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Abstract (for dissemination)	In this report we describe on the one hand the technical development of a prototype that provides binaural beat stimulation and brain activity monitoring, and on the other hand we report a pilot empirical analysis of the effect of binaural stimulation on the brain.
Keywords	Binaural Beat, BCI, EEG, Entrainment

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1 Introduction

BrainAble's main objective is to improve the quality of life of people with disabilities by providing user-friendly BCI-based technology that will help them to develop autonomy and social inclusion. The use of audiovisual material in the context of BCI research raises interesting questions about cognitive stimulation and rehabilitation.

The prototype presented here focuses on brain entrainment via auditory stimulation and is complementary to D4.3, which described a number of VR systems and their effect on the user. Here we take a closer look at a specific auditory stimulus called binaural beat that stimulates arousal, focus and awareness, all fundamental components of consciousness.

Along the lines of the perturbational approach to the study of consciousness described by [9], we propose the investigation of the usability and efficiency of binaural beats on patients with varying deficits of consciousness (coma, minimally conscious and locked-in syndrome). Binaural beats are a simple but powerful technique that allows entraining brain activity at specific frequencies that follow the frequency of the original binaural beat stimulus. Although there have been several scientific reports describing the merits of binaural beat stimulation e.g. for treating anxiety or improving cognitive skills (Cf. Paragraph 2.2), this technique is still not widely used in a clinical setting. In this prototype and pilot study with healthy controls, we take a first step towards a systematic study of binaural beats that paves the way for further experiments on the auditory stimulation of patients with consciousness deficits. The study of Binaural beat stimulation in the SMR frequency range is also of particular interest for potential improvement in SMR-based BCI training.

2 Binaural beat stimulation

2.1 Binaural beat and brain entrainment

Binaural beats are auditory brainstem responses originating in the superior olivary nucleus of each brain hemisphere (Figure 1). They are generated by stimulating each ear with two separate tones below 1 kHz that differ in frequency [11].

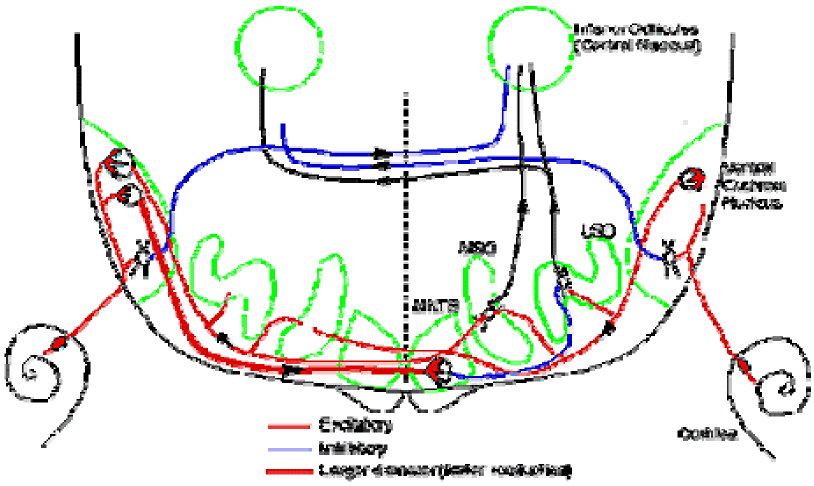


Figure 1: Binaural Pathway: the superior olivary complex

The human auditory system is extremely sensitive to the time delay (called Interaural Time Difference or ITD) observed between two ears in response to sound stimuli. ITD plays a fundamental role in the detection of the direction of sound sources and ITD cues are derived from interaural phase differences for frequencies below 1 kHz (below 1 kHz, the sound wave length is longer than the diameter of the human skull and diffracts) [2 ,16]. Thus, tones with a slight frequency difference delivered separately to the left and right ear can be perceived as being lateralized. Under normal circumstances, phase difference provides directional information. When stereo headphones are used, a perceptual integration takes place and a “third” beating frequency is heard. In that context, the binaural beat effect appears as the two out-of-phase waveforms at each ear are integrated within the superior olivary nuclei. The beating information is routed to the reticular formation and conducted to the cortex. This simple mechanism can be used to entrain the brain’s rhythmic activity following a Frequency Following Response (FFR) [5 ,18].

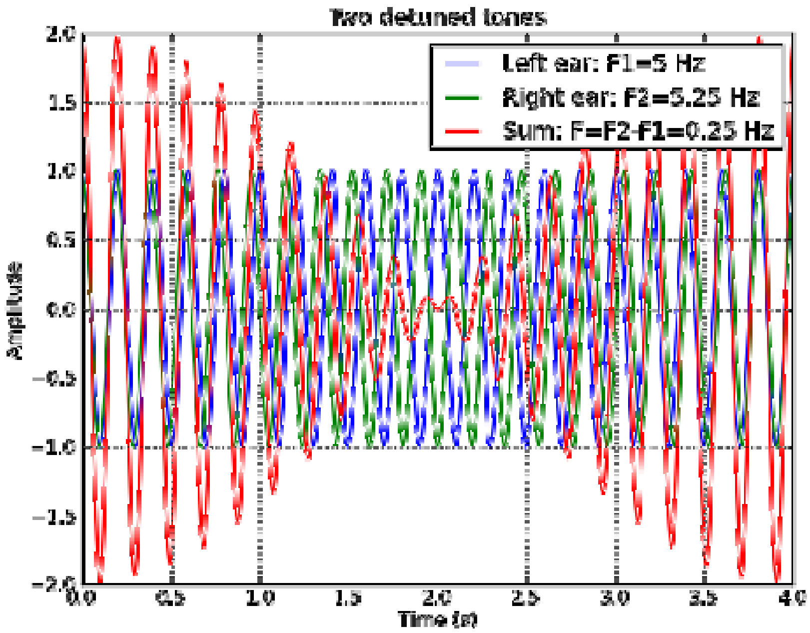


Figure 2: Two slightly detuned tones at each ear generate a binaural beat at a frequency that is the difference between the frequencies of the original stimuli.

2.2 Previous Clinical studies

Entrainment Binaural beats have been used to entrain the brain activity in specific frequency range such as alpha (corresponding to a relaxation state), beta (alertness) and have been shown to affect vigilance and mood [6 ,1].

Plasticity Studies have shown some effect of binaural beat training on the plasticity of the brain for the trained frequencies. Some symmetric hemispheric balancing was found [10 ,3].

Hormone secretion Beta-endorphin and dopamine secretion have been shown to be modulated by binaural beat training [13 ,21].

Learning and memory The presence of theta activity in the brain has been associated with learning [17] and theta stimulation has been shown to affect learning and cognitive tasks [4 ,20].

Sleeping There are some reports of using alpha binaural stimulation for lucid dreaming [19].

Addiction Alpha theta brainwave entrainment has been used in the treatment of addictions notably alcoholism [15 ,13 ,22].

Anxiety Binaural beats have been shown to decrease acute preoperative anxiety [12] and reduce general anxiety [21 ,8].

2.3 Binaural beat as a tool for the study of deficits of consciousness

Binaural beats provide potential consciousness-altering information to the brain's reticular activating system that interprets and react to this information by stimulating the thalamus and cortex. It provides a simple way to potentially alter arousal, focus and awareness, which are fundamental components of consciousness [14 ,7].

3 Prototype and pilot experiment

To study the effect of brainwave entrainment under binaural beat stimulation, we designed a first prototype validated by a preliminary pilot experiment where we recorded the EEG activity of one healthy subject while listening to a well-defined set of binaural beat stimuli (Figure 3).

Figure 3: The experimental setup using gUSBamp, Gammabox hardware by G.tec

3.1 Methods

3.1.1 Stimulus Presentation Software

The auditory stimuli were generated using the stimulus presentation software Gnaural [1]. We designed a stimulus with a beating frequency of 10 Hz and a base frequency of 440 Hz (corresponding to a brainwave in the Alpha range). The global volume was chosen by the user so that if felt comfortable and could perceive the binaural beat effect. The pink noise volume was set at ¼ of the binaural stimulus. The frequency for the binaural stimulus was set at 440 for the right ear, and 450 for the left ear.

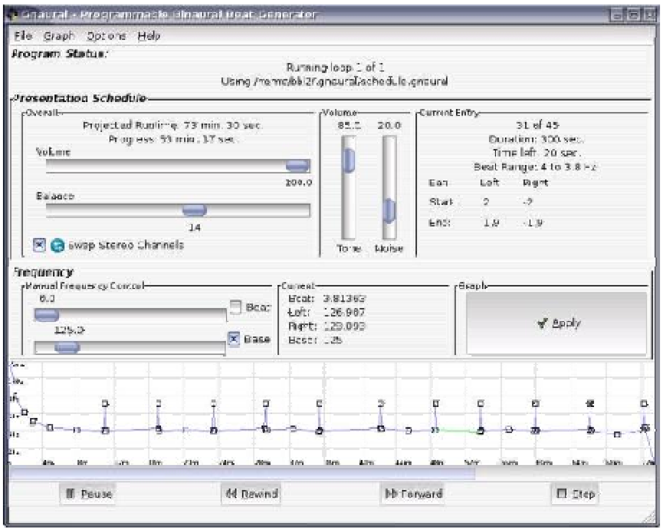


Figure 4: : Gnaural: the binaural beat stimulus presentation software allows defining the base and beating frequency as well as the volumes of beat stimulus and pink noise.

3.1.2 EEG recording system

EEG signals were acquired with G.tec equipment including gUSBamp amplifier and GammaBox preamplifier (Figure 3). The 16 recording electrodes were placed at standard locations following the international 10-20 system (Figure 5). Signals were acquired at a sampling rate of 256 Hz and pre-amplified in the range [0.5 60] Hz. A notch filter was used to reduce 50 Hz artefacts.

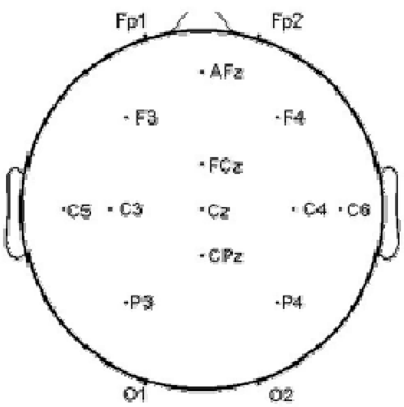


Figure 5: **16 electrodes setup according to the 10-20 standard**

1http://gnaural.sourceforge.net/

3.1.3 Protocol

The subjects were comfortably seated on a chair, with inner-ear stereo earphones on (Sennheiser CX 300-ii, Sennheiser electronic GmbH & Co) and were asked to close their eyes during the whole duration of the experiment (20 minutes). EEG was recorded before (5 min) , during (10 min) and after (5 min) binaural beat stimulation (Figure 6) while the pink noise background was kept constant.

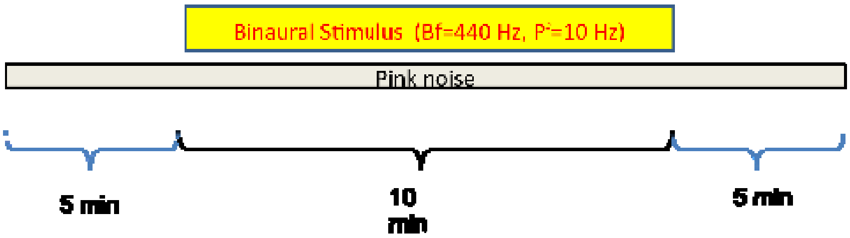


Figure 6: **The stimulus presentation protocol consists of 5 min of pre-stimulus baseline recording followed by 10 min of stimulation and 5 min of rest / post-stimulus recording. The level of pink noise was kept constant during the whole session.**

4 Results

Spectral analysis EEG data for each channel was imported into MATLAB (Mathworks) with EEGLAB[2] toolbox. Major visible artefacts were rejected by hand and the EEG data was then analyzed to extract the spectral power in the delta, theta, alpha and beta bands for each channel.

Signals corresponding to each EEG channel were divided in two main parts corresponding to the pre-stimulus (only pink noise) and the stimulus (pink noise + binaural beat) experimental blocks. We selected the whole pre-stimulus block (300 s long) and an equally long interval centered in the stimulus block.

For each of these two blocks we computed the power spectral density (PSD) (using the Welch's method) with overlapping windows of length 2 s and an overlap of 50%. For each window we computed the average absolute bandpower. We obtained, for each EEG channel, 300 values of absolute band power, 150 for the pre-stimulus block and 150 for the stimulus block. We averaged these values across the 16 channels.

We found a significant difference between averaged alpha and delta activities before and during stimulus (Table 1).

Table 1: Average difference over all electrodes of bandpower in theta, alpha and beta are statistically significant.

Bandpower	Mean ^{pre}	Mean ^{post}	t-test
Thetha	0.146	0.158	$t(300)=-2.34, p<0.05$
Alpha	0.410	0.454	$t(300)=-4.86, p<0.05$
Beta	0.112	0.95	$t(300)=7.35, p<0.05$

2 http://sccn.ucsd.edu/eeglab/

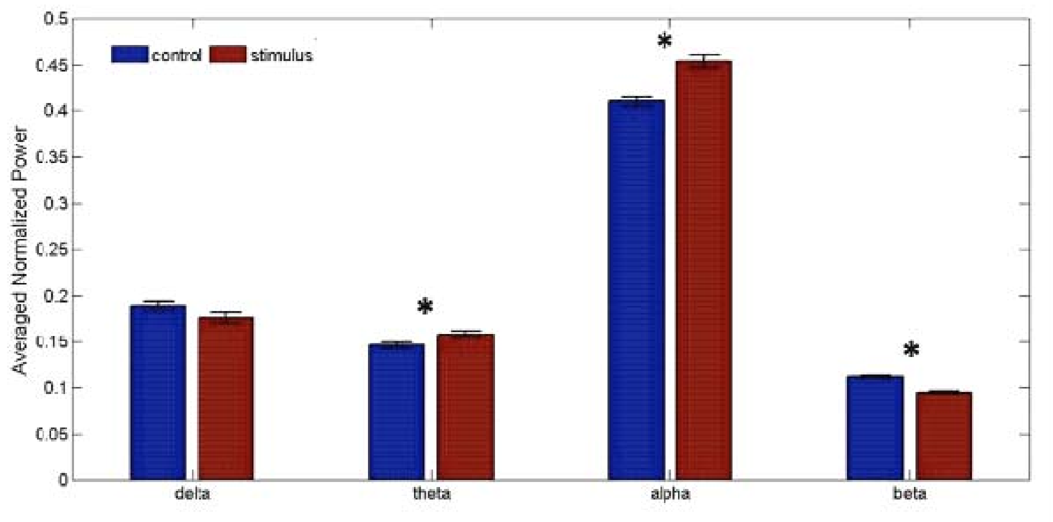


Figure 7: **Change in band power (averaged across electrodes) before and during stimulation.**

A detail t-test analysis for each EEG channel showed a statistically significant increase of alpha power for 9 channels (Table 2, Figures 8 and 9).

Table 2: **Significant difference in Alpha bandpower for specific electrodes**

channel	Mean pre	Mean post	t-test
Fp1	0.3072	0.3672	t(300)=-4.53, p<0.01
F3	0.2829	0.3638	t(300)=-6.88, p<0.01
C3	0.4088	0.4692	t(300)=-4.4, p<0.01
C5	0.3615	0.4296	t(300)=-5.63, p<0.01
FCz	0.3646	0.4236	t(300)=-4.50, p<0.01
FPz	0.3185	0.3716	t(300)=-3.99, p<0.01
F4	0.3503	0.3900	t(300)=-3.06, p<0.01
O2	0.4588	0.5540	t(300)=-7.38, p<0.01
Cz	0.4418	0.4892	t(300)=-3.59, p<0.01

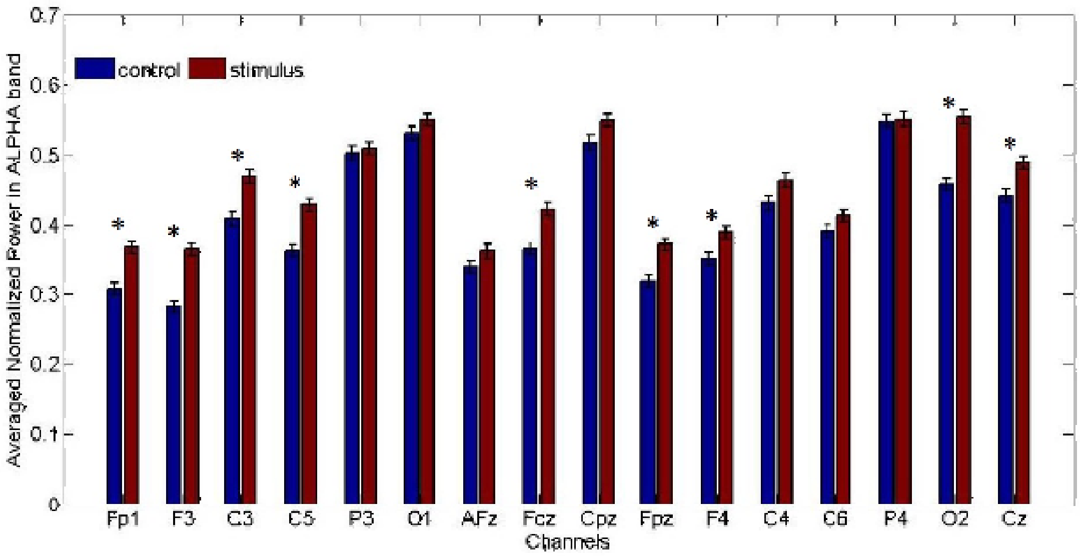


Figure 8: **Change in Alpha power for each electrode before and during stimulation.**

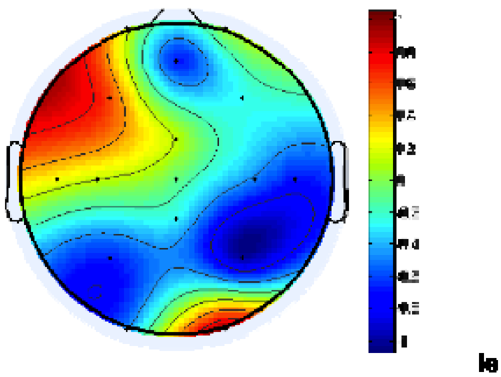
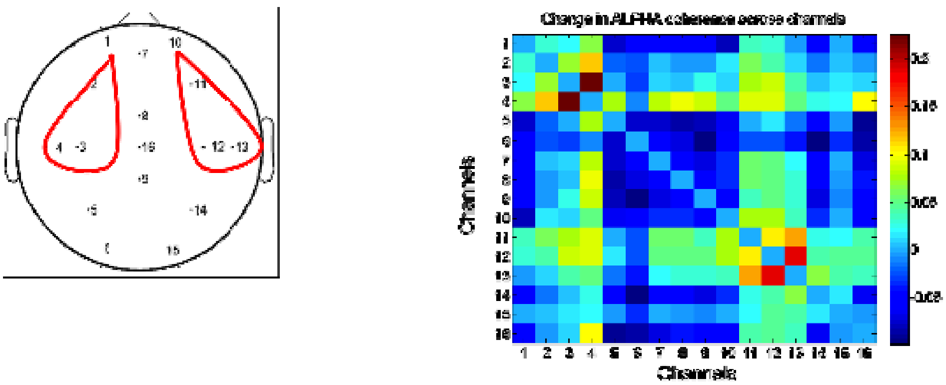


Figure 9: **Map of alpha power difference before and during stimulus**

Coherence analysis We computed the average change in coherence for each channel in the alpha band before and during stimulus with analysis windows of 2 s (Figure 10). The analysis showed an inter-hemispheric increase in coherence in the fronto-temporal areas.



(a) Location of EEG channels

(b) Coherence matrix for 16 EEG channels

Figure 10: **Change in coherence before and during stimuli accross channels. A larger value of the coherence matrix corresponds to a larger increase in coherence for a specific pair of electrode ($p<0.05$).**

5 Conclusion

We designed and implemented a binaural beat stimulation and evaluation prototype and proposed a preliminary study of the system. The first tests showed that simple auditory binaural beat stimulation in the alpha frequency range (10 kHz) could indeed be used to entrain brainwave activity in the same frequency range as the input stimulus. Moreover, we found that alpha binaural beat stimulation increased the coherence in fronto-lateral areas of the brain at the same frequency. It appears that binaural beat stimulation is a simple yet powerful technique to voluntarily modulate and possibly train brain activity in specific frequency ranges. These first results are encouraging, and this will prove an interesting paradigm to e.g. improve SMR training in the context of SMR-BCI applications. In the future we will also more specifically investigate the use of binaural beat as a tool to study and stimulate patients with deficits of consciousness whose auditory abilities are intact.

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