Cortical Evoked Potentials to an Auditory Illusion: Binaural Beats

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Abstract

Objective: To define brain activity corresponding to an auditory illusion of 3 and 6 Hz binaural beats in 250 Hz or 1,000 Hz base frequencies, and compare it to the sound onset response.

Methods: Event-Related Potentials (ERPs) were recorded in response to unmodulated tones of 250 or 1000 Hz to one ear and 3 or 6 Hz higher to the other, creating an illusion of amplitude modulations (beats) of 3 Hz and 6 Hz, in base frequencies of 250 Hz and 1000 Hz. Tones were 2,000 ms in duration and presented with approximately 1 s intervals. Latency, amplitude and source current density estimates of ERP components to tone onset and subsequent beats-evoked oscillations were determined and compared across beat frequencies with both base frequencies.

Results: All stimuli evoked tone-onset P_{50}, N_{100} and P_{200} components followed by oscillations corresponding to the beat frequency, and a subsequent tone-offset complex. Beats-evoked oscillations were higher in amplitude with the low base frequency and to the low beat frequency. Sources of the beats-evoked oscillations across all stimulus conditions located mostly to left lateral and inferior temporal lobe areas in all stimulus conditions. Onset-evoked components were not different across stimulus conditions; P_{50} had significantly different sources than the beats-evoked oscillations; and N_{100} and P_{200} sources located to the same temporal lobe regions as beats-evoked oscillations, but were bilateral and also included frontal and parietal contributions.

Conclusions: Neural activity with slightly different volley frequencies from left and right ear converges and interacts in the central auditory brainstem pathways to generate beats of neural activity to modulate activities in the left temporal lobe, giving rise to the illusion of binaural beats. Cortical potentials recorded to binaural beats are distinct from onset responses.

Significance: Brain activity corresponding to an auditory illusion of low frequency beats can be recorded from the scalp.

Keywords

Event-Related Potentials; Hearing; Source estimation; Functional imaging

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1. Introduction

1.1. Binaural beats

When two sinusoids with slightly different frequencies are superimposed, their interference results in periodic amplitude fluctuations whose frequency corresponds to the frequency difference between the sinusoids. When sound with slightly different frequencies is mixed in the same ear, the fluctuations in the intensity of the sound are perceived as beats, reflecting the acoustic properties of the stimulus and are thus called acoustic beats. When a tone of one frequency and steady intensity is presented to one ear and a slightly different frequency is presented to the other ear, a perception of beats is experienced, with a beat frequency corresponding to the frequency difference between the two ears. These beats do not reflect a physical property of the sound, but probably the convergence of neural activity from the two ears in the central binaural auditory pathways of the brain. The intensity changes in the perceived sound are therefore called "binaural beats". Binaural beats are present when the disparate frequencies to the two ears are low, and beats are difficult to hear at frequencies above 1000 Hz (Licklider et al., 1950).

The most widely accepted physiological explanation for binaural beats suggests that discharges of neurons that preserve phase information of the sound in each ear according to the volley principle (Rose et al., 1968; Palmer and Russell, 1986; Goldberg and Brownell, 1973) converge on binaurally activated neurons in the ascending auditory pathway (Kuwada et al., 1979; McAlpine et al., 1996; McAlpine et al., 1998; Spitzer and Semple, 1998) that, in turn, generate the neurophysiological correlate of binaural beats (Wernick and Starr, 1968) in the brainstem.

Normative human studies on binaural beats showed differences between the subjective rhythm perceived and the difference between the two frequencies, indicating a central effect (Fritze, 1985). Clinical studies of binaural beats in humans varied in their sensitivity to cortical damage. Some reported that binaural beats were not sensitive to cortical damage (Noffsinger, 1982) but others showed that binaural beats could not be perceived by patients with cortical lesions associated with severe aphasia (Barr et al., 1977). A detailed study of a single patient with Auditory Neuropathy reported that a marked impairment of binaural beats was observed in conjuction with impaired auditory perceptions dependent on temporal cues, such as lateralization of binaural clicks, change of binaural masked threshold with changes in signal phase, detection of paired monaural clicks, monaural detection of a silent gap in a sound, and monaural threshold elevation for short duration tones (Starr et al., 1991). Effects of binaural beats at the Beta EEG frequency on psychomotor performance, mood and arousal (Lane et al., 1998) have also been reported.

Thus, animal experiments indicate the auditory brainstem as the level of binaural beat formation, human studies agree that binaural beats are a central effect which is sensitive to temporal acoustic cues and which may interact with cortical function.

1.2. ERPs to binaural beats

Although the psychoacoustic effect of binaural beats has been well-studied in normals and patients, only very few studies reported ERP correlates of binaural beats. Two studies recorded auditory steady-state responses to a binaural beat frequency of 40 Hz. In the first (Schwarz et al., 2005), the right and left ears were stimulated with tones differing in frequency by 40Hz, and binaural beat steady-state potentials were recorded. A 40Hz binaural beat potential was evoked with a low base stimulus frequency (400Hz) but became undetectable when base frequency was above 3kHz. In another study (Karino et al., 2006), magnetic fields evoked by beats of 4.00 or 6.66 Hz in base frequencies of 240 and 480 Hz were described. The fields showed small but sufficient amplitudes to be distinguished from the noise in the recordings.

Spectral analyses of the magnetic fields revealed that the responses contained a specific spectral component of the beat frequency. Source estimates suugested multiple sources in the left and right auditory cortices and in parietal and frontal cortices. The phase of the beat-evoked waveforms showed great variability, suggesting that the responses did not represent changing interaural phase differences but a cognitive process corresponding to subjective fluctuations of binaural beats. More recently, 40 Hz binaural beats of a 500 Hz base frequency were used to evoke steady state magnetic fields which were also compared with the transient evoked N_{1m} (Draganova et al., 2008). The auditory steady-state sources were lateralized to the right hemisphere and were anterior, inferior, and medial compared with onset N_{1m} sources.

Two of the three previous reports on electrophysiological correlates of binaural beats used a beat frequency of 40Hz. This frequency is optimal for thalamic and primary cortical steady-state activity, but later cortical contributions associated with perception are markedly attenuated at this rate. Moreover, the filter properties of scalp and skull attenuate 40 Hz potentials relative to lower frequencies and this attenuation of a beat frequency of 40 Hz may impede the detection and characterization of the slower brain activity associated with the perception of binaural beats. There is disagreement among previous studies on the sources of the beat-evoked oscillations: One study found bilateral sources in temporal lobe (Karino et al., 2006) while in the other – sources were lateralized to the right (Draganova et al., 2008).

1.3. Purpose of this study

The purpose of this study was to define cortical auditory evoked potentials to binaural beats of 3- or 6 Hz in high- (1000 Hz) and low (250 Hz) base frequency tones, and to estimate their intracranial sources. Potentials to the onset of the tones were also recorded for comparison.

2. Methods

2.1. Subjects

Eighteen (16 men and 2 women) 18 to 25 years old right handed normal hearing subjects participated in the study. Subjects were paid for their participation and all procedures were approved by the institutional review board for experiments involving human subjects (Helsinki Committee).

2.2. Stimuli

Binaural tone bursts of 2,000 ms duration and 70 dBnHL intensity were presented through earphones (Sony MDR-CD770) with a flat frequency response (within 10 dB across the frequency range 100-10,000 Hz). Tones were presented at interstimulus intervals that randomly varied between 950 and 1050 ms. Low frequency tone bursts included synchronous presentation of 250 Hz to the left or right ear and 253 or 256 Hz to the opposite ear, resulting in binaural beats of 3 or 6 Hz, respectively (Figure 1, top). Similarly, 1,000 Hz tone bursts were presented to one ear and 1003 or 1006 Hz to the other, resulting in binaural beats of 3 or 6 Hz, respectively. In all, there were 4 stimulus conditions: 250 and 1,000 Hz base frequencies with 3 and 6 Hz binaural beats, which were randomly presented during the recording session, with equal probability for each stimulus condition (25%) and right (50%) or left (50%) ear receiving the sound with the higher base frequency. Each stimulus condition was randomly presented 400 times.

These stimulus parameters were selected following preliminary experiments in which subjects reported detection of beats in a series of binaural tones some of which had no beats while others had beats of different frequencies and intensities. In line with earlier psychoacoustic reports, perception of binaural beats was found sensitive to base frequency, intensity and beat rate. The

stimulus parameters of this study were chosen to optimize psychoacoustic and electrophysiological detection of beats.

2.3. Procedure

Twenty two 9 mm silver disc electrodes were placed according to the 10-20 system at: F_{p1}, F_7, F_3, F_z, F_4, F_8, F_{p2}, T_3, C_3, C_z, C_4, T_4, T_5, P_3, P_z, P_4, T_6, O_1, O_2, 1.5 cm above the left and right mastoids (M'_1 and M'_2), all referenced to the center of the chin, to record the electroencephalogram (EEG). The mastoidal electrodes were placed above their standard positions to avoid distortion in the source estimation procedures. In addition, an electrode below the left eye, referenced to F_z, was used to control for eye movements (EOG). In total, EEG was recorded from 21 electrodes and EOG was recorded from one diagonal differential recording below the left eye referenced to F_z. An electrode over the 7th cervical spinous process served as ground. Impedance across each electrode pair was maintained below 5 kOhms.

Subjects were subsequently seated in a comfortable reclining armchair in a sound-proof chamber and instructed to read a complicated text, on which they were to be examined, while stimuli were presented (subjects were actively distracted from the stimuli). The diverted attention of subjects from the auditory stimuli, the equal probabilities of the four stimulus conditions, as well as the randomness of beats and their timing were designed to reduce endogenous contributions to the brain potentials. In preliminary tests on 4 subjects, the beats-evoked potentials recorded while subjects indicated the detection of beats or their absence (attending to sound), were indistinguishable from the respective potentials when subjects were reading and not responding to the beats (actively distracted from sounds). This absence of attention-related effects indicated an exogenous nature of the beats-evoked potentials. Subjects were allowed breaks as needed.

2.4. Data acquisition

Potentials from the EEG (X100,000) and EOG (X20,000) channels were amplified, digitized with a 12 bit A/D converter at a rate of 256 samples/sec, filtered (0.1 to 100Hz, 6 dB/octave slopes) and stored for off-line analysis. EEG processing began with segmentation of the continuous EEG to epochs beginning 100 ms before until 2,300 ms after each tone burst onset. Eye movement correction (Attias et al., 1993) and artifact rejection (± 150 µV) followed segmentation. Average waveforms were then computed for the 3 Hz and 6 Hz beats in the 250 Hz and 1000 Hz base frequencies. Consequently, between 300 and 350 repetitions were averaged to obtain the potentials evoked by each stimulus condition. These 4 separate averages (2 beat frequencies × 2 base frequencies) were computed for each subject, as well as across subjects to obtain grand mean waveforms. After averaging, the data were band-pass filtered (FIR rectangular filter with a cutoff at 2-10 Hz) and baseline (average amplitude across the 100 ms before stimulus onset) corrected. This filter was chosen to enhance the detection of the beats-evoked oscillations and was found to have only a minor effect on the amplitudes of the onset-evoked potentials.

2.5. ERP waveform analysis

ERP analysis included peak latency and amplitude comparisons among stimulus types as well as comparisons of the respective source current density estimates. P_{50} was defined as the positive peak in the range of 20-85 ms, preceding N_{100} which was the most negative peak between 60 and 150 ms. P_{200} was defined between 130-220 ms and was usually followed by a positive peak between 230 and 370 ms from tone onset which we called P_{200}' (Figure 1, bottom schematic waveform). Periodic peaks and troughs following P_{200}', corresponding to the 3 Hz and 6 Hz beats, were also defined and measured. Group grand averaged ERPs for each condition determined the latency ranges for peak identification.

ERP peak amplitudes and latencies were subjected to a repeated measures analysis of variance (ANOVA) with Greenhouse-Geisser correction for violation of sphericity and Bonferroni corrections for multiple comparisons. Potentials to binaural beats were analyzed using repeated measures analysis of variance, for the effects of the following factors: Base frequency (250 Hz, 1000 Hz), beat frequency (3 Hz, 6 Hz) and 9 of the Electrodes (F_3, F_z, F_4,

C_3, C_z, C_4, P_3, P_z, P_4) representing left, right and midline locations in the frontal, central, and parietal scalp areas. Probabilities below 0.05, after Greenhouse-Geisser corrections for violations of sphericity (when deemed necessary), were considered significant.

2.6. ERP functional imaging

Standardized Low Resolution Electromagnetic Tomographic Analysis (sLORETA, Pascual-Marqui, 1994; Pascual-Marqui, 2002) was applied on the 21-channel ERP records to image the estimated source current density throughout the duration of the onset-evoked P_{50}-N_{100}-P_{200}-P_{200}' and the subsequent beats-evoked oscillations, in response to the 4 stimulus conditions (2 base frequencies × 2 beat frequencies) and to compare the current density distributions among stimulus conditions.

sLORETA is a functional brain imaging method that estimates the distribution of current density in the brain as suggested by the minimum norm solution. Localization inference is based on standardized values of the current density estimates. The solution space is restricted to cortical gray matter and hippocampus. A total of 6430 voxels at 5mm spatial resolution are registered to the Stereotaxic Atlas of the Human Brain (Talairach and Tournoux, 1988). In this study, differences in current density distributions between the onset response and the beats-evoked oscillations, across stimulus conditions, were assessed using Statistical non-Parametric Mapping (SnPM). The SnPM method estimates the probability distribution by using a randomization procedure, corrects for multiple comparisons and has the highest possible statistical power (Nichols and Holmes, 2002). The SnPM method in the context of ERP source estimation was validated in our previous studies by comparing its results with more conventional ANOVA results (Laufer and Pratt, 2003a; Sinai and Pratt, 2003). Specifically, in this study we used the 'pseudo-t' statistic which reduced noise in the data by averaging over adjacent voxels (Nichols and Holmes, 2002). In order to compare source current distributions between onset-evoked components and beats-evoked components we compared them across 45 ms (11 time frames) from 5 time frames before- until 5 after the peaks of the compared components. Of the repetitive beats-evoked peaks in the recording, the peak used for comparison with the onset components was the one with the source distribution closest to the grand-averaged source distribution of the beats-evoked potentials. Differences were considered significant if the results were significant either using 11 time frames from each comparison or using the average current density values across the 11 time frames.

Average current density values from the most active regions in the brain during the beats-evoked oscillations were analyzed using repeated measures analysis of variance, for the effects of the following factors: stimulus condition (2 base frequencies × 2 beat frequencies), brain region (BA 11, 20, 21, 37 and 38) and hemisphere (left and right). Probabilities below 0.05, after Greenhouse-Geisser corrections for violations of sphericity (when deemed necessary), were considered significant.

2.7. ERP spectral analysis

In addition to time-domain peak measures, the frequency content of the waveform following P_{200}' and preceding the offset response at the end of the waveform (Fig. 1 bottom), with a total duration of about 1400 ms (4 periods of 3 Hz oscillations, 8 periods of 6 Hz oscillations) was

determined and the spectral peaks defined and measured. Spectral content was quantified in arbitrary relative units and analyzed similarly to the time domain waveform peaks.

3. Results

All subjects reported perceiving beats in all four stimulus conditions (3 and 6 Hz beats in 250 and 1000 Hz base frequencies). The beats were described as faint to comfortable and as emanating from the center of the head. At onset, the binaural tones evoked components beginning with a P_{50}, N_{100} and P_{200}, followed by a positive peak labeled P_{200}' and a negativity termed N_0, followed by repetetive negative/positive oscillations corresponding to the frequency difference between left and right ear. We identify these oscillations at the positive peaks as P_1, P_2, P_3, etc. An offset complex of P_{50}, N_{100} and P_{200} occurred at the end of the stimuli (Figures 2 and 3). Descriptive statistics of the latencies and amplitudes of the peaks evoked by the four stimulus conditions are listed in Table 1. The interpeak latency differences between the oscillatory peaks following the onset response are listed in Table 2. Note that these latency differences correspond to the period of the respective beat frequency: approximately 330 ms for the 3Hz beats and about 165 ms for the 6 Hz beats. Also note that N_0 preceded P_1 by approximately half a period of the respective beat frequency and was therefore considered the initial negative peak of the beat oscillations.

The oscillations following the onset response were not the result of interaction of the disparate frequencies of the stimulus artifacts from the left- and right-earphones. This was determined in 5 subjects by comparing the potentials recorded with normal conditions and with the ears occluded. When ears were occluded sound intensity arriving at the ears was reduced by approximately 30-35 dB, while the electrical signal to the earphones was unaffected. With ears occluded the onset-evoked potentials as well as the beats-evoked oscillations were reduced in amplitude in contrast to artifactual beats that would not have been affected by the occlusion of ears.

3.1. Evoked potentials to sound onset

Tone onset-evoked components were larger and earlier to 1000 Hz than to 250 Hz base frequency and were occasionally marginally affected by beat frequency, as detailed below.

3.1.1. Waveform analysis—P_{50}, N_{100}, P_{200} and P_{200}' latencies to tone onset were significantly affected by the tones' base frequency [$F(1,16) = 104.62$; $p<0.001$ for P_{50}, $F(1,16) = 135.81$; $p<0.001$ for N_{100}, $F(1,16) = 287.32$; $p<0.001$ for P_{200} and $F(1,16)= 11.14$, $p<0.001$ for P_{200}'] with consistently longer latencies (by 10-20 ms, on average) with the 250 Hz base frequency. The effects of beat frequency on the latency of these components was marginal (4-8 ms - 1 or 2 dwell-times) albeit, at times statistically significant. P_{50}, N_{100}, P_{200} and P_{200}' amplitudes were significantly affected by base frequency [$F(1,16)= 7.82$, $p<0.006$ for P_{50}, $F(1,16)= 109.04$, $p<0.001$ for N_{100}, $F(1,16) =30.64$ $P<0.001$ for P_{200} and $F(1,16) =6.97$ $P<0.009$ for P_{200}'], with larger amplitudes to 250 Hz than to 1000 Hz base frequency. P_{50}, N_{100}, P_{200} amplitudes were also affected by beat frequency but in an inconsistent manner [$F(1,16)= 8.67$, $p<0.004$ for P_{50} (3 Hz>6 Hz), $F(1,16)= 5.82$, $p<0.02$ for N_{100} (6 Hz > 3 Hz) and $F(1,16) =17.40$ $P<0.001$ for P_{200} (6 Hz > 3 Hz)]. The amplitude of P_{200}' was unaffected by beat frequency. Significant electrode effects indicated largest P_{50} amplitudes frontally and smallest posteriorly [$F(8,128)=40.47$, $p<0.001$], lower N_{100} amplitudes at central scalp locations [$F(8,128)=15.06$, $p<0.001$] and larger P_{200} amplitudes at central and midline scalp locations [$F(8,128)=39.62$, $p<0.001$]. P_{200}' amplitude was not significantly affected by electrode location.

3.1.2. Source current density estimates—Source current density estimates for P_{50} were mostly localized to left lateral posterior and right anterior temporal lobe areas, with parietal

contributions as well, while N_{100} and P_{200} sources were estimated to bilateral inferior and lateral-posterior temporal lobe areas (BA 20, 21, 37), with somewhat lower current densities in the right hemisphere (Figure 4). P_{200}' activity was estimated to originate in bilateral parietal regions and right temporal lobe.

3.2. Evoked potentials to binaural beats

Binaural beats were associated with oscillatory brain activity at the beat frequency that was larger to the low- than to the high base frequency. For both high and low base frequencies 3 Hz beats evoked larger oscillations than 6 Hz beats. The oscillations did not have a clear scalp prominence and their sources were located to the left temporal lobe with a minor frontal contribution across all stimulus conditions, as detailed below.

3.2.1. Waveform analysis—P_1, P_2, P_3, and P_4 were the initial 4 positive peaks of the beat oscillations. Their latencies were not affected by base frequency nor by electrodes. Their amplitudes were all affected by beat frequency [$F(1,16)= 182.83$, $p<0.0001$ for P_1, $F(1,16)= 36.89$, $p<0.001$ for P_2, $F(1,16)= 38.21$, $p<0.001$ for P_3 and $F(1,16)=12.00$, $p<0.001$ for P_4] with larger amplitudes to 3 Hz beats than to 6 Hz beats. P_2 and P_3 amplitudes were also affected by significant base frequency effects [$F(1,16)= 10.32$, $p<0.002$ for P_2 and $F(1,16) =29.00$ $P<0.001$ for P_3] with larger amplitudes with a base frequency of 250Hz. The effects of base frequency and beat frequency interacted in their effects on P_3 [$F(1,16)=4.03$, $p<0.05$] with the larger amplitudes to 3 Hz beats more evident at the 1000 Hz base frequency. P_2, P_3 and P_4 amplitudes were also affected by a significant electrode effect [$F(8,128)= 5.58$, $p<0.001$ for P_2, $F(8,128) =3.89$, $p<0.001$ for P_3 and $F(8,128)= 6.17$, $p<0.001$ for P_4] with no obvious pattern except a tendency toward lower P_4 amplitudes in posterior scalp electrodes.

3.2.2. Source current density estimates—Source current density distribution of the oscillatory beat potentials were practically identical when estimated from scalp-recorded waveform peaks (e.g., peak P3, Figure 5, bottom) or from spectral peaks at the beat frequency (e.g., 3 Hz peak, Figure 5, top). In both cases activity peaked in the left lateral and inferior temporal lobe (in the general locations of BA 20, 21 and 38), in the temporo-parietal area (around BA 37) and to a lesser degree (pink areas in Figure 5) frontally (approximatey BA 11).

Analysis of variance indicated a significant effect of stimulus condition on source current density [$F(3,51)=4.13$, $p<0.007$] with higher values associated with low base frequency and low beat frequency. Brain region was also found to significantly [$F(4,68)=18.57$, $p<0.001$] affect source current density with lower values around BA 11 than in the vicinities of BA 20, 21, 37 and 38. Source activation was significantly [$F(1,17)=37.97$, $p<0.001$] affected by hemisphere and was larger in the left hemisphere regions than in their right hemisphere counterparts. A significant brain region × hemisphere interaction [$F(4,68)=3.55$, $p<0.008$] showed more pronounced differences among regions in the left hemisphere.

When analysis of variance procedures were applied to each brain region separately, for the effects of base frequency, beat frequency and hemisphere, significant effects of hemisphere were found on BA 20 [$F(1,17)=11.09$, $p<0.002$], BA 21 [$F(1,17)=13.76$, $p<0.001$], and BA 37 [$F(1,17)=10.26$, $p<0.002$], all showing more activation in the left hemisphere. BA 11 was not lateralized but showed a significant [$F(1,17)=17.21$, $p<0.001$] effect of beat frequency, with more activation with 3 Hz beats.

Figure 6 shows the time courses of activation in key brain areas in the left and right hemispheres, estimated to be involved in the potentials to stimulus onset (left) and the first three 3 Hz beats (right). Note the different amplitude calibrations because of the larger magnitude of onset-evoked activity. The intracranial activity peaked approximately at the time of the scalp recorded

peaks and troughs. Also note the lateralization to the left of beats-evoked activity in temporal areas, and the less lateralized activity in frontal areas and of the onset-evoked components.

SnPM comparison of the source current distributions of the beats-evoked oscillations at 3 Hz and 6 Hz did not differ significantly. Similarly, when source distributions were compared between high- and low base frequency, no significant distribution differences were noted.

3.3. Comparisons between onset- and binaural beat potentials

Components to stimulus onset were, in general, unaffected by changes in base frequency and beat frequency, whereas beat oscillations were markedly affected by stimulus conditions. In addition, although beat oscillations and the onset response N_{100} and P_{200} involved similar cortical areas, their hemispheric laterality and other source distribution differences were noted, as detailed below.

3.3.1. Waveform analysis—P_{50}, N_{100} and P_{200} to tone onset were similar to previously reported onset-evoked potentials. As detailed above, the onset-evoked potentials latencies were somewhat affected by base frequency, reflecting the tone onset envelope, and their amplitudes were practically unaffected across stimulus conditions. In contrast, the beat oscillations were markedly affected by base frequency and by beat frequency.

3.3.2. Source current density estimates—Onset-evoked P_{50} had superior parietal source activation that was absent in the beat oscillations and the temporal distribution of its sources (left lateral posterior and right anterior) was also different than that of the beat oscillations in the left lateral and inferior temporal lobe and the temporo-parietal area.

Statistical non-parametric t-value mapping of current density differences between onset-evoked N_{100} and beat oscillations of 3 Hz with a base frequency of 250 Hz found statistically significant differences during the 45 ms around the respective peaks, with temporo-parietal area (vicinity of BA 40) significantly more active in N_{100} than in beats-evoked peaks. A similar comparison of P_{200} indicated frontal areas (the vicinity of BA 11) significantly more active in P_{200} than in the beats-evoked oscillations. When these comparisons were conducted with beat oscillations of 6 Hz and base frequency of 250 Hz, N_{100} was found to be associated with significantly more frontal activity than the beats-evoked oscillations.

3.4. Summary of results

Overall, all stimulus conditions (3- and 6 Hz beats with 250- and 1000 Hz base frequencies) evoked tone onset and offset components P_{50}, N_{100} and P_{200}, straddling oscillations corresponding to the beat frequency. Beats-evoked oscillations were higher in amplitude with the 250 Hz compared to the 1000 Hz base frequency and to 3 compared to 6 Hz beat frequency. Sources of the beats-evoked oscillations were located mostly in the vicinity of the left lateral and inferior temporal lobe in all stimulus conditions. Onset components were not markedly different across stimulus conditions. P_{50} had significantly different sources than the beats-evoked oscillations, with more parietal activation; N_{100} and P_{200} sources located to the same temporal lobe regions as the oscillations, but with a more bilateral distribution and significantly larger activation of frontal and temporo-parietal areas.

4. Discussion

4.1. The results of this study

In this study brain potentials associated with the auditory illusion of binaural beats were recorded and compared across 2 beat frequencies with tone bursts of 2 base frequencies. Beat-evoked oscillations were preceded by tone-onset components P_{50}, N_{100} and P_{200}, and were

followed by tone-offset components. Sources of the beats-evoked oscillations across all stimulus conditions were mostly in the left lateral and inferior temporal lobe. This lateralized temporal activity is in line with other studies demonstrating the role of the left temporal lobe in processing binaural temporal auditory cues as in speech processing.

Beats-evoked oscillations were different than the onset-evoked responses in a number of aspects. Oscillations were higher in amplitude when beat frequency was lower (3 Hz vs 6 Hz) and with the low base frequency (250 Hz vs 1000 Hz). In comparison, onset-evoked components were similar across all stimulus conditions; P_{50} had significantly different sources than the beats-evoked oscillations; and N_{100} and P_{200} sources were located to the same temporal lobe regions as beats-evoked oscillations, but were bilateral and included frontal and parietal contributions.

The beats-evoked oscillations were not generated by interference of stimulus artifacts from the right and left earphones: When ears were occluded in 5 of the subjects, the onset-evoked potentials as well as the beats-evoked oscillations were significantly reduced, confirming that they depended on acoustic input to the ears as opposed to an artifact of interference of electrical signals from the right and left earphones. Moreover, the source estimation results indicated temporal activity which was consistently lateralized to the left, as opposed to a symmetrical and close to midline stimulus artifact from bilateral earphones.

Binaural beats are the perception of rapid acoustic changes in perceived intensity without such changes in the physical intensity or spectral content of the sound. The lateralization of beat-evoked oscillations to the left temporal lobe are therefore in line with behavioral, positron emission tomography evidence and clinical findings on specialization of the left-hemisphere auditory cortex for rapid acoustic changes and temporal processing (Johnsrude et al., 1997; Zatorre and Belin, 2001), distinct from the spectral processing specialization of the right temporal lobe (Zatorre, 1988; Zatorre and Belin, 2001). Moreover, the localization of activity to left hemisphere is compatible with the report that binaural beats could not be perceived by patients with cortical lesions associated with severe aphasia (Barr et al., 1977).

The electrophysiological correlates of binaural beats in this study are in line with suggestions that neural activity with slightly different volley frequencies from left and right ear converge and interfere in the central auditory pathway to generate beats of neural activity, giving rise to the illusion of amplitude modulation (Moore, 1997). The temporal pattern of firing of some auditory units (particularly those encoding low frequencies) follows the stimulus waveform in a 'phase locked' manner up to frequencies of about 4-5 kHz in auditory nerve (Rose et al., 1968; Palmer and Russell, 1986) and antero-ventral cochlear nucleus (Goldberg and Brownell, 1973) of experimental animals. In addition, binaurally-activated phase-sensitive neurons are found in the Superior Olivary Complex and Inferior Colliculus (Kuwada et al., 1979; McAlpine et al., 1996; McAlpine et al., 1998; Spitzer and Semple, 1998) as well as in auditory cortex (Reale and Brugge, 1990). In humans, measures of the frequency following response that reproduce low frequency tones (Moushegian et al, 1973) as well as psychoacoustic studies (Javel and Mott, 1988) suggest a sharp decline in phase locking in the ascending auditory pathway, beginning at about 1 kHz. This decline mirrors the decline in perception of binaural beats above 1000 Hz.

Binaural beats were demonstrated in field potentials of the superior olive (Wernick and Starr, 1968) sensitive to the phase and amplitude differences of the monaural stimuli. The sum of monaurally generated field potentials were suppressed during binaural stimulation at a rate consistent with the frequency differences between the ears. Estimating the source current density of the scalp-recorded potentials to the beats-evoked oscillations revealed activity that peaked in a number of brain structures approximately at the time of scalp recorded peaks and

troughs (Figure 6). This correspondence indicates that both surface recorded peaks and troughs in the beats-evoked oscillations are associated with increased intracranial activity.

In general, measures of scalp-recorded activity and of intracranial estimated source activity need not necessarily correspond: fields from different intracranial sources summate differently in different scalp locations, depending on distance from each source and the orientation of each source relative to the electrode. The uniform latencies, across electrodes, of the scalp-recorded beats-evoked oscillations and their temporal corrrespondence to the estimated source activity therefore indicate that they reflect a single major intracranial source. Indeed, observing Figures 5 and 6, the intracranial sources are mostly in the vicinity of the left lateral and inferior temporal lobe.

4.2. Comparisons with previous binaural beats studies

The involvement of left temporal and temporo-parietal areas in binaural beats is congruent with earlier observations that binaural beats could not be perceived by patients with cortical lesions associated with severe aphasia (Barr et al., 1977).

In two recent studies brain responses to binaural beats were recorded using the steady-state technique with a beat frequency of 40 Hz. In the first study (Schwarz et al., 2005), a 40Hz binaural beat potential was recorded when the EEG was band passed accordingly and averaged relative to stimulus onset. It was recorded with a low base frequency of 400Hz but became undetectable beyond 3kHz, its amplitude was maximal at fronto-central leads and it displayed a fronto-occipital phase delay of several ms. The phase shift across electrodes suggested more than one origin of the 40Hz oscillations. In our study, no consistent scalp prominence or significant effect of electrode on latency was observed for the beats-evoked oscillations except for a tendency toward lower P_4 amplitudes in posterior scalp electrodes. Consistent with the previous study, amplitudes were higher with low (250 Hz) than with the higher (1000 Hz) base frequency. Thus, the previously reported 40 Hz binaural beats-evoked potential oscillations were similar to our results in terms of the effects of base frequency, similar to some extent in their tendency for lower amplitudes posteriorly, but different from our results in terms of latency differences across the scalp and the distribution of intracranial sources.

More recently, 40 Hz binaural beats of a 500 Hz base frequency were used to evoke steady state magnetic fields which were also compared with the transient-evoked N_{1m} (Draganova et al., 2008). These components were modeled with a single spatiotemporal equivalent current dipoles in each hemisphere, with steady-state sources lateralized to the right hemisphere and more anterior, more inferior, and more medial compared with the N_{1m} sources. In our study, beats-evoked oscillations across all stimulus conditions were lateralized to the left, suggesting involvement of different brain processes in the two studies. On the other hand, in our study frontal (~BA 11) and anterior temporal (~BA 37) activity, in addition to lateral-inferior temporal regions, was estimated to contribute to the difference between the onset- and beats-evoked N_{100} potential. In the previous study 40 Hz beats-evoked fields were more anterior than onset N_{1m}, perhaps because only a single-dipole source model was used, collapsing the additional, more anterior, beats-evoked sources into the single dipole, moving it forward.

The two earlier studies on 40 Hz binaural beats differed in the distribution of their responses. The 40 Hz potentials of the first study (Schwarz et al., 2005) had maxima at fronto-central leads and displayed a fronto-occipital phase delay of several ms. This distribution is similar to onset responses, and the phase shift across the electrode array was interpreted to suggest more than one origin of the oscillations (Schwarz et al., 2005). The second study (Draganova et al., 2008) reported magnetic field sources that were lateralized to the right hemisphere and were more anterior, more inferior, and more medial compared with onset-evoked N_{1m}. These differences between the earlier studies in distribution and sources of their beats-evoked

oscillations may be reconciled by differences in the fields recorded: electric potentials (Schwarz et al., 2005) are affected by the filter properties of tissues, while magnetic fields (Draganova et al., 2008) are not. Thus the relative contributions of different intracranial sources to the scalp-recorded responses were different between these earlier studies.

Another earlier study of magnetic field correlates of low frequency binaural beats (Karino et al., 2006) indicated bilateral temporal sources for the fields, while the present study found the temporal sources lateralized to the left. Moreover, that previous study found that the phase of the beat-evoked oscillations showed great variability, suggesting that the responses were affected by subjective fluctuations. In contrast, in the present study clear averaged oscillations could be recorded, suggesting a stable phase throughout the recording. In the earlier study, symetrical contributions of thalamo-cortical magnetic fields were likely more prominent than in this study in which their higher frequency electric waveforms may have been attenuated by the filter properties of tissues. Moreover, in the previous study subjects watched a silent video during recording, and their level of vigilance may have varied during the recording, resulting in fluctuating contributions of the late cortical potentials and a relative augmentation of thalamo-cortical components. In the present study vigilance was maintained by subjects reading a challenging text on which they were tested, and the potentials were therefore predominantly late cortical oscillations with stable vigilance throughout the recording, resulting in constant phase of the response.

Two of the previous studies on ERP correlates of binaural beats used a beat frequency of 40 Hz which is optimal for recording steady-state potentials (Galambos et al., 1981; Kileny and Shea, 1986) from primary auditory cortex and thalamus (Hashimoto, 1982; Lee et al., 1984; McGee et al., 1992; Zaaroor et al., 2003). In contrast, the beat frequencies of 3 and 6 Hz used in the present study and the 4 and 6.66 Hz used in another study (Karino et al., 2006) augment the contribution of slower cortical activity from secondary and non-specific cortex, overlapping with the smaller middle latency activity from specific auditory cortex. However, the contribution of cortical activity may have been diminished by the unstable phase of the low frequency oscillations in the previous study (Karino et al., 2006). These beat-frequency and phase stability differences may explain the differences in sources across studies. The earlier studies and this study thus complement each other, showing that binaural beats, most probably arising in the brainstem, persist through auditory processing at the thalamic and specific auditory cortex (previous studies) and further involve secondary and non-specific auditory areas (this study).

In summary, the results of this study are in general agreement with previous studies that recorded brain potentials to binaural beats. The differences in findings are attributable to the beat frequency, and hence the cortical structures involved, and to the models used for source estimation.

4.3. Comparison of potentials to stimulus onset with beats-evoked oscillations

Onset- and beats-evoked potentials were clearly different, both in terms of the effects of stimulus conditions on them and in their estimated intracranial sources. Whereas onset-evoked components were barely and inconsistently affected across the stimulus conditions of this study, beats-evoked oscillations were appreciably smaller to the higher frequency beats and with the higher base frequency. Of the onset-evoked components, only the sources of N_{100} and P_{200} located to similar regions as the beats-evoked oscillations. But whereas the beats-evoked oscillations were associated with a left-lateralized temporal activity, the sources of N_{100} to tone onset had a more bilateral temporal distribution and some frontal and temporo-parietal contributions.

Overall these differences and similarities show that the beats-evoked oscillations involve the same temporal lobe structures activated during the onset-evoked vertex potential, but with a left hemisphere prominence. The difference in lateralizations mirrors the different processes involved in beats-evoked and in the onset-evoked N_{100}. These findings are in line with previous evidence that the time period of N_{100} involves a variety of distinct processes that have all been estimated to arise in auditory cortex (Vaughan and Ritter, 1970; Scherg and von Cramon, 1985, 1986; Scherg and Picton, 1991; Ponton et al., 2002; Laufer and Pratt, 2003b, 2005) as well as lateral temporal lobe with some activity possibly originating in the anteror cingulate cortex or supplementary motor areas of the prefrontal cortex (Picton et al., 1999).

In general, the temporal lobe and frontal N_{100} has been suggested to reflect the detection of acoustic change in the environment (Hyde, 1997). Change can be effected by the transient onset and offset responses (Michaelewski et al., 2005; Pratt et al., 2005, 2007); by the M-process in response to deviation ('Mismatch') from the preceding sequence of auditory events (Jones et al, 1998, Vaz Pato and Jones, 1999); the C-process in response to acoustic 'Change' within an ongoing stream (Martin and Boothroyd, 2000, Jones, 2003, Jones and Perez, 2001); and the F-process associated with 'Fusion' of acoustic elements to form a new auditory object (Laufer and Pratt, 2003b, 2005). The evoked activity to binaural beats is yet another type of change processing taking place at this latency in the same general areas. However, unlike the other constituents, this activity is associated with an auditory illusion and not a physical acoustic change.

4.4. Conclusions

The results of this study confirm that brain activity corresponding to an auditory illusion can be recorded from the scalp. The oscillations associated with binaural beats were larger to low- than to high frequency sound, congruent with the involvement in this illusion of 'volley principle' neural encoding. The results are in line with the suggested mechanism of binaural beats: neural volleys with slightly different frequencies from left and right ear converge and interfere in the central auditory pathway to generate beats of neural activity. The beats of neural activity recorded in this study originated in the same temporal lobe regions as onset responses, but were lateralized to the left hemisphere. Thus, potentials recorded to binaural beats involve the same brain structures, but are distinct from onset responses.

Acknowledgements

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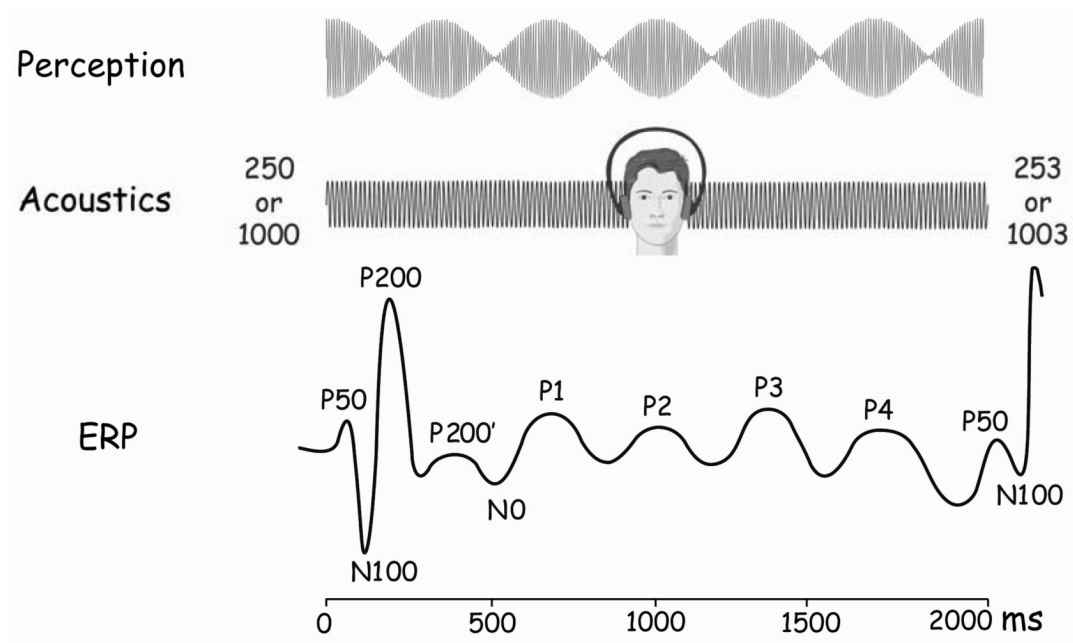
Fig. 1.
Time courses of the stimuli that evoked 3 Hz binaural beats (top) and the ERP waveforms evoked by them (bottom). Stimuli consisted of tone bursts with frequencies of 250 Hz or 1000 Hz presented to one ear, and frequencies 3 Hz higher to the other. Similarly, 6 Hz beats were evoked by 250 and 256 Hz or 1000 and 1006 Hz tones. Brain potentials were recorded in response to the binaural stimuli and the onset, beat and offset evoked components are indicated on the waveform.
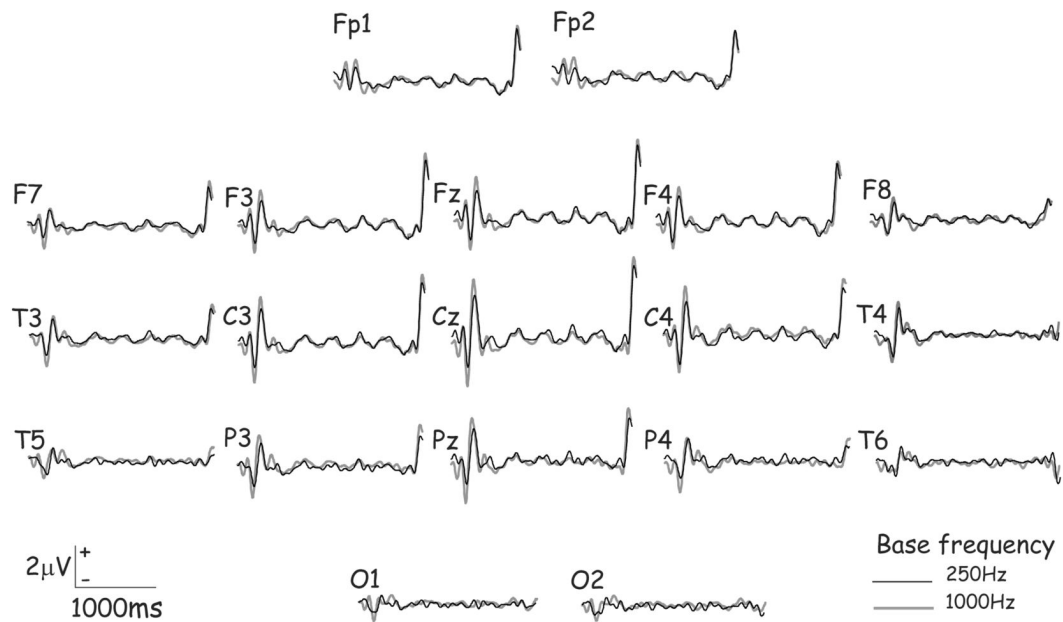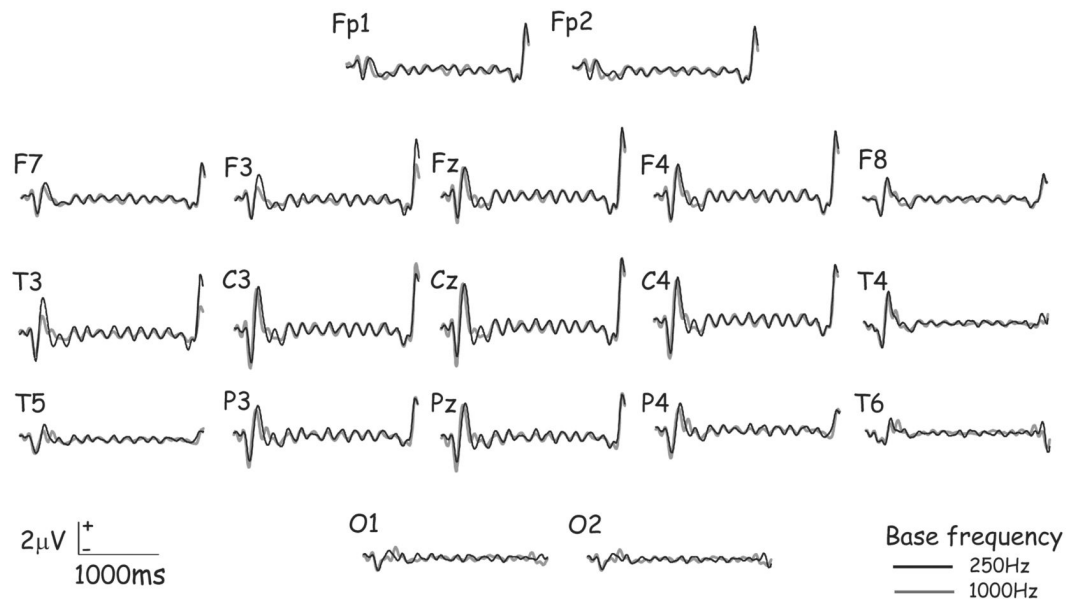
Fig. 2.
Scalp distribution of the potentials to tone onsets and the 3 Hz binaural beats with the low (250Hz) and high (1000 Hz) base frequencies. Grand average across 18 subjects. The plots include a baseline of 100 ms before tone onset and the initial components of the offset responses.

Fig. 3.
Scalp distribution of the potentials to tone onsets and the 6 Hz binaural beats with the low (250Hz) and high (1000 Hz) base frequencies. Grand average across 18 subjects. The plots include a baseline of 100 ms before tone onset and the initial components of the offset responses.
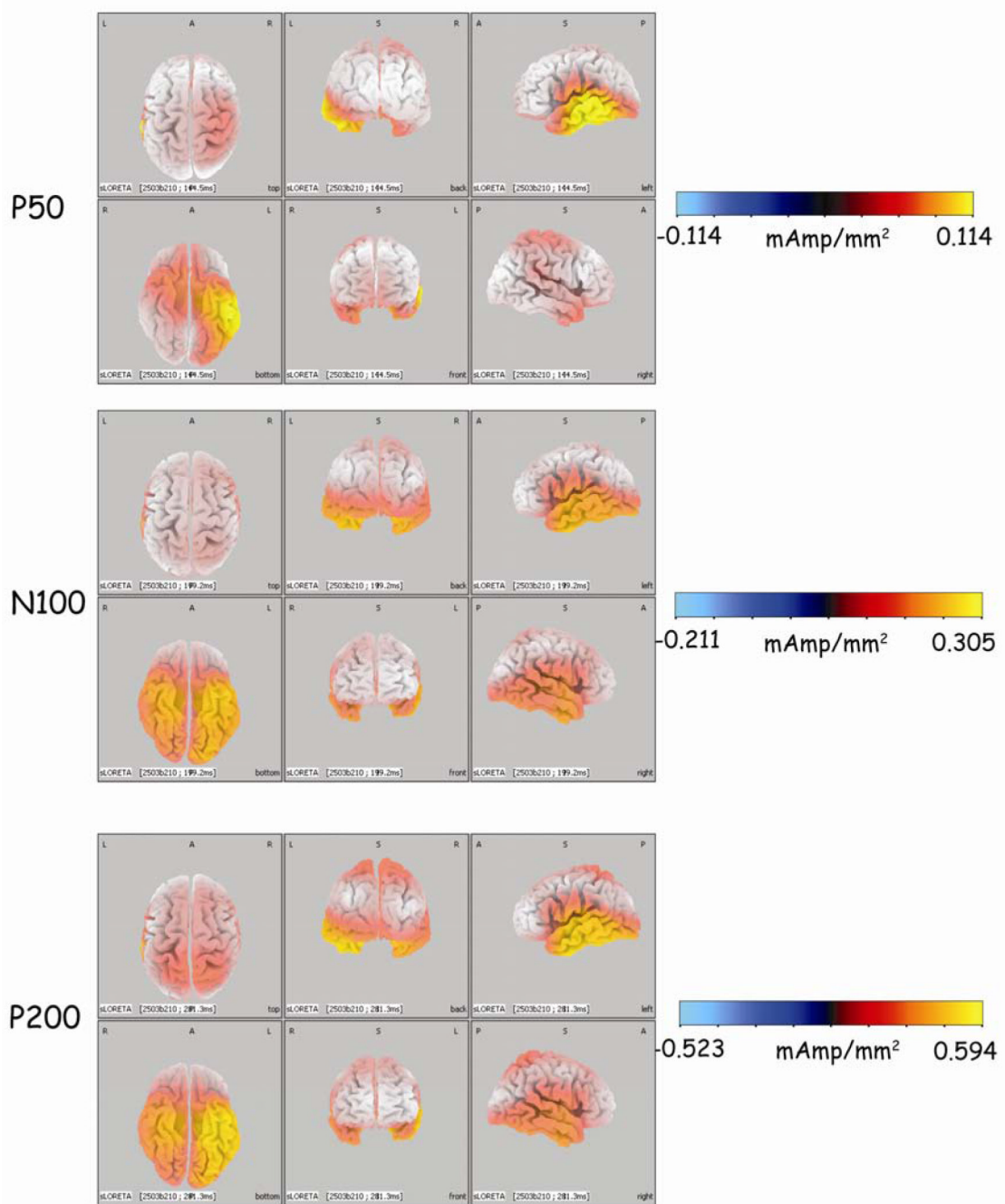
Fig. 4.
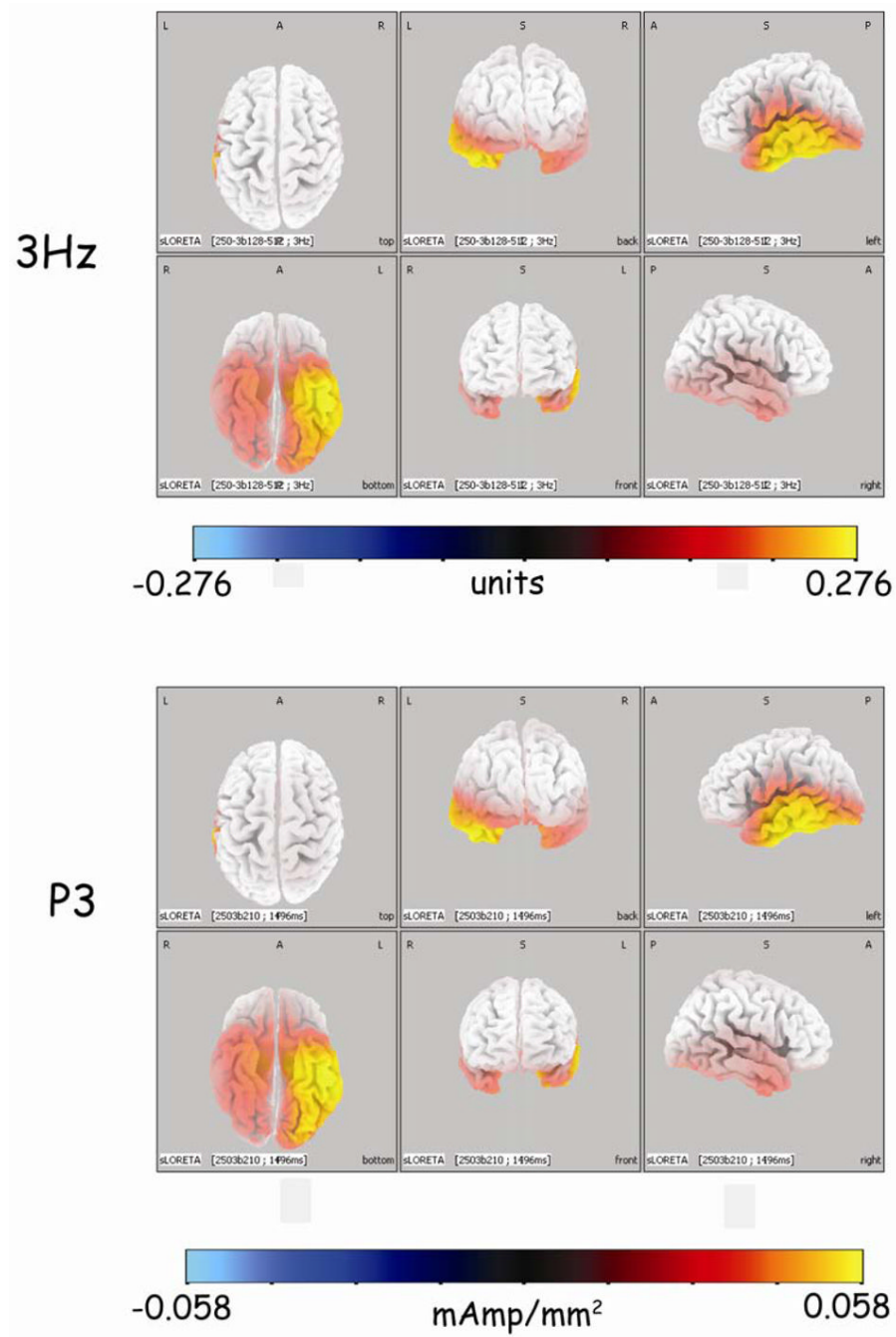Average source current density estimates associated with P_{50}, N_{100} and P_{200} to stimulus onset in the 250 Hz base frequency and 3 Hz beat condition. Six views of the brain are presented for each component, as indicated on each view.

Fig. 5.
Average source strength estimates associated with the spectral peak at 3 Hz (top) and with the 3 Hz beats-evoked oscillation peak P_3 with 250 Hz base frequency (bottom). For the spectral peak, strength is given in arbitrary relative units, while for peak P_3, strength is given in current density. Six views of the brain are presented for each display, as indicated on each view.
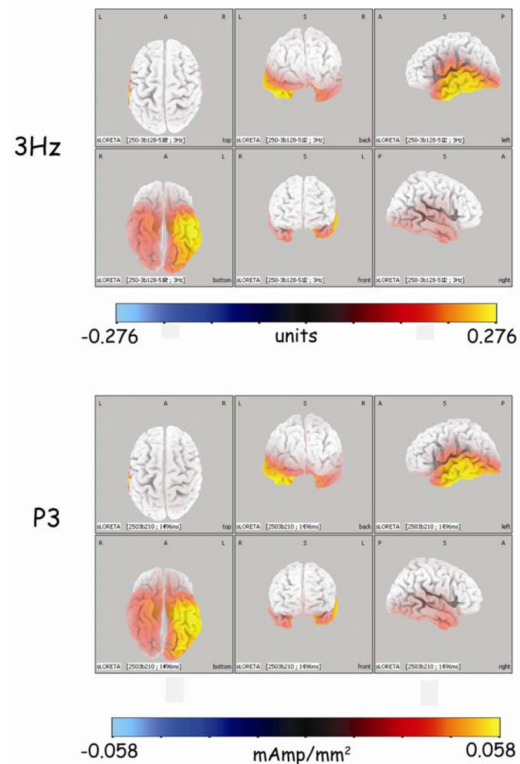
Fig. 6.
Time courses of average current density values in the left and right hemisphere regions that were most involved with 3 Hz binaural beats: Lateral temporal areas (BA 20, 21, 37) anterior-temporal lobe (BA 38) and frontal region (BA11) with the 250 Hz base frequency. The grand-averaged waveform recorded at C_z, including components P_{50}, N_{100}, P_{200}, P_{200}', N_0, P_1, P_2 and P_3 peaks are plotted at the top. Note the correspondence of current density peaks to the scalp-recorded positive and negative peaks. Time 0 corresponds to stimulus onset.

Table 1

Averages and standard deviations of latencies and amplitudes of components to onsets of tones and the first four binaural beat peaks. Latencies are listed in ms, amplitudes in μV. Avg represents average, SD stands for Standard Deviation, Base is for the base frequency and Beats denotes the beat frequency.

	Beats	Base	P50	N100	P200	P200'	N0	P1	P2	P3	P4
Latency (ms)											
Avg	3	250	45	103	176	344	465	693	1034	1364	1680
SD			14.4	19.5	19.4	63.7	73.1	80.5	106.1	147.8	196.7
Avg	3	1000	39	95	166	324	426	678	1022	1354	1654
SD			10.3	12.2	17.4	49.7	50.8	62.5	101.3	144.4	187.4
Avg	6	250	45	107	188	287	362	451	617	786	954
SD			16.4	20.8	21.2	58.0	74.4	72.0	75	84.2	75.6
Avg	6	1000	37	95	170	287	368	473	641	799	964
SD			10.4	13.9	17.0	31.6	45.0	70.7	85	86.4	83.7
Amplitude (μV)											
Avg	3	250	1.09	1.84	2.72	0.60	-1.19	0.88	0.83	0.88	0.73
SD			0.88	1.39	1.46	0.71	0.66	0.43	0.31	0.31	0.35
Avg	3	1000	1.16	2.63	3.64	0.76	-1.25	0.89	0.85	0.66	0.80
SD			0.76	1.66	1.38	0.85	0.50	0.32	0.32	0.26	0.36
Avg	6	250	0.86	2.06	3.47	0.77	-1.36	0.43	0.76	0.71	0.73
SD			0.71	1.64	1.59	1.18	0.90	0.72	0.41	0.51	0.30

	Beats	Base	P_{50}	N_{100}	P_{200}	P_{200}'	N_0	P_1	P_2	P_3	P_4
Avg	**6**	**1000**	3 0.7	2.84	3.83	0.71	−1.31	0.30	0.63	0.59	0.75
SD	**6**	**1000**	5	1.57	1.45	1.13	0.71	0.54	0.37	0.39	0.42

Table 2

Averages and standard deviations of latency differences (in ms) between consecutive peaks in the beats-evoked waveforms. Avg represents average, SD stands for Standard Deviation, Base is for the base frequency and Beats denotes the beat frequency.

	Beats	Base	P_1-N_0	P_2-P_1	P_3-P_2	P_4-P_3
Avg	3	250	338.29	333.73	314.63	341.54
SD	3	250	65.15	63.42	72.93	77.02
Avg	3	1000	341.11	335.90	298.14	346.31
SD	3	1000	68.46	66.55	76.89	92.41
Avg	6	250	89.14	166.11	169.10	167.72
SD	6	250	24.67	21.93	23.10	31.11
Avg	6	1000	104.31	168.18	157.84	165.88
SD	6	1000	44.81	25.33	28.87	30.16