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Research paper

## Binaural beats increase interhemispheric alpha-band coherence between auditory cortices

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## ABSTRACT

Binaural beats (BBs) are an auditory illusion occurring when two tones of slightly different frequency are presented separately to each ear. BBs have been suggested to alter physiological and cognitive processes through synchronization of the brain hemispheres. To test this, we recorded electroencephalograms (EEG) at rest and while participants listened to BBs or a monaural control condition during which both tones were presented to both ears. We calculated for each condition the interhemispheric coherence, which expressed the synchrony between neural oscillations of both hemispheres. Compared to monaural beats and resting state, BBs enhanced interhemispheric coherence between the auditory cortices. Beat frequencies in the alpha (10 Hz) and theta (4 Hz) frequency range both increased interhemispheric coherence selectively at alpha frequencies. In a second experiment, we evaluated whether this coherence increase has a behavioral aftereffect on binaural listening. No effects were observed in a dichotic digit task performed immediately after BBs presentation. Our results suggest that BBs enhance alpha-band oscillation synchrony between the auditory cortices during auditory stimulation. This effect seems to reflect binaural integration rather than entrainment.

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## 1. Introduction

Human brain function crucially depends on interregional neural communication (Varela et al., 2001). Such interactions are thought to be accompanied by a synchronization of oscillations between different brain regions (Aertsen et al., 1989; Gray and Singer, 1989; Engel et al., 1992; Fries, 2005). Interregional synchronization can be quantified with the concept of functional connectivity (FC), which is a measure of the statistical dependency between activities in different brain regions. Interestingly, FC has been shown to linearly correlate with behavioral performance in a variety of cognitive and motor functions. In other words, the more synchronous neural oscillations are between nodes of a given network, the better is the behavioral performance in tasks relying on that network (Hummel and Gerloff, 2005; Fox et al., 2007; Guggisberg et al., 2015). Therefore, interventions leading to modulation of FC should have beneficial behavioral effects and could lead to new applications and therapies.

One intervention that has been suggested to provide such

modulation of neural oscillation synchrony is the binaural presentation of tones with slightly different frequencies (Atwater, 2004). If two sinusoidal tones with slightly different frequencies are played simultaneously, one perceives a tone with their average frequency plus a so-called beat, i.e., a modulation of the amplitude at a rate equal to the difference between them. For instance, a tone of 395 Hz presented together with a tone of 405 Hz will produce a perceived frequency of 400 Hz, which modulates in amplitude with a frequency of 10 Hz (Moore, 2012). If the two tones are presented separately to each ear, a similar beat is perceived by the subject although no such physical sound exists (Oster, 1973). This auditory illusion is known as BBs and has been interpreted as arising from the convergence of phase preserved neural activity from the two ears in binaurally sensitive neurons within the medial superior olivary nucleus (Wernick and Starr, 1968; Kuwada et al., 1979).

A common assumption of binaural beats is that they can elicit an entrainment effect of neural oscillation at their proper frequency (Vernon, 2009). Many electrophysiological studies have explored the effect of BBs on oscillatory amplitude with contradictory results. Some authors have reported increases in amplitude following exposure to binaural beats compared to resting state (Karino et al., 2004; Schwarz and Taylor, 2005; Karino et al., 2006; Draganova et al., 2008; Pratt et al., 2009; Pratt et al., 2010; Grose and Mamo,

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2012) whilst others have failed to find evidence of such a change (Wahbeh et al., 2007; Goodin et al., 2012; Vernon et al., 2014). In any case, it seems that if BBs increase power, it is to a smaller extent than the modulation occurring under the corresponding monaural beat (MB) condition (Schwarz and Taylor, 2005; Draganova et al., 2008; Pratt et al., 2010).

It has further been argued that BBs enhance the synchrony of neural activity between the two brain hemispheres (Atwater, 1997, 2004). Recently, two studies have tested the effect of BBs on FC. Gao and colleagues quantified frequency-specific synchronization between pairs of scalp electrodes (Gao et al., 2014). They detected both increases and decreases in FC during BB stimulation compared to a resting state without stimulation, depending on oscillation frequency and electrode location. In another study, Becher and colleagues (2014) measured phase synchronization between channel pairs using intracranial signals mainly in the temporo-lateral and temporo-basal area. Synchronization increases were essentially found for stimulation with monaural 10-Hz beats at medio-temporal sites and for stimulation with binaural 5-Hz beats at temporo-lateral sites.

These two recent studies suggest that BBs could modulate oscillation synchrony. However, it remains unclear whether these changes occur in the beat frequency, which brain structures are concerned, and if they are associated with behavioral changes.

This last point is of particular interest because BBs have been praised for supposedly beneficial behavioral effects, such as relaxation, pain reduction, and other mental states (Wilson, 1990; Rhodes, 1993). Several studies have demonstrated behavioral changes following BBs such as improvement of vigilance (Lane et al., 1998), increase in hypnotic susceptibility (Brady and Stevens, 2000), reduction of self-reported anxiety (Le Scouarnec et al., 2001; Padmanabhan et al., 2005), or increase in some forms of creativity (Reedijk et al., 2013), although their robustness remains to be demonstrated. Given the assumed positive effect of BBs on synchronization between hemispheres, it would be particularly interesting to test whether such improved interhemispheric integration can be measured on the behavioral level. However, no study has probed the effect of BBs on tasks specifically requiring the collaboration between cerebral hemispheres in general or between both auditory cortices in particular.

The purpose of this study was therefore to directly test the hypothesis that BBs synchronize activity between hemispheres both at the neural and at the behavioral level. Experiment 1 examined the effect of BBs on interhemispheric oscillation synchrony in the auditory cortex using high-density scalp EEG and advanced source localization. Experiment 2 probed behavioral effects in a task requiring binaural listening. A dichotic listening task was used to assess the ability of participants to discriminate numbers presented simultaneously to different ears. This task has been validated for behavioral assessment of information exchange between the hemispheres across the corpus callosum (Musiek, 1983; Bellis and Wilber, 2001; Westerhausen and Hugdahl, 2008). We therefore used it to examine whether BBs improve the ability to exchange information between the auditory cortices even after stimulation.

## 2. Materials and methods

The University Hospital of Geneva Ethics Committee approved all procedures and all subjects gave informed written consent for their participation to the study.

### 2.1. Experiment 1

#### 2.1.1. Data acquisition

Sinusoidal tones of 395 Hz and 405 Hz (producing a beat of

10 Hz), as well as 398 Hz and 402 Hz (producing a beat of 4 Hz) were created using Matlab<sup>®</sup> (The MathWorks Inc., Natick, USA). These pairs of tones were presented with stereo headphones in two different conditions. In the monaural beat (MB) condition, which was used as control, both tones were played to both ears (i.e. the beat is a purely physical phenomenon perceived by each ear). In the binaural beat condition, which was of interest here, each tone was played to separate ears (i.e. the beat is created by binaural integration and doesn't exist at the single ear level). Sound intensity was determined for each subject to be comfortably loud and kept constant between conditions.

Nine normal-hearing subjects (6 females, mean age of 28 years ranging from 25 to 34 years old) were asked to listen to 10 Hz BBs and 10 Hz MBs. Five participants were also exposed to 4 Hz BBs and the corresponding MBs. Each sound was presented continuously for 4 min in a counterbalanced order while a continuous EEG was recorded at a sampling rate of 1024 Hz using a 128-channel Biosemi Active Two EEG system (Biosemi B.V., Amsterdam, Netherlands). The participants were asked to listen to the sound. A resting state condition was also recorded before any auditory stimulation. All conditions were recorded with the eyes closed. Vigilance was checked by monitoring the EEG signal for signs of drowsiness or sleep and by asking the subjects whether they had fallen asleep after each condition. Artifacts like eye movements, muscular contractions and electrode artifacts were excluded by visual inspection. About 3 min of clean data were retained for each condition and each subject. Channels containing artifacts over prolonged periods were completely excluded from further analyses.

#### 2.1.2. Analysis

Analyses were performed in Matlab with NUTMEG (<http://nutmeg.berkeley.edu>) (Dalal et al., 2011) and its functional connectivity maps (FCM) toolbox (Guggisberg et al., 2011).

We divided the 3 min artifact-free data into non-overlapping segments of 1s duration. Recordings were bandpass filtered between 1 and 20 Hz. A spherical model with anatomical constraints (SMAC) (Spinelli et al., 2000) was created from the individual coregistered magnetic resonance image of the head and used to compute the lead potential. The signal was then projected to grey matter voxels with an adaptive spatial filter (scalar minimum variance beamformer) (Sekihara et al., 2004).

The Heschl Gyrus was defined as region of interest (ROI) using the Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) since we expected changes in the primary auditory cortex during auditory stimulation.

Power spectrogram was computed using Fourier transformation. The difference in power between resting state, MBs and BBs conditions was compared in the Heschl Gyrus and tested against the null-hypothesis of zero change using two-tailed paired *t*-test.

The detailed steps of FC analysis and their validation have been described previously (Guggisberg et al., 2008; Guggisberg et al., 2011). We calculated the imaginary component of coherence (IC) (Nolte et al., 2004) between each voxel and its homologous contralateral region during the entire auditory stimulus, hence resulting in a measure of interhemispheric coherence or interhemispheric oscillation synchrony. We calculated the spectrum of interhemispheric coherence between 1 and 20 Hz in the Heschl Gyrus by averaging across its voxels. Differences between rest, MBs and BBs conditions were specifically tested in alpha and theta band given the auditory stimulation that we used, using a two-tailed paired *t*-test.

Finally, to ensure not to miss coherence changes in other brain areas, we created an interhemispheric FC map of the whole brain in a voxel-wise manner. Differences between rest, MBs and BBs

conditions were tested with statistical non-parametric mapping for the voxel-wise map.

## 2.2. Experiment 2

We created two sets of a dichotic digit task to assess if BBs could increase binaural auditory discriminability. Each set contained 20 trials, composed of numbers ranging from 1 to 12 spoken by a male native French speaker. Four different numbers were simultaneously presented to both ears, two per ear, and the participants were instructed to recognize the four different numbers of each trial. One set of the test was presented before and after having listened to 3 min of 10 Hz BBs (395 Hz and 405 Hz tones) and the other set before and after the corresponding MBs. Sounds and tests were presented in counterbalanced order.

Eighteen healthy subjects participated (10 females, mean age of 26 years ranging from 21 to 32 years old). Performance was quantified by calculating the number of correct answers out of the 80 total heard numbers (20 trials with 4 digits each). Improvement was computed for each condition by subtracting the number of correct answers after the auditory stimulation from the number of correct answers before stimulation. Differences in improvement between BBs and MBs conditions were tested for significance with a two-tailed paired *t*-test. We then confirm null effects using JZS Bayes factor tests with default prior scales (Morey and Rouder, 2011) so that a Bayes factor ( $B$ ) < 0.33 implies substantial evidence for the null hypothesis. Analyses were performed with R (R Development Core Team, 2013) including the Bayes Factor package (Morey and Rouder, 2011).

## 3. Results

### 3.1. Experiment 1

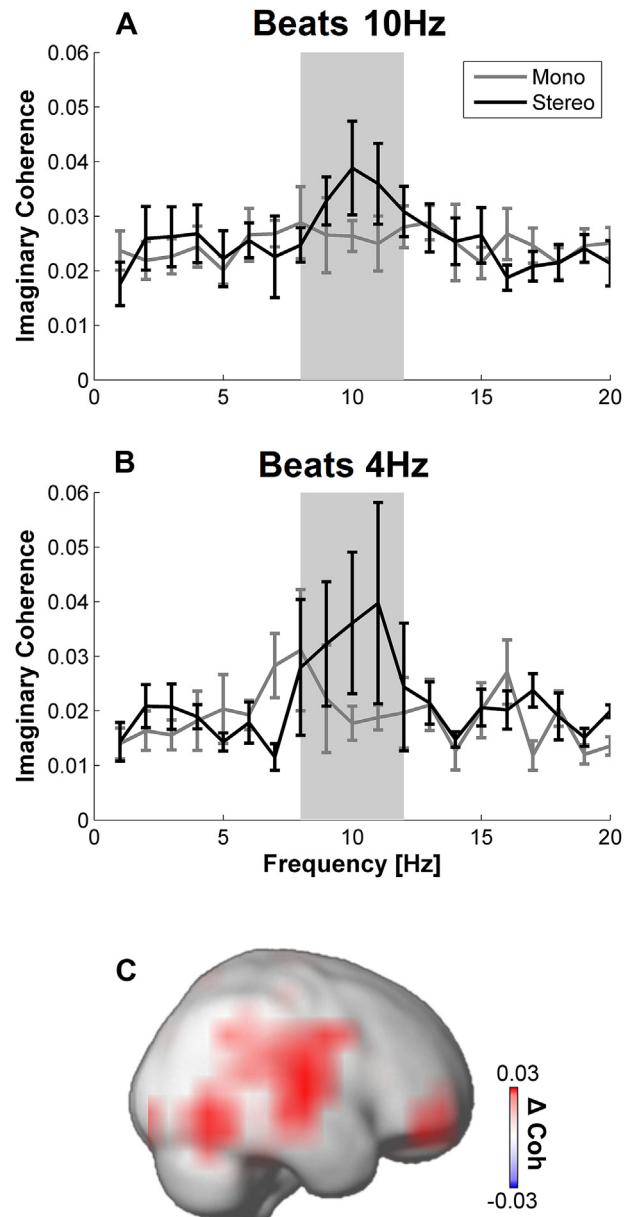
No significant differences were found in oscillation power in the auditory cortices between BBs, MBs and resting state conditions during 4 Hz and 10 Hz beats (minimal voxel value in 9–11 Hz band:  $p > .26$  and  $p > .39$  respectively).

Conversely, interhemispheric coherence between the Heschl gyri was significantly greater in the alpha band (9–11 Hz) during 10 Hz BBs stimulation compared to a 10 Hz MB condition ( $t_8 = 3.24$ ;  $p = .012$ ) (Fig. 1A) and resting state ( $t_8 = 3.83$ ;  $p = .005$ ). A similar coherence spectrogram pattern was found during 4 Hz BBs stimulation compared to 4 Hz MB (Fig. 1A and B), with a significant increase in interhemispheric coherence at 9 Hz ( $t_4 = 3.87$ ;  $p = .018$ ) and no significant difference observed around 4 Hz (minimal  $p$  value found at 3 Hz = 0.17) (Fig. 1B).

A voxel-wise analysis of interhemispheric coherence showed that this increase during the BBs condition was relatively specific to the primary auditory cortex, although changes were also observed in frontal and occipital areas (Fig. 1C).

### 3.2. Experiment 2

We observed an improvement in the dichotic digit test in both conditions (BBs  $t_{17} = 5.55$ ,  $p < .001$ ; MBs  $t_{17} = 2.64$ ,  $p = .02$ ) but no statistically significant difference between conditions ( $t_{17} = 0.268$ ;  $p = .79$ ) (Fig. 2). Bayes factor confirmed the null effect showing that  $H_0$  was around 5 times more likely than the alternative hypothesis ( $B = 0.18$ ). Complementary statistical analysis revealed that the performance achieved before the auditory stimulus (i.e. baseline score) was negatively correlated to the improvement after exposition to BBs ( $r = -0.576$ ;  $p = .01$ ). Conversely no similar correlation was observed with improvement under MBs ( $r = -0.11$ ;  $p = .65$ ).

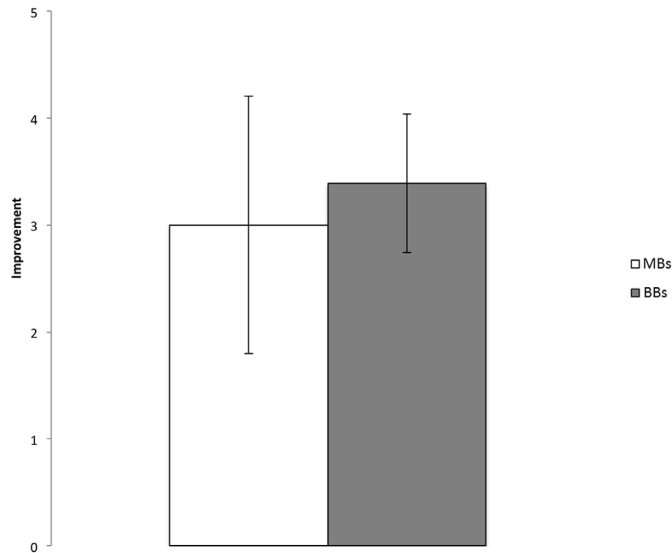


**Fig. 1.** Effect of BBs on interhemispheric coherence. Both (A) 10 Hz BBs and (B) 4 Hz BBs produced a significant increase in interhemispheric coherence in alpha frequencies (9–11 Hz) between the primary auditory cortices compared to MBs. Note the similarity of the patterns of the two graphs. (C) Subtraction of FC map during BBs from the FC map during MBs shows a significant increase in interhemispheric alpha-band coherence in fronto-temporo-parietal areas around the auditory cortex ( $p < .05$  uncorrected).

## 4. Discussion

In this study we found that, compared to MBs and resting state, BBs increased interhemispheric coherence between the auditory cortices. Moreover, both 10 Hz and 4 Hz beats increased coherence selectively in the alpha band. These changes in oscillation synchrony were not associated with changes in amplitude. Despite these electrophysiological findings, no corresponding behavioral effect could be demonstrated after the stimulation.

Our study provides the first evidence for the long suspected increased interhemispheric synchrony under BBs and insights into underlying mechanisms. Our observation is comparable to previous



**Fig. 2.** Behavioral performance in dichotic digit test. Subjects improved after both stimulation conditions, but no statistically significant difference between BBs and MBs was found ( $p = .79$ ).

reports that cognitive tasks can modify alpha-band coherence. For example, increased alpha oscillation synchrony has been reported during object recognition (Mima et al., 2001), spatial attention (Doesburg et al., 2009), error processing (van Driel et al., 2012), mental calculation (Palva et al., 2005) or memory tasks (Haegens et al., 2010). We consider BBs as a challenging listening situation with a binaural perceptual conflict that the auditory system solves by increasing communication between both auditory cortices. This in turn leads to an increase in phase locked synchrony among neurons oscillating in alpha band. Hence, we surmise that the increase in the alpha-band coherence observed here reflects binaural integration.

One might be surprised by the selective effect in alpha frequencies only. Neurons preferably oscillate at certain frequencies that are typically biologically important (Herrmann, 2001). As for several other sensory modalities, alpha oscillations are the predominant frequency in the auditory cortex and can be modulated by auditory stimuli (Hartmann et al., 2012; Strauß et al., 2014). We postulate that the effect of BBs on interhemispheric communication is restricted to the alpha band because it is the main spontaneous oscillation band and is involved in most of the interactions between cortical areas (von Stein et al., 2000).

Conversely, we didn't find an increase in power during 10 Hz and 4 Hz BBs compared to rest or the corresponding MBs. The absence of alpha power modulation during 10 Hz BBs is consistent with previous studies (Goodin et al., 2012; Vernon et al., 2014). Regarding the lack of modulation of theta power during 4 Hz BBs, both similar (Wahbeh et al., 2007) and opposite results (Brady and Stevens, 2000; Karino et al., 2006; Pratt et al., 2010) have been reported in the literature. These studies have different designs in terms of recording device (EEG vs MEG) or exposition time (from 2 s up to 20 min) that could account for these discrepancies. In any case, consistent with our findings, increase in alpha oscillation synchrony has already been reported several times without corresponding modification of oscillation power (Mima et al., 2001; Vanni et al., 1997).

Some authors have hypothesized that EEG changes observed under BBs are elicited through an entertainment effect (Vernon, 2009), but our findings cannot be explained by this mechanism. We found that BB stimulation with 4 Hz beats increases

interhemispheric coherence in non-harmonic alpha frequencies, which is difficult to bring in line with entrainment. Moreover, in our study coherence increased independently of power changes whereas synchronization of neuronal firing to the frequency of the beating stimulus would theoretically lead to an amplitude increase of the corresponding EEG frequency. On the basis of these findings, we assume that the increase in interhemispheric coherence observed here could not be explained by synchronization to the external rhythmic stimulus.

Given the observed electrophysiological effect, we tried to improve binaural auditory discrimination abilities using BBs in healthy subject. However, no significant effect was observed compared to a monaural control condition. One possible explanation for this finding is that our behavioral task was not sufficiently sensitive to reveal an improvement in auditory function. However, dichotic digit tests have been successfully used to assess interhemispheric integration (Musiek, 1983; Bellis and Wilber, 2001; Westerhausen and Hugdahl, 2008). A more likely explanation is that the increase in interhemispheric collaboration was limited to the stimulation period and not associated with a corresponding aftereffect at the time at which we performed our dichotic digit task. It would have been interesting to record EEG not only during, but also after auditory stimulation in order to confirm the lack of aftereffect also on the neural level.

Our study does not exclude that repetitive BBs stimulation over several days would eventually result in measurable aftereffects. However, there is currently no evidence for this possibility. Finally, we found that the less the subjects were able to distinguish binaurally presented numbers at baseline, the more BBs increased their performance. Since no such correlation was found for MBs, we might speculate that BBs could be more beneficial for patients with impairment in interhemispheric interaction. This is consistent with previous observations. For instance, Brady and Steven found that hypnotic susceptibility increased only among low and medium-susceptible subjects (Brady and Stevens, 2000). However, this will need to be confirmed by more robust evidence.

In conclusion, this study demonstrates for the first time a modulation of interhemispheric coherence by BBs. However, a single session of BBs does not seem to result in corresponding behavioral aftereffects of improved interhemispheric communication.

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