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Cumulative effects of theta binaural beats on brain power and functional connectivity

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ABSTRACT

Audiovisual stimuli with specific frequency can cause the brain to oscillate in the same frequency, something which is also called brain entrainment. One method to entrain the brain through the auditory system is binaural beats. Binaural beats are two rhythmic tones with slightly different frequency which are presented separately to each ear. The brain perceives an illusionary signal with the frequency of the difference of the two exerted tones and oscillates in that frequency. There are contradictory findings in the previous studies in which some researchers could not entirely observe this phenomenon. In this paper we propose a protocol to inspect whether binaural beats can change the power and connectivity of the brain and also how lengthening the stimuli, interchangeably with pink noise, will affect the outcomes. Fifteen healthy participants attended this study and their EEG signals were recorded during presentation of 200 Hz and 207 Hz sinusoidal tones to their left and right ears respectively. Total 9 min of binaural beats were divided into three 3-min blocks which were separated by 1 min of pink noise to prevent the brain from habituating to the stimuli. Our results showed that 3 min of 7 Hz binaural beats is not enough to entrain the brain, but applying 6 min of stimulation could change the relative power in the temporal and parietal lobes and further exposure to 9 min of stimuli could also alter the brain network, evaluated by the graph theory.

1. Introduction

Paired sense organs such as the eyes or ears can work together to send information from the outside world to the brain. The concept of *binocular vision* has a richer history as it was introduced and examined in the 17th and early 18th century, whereas the idea of *dichotic listening* was first brought up by Wells in 1792. Almost half a century later in 1841, Dove verified Well's 'thought experiment' with a simple tuning forks test, and it was the first time *binaural beats* underwent a tryout [1].

Binaural beating is an auditory illusion that is perceived when two carrier tones of slightly different frequency are presented separately to each ear, resulting in sensing a third tone with a frequency equal to the difference of the two separate tones [2]. For example, if a tone of 300 Hz is presented to the right ear and 310 Hz to the left ear, a tone of 10 Hz will be perceived in the brain. It has been suggested that the carrier frequency is best to be kept below 1 kHz [3].

Why such a phenomenon is of any interest, is because it is believed binaural beats can be a source of entrainment [4]. In other words, it can cause neurons in the brain to fire synchronously with the frequency of binaural beat and thus changing the brain activity and its state [5]. But whether this theory is a fact or fiction is yet to be determined. Centuries later after Dove designed a simple tuning forks experiment, much more sophisticated studies have been taking place on the topic and not all of the outcomes were identical. For instance, Brady and Stevens first reported binaural beats can increase the level of hypnotic susceptibility [6], but when they assembled a larger statistical population including a randomized control group they failed to find the similar results [7]. Lane improved vigilance by exposure of binaural beats [8], but Goodin failed to meet the same conclusion with a different protocol [9]. Other positive effects of binaural beats have been reported on verbal memory [10], relaxation [11], dual cognitive tasks [12], working memory [13], pain and anxiety reduction [14–16], and severity ratings of tinnitus [17], but on the other side of the debate there are other reports that indicate no changes occur on attention [18], blood pressure or heart rate variability (HRV) [19] and reduction the symptoms of children diagnosed with attention deficit hyperactivity disorder (ADHD) [20].

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The studies on binaural beats have not been limited to behavioral responses. Some researchers tried to explore how these stimuli can alter the brain signals and more specifically the brainwaves such as the theta and alpha bands. Because of the nature of the study, high temporal resolution investigation is required to probe any changes in the brainwaves [21], so mostly used modalities for binaural beats are electroencephalography (EEG) and magnetoencephalography (MEG). Although such studies could help us gain a deeper understanding of the phenomenon, but again they have not all added up to a unified explanation. For instance, whilst Pratt could detect activities in the left temporal lobe due to binaural beats [22,23], a pilot study by Wahbe dismissed any variations related to this stimulation in the brain [5]. Two other works utilized MEG and both found out the cerebral cortex can be synchronized with slow binaural beating [24,25], and another study examined power and phase synchronization changes on intracranial electroencephalography (iEEG) for epilepsy patients and reported significant modulation in different parts of the brain [26].

Exploring separated parts of the brain is more of a traditional method to seek brain responses to various tasks. This approach, which is also considered as segregation view of the brain, implies a cortical area is specialized for some specific tasks and can be segregated from other parts of the brain. Given the anatomical independencies among different regions of the brain, even a single-function area of the brain can mediate other connected parts of the brain. So segregation is only meaningful in the context of integration view [27]. Therefore it seems a more exhaustive approach for brain study is functional integration, or what is commonly known as brain connectivity.

Execution of disparate tasks warrants coordinated flow of information within the brain network. Synchronization of rhythms in different specialized parts of the brain can provide coordination among them [28]. The ability of this highly complex network to modify the strength and pattern of oscillations within its nodes is crucial for high efficiency in broad ranges of tasks, and thus the brain connectivity methods come in handy to capture such oscillations. Among some forms of different connectivity methods, functional connectivity has enjoyed a wide attention from EEG and MEG studies because of their high temporal resolutions. Functional connectivity is mostly useful when the direction of information flow is not the point of the study, because they only capture statistically significant dependence between different cortical regions, regardless of the direction of the transmission [29].

Therefore, functional connectivity can help us to further examine the effects of binaural beats, beyond the variations in the absolute and relative power of the EEG bands. For example, Ioannou did not see any meaningful changes in the power spectrum of EEG, but in the same study, functional connectivity was reported to be affected by binaural beats [30]. Other researchers also explored functional connectivity for different frequency bands and while they observed some fundamental changes, they couldn't find enough evidence for vivid brain entrainment [31,32].

Why such different results have been reported is probably because of so many distinct experimental designs. There are some vital elements that may cause these differences including the length of stimulation, choice of the carrier frequency, brain adaptation to stimuli and etc. As an example, the importance of the duration of stimuli is often neglected. It doesn't seem just a matter of lengthening the stimulation because shorter (e.g., 2 min in [9]) or longer (e.g., 40 min in [7]) exposure to binaural beats both have failed to produce any meaningful results in some cases. It has been suggested continuous exposure to binaural beats leads the brain to habituate to the signal, filtering the uncomfortable sound of binaural beats as time progresses [33,34] or it may even cause blocking of the specific frequency in the brain [7]. So if this theory is in fact true, presenting some non-binaural beats sound (e.g., pink noise) to refuse the brain from habituating to the signal, may lead to better results in longer exposures. This only holds true if binaural beats are not limited to online effects, and can attain after-effects as well. Only under this premise, cumulative effects of separated blocks of binaural beats, split by a short period of noise, can be observed as the stimulation goes along.

In this study, the effects of 7 Hz binaural beats on the power spectrum (absolute and relative) of EEG signals are investigated. For further analyses, we will also explore functional brain connectivity to see how brain synchronization will be affected by this stimulation. The rest of the paper is as follows: In Section 2 the experimental protocol is introduced, how EEG signals were recorded and how they were processed. In Section 3 the results of the study are reported. Data analysis and outcomes are discussed in Section 4 and in Section 5 a brief summary and conclusion are presented.

2. Methods

2.1. Subjects and EEG recordings

Fifteen healthy adult subjects (8 males, 7 females; 25.5 ± 3.5 years old) participated in this study. All participants were informed about the nature of the task and provided written consent. None of them reported any history of neurological disorders nor hearing problems. Subjects also participated in a hearing threshold test for a continuous pure tone of 200 Hz and none of them had any abnormal hearing. The protocol was approved by the Iran University of Medical Science.

EEG signals were recorded unilaterally from 19 active electrodes that were placed according to 10–20 system of electrode positioning with 512 Hz sampling frequency. The reference electrode was placed on the right earlobe. Active electrode impedances were verified <30 kΩ prior to data collection. All the recordings took place in the National Brain Mapping Lab (NBML) of Iran using g.HIamp device.

2.2. Experimental protocol

In order to study the effects of binaural beats on the human brain activities, two separate tones were presented to the participants. Pure sinusoidal tones of 200 Hz to the left ear, and 207 Hz to the right ear of the subjects were presented to origin the perception of 7 Hz which lies within the theta band. The effectiveness of binaural beats in the range of 100–300 Hz have already been tested in [26,30,35]; thus, 200 Hz was chosen as the main carrier frequency in this research. The tones were created and assembled in the Audacity® software (http://www.audacityteam.org) and were presented by an in-ear headphone as suggested in [36]. The volume of stimuli was set at 40 dB above the estimated hearing threshold of each subject.

The experiment consisted of 7 different blocks and lasted 15 min which is shown in detail in Fig. 1. Participants were instructed to have their eyes closed throughout the experiment. The first block consisted of 3 min of pink noise for the baseline recording (the Ctrl block) and it was followed up by 3 min of 7 Hz binaural beats (the BB1 block). To make the sound more pleasant for the subjects as suggested in [18,8], 10% of the stimuli consisted of a background pink noise. In order to prevent habituation of the subjects to the stimuli, 1 min of pink noise was presented in the third (PN1) block. The sequence of BB1 and PN1 was repeated two more times as BB2, PN2, BB3 and PN3 respectively. EEG signals were recorded during all 7 blocks.