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Magnetoencephalographic study of human auditory steady-state responses to binaural beat

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Abstract. Presentation of one sinusoid to each ear with a small difference of frequency elicits subjective fluctuations called binaural beat (BB). BB is a classic example of binaural interaction and provides a typical demonstration that the discharges of the auditory nerve fibers preserve information on the phase of the acoustic stimuli. Neural spikes tend to occur at a particular phase of the sinusoidal waveform (phase locking). The central auditory system utilizes the information of interaural phase difference (IPD) with continuous and periodical oscillation. The apparent beat frequency heard is equal to the IPD provided. In order to confirm the cortical representation of fluctuation of BB, we recorded the magnetic field of the auditory steady-state response (SSR) evoked by BBs in six normal-hearing right-handed subjects. Periodical responses with small amplitude were recorded around the bilateral temporal areas by a wholescalp neuromagnetometer under presentation of slow BB (4 and 6.66 Hz). Spectral analysis detected peaks of the BB frequency in the channels of bilateral temporal areas. These results suggested that activity of cerebral cortex, especially auditory cortex, can be synchronized with slow BB and have capacity for preserving the information of IPD.

Keywords: Binaural beat; MEG; Steady-state response; Interaural phase difference

1. Introduction

Presentation of one sinusoid to each ear with a small difference of frequency (Δf) provides an orderly and continuously changing interaural relative phase through one cycle of Δf. When Δf is smaller, a single auditory image moves toward the leading ear to which a

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tone of higher frequency is presented [1,2]. As Δf is increased, subjective periodic fluctuations called binaural beats (BBs) are elicited at a rate equal to Δf. Perrott and Nelson [3] have reported that, when the frequency of sinusoidal tone presented unilaterally to one ear is 250 Hz, BBs are detected when Δf at the other ear is between about 2 and 30 Hz. BBs demonstrate that the discharges of the auditory nerve fibers preserve information on the phase of the acoustic stimuli. Neural spikes tend to occur at a particular phase of the sinusoidal waveform (phase locking) and the central auditory system has capacity for preserving temporal information (frequency coding). In most mammals, phase locking becomes progressively less precise at frequencies above 1 kHz, and it disappears completely at approximately 4–5 kHz [4]. BBs are essentially a low-frequency phenomenon and are heard most distinctly for frequencies between 300 and 600 Hz [5]. Perception of BBs depends on detecting the continuously changing IPD. The goal of this study is to demonstrate the cortical representation of fluctuation of BBs by magnetoencephalography (MEG) and to confirm that IPD is coded in the human auditory cortex.

2. Material and methods

2.1. Subjects

Six normal-hearing, right-handed subjects (four males, two females; ages 24–57 years; mean $\pm$ S.D. age of 40.3 $\pm$ 11.5 years) participated in this study. Subjects had no history of otological and neurotological disorders and had normal audiological status.

2.2. Stimulation

Continuous pure tones were played on an Apple personal computer via MOTU 828 (Mark of the Unicorn, Massachusetts, USA) audio interface and led to foam insert earphones through plastic tubes. As frequency of BB, 4 and 6.66 Hz were employed, and the combination of pure tone of 240 and 244 Hz, 240 and 246.66 Hz, 480 and 484 Hz, and 480 and 486.66 Hz were presented to elicit BB. Measurement under control condition with binaural presentation of same pure tones (240 or 480 Hz) was also performed to elucidate the characteristics of response evoked by BB. Triggers for averaging had an interval of four BB cycles to display periodical fluctuation of signals evoked by four BBs.

2.3. Recording

Neuromagnetic cortical signals were recorded with a wholescalp neuromagnetometer (Vectorview; Neuromag, Helsinki, Finland), which has 204 first-order planar gradiometers. During the recordings, the subjects were seated under the helmet-shaped dewar in a magnetically shielded room. The position of the head under the helmet was determined by attaching four coils to the head surface and measuring the coil positions with respect to landmarks on the skull with a three-dimensional (3-D) digitizer; the coil locations in the magnetometer coordinate system were determined by leading current through the coils and measuring the corresponding magnetic fields. The recording passband was 1.0–200 Hz, and the data were digitized at 600 Hz. The averaged signals were low-pass filtered at 40 Hz.

2.4. Data analysis

To obtain steady-state responses, 1000–2000 epochs synchronized with BBs were averaged. The analysis period of four BB cycles was used to display periodical fluctuation of signals evoked by BBs.

Fast Fourier transform (FFT) spectra were calculated across 8192 samples of the continuously recorded MEG signals, and the FFT window was moved in steps of 4096 samples; this procedure resulted in frequency resolution of 0.074 Hz. In order to explore the channels in which MEG signals were synchronized to BB, first, we extracted the channels whose amplitude of just BB frequency (4 or 6.66 Hz) was maximum in the range of 2 Hz width (3–5 and 5.66–7.66 Hz). Then, the channel with maximum amplitude of BB frequency in each hemisphere was selected.

3. Results

Steady-state responses with dominant amplitudes in bilateral temporal areas were observed in all the subjects. In some channels of these regions, four peaks were clearly recognized in the time window which corresponds to four cycles of BBs (Fig. 1a). Spectral analysis detected evident peaks of the frequency of BB (4 or 6.66 Hz) in several channels of the bilateral temporal areas (Fig. 1b).

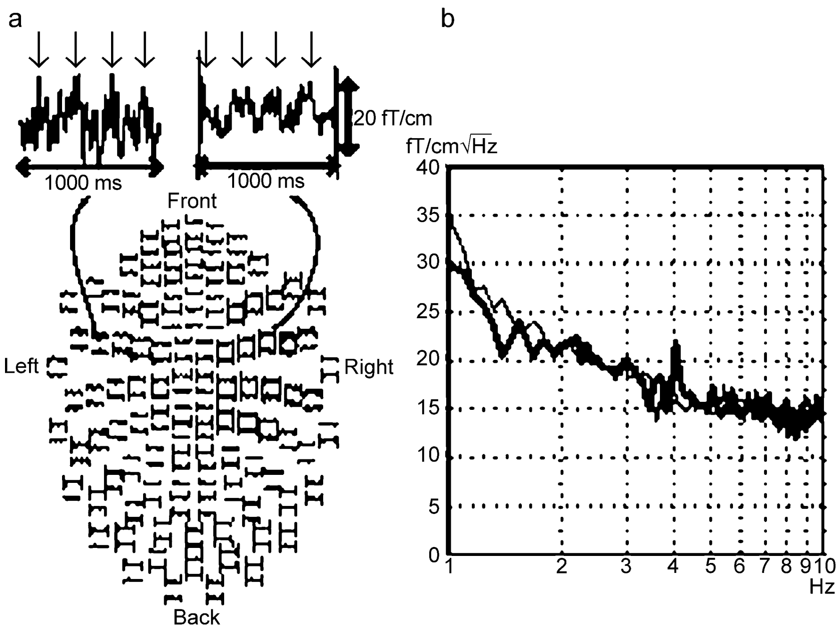

Fig. 1. (a) Typical waveforms of steady-state fields of one subject. Four peaks (arrows) during analysis time of 1000 ms were clearly demonstrated in bilateral temporal areas under the presentation of 240 Hz tone to the left ear and 244 Hz tone to the right ear (BB of 4 Hz). (b) FFT spectra in demonstrative channel of one subject under the presentation of 240 Hz tone to the left ear and 244 Hz tone to the right ear (thick line) and the presentation of 240 Hz tone to both ears (thin line). An evident peak of 4 Hz was confirmed in case of BB.

4. Discussion

BBs provide a classic example of binaural interaction, considered to result from neural interaction in the central auditory pathway that receives input from both ears. Some papers reported that the central auditory system utilizes the information of continuously changing IPD when BBs are presented to mammals. Kuwada et al. [2] found that the responses of cat inferior colliculus neurons are phase-locked to the frequency of BBs. Reale and Brugge [6] studied the interaural phase difference sensitivity of single neurons in the primary auditory cortex of the anesthetized cat. Approximately 26% of the cells that showed sensitivity to static changes in IPD also showed sensitivity to dynamically changing IPD created by BBs. The discharges were highly periodic and tightly synchronized to a particular phase of the BB cycle. Malone et al. [7] revealed the responses to dynamic IPD in the auditory cortex of awake macaques. In our study, periodical steady-state responses with small amplitude were evoked by slow BB, especially around the bilateral temporal areas. Spectral analysis detected peaks of the BB frequency. These results suggested that activity of human cerebral cortex, especially auditory cortex, can be synchronized with slow BB and have capacity for preserving the information of IPD.

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