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Human auditory steady state responses to binaural and monaural beats

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Abstract

Objective: Binaural beat sensations depend upon a central combination of two different temporally encoded tones, separately presented to the two ears. We tested the feasibility to record an auditory steady state evoked response (ASSR) at the binaural beat frequency in order to find a measure for temporal coding of sound in the human EEG.

Methods: We stimulated each ear with a distinct tone, both differing in frequency by 40 Hz, to record a *binaural beat ASSR*. As control, we evoked a beat ASSR in response to both tones in the same ear. We band-pass filtered the EEG at 40 Hz, averaged with respect to stimulus onset and compared ASSR amplitudes and phases, extracted from a sinusoidal non-linear regression fit to a 40 Hz period average.

Results: A 40 Hz binaural beat ASSR was evoked at a low mean stimulus frequency (400 Hz) but became undetectable beyond 3 kHz. Its amplitude was smaller than that of the acoustic *beat ASSR*, which was evoked at low and high frequencies. Both ASSR types had maxima at fronto-central leads and displayed a fronto-occipital phase delay of several ms.

Conclusions: The dependence of the 40 Hz binaural beat ASSR on stimuli at low, temporally coded tone frequencies suggests that it may objectively assess temporal sound coding ability. The phase shift across the electrode array is evidence for more than one origin of the 40 Hz oscillations.

Significance: The binaural beat ASSR is an evoked response, with novel diagnostic potential, to a signal that is not present in the stimulus, but generated within the brain.

Keywords: Binaural; Beat; ASSR; EEG; Auditory; Steady state response; Temporal code

1. Introduction

Two simultaneous pure tone stimuli of frequencies within the same critical band (Fletcher, 1940; Greenwood, 1961a,b; Moore, 2003) may be heard as one tone with a pitch at the mean frequency of both inputs, beating at a rate equal to the difference between both input frequencies (cf. Moore et al., 1998). Because both tones are summed before entering the cochlear filter, acoustic beating tones can be heard at pitches throughout the auditory frequency range. Beat stimuli are similar to amplitude-modulated (AM) tones that are commonly used in auditory steady-state response (ASSR) audiometry (Picton et al., 2003). An important difference is that, at supra-threshold intensities, the two-component beat stimulus may excite a narrower cochlear frequency band than an AM stimulus, which consists of three spectral components, spread over twice the frequency range at an identical pitch and envelope oscillation rate. Thus, the ASSR in response to beat stimuli (*beat-ASSR*) may, in special cases, offer improved frequency resolution in objective audiometry, justifying its exploration in human subjects.

A beating tone may also be heard when each sinusoidal component is presented, in isolation, to a different ear (Tobias, 1963). This *binaural beat*, a much fainter sensation, is restricted to relatively low component frequencies of a few hundred Hz (Licklider et al., 1950) that are temporally encoded as spike firing phase-locked to the sound wave (Rose et al., 1968). In the mammalian auditory system robust phase locking, to tone frequencies up to a few kHz, has been demonstrated in cochlear nerve fibers (Palmer and Russell, 1986) and in the spherical bushy cells of the antero-ventral cochlear nucleus (Goldberg and Brownell, 1973) whose

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axons project to the medial superior olivary (MSO) nucleus (Goldberg and Brown, 1969; Smith et al., 1993). MSO neurons receive the inputs from both ears separately, each at one of their two dendritic trees (Ramon Y Cajal, 1909; Schwartz, 1977), where the sound waves are, presumably, replicated (Agmon-Snir et al., 1998). The membrane potential at the MSO neuron spike trigger zone, close to the soma, is thought to reflect a combination of the sound waves from both ears, and the output spike rate of MSO neurons is modulated at the envelope time pattern of the sum of both input waveforms (Yin and Chan, 1990). Thus, firing patterns of inferior colliculus neurons, the target of MSO axon projections, can reflect a binaural beat (Kuwada et al., 1979). In the tonotopic array of the MSO, each neuron is tuned to a narrow frequency band, similar to cochlear nerve fibers, and different tones in both ears may be combined only if they fall in the same critical frequency band. Thus, different tones in each ear can be heard as binaural beat only if they are separated in frequency by less than a critical band (like acoustic beats) and have frequencies sufficiently low to be temporally encoded (unlike acoustic beats). An EEG response to binaural beat stimuli will, therefore, functionally assess the temporal coding mechanisms in the lower auditory brainstem.

A binaural beat stimulus should, hypothetically, be able to evoke an ASSR, since it should cause firing rates in the MSO output, and thus in cortical afferents, to be modulated in a manner similar to the AM tones commonly used in ASSR audiometry. We did not doubt that we could record an *acoustic beat ASSR* from the human brain, since this response type had already been reported for non-human mammals (Dolphin et al., 1994). Our ability to detect a binaural beat ASSR was less certain, however, for several reasons. (1) The binaural beat usually is a faint sensation. Thus, a corresponding EEG signal could be small and difficult to separate from larger EEG oscillations. (2) Maximal steady state responses have been recorded at stimulus repetition- or amplitude modulation rates in the gamma range, close to 40 Hz (cf. Picton et al., 2003). The human auditory system may interpret a 40 Hz modulation rate as a distinct low pitch tone rather than a beat. (3) A human subject may have a choice to listen to two tones in different ears separately or combine them as one beating sound. Here, one perception could exclude the other, as in Edgar Rubin's famous picture showing mutually excluding contours of either two faces or a vase (cf. Kandel, 1991). During dichotic sound stimulation two mutually exclusive perceptions may also occur. For example, a dichotic presentation of the second of two noises, delayed between the ears, can cause either a noise sensation at a specific location in space or a musical pitch (Fourcin, 1970). A binaural beat ASSR could, therefore, depend upon a focus of attention on the beat sensation. Using a time domain analysis, we attempted to optimize a distinction of small steady state responses from the ongoing EEG and noise. Hink et al. (1980) reported a beating binaural frequency following response. Here we show that two pure tone stimuli in separate ears can evoke a binaural beat ASSR at a 40 Hz difference frequency in normal hearing subjects. The binaural beat ASSR differed qualitatively from a much more robust monaural, acoustic *beat ASSR*.

2. Methods

2.1. Subjects

Eighteen healthy subjects (11 females and 7 males, ages from 16 to 47 years) without otological or neurological disease in their histories and with normal pure tone audiometric thresholds were recruited for experiments. The subjects were paid to participate in the study, informed in writing about purpose and procedures and signed a consent form, according to procedures approved by the Human Ethics Committee of the University of British Columbia, in compliance with the Helsinki Convention.

2.2. Stimuli

Stimuli were two simultaneous pure tones differing in frequency by 40 Hz, with frequency means of 400 or 3200 Hz. For example, a 40–400 stimulus, in our nomenclature, consisted of components at 380 and 420 Hz. Stimuli were generated with Labview-6 software on a National Instruments I/O board, in a Pentium IV-based computer, at a 200 kHz D/A update rate. The two components were either separately fed through the two channels of an Amcron stereo power amplifier into two separate channels of Etymotic ER-2 insert earphones (binaural beat stimuli), or they were digitally summed into one output channel and fed to one of the insert earphones for presentation in the right ear in 16 cases, or the left ear in two cases (acoustic beat stimuli). Attenuation between stimuli delivered by an insert earphone and the opposite ear was greater than 70 dB at all frequencies used in this study. The components were presented as tone bursts of 1.2 s duration, starting at a fixed phase of 0° and gated on and off with 5 ms cosine ramp functions. The stimulus bursts were alternated with stimulus-free intervals of 1.2 s and 180 of these 2.4 s stimulus/interval epochs were repeated per typical recording session. Individual thresholds were determined at component frequencies, and stimuli were presented at intensities of 70 dB above the thresholds in all subjects and at 30 dB in nine of these subjects.

2.3. Focus of attention

A few subjects with musical training attempted to assign a musical interval value to the difference between both component tones. As this effort appeared to suppress the generation of a binaural beat ASSR, we instructed subjects