Attending or Discriminating 40 Hz Modulated Tones Induces Phase-Locked Subharmonic Resonances in EEG

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Introduction

Recently, Galambos et al. (1981) published a study of brain potentials evoked by trains of tones or clicks at high rates, reporting that the human auditory evoked potential response shows a resonance near 40 Hz. The amplitude of this 40 Hz driven response decreases markedly in sleep. This fact, and the body of experiments linking spontaneous and evoked 40 Hz activity to cognition (Sheer 1970; Spydell 1979), suggested to the authors that the 40 Hz response might be usable to probe level of arousal. What follows is a preliminary report of an experiment designed to explore the effects of attention on the 40 Hz response.

Method

The stimuli consisted of trains of low (800 Hz), middle (1000 Hz), and high (1200 Hz) tonebursts, modulated at 40 Hz, and presented to six subjects under four task conditions — "count the low tones," "count the middle tones," "count the high tones," and "don't count."

The low and high tonebursts were relatively rare (each 12-20% of the total), and the middle tonebursts relatively frequent (60-84%). Four to eight blocks of data were collected from each subject, each block consisting of one run in each of the four conditions. Order of runs within blocks and order of tones within runs were randomized under direct computer control.

Each run lasted about 100 seconds and consisted of 96 tonebursts. Each toneburst consisted of ten tone pips (duration 5 msec), with an interpip interval of 25 msec (onset-to-onset). Each tone pip was composed of four, five, or six half-sinewave clicks. The interval between tonebursts was approximately one second (onset-to-onset), with 200 msec of random jitter introduced in inter-burst intervals to avoid phase-locking to ongoing electroencephalograph (EEG) rhythms.

Subjects were seated with eyes closed in a quiet room. Stimuli were delivered to the right ear at 30 dB above threshold. Subjects reported the task to be difficult, owing to the low level of the signal, the small differences between frequencies, and the necessity of sustaining attention throughout the 2-minute runs. Four channels of evoked responses were collected using Grass EEG amplifiers (bandpass 3-300 Hz) and a Nicolet averaging computer. Results from the bipolar derivation (Cz-Oz) are reported here.

Results

The top two traces of Figure 1 show the averaged (Cz-Oz) responses of one subject to the same

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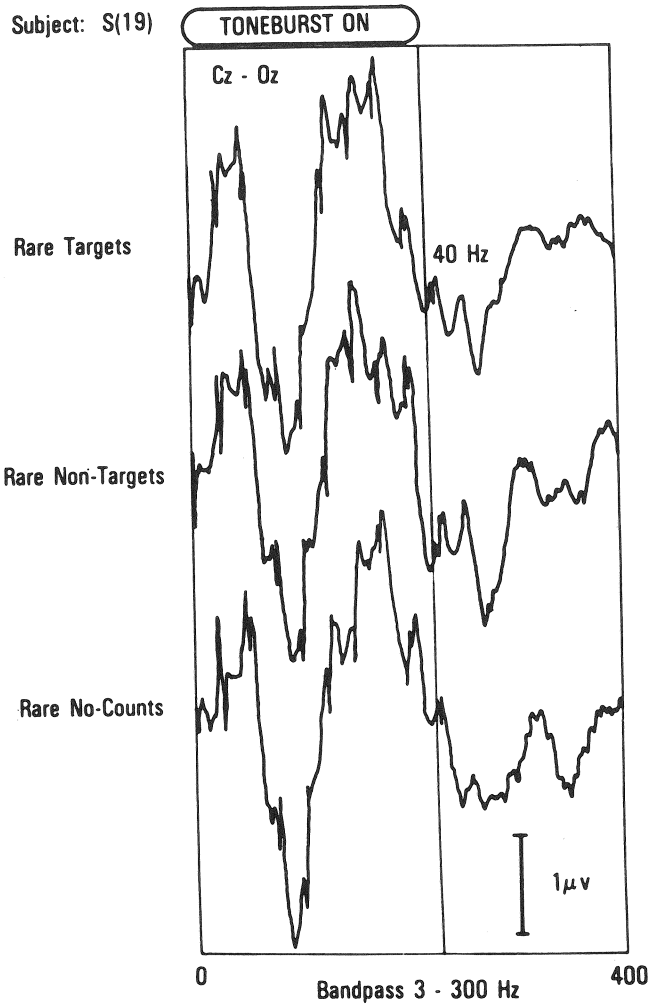

FIGURE 1. Average responses to rare targets (top trace), and rare non-targets in the "count high tones" and "count low tones" conditions (middle trace). Bottom trace is the response to the rare tones in the "don't count" condition. Each response is the sum of responses to about 200 tonebursts, in a total of eight blocks of trials over 80 minutes. The thin downward spikes in the responses during the time the toneburst is on are stimulus artifacts. (In these figures Cz positive is upward.)

stimuli (high and low tonebursts in the "count highs" and "count lows" conditions), segregated into "rare target" and "rare nontarget" responses. ("Rare nontargets" are the high tones in the "count lows" condition plus the low tones in the "count highs" condition.) The bottom trace is the responses to these same stimuli in the "don't count" condition (the "rare no counts"). Note in each of these traces the circa 1 μv 40 Hz modulation superimposed on the slower evoked response by the 40 Hz modulation of the toneburst.

The differences between pairs of the three responses shown in Figure 1 are seen in Figure 2. The (target-nontarget) and (nontarget-no count) difference waves each show a regular oscillation at circa 20 Hz which becomes locked in both frequency and phase to the moments of occurrence of tone pips within the toneburst (i.e., to multiples of 25 msec), and continues to at least the end of the sweep (400 msec after onset). A similar 20 Hz characteristic may be seen, less distinctly, in the (target-no count) comparison (Figure 2, bottom trace).

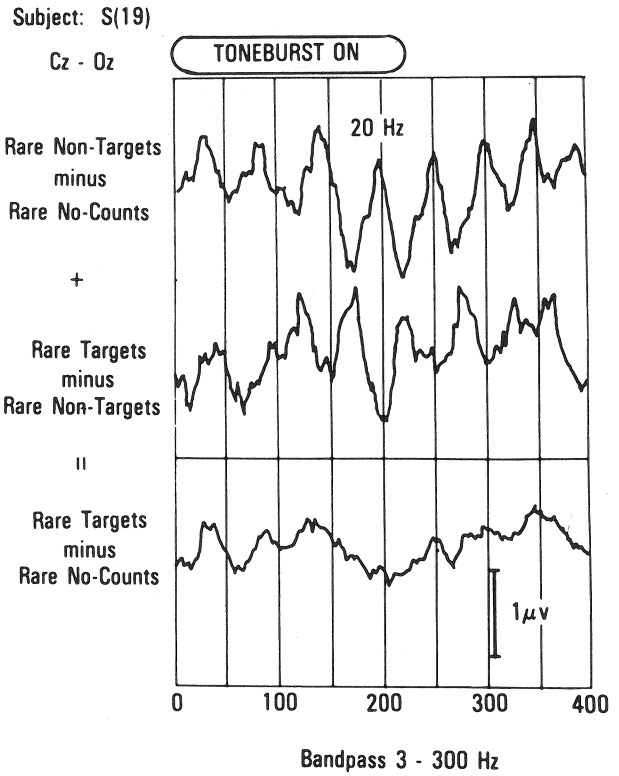

FIGURE 2. Difference waves between pairs of the three responses shown in Figure 1. Vertical lines are drawn every 50 msec. Note the progressive frequency and phase-locking of the difference waves and the stability of this phase-locking after offset of the toneburst.

Figure 3 shows the same difference wave comparisons for a second subject. Here frequency-and phase-locked rhythmic difference waves are also evident—but for this subject they are locked predominantly to about 10 Hz.

The (target-nontarget) comparisons for two other subjects are shown in Figure 4. Rhythmicities at about 13 Hz are evident (i.e., at about 1/3 of 40 Hz). In further experiments, evoked rhythmicities at 26 and at 32 Hz (2/3 and 4/5 of 40 Hz) have also been seen. However, rhythms evoked at frequencies other than 10 and 20 Hz have not been seen to "ring" on after toneburst offset, as do difference waves at 10 and 20 Hz (*see* Figure 4).

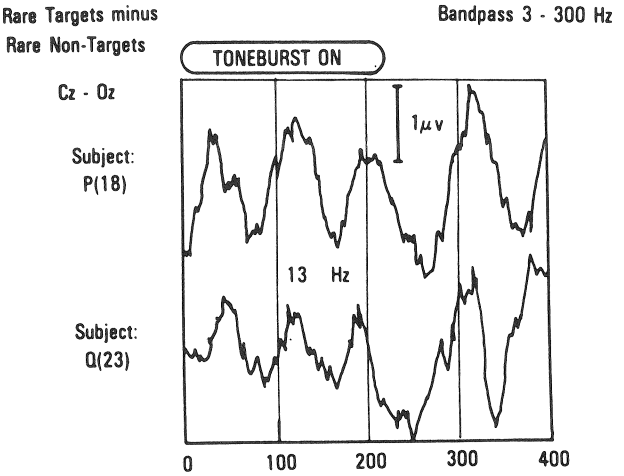

FIGURE 4. The target-nontarget comparisons for two other subjects who show a circa 13 Hz characteristic during the toneburst.

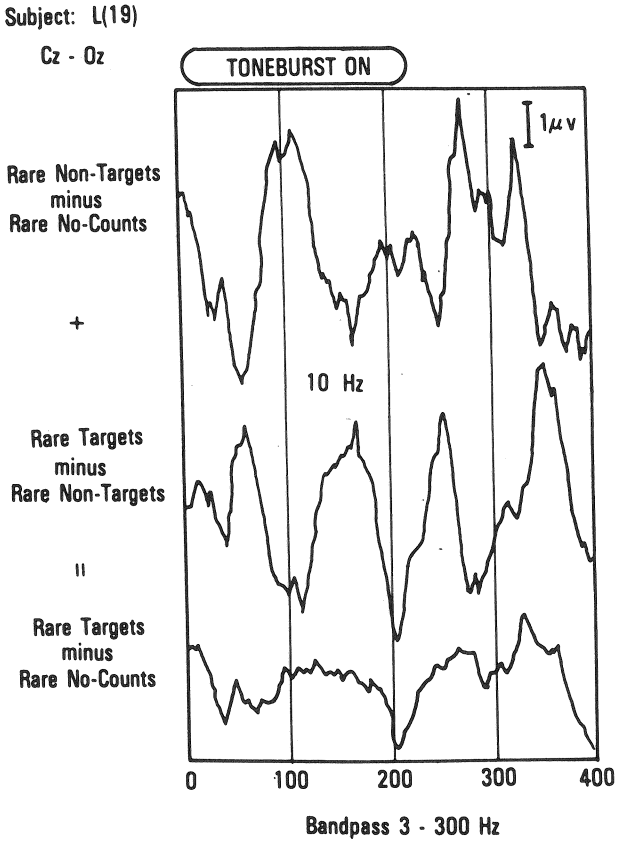

FIGURE 3. The same difference waves as shown in Figure 2 for another subject. Note again the progressive frequency- and phase-locking of the difference waves and their amplitude stability, in this case showing a 10 Hz characteristic.

Tentative Conclusions

Results of these first experiments suggest:

1. Difference waves between responses evoked by target and nontarget 40 Hz-modulated tonebursts reveal differences in amount of nonlinear brain resonance to the modulating frequency of the bursts. These rhythmic difference waves reflect differences in task-relevance of the stimuli, and thus are a new class of endogenous cognitive evoked response, possibly related to the event-related rhythmicities (ERR) discussed by John (*see* Galambos & Hillyard 1981).

2. The rhythmic character of the difference responses seems to be most pronounced in comparisons involving *non*-targets in the "count" conditions. The authors note that similar stimulus-evoked "alpha-like" EEG activity has previously been associated with nontarget stimuli and "inhibitory" cognitive processes (*see* Morrell 1966).

3. The remarkable phase-locking and amplitude stability of the circa 20 and 10 Hz subharmonic difference waves (*see* Figure 2) may be related to the theorized relative stability of successive bifurcations in a variety of physical dynamic systems (Feigenbaum 1979), as well as to bifurcations at these same (40 Hz, 20 Hz, 10 Hz) frequencies reported in various psychophysical (Kristofferson 1980; Augenstein 1955) and electrophysiological (Barnett et al. 1971; Freeman 1961, 1962) experiments.

4. Of the few derivations studied so far, the rhythmic characteristic is seen most clearly in the (Cz-Oz) derivation. This suggests the operation of a central dipole oriented front-to-back.

5. The phase of the circa 10 Hz (target-nontarget) differences corresponds to the same phase of the ongoing alpha rhythm (Oz-positive) which has recently been reported to result in quickest two-flash discrimination (Varelo et al. 1981). The phase of the difference wave could thus indicate a process of central modulation of sensitivity to the intermittent high-frequency information in the 40 Hz modulated bursts.

6. The "after-ringing" portion of the 40 Hz response is augmented for targets and attended tones in some subjects, but not augmented in others.

7. While the degree of stability of these responses within subjects has not been fully assessed, within the sessions reported here these responses seem to be remarkably stable, save perhaps in the "don't count" condition.

Discussion

The authors plan systematic investigations of the range and stability of the responses, and on the effects of changing modulating frequency and modality of the stimuli. They also intend to explore the relation of these phenomena to the endogenous responses (N1, P3, N4, etc.) seen in experiments using unmodulated stimuli (Hillyard et al. 1978).

The present evoked rhythmicities may bear some relation to the harmonic nonlinear phenomena seen in transition to turbulence of driven responses in physical (Feigenbaum 1979; Keolian et al. 1981) and biological (Mandell & Russo 1982) systems. Their range is similar to the variety of harmonic responses to photic driving seen in the raw EEG by Mundy-Castle (1953) and Fukushima (1975). They may also relate to the body of psychophysical theory and experiment relating to "perceptual moments" and "excitability cycles" (reviewed in Harter 1966). While these results are not yet thoroughly tested, they renew interest in exploring the role of nonlinear resonant brain dynamics in cognition.

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