleep on the EFR. Three individuals were evaluated both asleep and awake using 25% amplitude modulated noise presented at 60 dB SPL for the ranges 20 to 100 Hz, and 100 to 600 Hz. Data from a single individual are shown in Fig. 4. For the 20- to 100-Hz range while awake, the responses were highly significant except near the amplitude minimum of 70 Hz. In sleep, the responses remained highly significant except below 33 Hz, and near the broader amplitude minimum at 66 Hz. For the 100- to 600-Hz range, both waking and sleeping responses became insignificant after 500 Hz. There was a deep valley in the amplitude response near 27 Hz during both sleep and wakefulness.

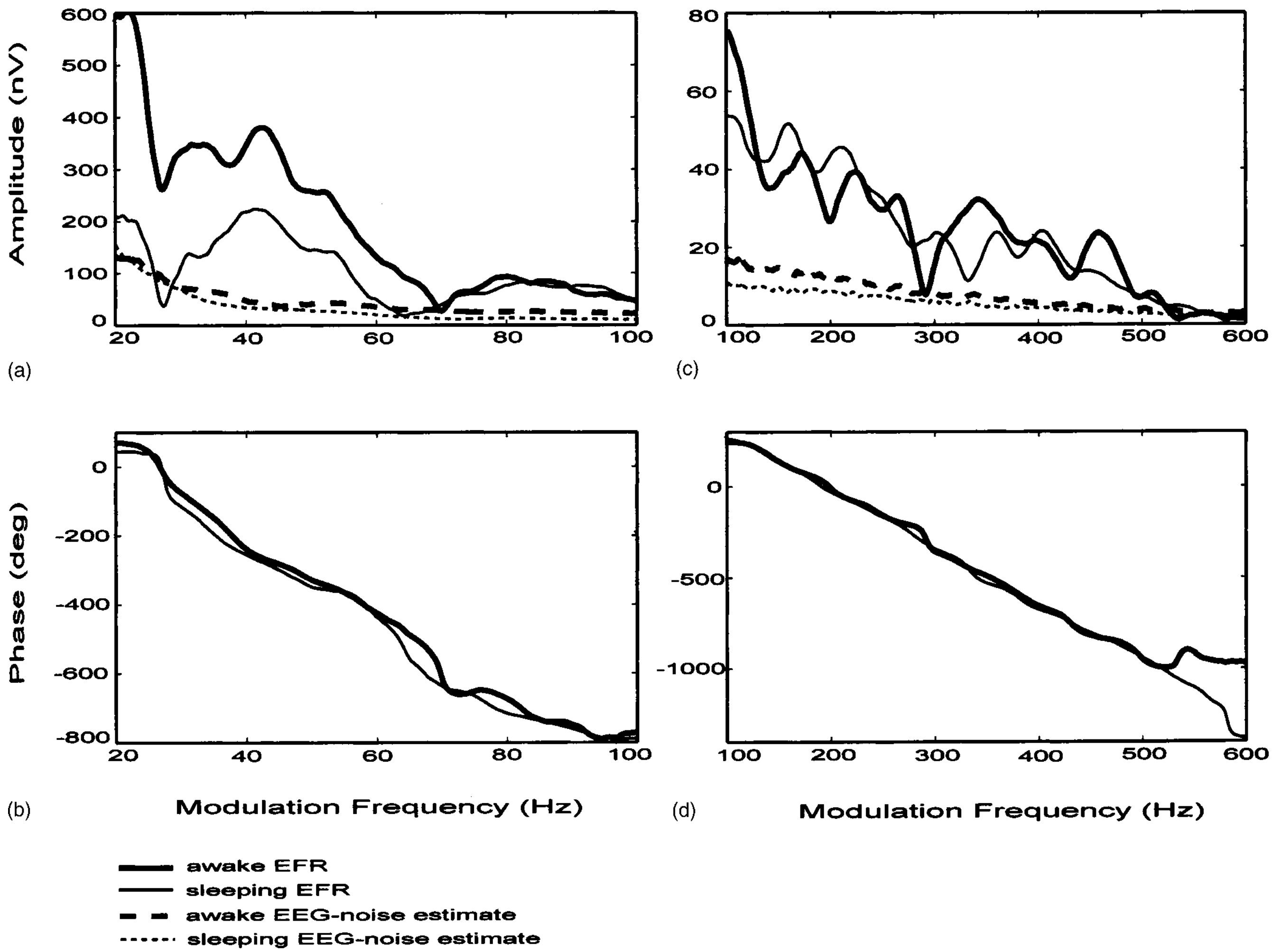

FIG. 4. Individual response during waking and sleeping. Panels (A) and (B) show the amplitude and phase for the range 20 to 100 Hz from a single individual in response to 25% amplitude modulated white noise presented at 60 dB SPL. Similarly, panels (C) and (D) are for a 60-dB SPL stimulus 25% modulated from 100 to 600 Hz. The continuous thick line indicates the responses when the individual was awake, and the continuous thin line shows the responses during sleep on a different date. The dashed thick and thin lines are the EEG-noise estimates at the response frequency during wakefulness and sleep, respectively.

The peak amplitude of the EFR was significantly larger during wakefulness than during sleep for all three subjects (sign test between 35 to 50 Hz, $p < 0.000\,01$). At higher frequencies, there was no significant difference in response amplitude between sleep and wakefulness for two of three subjects (including the subject in Fig. 4). For the third subject, the amplitude during wakefulness was on average 4 nV larger than during sleep. The mean EEG-noise estimate was smaller during sleep for all three subjects.

For the subject shown in Fig. 4, the apparent latencies in the band 35 to 50 Hz were 27.1 and 31.2 ms during sleep and wakefulness. The other two subjects had apparent latencies of 12.0 and 25.4 ms while asleep, and 23.6 and 28.7 ms while awake. In the frequency band 100 to 400 Hz, the subject shown in Fig. 4 had apparent latencies of 9.0 and 8.8 ms while asleep and awake. For the other two subjects, the apparent latencies were correspondingly 9.3 and 9.4 ms during sleep, and 9.5 and 9.1 ms during wakefulness.

B. Main experiment

Based on the preliminary data, it was decided to use white noise at 60 dB SPL as the stimulus, since this gave the highest signal-to-noise ratio (SNR) of the three stimuli tested in the first experiment. The sweep approach was justified since there were no significant differences between swept and fixed rates of modulation. Finally, it was decided to have the subjects sleep through the recording since the residual EEG noise was lower during sleep, and since the response at the higher frequencies was not affected by the subject state. The stimulus was 25% amplitude-modulated white noise in two sweep ranges: from 20 to 100 Hz, and from 100 to 600 Hz. The reason for using 25% modulation depth was that this depth evoked responses that were typically statistically significant only up to about 500 Hz. A larger modulation depth would have increased this frequency, and thereby increased the maximum modulation rate required in the stimulus and the test time needed. The stimulus for the behavioral modulation detection task also requires less adjustment for intensity effects at lower frequencies (Viemeister, 1979). By employing 25% modulation, the detection threshold was at a frequency low enough to minimize intensity artifacts.

Figure 5 shows two grand vector averages: one of 14 individuals from the younger group, and the other of 13 individuals from the older group. During each measurement session, 60 and 90 sweeps were averaged for the two ranges 20 to 100, and 100 to 600 Hz. As noted above, the younger

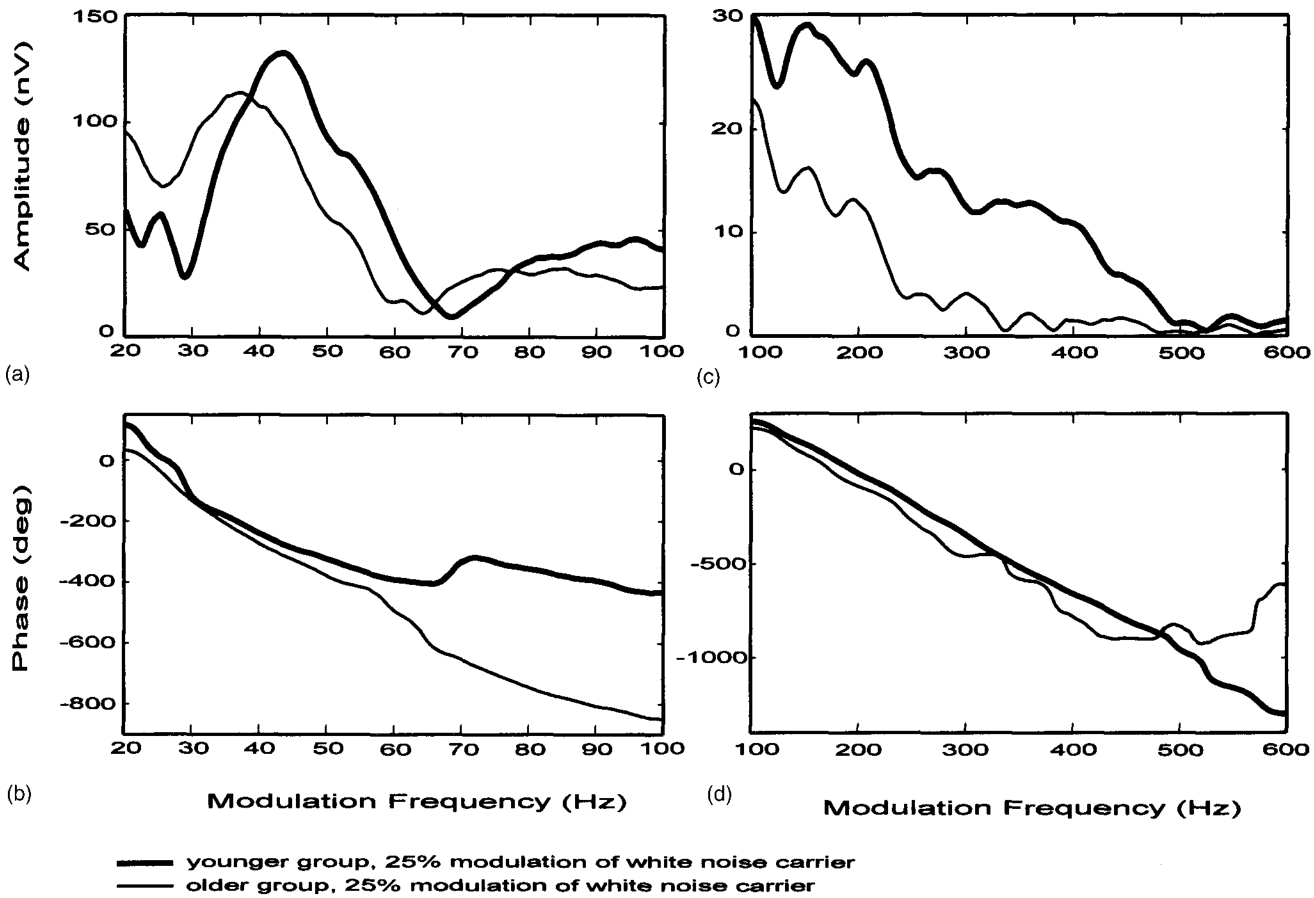

FIG. 5. Grand average of responses from sleeping individuals. Panels (A) and (B) show the responses to 25% amplitude modulated white noise presented at 60 dB SPL in the range 20 to 100 Hz. Similarly, panels (C) and (D) show the responses for the range 100 to 600 Hz. The thick lines indicate the average response from 14 individuals in the younger group. The thin lines show the average response from 13 participants in the older group.

group attended one session, whereas the older group attended two. For the younger group in the 20- to 100-Hz range, responses were highly significant except below 31 Hz, and near the response amplitude minimum at 69 Hz. A reversal in phase slope also occurred near 69 Hz. Between 35 and 55 Hz, the apparent latency was 24.3 ms, whereas it was 11.2 ms between 75 and 90 Hz. For the higher modulation range from 100 to 600 Hz, the responses were highly significant until 485 Hz. The apparent latency between 110 and 450 Hz was 8.8 ms.

Responses were highly significant for the older group in the 20- to 100-Hz range, with the exception of responses near the minimum at 64 Hz where the phase slope changed, but did not reverse. The apparent latency was 29.3 ms between 35 and 55 Hz, and 19.0 ms between 75 and 90 Hz. In the higher frequency range, the response was highly significant until 235 Hz. Between 120 and 235 Hz, the apparent latency was 9.1 ms.

Both groups showed a valley in the magnitude response below 30 Hz, and a peak near 40 Hz. Regarding the amplitude minima near 70 Hz, all but one subject had at least one region where the EFR amplitudes were not significantly different from the noise estimates, between 50 and 80 Hz. In the younger group, nine participants had a single amplitude minimum near 70 Hz, whereas in the older group only four had simple distinct minima. Many older participants had more complex amplitude functions with multiple local minima between 50 and 90 Hz.

Table I summarizes the results for those variables where the group means were significantly different. While the frequency of the amplitude peak in the band 30 to 50 Hz was significantly lower for the older group [see Table I and Fig. 5(A)], the peak amplitude itself was not significantly different between the two groups. In the same band, the older group had a significantly longer apparent latency than the younger group. This is evident in Fig. 5(B), where the older group's phase versus modulation frequency slope is steeper than for the younger group. The mean amplitudes were also significantly larger for the younger group in the bands between 100 and 500 Hz, as visible in Fig. 5(C).

The behavioral responses for the two subject groups are plotted in Fig. 6. Both the threshold for detecting 25% modulation of a white-noise carrier, and the threshold for detecting a gap between brief white-noise markers are plotted against the objectively determined frequency at which the phase-weighted EFR amplitude was no longer reliably different from noise. The number of reversals available for calculating the behavioral thresholds varied with the individual. On average, 9.8 and 10.3 reversals (SD 2.2 and 1.6 reversals) were available for the older and younger groups, respectively. As shown in Fig. 6, the two groups were largely separated with only a couple of individuals overlapping. Two participants

TABLE I. Significant results from two-tail separate variance *t* tests that evaluated whether the means for the younger and older groups were equal for different variables. These variables included the behavioral thresholds, age, and values derived from the EFR measurements. A low probability indicates that the means were unequal for the younger and older groups. The one nonsignificant result is included because this variable derived from the EFR was significantly correlated with a behavioral measurement in Table II.

	Modulation detection (Hz)	Gap detection (Hz)	Gap detection (ms)	Pure-tone hearing threshold (dB HL)	Maximum EFR frequency (Hz)	30–50-Hz frequency of amp. peak (Hz)	30–50-Hz apparent latency (ms)	100–600-Hz apparent latency (ms)	100–200-Hz mean amp. (nV)	200–300-Hz mean amp. (nV)	300–400-Hz mean amp. (nV)	400–500-Hz mean amp. (nV)	Low-pass model cutoff frequency (Hz)	Age (yrs)
Younger group mean (SD)	567 (95)	460 (197)	2.7 (1.5)	2.1(3.9)	494(114)	41(5)	25.6(6.2)	8.4(0.5)	31(10)	21(8)	15(6)	8(4)	260(108)	28(6)
Older group mean (SD)	264 (131)	274 (77)	4.0 (1.6)	20.8(12.6)	294(131)	37(4)	35.5(4.8)	8.6(1.5)	18 (8)	10(4)	6(4)	3(2)	165 (39)	69(6)
Significance	***	**	*	***	***	*	***		**	***	***	***	**	***

*$p<0.05$.
**$p<0.01$.
***$p<0.001$.

from the younger group and one from the older group had maximum EFR frequencies at the highest frequency present in the amplitude-modulated stimulus.

The younger group performed significantly better in the behavioral measurements (see Table I). The maximum EFR frequency was also significantly higher for the younger group. Table II summarizes the significant correlations between the objective EFR and behavioral variables. The best correlations between objective and behavioral measurements were obtained between the maximum EFR frequency and behavioral modulation detection ($r=0.72, p<0.001$), or mean pure-tone hearing threshold ($r=-0.76, p<0.001$). When correlations were calculated for the older and younger groups separately, some variables were significant within a given group, but none was significantly correlated in both groups.

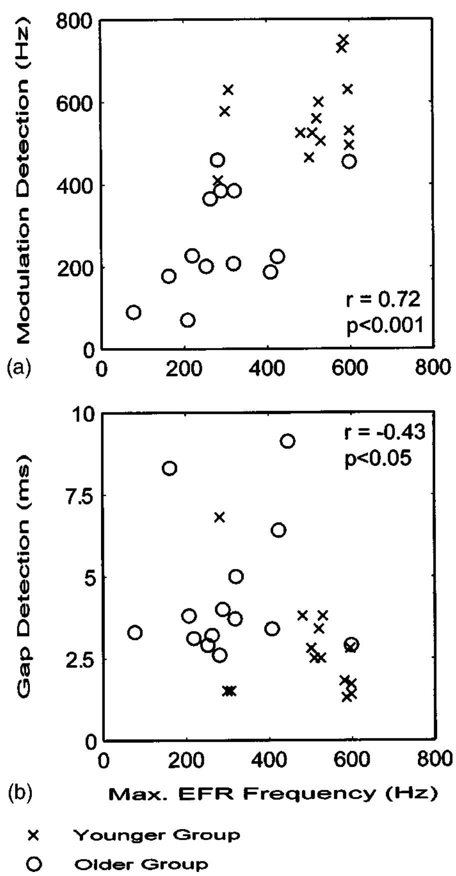

FIG. 6. Behavioral responses versus maximum EFR frequency. Panel (A) shows the behavioral threshold for detecting 25% amplitude modulation of white noise plotted against the highest frequency at which the phase-weighted EFR amplitude was reliably different from zero. Similarly, panel (B) shows the threshold for detection of a gap between brief Gaussian white-noise markers versus the same EFR threshold. The open circle ○ demarks each participant from the older group, and crossed symbol X shows the individuals from the younger group.

IV. DISCUSSION

A. Preliminary experiments

1. Different carriers

The results shown in Fig. 2 demonstrate the effects of carrier type and level. The largest responses were obtained for amplitude-modulated noise, presented at 60 dB. The 50-dB SPL modulated noise also generated a larger response than the 1-kHz carrier tone presented at 60 dB SPL. This is presumably because the noise will stimulate a larger region of the cochlea, and hence activate more afferent fibers (Picton *et al.*, 2003a; John *et al.*, 2003). While these may not all add in phase, the net result is a larger response than for the modulated tone.

The apparent latency of the modulated tone was larger than either of the noise stimuli. This may be because the dominant latency in the noise response was from a higher frequency band, and therefore more basal region of the cochlea, than for the 1-kHz carrier. The traveling wave delays are longer for the lower frequency pure-tone carrier.

2. Swept and fixed modulation rates

Similar responses were obtained using swept or fixed rate modulation of noise carriers. As shown in Figs. 2 and 3, the correspondence of the phase measurements between the FA (swept rate) and DFT (fixed rate) analyses was excellent. The amplitude results were also similar, and no significant differences were found. This suggests that the rate of change of the sweep stimulus was sufficiently low that response attenuation did not occur. An altered response might be ex-

TABLE II. Relationship (Pearson r) between behavioral thresholds, age, and values derived from the EFR measurements. Variables that are shown were significantly correlated with at least one behavioral threshold.

Behavioral threshold	Modulation detection	Gap detection in Hz	Gap detection in ms	Pure-tone hearing threshold	Maximum EFR frequency	30–50-Hz frequency of amp. peak	30–50-Hz apparent latency	100–600-Hz apparent latency	100–200-Hz mean amp.	200–300-Hz mean amp.	300–400-Hz mean amp.	400–500-Hz mean amp.	Low-pass model cutoff frequency	Age
Modulation detection	1	0.64***	−0.54**	−0.74***	0.72***	0.42*	−0.59***	−0.34	0.65***	0.67***	0.63***	0.64***	0.42*	−0.81***
Gap detection in Hz		1	−0.84***	−0.42*	0.42*	0.12	−0.19	−0.07	0.59**	0.54**	0.49**	0.44*	0.16	−0.51**
Gap detection in ms			1	0.36	−0.43*	−0.24	0.11	−0.02	−0.58***	−0.54***	−0.51***	−0.44*	−0.14	0.42*
Pure-tone hearing threshold				1	−0.76***	−0.26	0.53**	0.63***	−0.42*	−0.46*	−0.51**	−0.45*	−0.35	0.70***

*$p<0.05$.
**$p<0.01$.
***$p<0.001$.

pected at very high sweep rates, since the sources of the EFR in the auditory nervous system could have difficulty tracking very rapid changes in modulation rate. However, Artieda *et al.* (2004) have recently described a technique that can follow the brain's response to modulated sounds by averaging responses to a 1.6-s ‘‘chirp’’ that increased in modulation frequency from 1–120 Hz. They were able to demonstrate clear responses with maximum amplitude near 40 Hz.

The EFR amplitude null observed near 27 Hz in Figs. 3(A) through 5(A) may be due to the superposition of middle latency responses (MLRs) and auditory brainstem responses (ABRs, Galambos *et al.*, 1981), since the MLR and ABR waves occur with interpeak intervals of approximately 25 ms. Therefore, the responses will be in phase for successive occurrences elicited at 40 Hz, and out of phase when elicited every 37.5 ms, or at the rate of 26.7 Hz. Similar interference might occur for successive responses elicited every 12.5 ms, or at the rate of 80 Hz, but at these rates the MLR is likely too attenuated to have any effect, leaving only a periodic ABR.

3. Subject state

The response amplitude near 40 Hz was larger during wakefulness than sleep. This is consistent with other studies that show a reduction in the 40-Hz response with sleep (Linden *et al.*, 1985; Cohen *et al.*, 1991; Picton *et al.*, 2003b), or sedation (Plourde and Picton, 1990; Dobie and Wilson, 1998). At frequencies above 100 Hz, the three subjects tested here had the same EFR amplitudes during sleep and wakefulness, but noise estimates were consistently lower during sleep. The goal of the main experiment was to compare behavioral thresholds with relatively high-frequency EFRs. It was therefore decided to measure the EFR during sleep for the main experiment, in order to optimize SNR for a given measurement duration.

B. Main experiment

1. Age effects on psychophysical measurements of auditory temporal acuity

The behavioral tasks were performed with relatively few trials for a psychoacoustic measurement, in order to maintain a reasonable test time for one or two sessions. Fewer reversals were therefore available for calculating the behavioral thresholds, and some increased variability is expected. Nevertheless, a clear decrease in temporal auditory acuity was found with age, replicating the reports of others. Although most studies have not used noise stimuli, similar decreases in gap detection threshold with increasing age have been found. Schneider and Hamstra (1999), for example, determined that the gap detection threshold increased from 1.7 to 3.4 ms from young adults to old adults using 2-kHz tones of 5-ms duration.

2. Age effects on the EFR

There was no age-related difference in the amplitude of the EFR measured in the frequency range of 30–50 Hz. Similar findings have been obtained in other studies (Muchnik *et al.*, 1993; Boettcher *et al.*, 2001). Under some conditions the 40-Hz response to frequency modulation may be larger in elderly subjects (Boettcher *et al.*, 2002). One problem in assessing age-related changes is the fact that the response is very susceptible to drowsiness and sleep, and elderly subjects may be less able to sleep through the recordings than younger subjects (Dimitrijevic *et al.*, 2004). The age-related decrease in the peak frequency in this range and the increase in the apparent latency has not been reported before. These changes suggest some change in the timing and responsiveness of the cortical generators. Both effects are significantly related to the decrease in the maximum modulation frequency that can be perceived (Table II).

The EFR at frequencies greater than 100 Hz was significantly smaller in the elderly subjects, but this was not the case in the band 80 to 100 Hz. The apparent latency for these responses was, however, not affected by age. Boettcher *et al.*

(2001) and Dimitrijevic *et al.* (2004) also found no change in the amplitude of the 80-Hz response in normal-hearing elderly subjects. The age-related decrease in amplitude found here above 100 Hz may have been related to the mild hearing loss in the elderly subjects, but the correlations between amplitude and pure-tone thresholds were low (Table II). One might therefore postulate that the decreased size of the response reflects the decreased temporal acuity of the aging nervous system—an inability of the auditory brainstem to follow frequencies near 100 to 200 Hz as well as in the younger subjects.

3. Relations between the EFR measurements and the psychophysical findings

A good correlation between the maximum EFR frequency and modulation detection thresholds is shown in the data of Fig. 6. There was a clear separation of groups and a wide spread of individual thresholds across the test range for the modulation detection task. The gap detection thresholds were more closely clustered at values less than 5 ms. Interindividual discrimination may have improved if the step changes between gap stimuli had been smaller than 1 ms. In Fig. 6, three participants had maximum EFR frequencies that were at the ceiling of 600 Hz. In these individuals, it would probably have been possible to measure the EFR to higher frequencies, but the highest modulation rate in the stimulus was 600 Hz.

The lack of significant psychophysiological correlations within each group separately was likely due to the small numbers of subjects, and the lack of variation of the psychophysical findings within the groups. Unfortunately, the results therefore do not have sufficient power to disentangle the effects of temporal acuity from other effects of aging.

The EFRs generated in the brainstem or cortex cannot distinguish between peripheral (cochlear and auditory nerve) and brainstem causes for decreased auditory acuity. It may, however, be possible to distinguish between brainstem and cortical problems if different frequency bands of the response are evaluated (e.g., 30–50 Hz, and 100–200 Hz). Amplitude and latency values are different for the brainstem and cortical sources, and this may help evaluate changes in each region.

C. Model of EFR sources

For the correlation analysis, a simple first-order low-pass filter model was fit to the EFR amplitude data above 80 Hz. The optimal cutoff frequencies were significantly different between subject groups (Table I), but the correlation with behavioral measures was relatively poor (Table II). The model gain was calculated as the mean amplitude from 80 to 100 Hz, and was neither significantly different between groups nor correlated. The physiology is more complex than can be easily fit with such a model. There are at least two subsystems (brainstem and cortex) with different response characteristics and latencies.

The grand vector average amplitude functions had nulls near 70 Hz [Fig. 5(A)], and the presence of two distinct apparent latencies. Similar decreases in amplitude have been

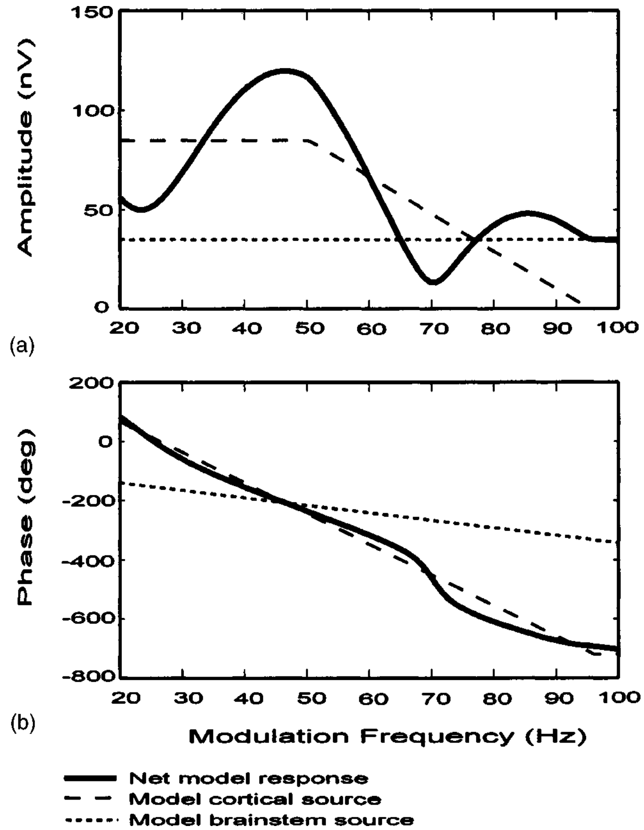

FIG. 7. Model EFR resulting from the sum of two sources. Hypothetical cortical and brainstem sources are shown with long dashed and short dashed lines, respectively. Amplitude is shown in panel (A), and phase in panel (B). The cortical source had a true delay of 29 ms, and constant amplitude from 20 to 50 Hz of 85 nV. The amplitude decreased linearly to zero from 50 to 95 Hz. The brainstem source had a true delay of 7.3 ms and constant amplitude of 35 nV. The continuous thick line indicates the sum of the two sources as might be recorded at scalp electrodes.

reported previously (see Fig. 10, Picton *et al.*, 2003a). This morphology suggested a two-component model of the EFR (Fig. 7). The model postulates two separate sinusoidal generators, each responding at the envelope frequency, one in the brainstem and one in the cortex, with latencies of 7.3 and 29 ms, respectively. The cortical source has a constant amplitude of 85 nV up to 50 Hz, and then decreases linearly to 0 nV at 95 Hz. The brainstem source had constant amplitude of 35 nV across the plotted frequency band, but would be expected to decrease to zero from 100 to 500 Hz [see Fig. 5(C)]. The total net response measured at a hypothetical electrode on the scalp was determined at each simulation frequency by summing the steady-state sinusoidal responses of the two sources in the time domain, and then obtaining the amplitude and phase of the resultant net sinusoid. The amplitude of each source in the sum was determined from the amplitude versus frequency plot in the top half of Fig. 7, and the phase of each source across frequency was determined by the source's latency. Summation was justifiable since the scalp fields for the two sources are similar and superimpose without interaction (Herdman *et al.*, 2002). Since the phase of each generator will change when the latency is constant and the envelope frequency varies, the sources sum constructively in some frequency regions, and destructively in others.

No correction was attempted for transmission from the two sources to the hypothetical electrode.

For the total net response, an amplitude minimum occurred near 70 Hz due to destructive interference between the two sources, and the apparent latency was 22.8 ms for the band 35 to 55 Hz. It can be seen in Fig. 7(B) that the net phase slope was determined by the relative amplitudes of the cortical source with its relatively long delay (steeper slope), and the brainstem source with its shorter delay (shallower slope). In other words, when the cortical source amplitude is large relative to the brainstem source (e.g., near 45 Hz) then the total net phase slope is closer to that of the cortical source, and this is reflected in the apparent latency estimate. This simple model reproduces the peak near 45 Hz and null near 70 Hz that occur in the grand vector average amplitude response of the younger group shown in Fig. 5(A).

If the model source amplitudes and delays are adjusted, the net output can be made to resemble the average response of the older group. The frequencies of the amplitude peak and null are controlled by the relative delays of the two sources. As shown in Table I, the older group had a peak response in the 40-Hz region that was significantly lower in frequency than for the younger group. Their apparent latency in that region was also significantly longer. While the amplitude in the 40-Hz region was not significantly different between groups, the mean amplitude between 100 and 200 Hz was significantly larger for the younger group. For the older group, the model may be adjusted such that both sources have lower cutoff frequencies, and steeper decay. The relative amplitudes of the sources could also be manipulated to emphasize the cortical source.

The average experimental apparent latency results are congruent with the simple model. For the younger group, the measured EFR amplitude between 100 and 200 Hz suggests that a brainstem source may make a larger relative contribution to the net response in the 40-Hz region than for the older group. The apparent latency of the presumed brainstem source measured at high frequencies ($>$100 Hz) was low for both groups ($<$10 ms). For the younger group, the relatively large amplitude of this source may in part be responsible for the lower apparent latency estimated in the 40-Hz region.

In the fourth preliminary experiment, the apparent latency in the 40-Hz region was shorter during sleep for three subjects. This could be due in part to the relatively larger contribution of the brainstem source when the cortical source amplitude was attenuated by sleep.

V. CONCLUDING REMARKS

As discussed in the Introduction to this paper, it would be very helpful to have a simple objective test of temporal auditory acuity that could be used to assess patients who cannot give reliable data from psychophysical testing. Werner *et al.* (2001) have shown that auditory brainstem responses can be recorded to gaps in noise, and that the thresholds for recognizing these responses were related to psychophysical gap detection thresholds in adults. They found similar ABR thresholds in infants, although their psychophysical thresholds were much longer. The results presented here show the maximum frequency for recognizing the EFR correlates well with the psychophysical measures of the maximum perceptible threshold. This could then serve as an objective test of temporal auditory acuity.

The techniques investigated here for objectively assessing temporal acuity are neither simple nor rapid. The test could be made faster by only eliciting the response from a narrower range of frequencies (e.g., 100 to 600 Hz). Even then, the measurement could take 45 to 90 min (i.e., two sessions for the older subjects) depending on the background EEG noise of the recording. The limiting factor is that the system must determine when a near-threshold response is not present, and time is required to reduce the background EEG noise sufficiently to make this judgment. Accordingly, a better approach might be to derive a simple measurement at suprathreshold levels that relates well to the psychophysical measurement. Shorter testing durations can be achieved when the evoked responses are larger, since the background EEG noise need not be reduced as much to achieve a given SNR. The peak frequency of the 40-Hz response is significantly related to the maximum perceptible modulation frequency, but the correlation is not high.

This study relied upon 25% modulation, which elicits a relatively small EFR. Future studies could examine the utility of recording responses with stimulus parameters that are optimized for short recording times. For example, these could employ a brief sweep of frequencies (e.g., 100–300 Hz) using 50% or 100% amplitude modulation, to produce larger responses. The amplitudes over this limited range of modulation rates might be used to predict the threshold. Response amplitudes can also be increased by using bandlimited noise (e.g., 1000–2000 Hz) rather than broadband noise (John *et al.*, 2003). Further, since the behavioral gap threshold increases with decreasing carrier frequency for pure-tone markers, using pure tones or bandpass noise may be anticipated to cause a more pronounced decrease in EFR amplitude with increasing modulation frequency. Additionally, when testing both ears, the testing time can be reduced to that of one single ear, since both ears can likely be tested simultaneously using different modulation rates in each ear. Ultimately, one would like a measurement that would reliably indicate good or bad temporal auditory acuity within about 10 min.

Despite these reservations about test time, the sweep EFR techniques investigated here can provide an objective measurement of human auditory temporal acuity that is reasonably well correlated to behavioral measurements.

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