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Auditory Cortex Responses to the Transition from Monophonic to Pseudo-stereo Sound

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ABSTRACT

Human cortical responses to the change in spaciousness of sound were recorded with the method of magnetoencephalography (MEG). The phases of dichotically presented 500-Hz tones were shifted so that the sound was perceived as originating either from a point-like source centered in the head or from separated sources in space. The phase shift was embedded in 40-Hz amplitude modulation. Thus, the phase shift could not be detected from a monaural signal. The transition between 'mono' and 'pseudo-stereo' quality of the sound elicited a P1-N1-P2 response similar to the onset response as well as a decrement in the steady-state response. The responses were discussed as reflecting binaural processing in the central auditory system.

KEY WORDS

Spatial hearing, Dichotic listening, Binaural interaction, Pseudo-stereo sound, Auditory space perception, MEG.

INTRODUCTION

Listening to a stereo-phone recording of music via a pair of headphones induces the illusion of a spacious sound outside the head. In contrast, a mono-phone sound (i.e., same sound to both ears) is perceived as originating from a point-like source centered inside the head. The illusion of a sound in space is induced by central processing of multiple acoustical parameters like the inter-aural time- and intensity differences and correlations between sounds in the left and right ears [Blauert, 1983]. A single sound can be modified to create the illusion of spatial sound by phase shifting the sound between both ears [Schroeder, 1961]. Such a sound is called a 'pseudo-stereo' sound. The aim of this study was to record cortical responses to a change in the stimulus quality, which could only be perceived by central binaural processing. The observed brain activity may serve as a complement or replacement of the binaural interaction component, which is conventionally used to indicate central auditory processing.

METHODS

Twelve healthy, normal-hearing, right-handed subjects (seven female) of 24 to 50 years of age participated in the study, which was reviewed by the Ethics Commission of the Baycrest Centre for Geriatric Care. Stimuli were 40-Hz amplitude modulated (AM) tone-bursts (500 Hz) of 4,000 ms duration. Stimuli were dichotically presented at an intensity of 60 dB above the individual sensation level through earphones connected with plastic tubes and silicon ear-pieces. At 2,000 ms, half the stimulus duration, a phase shift of 90º was introduced in the right-ear carrier signal and a phase shift of -90º in the left-ear carrier signal (Fig. 1a). Thus, signals were in phase for the first two seconds ('mono' condition) and out of phase for the last two seconds (‘pseudo-stereo’ condition). A total of 128 stimuli were presented with an ISI of 4±0.5 s between succeeding stimuli. A second block contained 128 stimuli, which were out of phase for the first 2 s and in phase thereafter. MEG was recorded with a 151-channel whole head magnetometer (OMEGA, CTF Systems Inc, Port Coquitlam, Canada) in a silent magnetically shielded room with the subjects in seated position. Subjects passively listened to the stimuli while watching a soundless movie. The sources of auditory N1-response were localized by approximating the magnetic fields of single equivalent current dipoles in each hemisphere to the 0-24 Hz low-pass filtered averaged data around the time point of the N1 maximum. Correspondingly, sources of the auditory steady-state response (ASSR) were localized after averaging multiple 25-ms epochs of 32-48 Hz band-pass filtered averaged data. Time-series of magnetic dipole moments were calculated based on both sets of source coordinates.

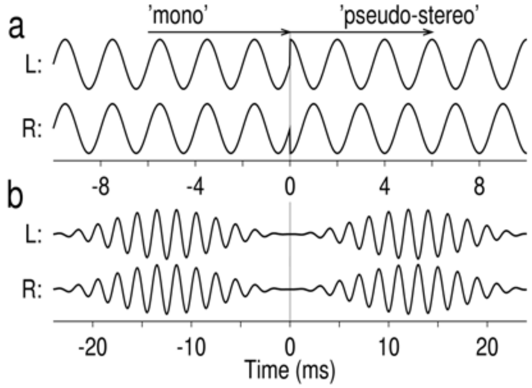

Figure 1. (a) Phase shift of 500-Hz carrier signal, (b) embedded in 40-Hz amplitude modulation. Zero time refers to the midpoint of the stimulus burst of 4 s duration.

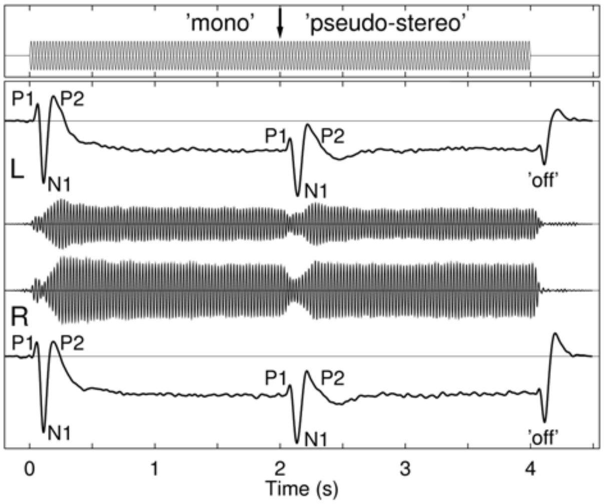

Figure 2. Grand averaged (n=12) waveforms of low-pass filtered responses containing the transient P1-N1-P2 waves to the onset, phase-shift, and offset of a stimulus, as well as the sustain field. Band-pass filtered responses containing ASSR waveforms in right (R) and left (L) hemispheres are shown in the middle traces.

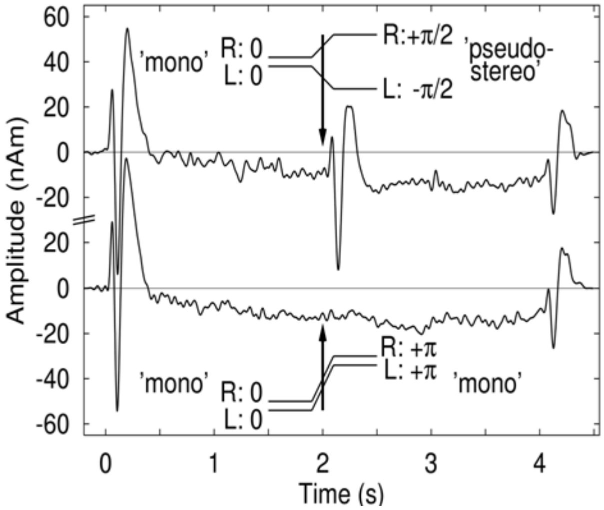

Figure 3. Individual responses to the stimulus containing a ‘mono’ to ‘pseudo-stereo’ transition (upper trace) and a control stimulus containing phase shifts in the same direction in both ears (lower trace).

RESULTS

All subjects reported to clearly perceive the sound source centered inside the head shift to distributed sound source in space. Clearly identifiable transient and steady-state responses were recorded from all subjects. The grand averaged response waveforms exhibit P1-N1-P2 waves after the stimulus onset and the transition from mono to pseudo-stereo quality (Fig. 2). The low-pass filtered waveforms also reveal a distinct sustained field and an 'off' response as well. The N1 amplitude was about 10% larger at the onset of a pseudo-stereo than a mono stimulus ($p<0.01$). Additionally, N1 amplitude was about 10% larger for the transition from mono to pseudo-stereo as compared to the reverse transition ($p<0.01$). A P1-N1-P2 response to the phase shift was superimposed on the sustained field and the N1 amplitude resembled the N1 onset response when measured with reference to the pre-stimulus baseline. The P1-N1 response amplitude to the phase-shift, however is 25% smaller than onset P1-N1 response amplitude. No significant differences in the P1-N1-P2 responses were found between hemispheres. In contrast, ASSR amplitude was significantly larger in the right hemisphere. Time-course of the 40-Hz response showed the transient response after stimulus onset, a shallow slope of the ASSR onset, and the almost constant amplitude in the steady-state. Immediately after the phase shift, the ASSR amplitude was noticeably reduced for 250 ms. Fig. 3 shows the individual results of a control condition, in which the phase shift in the stimulus signal followed the same direction in both ears. Thus, the stimulus contained a phase shift but it did not elicit any perceived change in sound source location or neural responses to the phase shift. Consistent with previous results, ASSR sources were significantly more medially located than the N1 responses. This suggests that ASSR are generated in the primary auditory cortex and N1 responses are generated in primary and non-primary auditory cortices. Detailed results of the source localization using the method of synthetic aperture magnetometry were recently presented [Herdman, 2003]

DISCUSSION

A phase shift of 90º as introduced in the 500 Hz tone is clearly perceived when presented monaurally. Such a phase shift, indicated by sudden change in sound signal (Fig. 1a), produces a small dip in amplitude of less than 10 ms duration at the output of the auditory filter and is clearly perceived [Shailer, 1987]. However, when the phase-shift is embedded in the 25 ms wide trough of the amplitude modulation no transient occurs in the sound waveform (Fig. 1b) and the phase-shift in the carrier of the AM signal cannot be perceived. The control condition in the present study demonstrated clearly that no evoked response is elicited by the phase-shift in the monaural stimulus. This indicates that the binaural processing of inter-aural time differences elicits the auditory responses.

Almost identical P1-N1-P2 responses were recorded from both hemispheres with prominent N1 amplitudes. Utilizing 40-Hz amplitude modulated stimuli in this study allowed us to simultaneously record the ASSR. The observation of different source localizations for the N1 and ASSR, with the ASSR sources being more medial compared to the N1 sources, is consistent with earlier reports [Hari, 1989, Engelien, 2000]. , 40-Hz ASSR are most likely generated in the primary auditory cortex. A clear reaction to the 'mono'-'pseudo-stereo' transition was observed in the ASSR with pronounced decrease in the ASSR amplitude. This indicated that the binaural processing is already performed in the primary auditory cortex or below in the auditory pathway, which is consistent with the assumption that the inter-aural time differences are processed in the inferior colliculus.

Another experimental observation was the larger N1 response to the onset of the 'pseudo-stereo' stimulus as compared to the onset of the 'mono' stimulus. Furthermore, N1 responses were larger for the transition from 'mono' to 'pseudo-stereo' than for the reversed transition. Stimuli contained no power or spectral differences, however, the more 'spacious' sound may bear more complexity and thus it might cause larger N1 responses and ASSR resetting.

The inter-aural time difference, equivalent to a phase difference, is the most important cue for sound localization at 500-Hz carrier frequency used in this study. However the phase difference cannot be discriminated in pure tones above 1,500 Hz [Zwislocki, 1956]. At higher frequencies the time (phase) differences in the sound envelope become the relevant cue for sound localization [Bernstein, 2001]. For this case it seems straightforward to create corresponding stimuli with a phase shift in the stimulus envelope instead of the carrier signal and record equivalent responses.

Binaural hearing is frequently impaired in patients with central auditory processing disorders (CAPD). This causes, for example, severe problems in discriminating speech in a noisy environment. The detection of the binaural interaction component (BIC) is of diagnostic interest for children at risk for CAPD [Delb, 2003]. The BIC is a component of the auditory evoked brainstem responses, which is derived from sequential ABR recordings as differences between the binaural and the sum of the two monaural responses. Unfortunately, the BIC is a very small evoked potential and not always detectable with sufficient reliability. The auditory evoked response observed in the present study is in contrast a robust indicator for binaural processing and might serve as a complement or replacement for the BIC in clinical screening procedures.

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