Inter-hemispheric and spectral power analyses of binaural beat effects on the brain

Joseph Lefournour, Ramaswamy Palaniappan, Ian V McLoughlin
School of Computing, University of Kent

Correspondence
r.palani@kent.ac.uk

Disciplines
Neuroscience

Keywords
Entrainment
Binaural Beat
Electroencephalography
Brain
Psychological Stress

Type of Observation
Standalone

Type of Link
Standard Data

Submitted Jun 14, 2016
Published Sep 26, 2016

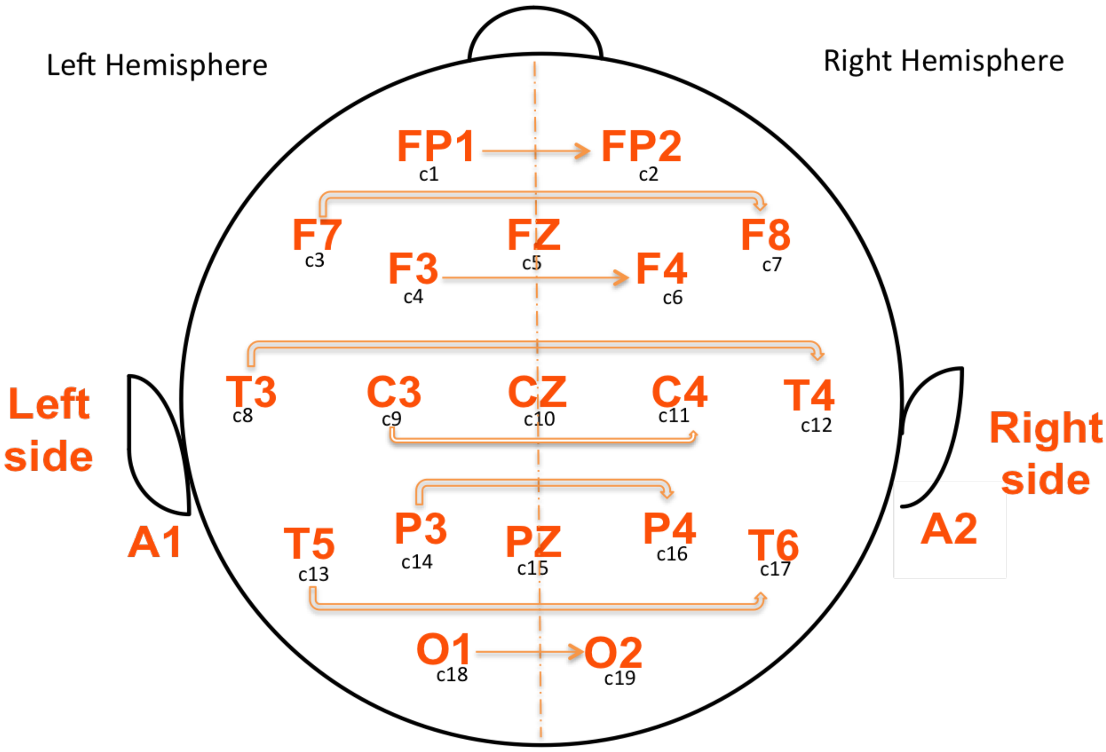
Abstract
Binaural beats are said to occur when two tones of different frequencies are presented to each ear, with the resulting perception being that of a single tone and a frequency midway between the two stimuli. It has found use in applications that purport to have the ability to relax the brain and other positive medical outcomes. This research considers the effects of binaural beats on the brain, following the assumption that the human brain has the tendency to change its dominant electroencephalography (EEG) frequency towards the frequency of the external stimulus. First, we considered the difference in spectral power of EEG frequencies for a group of individuals when in an entrained state (exposed to binaural beats) and a relaxed state (not exposed to binaural beats). Secondly, we assessed whether the effects of binaural beats affect the right and left hemisphere of the brain uniformly, and if so, to what extent this interhemispheric relationship can be seen. The results of this research show that hemispheric synchronisation affects all 5 subjects. Spectral power analysis revealed that 3 of the 5 subjects exhibited a difference in spectral power in the entrained state versus the relaxed state, especially in the frontal cortex but rather, in contradiction to the reports by others, as the effect was opposite, that is, entrainment reduces the spectral power, instead of causing an increase. The conclusion (based on the limited pool of subjects) is that there is some evidence to support that binaural beats do affect the brain but, in certain cases, negatively, and therefore, its usage should be weighed carefully.

Introduction
Binaural beats occur when a tone of steady intensity and frequency is presented to one ear, and another of similar intensity but slightly different frequency is presented to the other ear. The brain perceives a resulting single tone whose frequency is equal to the difference between the two tones [1]. For example, a tone of 200 Hz presented to the left ear and another of 210 Hz presented to the right ear will evoke a third pseudo-tone of around 10 Hz. This was first discovered in 1839 by German experimenter H. W. Dove, who found that by striking two forks in unison and presenting one to either ear, a third single explainable tone seemed to be perceived in the brain. However it was not until 1916 that binaural beats were considered to be different to monaural beats or tones. Monaural beats are typically perceived in nature and characteristically produced by tones of loud pitch. They are believed to originate in the Basilar membrane. Binaural beats, on the other hand, are thought to originate from the cortical region of the brain [2] and can only be heard when the tones used to produce them are of low pitch. A single ear is sufficient to detect monaural beats, whereas binaural beats can only be detected by both ears. Binaural beats have the same apparent strength regardless of the relative frequencies of the beats used to produce them and are often produced by mechanical processes [3] such as engines on a plane. Binaural beats are said to be best perceived at frequencies of around 500 Hz with a range between 90 Hz and 1000 Hz. The optimum spectral difference between any two tones is around 2–30 Hz [4]. Humans are not normally able to hear tones of less than 20 Hz, meaning perception of binaural beats is, in fact, a result of the human brain perceiving them via the cortical region, that is, inside the brain rather than outside the brain [3]. In animals, it has been observed that cells periodically respond to the rate of the frequency of the binaural-beat stimulus. This synchronisation, sometimes known as *neural phase locking*, seems to begin in the auditory system and propagates to the inferior colliculus [5] [6]. In humans, binaural beats have been observed to affect cognitive functioning and mood [7] [8]. Binaural beats seem to affect the firing patterns of neurons in the brain with the reticular activation system and the inferior colliculus having a part in this.
Many studies have tried to link binaural beats to some form of physiological and psy-

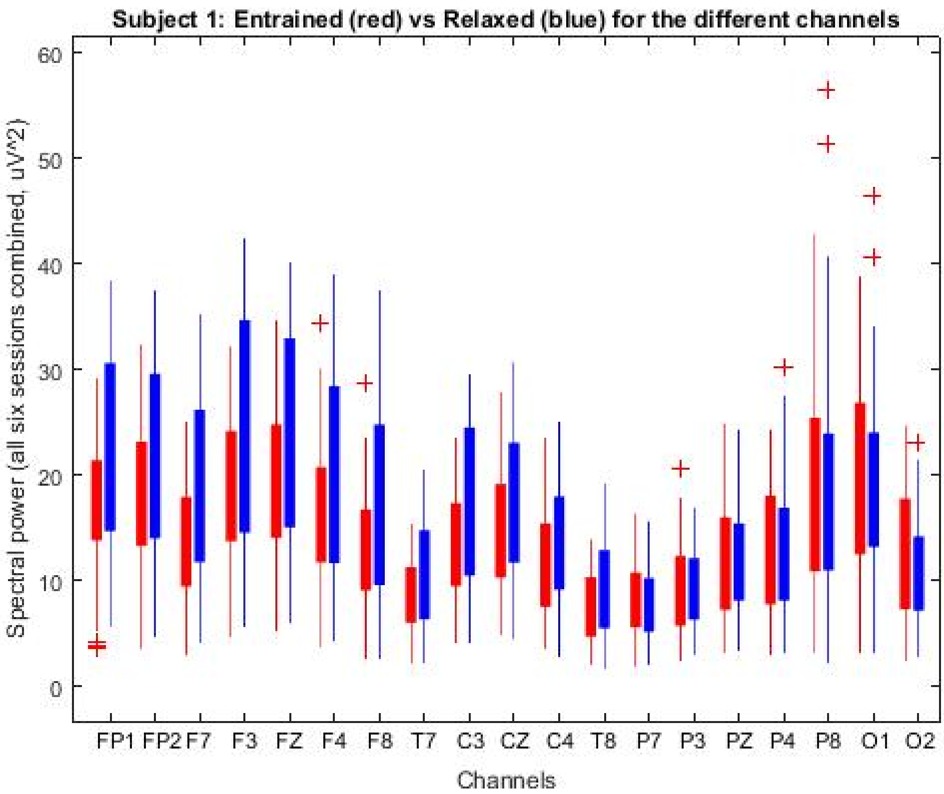
chological effects as a result. Lane et al. [8] looked at binaural beats in the theta/delta frequency range and the effect this had on vigilance and mood. They found evidence of improved performance and less negative moods in a group of 29 participants. Padmanabhan et al. [9] looked at 108 patients undergoing general anaesthesia and found that listening to binaural beats decreased the average anxiety result by 26.3 percent. Another study on anxiety was carried out by Wahbeh et al., who also concluded that there was evidence of a reduction in anxiety across the group of participants for the duration of the study [10]. Kennel et al. [11] investigated whether binaural beat entrainment could reduce symptoms of ADHD in children and found that whilst the symptoms did not significantly improve, homework problems due to inattention improved during the 3 week study. A more recent study on working memory found that exposure to binaural beats had a positive effect on participants exposed to a frequency in the alpha range of brain activity, showing significant improvement in working memory compared with the control group [12].

Objective

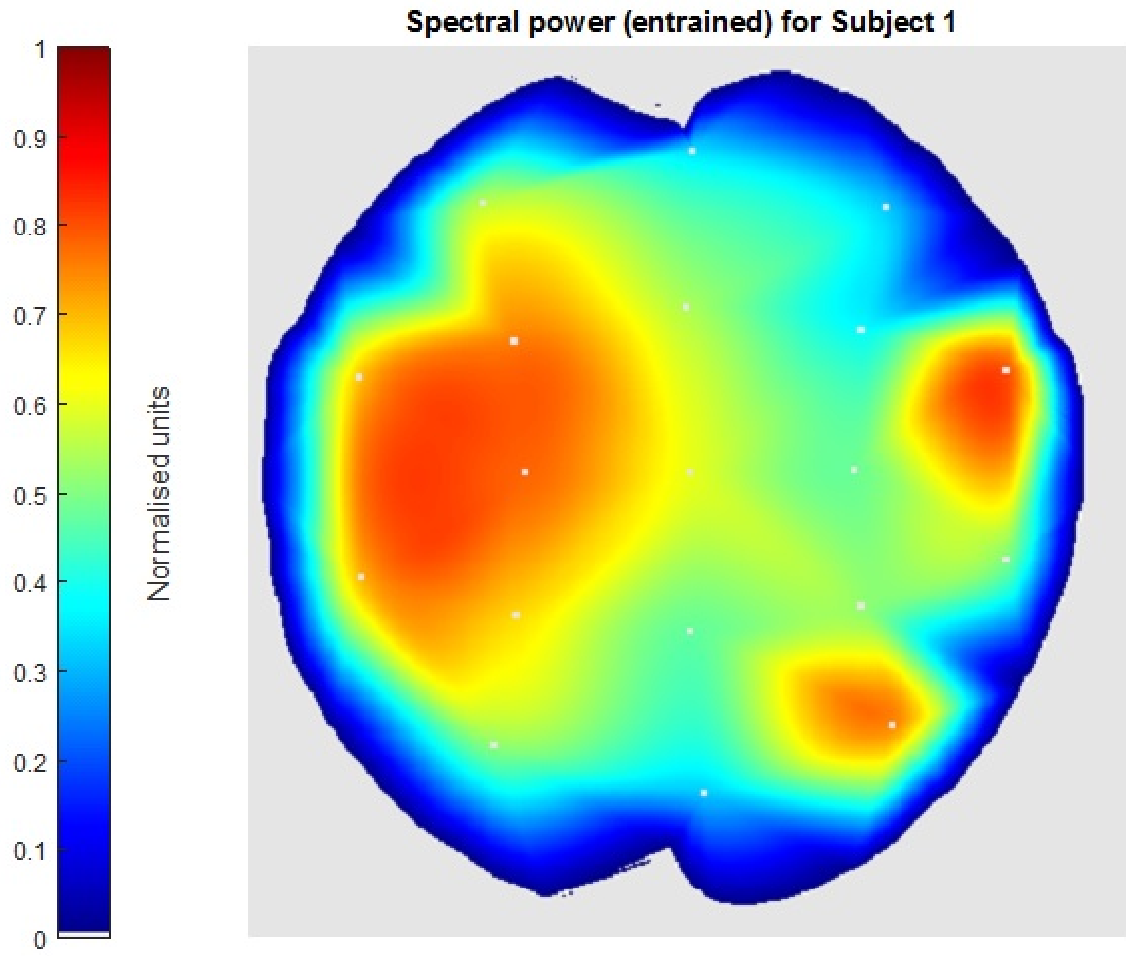
Some of the research above is based on observational data, and thus, the objective of this study is to further assess the effects of binaural beat entraining on the brain, using brain signal analysis in the form of an electroencephalogram (EEG)-based experiment. EEG is a biological signal produced by the human brain. Electrodes are placed on the human scalp and EEG data is collected (an example is the 10–20 standard using 19 locations on the scalp [13], which is also used here). This is a different technique to behavioural responses and, therefore, can be expected to produce a more robust assessment of binaural beat effects on the brain.



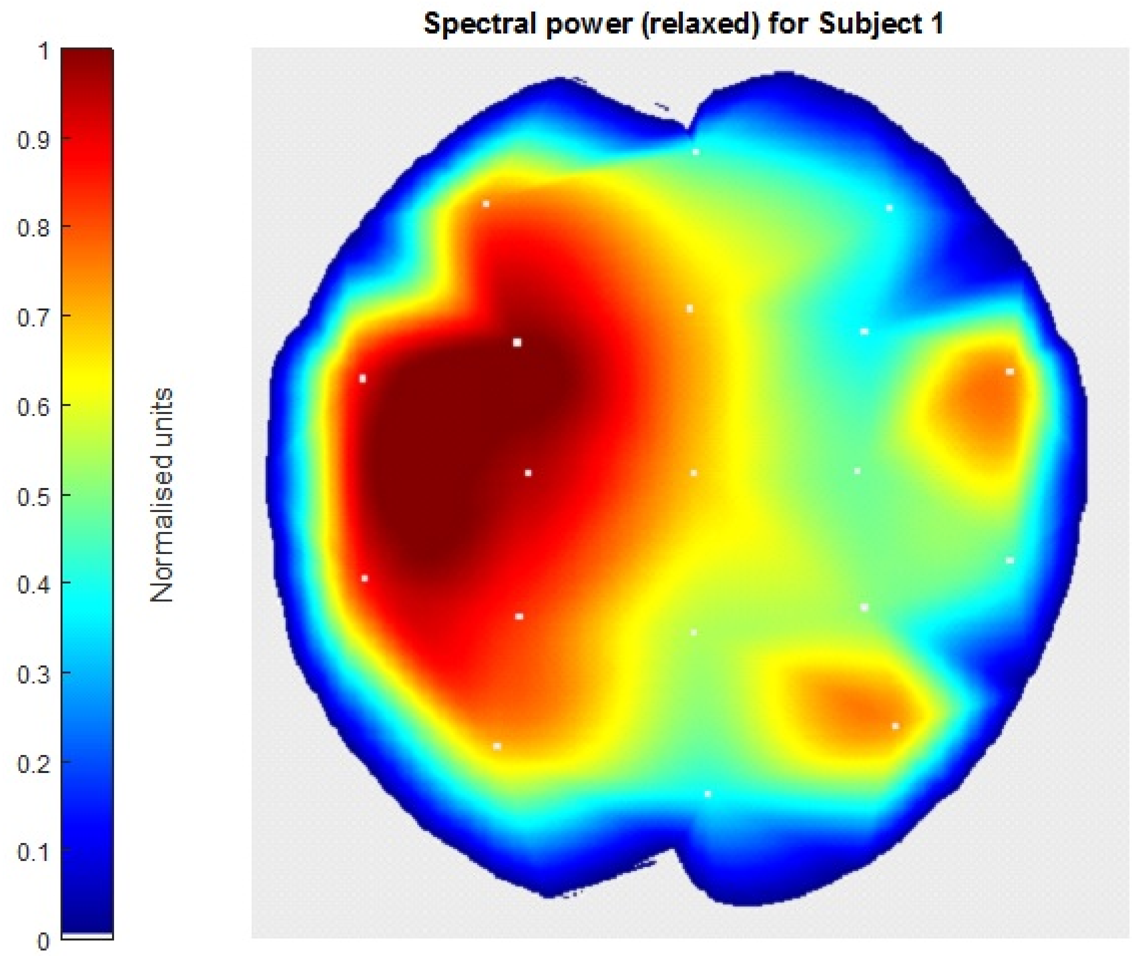
a


Subject 1: Entrained (red) vs Relaxed (blue) for the different channels
Spectral power (all six sessions combined, uV^2)
60
50
40
30
20
10
0
FP1 FP2 F7 F3 FZ F4 F8 T7 C3 CZ C4 T8 P7 P3 PZ P4 P8 O1 O2
Channels

b


Spectral power (entrained) for Subject 1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Normalised units

c


Spectral power (relaxed) for Subject 1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Normalised units

d

	Subject				
Channel	S1	S2	S3	S4	S5
FP1	**6.1E-08**	0.59	0.47	**0.05**	**0.009**
FP2	**3.7E-06**	0.51	0.43	**0.025**	**0.008**
F7	**8.3E-08**	0.058	0.68	**0.006**	**0.012**
F3	**5.6E-08**	0.28	0.49	**0.004**	**0.015**
FZ	**1.2E-06**	0.7	0.49	**0.002**	**0.005**
F4	**2.5E-06**	0.46	0.47	**0.003**	**0.006**
F8	**5.8E-07**	**0.021**	0.68	0.072	**0.007**
T7	**1.4E-05**	0.45	0.77	0.28	**0.022**
C3	**3.8E-07**	0.62	0.6	0.059	**0.008**
CZ	**2.3E-04**	0.92	0.63	0.082	**0.004**
C4	**5.2E-05**	0.28	0.85	**0.013**	**0.007**
T4	**2.6E-06**	0.42	0.94	**0.006**	**0.017**
T5	0.59	0.59	0.7	0.084	**0.008**
P3	0.53	0.66	0.76	**0.011**	**0.006**
PZ	0.47	0.76	0.81	**0.048**	**0.005**
P4	0.63	0.73	0.92	**0.049**	**0.003**
P8	0.84	0.87	0.84	0.15	**0.007**
O1	0.93	0.22	0.73	0.4	**0.007**
O2	**0.96**	0.34	**0.98**	0.11	**0.01**

e

Asymmetry ratio	Subject									
	S1		S2		S3		S4		S5	
	Entrained	Relaxed	Entrained	Relaxed	Entrained	Relaxed	Entrained	Relaxed	Entrained	Relaxed
FP1-FP2	**0.0344**	0.0369	**0.0482**	0.0556	**0.0258**	0.0296	**0.0473**	0.0510	0.0329	0.0311
F7-F8	0.0880	0.0856	**0.1091**	0.1132	**0.0579**	0.0790	0.0936	0.0878	**0.0659**	0.0755
F3-F4	**0.0801**	0.0976	0.1194	0.1190	**0.0364**	0.0555	0.0820	0.0770	0.0615	0.0572
T3-T4	**0.1037**	0.1135	0.2073	0.2030	**0.1349**	0.1783	**0.0940**	0.1168	**0.0859**	0.1053
C3-C4	**0.0986**	0.1305	**0.0942**	0.1053	**0.0615**	0.0725	0.0641	0.0588	0.0733	0.0651
P3-P4	**0.1503**	0.1506	**0.0753**	0.0783	**0.0547**	0.0600	0.0794	0.0662	**0.1131**	0.1275
T5-T6	0.3424	0.3372	0.2252	0.2094	**0.0862**	0.1129	**0.1666**	0.1905	**0.2415**	0.2546
O1-O2	**0.2200**	0.2459	0.0657	0.0649	**0.0443**	0.0803	0.0884	0.0828	**0.1281**	0.1441
Grand average	**0.1397**	0.1497	**0.1181**	0.1186	**0.0627**	0.0835	**0.0894**	0.0914	**0.1003**	0.1076

f

Figure Legend

Figure 1.

(A) Inter-hemispheric comparison of different electrode channels.
(B) EEG spectral power of entrained and relaxed state for subject 1.
(C) EEG spectral power (entrained) topographic map.
(D) EEG spectral power (relaxed) topographic map.
(E) p-value for Wilcoxon signed-rank test (blue indicating entrained < relaxed and red vice-versa).
(F) Asymmetry ratio (mean values, blue indicating entrained mean < relaxed mean).

Results & Discussion

A. Spectral Power

Spectral power describes how the power of a signal is distributed over different frequencies. In this research, it was calculated by computing the variance of the filtered signal in the 8 Hz frequency band. From this, a difference in spectral power between the entrained and relaxed states can be observed as shown in figure 1B for subject 1, as an example. To assess whether this difference is statistically significance, pair-wise Wilcoxon sign-rank (as normality of data was not tested) was computed. The hypothesis was set at 5 percent confidence level and was investigated whether the median spectral power exhibited by EEG signals in the binaural state were lower than that in the relaxed state. Figure 1E shows the p-values for the one-tailed signed-rank test. From this, it can be seen that for participants 1, 4 and 5, there is evidence to support that binaural beat entrainment had an effect. Given that 3 participants were affected, this provides evidence (at least for these participants) that the effect of binaural beat entrainment was a reduction in spectral power, especially in the frontal cortex. This means that the alpha frequency spectral power was lower in the binaural state than in the relaxed state. Participants 2 and 3 do not seem to have been affected by binaural entrainment. For these participants, binaural entrainment had increased the spectral power but only in channel O_2.

Therefore, from the statistical test, it can be seen that 3 out of 5 participants have been affected by binaural beat entrainment. The binaural beat presented to the subjects was in the alpha (8 Hz) frequency band, typically associated with a reduced level of brain activity. This reduced activity could explain the reduction in power or amplitude in the entrained state as opposed to the normal state the participants would have been in at the start.

B. Asymmetry Ratio

Asymmetry ratio gives an indication of the degree of synchronisation between the left and right hemispheres of the brain. It is calculated by computing the power between two channels. To compare whether there was a greater degree of synchronisation in the entrained state versus the relaxed state, the asymmetry ratio was computed. The lower the ratio, the greater the inter-hemispheric synchronisation, and the higher the likelihood that entrainment had an effect on the participants. Figure 1F shows the mean values of the asymmetry ratio calculation for the participants in the relaxed and entrained states. From this, it is possible to observe that, for all participants, in general, asymmetry ratio was lower in the entrained state than in the relaxed state, which suggests that, for these participants, binaural entrainment had an effect. However, the difference was not statistically different.
The last row of figure 1F shows the values for the grand averaged ratios from 8 pairs of electrodes. The grand average values of the asymmetry ratios in the entrained state are lower than the values of the relaxed state asymmetry ratios for all the participants. Therefore, it can be said that binaural entrainment had an effect and increased inter-hemispheric synchronisation in the brain. This confirms that binaural entrainment does affect cortical synchronisation, which was also found in another study [14]. The synchronisation starts from the auditory system and the inferior colliculus in the cortex, spreading across the brain, and, in turn, affecting the processes which depend on such synchronisation. Inter-hemispheric synchronisation often occurs in brain signals and as such, is widely believed to be a result of synchronisation of neuronal activity, reflecting changes of neuronal brain membrane potential [15]. Asymmetry ratio provides both an indication of the degree of synchronisation between the left and right hemispheres of the brain and a good method to assess further the effect of binaural entrainment on the different participants in this study. The underlying idea is that brain activity is propagated via cortical oscillations, which is related to the information flow from one brain structure to another. Different frequency bands are considered to represent the messenger frequency of cognitive processes, and such processes are considered in terms of communication across different parts of the brain. Short-range communication in the brain is normally associated with neural synchronisation in the gamma frequency, while long-range communication is associated with neural synchronisation in the alpha/beta frequency bands [14] [16]. Taking this assertion further, it is possible to assess the effect of binaural entrainment by comparing the values in oscillations observed in the different hemispheres or parts of the brain between the entrained state and the relaxed state. The pair-wise asymmetry ratio for a given brain structure provides information about functional coupling between similar structures in a closed system. The ratio provides insight into the interaction of the different brain structures. More specifically, the higher the value of this ratio, the weaker the relation of a selected structure with another structure, and the less there is interhemispheric coherence, which is widely believed to be critical to mental processes. Considering the basic assumption, it can be seen from the results that all 5 participants exhibited a reduction in asymmetry ratio, which implies a greater degree of interhemispheric synchronisation in the entrained state relative to the relaxed state. This provides evidence that binaural entrainment does effect the information flow process in the brain, therefore providing further evidence on the effect of binaural beats on the brain.

Conclusions

The results of this study provide evidence of the effect of binaural beat entrainment on the brain. It is consistent with some of the early work done on animals [5] [6], and later on the human brain [17] [18], suggesting that neural activity at different frequencies from the left to the right ear converge and interfere in the auditory pathway to generate beats of neural activity, thereby providing the illusion of amplitude modulation. The results of such studies suggest that it is possible to detect neural responses to binaural beats in the human EEG, thereby supporting the assumption that the human brain has a tendency to modify its basic EEG frequency under entrainment. However, based on the limited pool of subjects, there is evidence that entrainment has an effect on the spectral power of brain frequencies, but entrainment seems to lower rather than elevate the power of brain frequencies (which is contrasting to some earlier studies). Nevertheless, entrainment does increase the degree of interhemispheric synchronisation in the brain.

Limitations

The study had only considered data from 5 participants and this limited pool of subjects should be considered when taking the conclusions into account. The period of entrainment was only 6 min per session, which could perhaps be too short and may include transient rather than steady-state effects.

The results of this study show evidence of the effects of binaural beats on the brain. All 5 participants who took part in this study exhibited some form of binaural beat entrainment effect in their EEG signals. The main conclusions are that binaural entrainment has an impact on the spectral power of brain frequencies, and it seems to lower rather than elevate the power of brain frequencies. Lastly, binaural entrainment seems to increase the degree of interhemispheric synchronisation in the brain. Further research is necessary to establish whether these effects are indeed beneficial to the health as claimed by some research.

Additional Information

Methods

Supplementary Material

Please see https://sciencematters.io/articles/201607000001.

Ethics Statement

The study received ethics approval from Research Ethics Advisory Group, Faculty of Science, University of Kent. All participants received a small payment of £15 per subject for their time. They were briefed on the experiment and written consents were obtained. Ethics ref: 0751516.

Citations

[1] Xiang Gao et al. "Analysis of EEG activity in response to binaural beats with different frequencies". In: *International Journal of Psychophysiology* 94.3 (Dec. 2014), pp. 399–406. DOI: 10.1016/j.ijpsycho.2014.10.010. URL: http://dx.doi.org/10.1016/j.ijpsycho.2014.10.010.

[2] Joseph Peterson and. "The nature and probable origin of binaural beats." In: *Psychological Review* 23.5 (1916), pp. 333–351. DOI: 10.1037/h0070767. URL: http://dx.doi.org/10.1037/h0070767.

[3] Gerald Oster. "Auditory Beats in the Brain". In: *Scientific American* 229 (1973), pp. 94–103.

[4] J. C. R. Licklider, J. C. Webster, and J. M. Hedlun. "On the Frequency Limits of Binaural Beats". In: *The Journal of the Acoustical Society of America* 22.4 (1950), p. 468. DOI: 10.1121/1.1906629. URL: http://dx.doi.org/10.1121/1.1906629.

[5] S. Kuwada, T. Yin, and R. Wickesberg. "Response of cat inferior colliculus neurons to binaural beat stimuli: possible mechanisms for sound localization". In: *Science* 206 (1979), pp. 586–588.

[6] David McAlpine, Dan Jiang, and Alan R. Palmer. "Interaural delay sensitivity and the classification of low best-frequency binaural responses in the inferior colliculus of the guinea pig". In: *Hearing Research* 97 (1996), pp. 136–152.

[7] D. Vernon et al. "Tracking EEG changes in response to alpha and beta binaural beats". In: *International Journal of Psychophysiology* 93.1 (July 2014), pp. 134–139. DOI: 10.1016/j.ijpsycho.2012.10.008. URL: http://dx.doi.org/10.1016/j.ijpsycho.2012.10.008.

[8] James D Lane et al. "Binaural Auditory Beats Affect Vigilance Performance and Mood". In: *Physiology and Behavior* 63.2 (Jan. 1998), pp. 249–252. DOI: 10.1016/s0031-9384(97)00436-8. URL: http://dx.doi.org/10.1016/S0031-9384(97)00436-8.

[9] R. Padmanabhan, A. J. Hildreth, and D. Laws and. "A prospective, randomised, controlled study examining binaural beat audio and pre-operative anxiety in patients undergoing general anaesthesia for day case surgery". In: *Anaesthesia* 60.9 (Sept. 2005), pp. 874–877. DOI: 10.1111/j.1365-2044.2005.04287.x. URL: http://dx.doi.org/10.1111/j.1365-2044.2005.04287.x.

[10] Helané Wahbeh et al. "Binaural Beat Technology in Humans: A Pilot Study to Assess Neuropsychologic, Physiologic, And Electroencephalographic Effects". In: *The Journal of Alternative and Complementary Medicine* 13.2 (Mar. 2007), pp. 199–206. DOI: 10.1089/acm.2006.6201. URL: http://dx.doi.org/10.1089/acm.2006.6201.

[11] Susan Kennel et al. "Pilot Feasibility Study of Binaural Auditory Beats for Reducing Symptoms of Inattention in Children and Adolescents with Attention-Deficit/Hyperactivity Disorder". In: *Journal of Pediatric Nursing* 25.1 (Feb. 2010), pp. 3–11. DOI: 10.1016/j.pedn.2008.06.010. URL: http://dx.doi.org/10.1016/j.pedn.2008.06.010.

[12] Jakub KRAUS and Michaela PORUBANOVÁ. "The Effect of Binaural Beats on Working Memory Capacity". In: *Studia Psychologica* 57 (2015), pp. 135–145.

[13] H.H. Jasper. “Report of the committee on methods of clinical examination in electroencephalography: 1957”. In: *Electroencephalography and Clinical Neurophysiology* 10 (1957), pp. 370–375.

[14] Alfons Schnitzler and Joachim Gross and. “Normal and pathological oscillatory communication in the brain”. In: *Nature Reviews Neuroscience* 6.4 (Apr. 2005), pp. 285–296. DOI: 10.1038/nrn1650. URL: http://dx.doi.org/10.1038/nrn1650.

[15] Anna Korzeniewska et al. “Determination of information flow direction among brain structures by a modified directed transfer function (dDTF) method”. In: *Journal of Neuroscience Methods* 125.1-2 (May 2003), pp. 195–207. DOI: 10.1016/s0165-0270(03)00052-9. URL: http://dx.doi.org/10.1016/s0165-0270(03)00052-9.

[16] Astrid von Stein and Johannes Sarnthein and. “Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization”. In: *International Journal of Psychophysiology* 38.3 (Dec. 2000), pp. 301–313. DOI: 10.1016/s0167-8760(00)00172-0. URL: http://dx.doi.org/10.1016/s0167-8760(00)00172-0.

[17] D.W.F. Schwarz and P. Taylor and. “Human auditory steady state responses to binaural and monaural beats”. In: *Clinical Neurophysiology* 116.3 (Mar. 2005), pp. 658–668. DOI: 10.1016/j.clinph.2004.09.014. URL: http://dx.doi.org/10.1016/j.clinph.2004.09.014.

[18] Hillel Pratt et al. “Cortical evoked potentials to an auditory illusion: Binaural beats”. In: *Clinical Neurophysiology* 120.8 (Aug. 2009), pp. 1514–1524. DOI: 10.1016/j.clinph.2009.06.014. URL: http://dx.doi.org/10.1016/j.clinph.2009.06.014.