Research Paper

# Investigating the Efficacy of Theta Binaural Beat on the Absolute Power of Theta Activity in Primary Insomniacs

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## ABSTRACT

**Introduction:** The brain waves pattern in primary insomniacs is different from healthy subjects. Studies have shown that binaural beats can alter the pattern of brain waves in healthy individuals; however, the efficacy of binaural beats in altering the pattern of brain waves in primary insomniacs has not yet been investigated. This study aims to evaluate the efficacy of theta binaural beat on the absolute power of theta activity in primary insomniacs.

**Methods:** This study was a randomized clinical trial with experimental and control groups. The primary insomniacs received theta binaural beats in the experimental group while the control group received white noise. Their brain waves were recorded by electroencephalogram for 25 min; the first 5 min was without stimulus (first block), the next was followed by 15 min of receiving stimulus (binaural beat or white noise), and the last 5 min without stimulus (fifth block). The Matlab software, version R2019a, EEGLAB toolbox, and SPSS software, version 24 were used to analyze the data.

**Results:** The absolute power of theta activity in the experimental group was significantly higher in the last block compared to the first block in all brain lobes ($P<0.05$). The largest changes in theta activity were in the temporal and parietal lobes, and the last one was in the prefrontal lobe. In the control group, none of the brain lobes showed significant differences in the last block compared to the first block.

**Conclusion:** Theta binaural beat can alter the absolute power of theta activity in primary insomniacs. The implications of the study are discussed.

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## Highlights

• Theta binaural beat can be effective in changing the brain wave pattern of primary insomniacs.

• The amount of changes in the absolute power of theta wave activity in different brain regions of primary insomniacs under the influence of theta binaural beat was not the same.

• The effect of theta binaural beat on temporal and parietal was higher than other brain areas, whereas the prefrontal and occipital had the least significant changes in the absolute power of theta activity.

## Plain Language Summary

Different people experience different brain waves based on the type of activity they do in their life at the same time. This brain wave pattern can change especially after a person decides to go to bed and experience an ideal sleep. Theta brain wave, which plays a role in important activities such as memory, deep relaxation, and day-dreaming, helps a person to change from wakefulness to sleep faster. Research literature has shown that people with insomnia have different brain waves than healthy people, especially in the theta brain wave. Accordingly, many interventions have been carried out to improve the sleep quality of these people and change their brain waves. It has been shown that binaural beat as a low-cost method based on sound waves, can change the brain waves of healthy people, but so far, no study has been done to investigate the effect of these sound waves (especially theta waves) on the brain waves of people with insomnia. The current study was conducted with the aim of investigating a non-invasive method (theta binaural beat) to improve the brain wave pattern of people suffering from insomnia. The findings of this study showed that theta binaural beat can be effective in changing the brain wave pattern of people suffering from insomnia.

## 1. Introduction

Sleep is a psycho-physiological and natural phenomenon associated with decreased consciousness toward the environment; however, this is not always the case. People with sleep problems experience this phenomenon differently. Insomnia is one of the most common of these problems. According to the diagnostic and statistical manual of mental disorders-5th Edition (DSM-5), insomnia is a complaint of inadequate or nonrestorative sleep with difficulties in onset, maintenance of early morning sleep, and wakefulness (Association, 2013), if not accompanied by significant psychiatric comorbidity and physical illness, it is known as primary insomnia (De Zambotti et al., 2011). The incidence of primary insomnia is about 2% to 4% and it imposes huge costs on the economy of any country (Ohayon et al., 2012). These cases indicate the need for further investigation of primary insomnia.

The electroencephalogram (EEG) activity of sleep and wakefulness can be calculated by power spectral density (PSD) at different frequencies or frequency bands (e.g. delta [0.5 to 4 Hz], theta [4 to 8 Hz], alpha [8 to 12 Hz], sigma [12 to 16 Hz], Beta I [16 to 20 Hz], and Beta II [20 to 30 Hz]). Several quantitative electroencephalographic (QEEG) studies have been performed to investigate arousal during sleep and wakefulness in people with insomnia (Appleton et al., 2019; Christensen et al., 2019; Kwan et al., 2018; McCloskey et al., 2019; Perrin et al., 2019; Tang et al., 2019) and various evidence, including increased beta (Fernandez-Mendoza et al., 2019; Lamarche & Ogilvie, 1997; Wołyńczyk-Gmaj & Szelenberger, 2011) and gamma (Knyazev, 2012; Makeig & Jung, 1996) at different stages of sleep and during wakefulness have been discussed. Other studies have also focused on cortical arousal and its association with insomnia and given that gamma, beta, and alpha frequencies in insomnia patients during the sleep-wake transition are higher compared to healthy individuals (Cervena et al., 2014; Figueredo-Rodriguez et al., 2009; Maes et al., 2014). Likewise, the prefrontal cortex and hindbrain connections have been identified as trigger areas in insomnia patients as they attempt to sleep (Corsi-Cabrera et al., 2017). In 2010, Tononi showed higher beta power and density in the frontal cortex and left-sided areas in insomnia patients than in healthy controls (Tononi, 2010). These studies showed that in the EEG structure of sleep and wakefulness in primary insomniacs, changes have been observed; therefore, they can be altered through specific interventions.

A range of interventions has been performed to improve sleep in insomniac patients, including medication and psychological interventions (Morin et al., 2007; Schroeck et al., 2016). These interventions are usually costly and have a slow and varied impact on sleep structure; however, there is a range of noninvasive interventions that can influence the pattern of brain waves at a lower cost. Binaural beats are among these interventions.

Binaural beats are illusions that can be considered a type of neurological or cognitive coordination (Turow & Lane, 2012; Vernon, 2009). When two tones with slightly different frequencies reach each ear, for example, a 335 Hz tone to the right ear and a 345 Hz tone to the left ear, mentally, a 10 Hz binaural is perceived. When listening to two different tones, most people hear only one tone that fluctuates in its frequency or loudness as a beat (Oster, 1973). Some researchers believe that the binaural beat responses occur in the right hemisphere (Draganova et al., 2007; Magezi & Krumbholz, 2010; Schwarz & Taylor, 2005) and some consider the responses dependent on the other hemisphere (Chakalov et al., 2014; Pratt et al., 2010). In addition, the areas of the brain that are activated during audio stimulation and cause this illusion are not fully understood. The binaural beat generates excitatory conditions that ultimately result in specific neural firing patterns in the inferior colliculus that can reflect a binaural beat (Hancock et al., 2017). Through this process, the pattern of the brain waves is entrained by the difference in the frequency of characteristics of the two heard tones (binaural beat). Numerous studies have investigated the effects of binaural beats on entrainment, such as mood (Perales et al., 2019), relaxation (Lee-Harris et al., 2018; Sharma et al., 2017), attention and memory (Beauchene et al., 2017; Colzato et al., 2017; Garcia-Argibay et al., 2017; Shekar et al., 2018), and other psycho-physical problems. However, their exact effect is still unknown. The beat frequency is important due to neural synchronization; therefore, beta waves are fast brainwaves that are associated with thinking, focusing, and processing information, alpha waves with relaxed attention, theta waves with memory, deep relaxation and day-dreaming and delta waves with deep sleep (Thatcher et al., 2009). This pattern of brain waves is important in exploring the state of consciousness (Murat et al., 2011) which is also seen in the structure of sleep. For example, a study by Abeln et al. (Abeln et al., 2014) investigated the effect of binaural beats on subjective sleep quality and the improvement of mental health in athletes. They were stimulated with binaural beats of about 2 to 8 Hz every night before bedtime for 8 weeks. The findings showed that the subjective's quality of wakefulness, sleep, and motivational state was significantly improved in the binaural group; however, it did not affect their physical state. In another study, Seifiala et al. examined the cumulative effects of the binaural beat of theta on brainpower and functional connectivity in 15 healthy subjects via EEG, the findings showed that the relative power of theta activity was significantly observed in parietal and temporal segments, but such effect was not observed in the prefrontal, frontal, and central areas. Besides, no significant change was observed in the absolute power of the different frequency bands in any area of the brain (Seifiala et al., 2018). These studies showed that binaural beats can alter the pattern of brain waves in healthy individuals but do not provide enough information concerning people with certain disorders, such as insomnia.

Based on the above information, regarding the impact of binaural beats on the EEG structure, and cognitive and psychological processes, we hypothesized that binaural beats could influence the brain wave structure of primary insomniacs as well as healthy individuals. Moreover, theta waves are associated with memory, deep relaxation, and day-dreaming, and it has been shown that before bedtime, the frequency of brain waves is gradually reduced (Finelli et al., 2000; Guerrero & Achermann, 2019). Accordingly, to achieve deep sleep (more delta wave activity), an individual must also experience theta frequency. As noted earlier, the impact of theta binaural beat is mostly seen on the parietal, temporal, and posterior cortical areas (Seifiala et al., 2018), which differs from cortical activity in primary insomniacs. These people experience over-stimulation in the prefrontal areas (Perrier et al., 2015). Yet, if binaural beats work to change the patterns of primary insomniac brainwaves, it will provide a scientific breakthrough for implementing a new, low-cost, non-invasive way to improve these people. This study aims to evaluate the efficacy of theta binaural beat on the absolute power of theta activity in primary insomniacs.

## 2. Materials and Methods

### Study participants

The statistical community consisted of people with primary insomnia who live in Kermanshah City, Iran. Based on inclusion and exclusion criteria, 31 adults with primary insomnia (15 females) were selected and evaluated (Table 1). The inclusion criteria were providing informed consent, diagnosis of insomnia in a clinical interview by a psychiatrist, insomnia severity score at the clinical level (ISI >15), severe neurological and psychiatric disorders, healthy physical and hearing status, abstinence from alcohol, and medication consumption 12 h before the intervention, no history of drug abuse, no cardiovascular problems, and no pregnancy in female participants. The exclusion criteria were any discomfort as a result of hearing the sounds and unwillingness to continue performing the protocol for any reason.

## Intervention protocol

Each participant was evaluated in two sessions. The first session was for diagnosing primary insomnia through the clinical interview of DSM-5, completing the insomnia severity index (ISI), as well as assessing the inclusion and exclusion criteria along with their willingness to participate in the study. The subjects were randomly divided into intervention and control groups. The randomization method was that participants were asked to choose one of two closed envelopes that contained experimental or control words. In the second session (intervention session), as the baseline, the participants were at first evaluated by EEG for 5 min with closed eyes. Then, they were stimulated with theta binaural beat or white noise for 15 min (with closed eyes), during that time, the EEG was recorded. Finally, 5 min after the intervention, EEG was again recorded without any binaural beat and white noise. All participants were assessed at the same time of day (11:00 AM). Based on research blocks, EEG recording changes were compared. The intervention protocol consisted of 5 blocks as shown in Table 1. The experimental group received binaural beats in the theta frequency range. Accordingly, binaural beat stimulation for this study was specifically designed through Audacity software, version 3.3.3 (created by Audacity team) and provided through headphones recommended by Light et al. (Light et al., 2010). A 250 Hz carrier tone to the right ear and a 256 Hz offset tone to the left ear of the participants in the experimental group were presented and the impact of 6 Hz binaural beat (in the theta domain) was investigated. The control group received white noise. White noises are random signals with the same intensity at different frequencies (Carter & Mancini, 2017). It is a statistical model for signals and their sources rather than any specific (e.g. theta) signal (Stein, 2012). Other studies have also used this type of signal as a placebo intervention (Coull et al., 2004; Davidson & Smith, 1991; Terzano et al., 1988). The method of data recording and research blocks are shown in Table 1.

## Electroencephalographic processing

The recording time for EEG signals was 25 min for each participant. According to specific criteria, the signals were collected in 5 min intervals. These include clear signals without noise, artifacts, and blinking effects. Components associated with direct current power fluctuations were eliminated by a 1-hertz high-pass at zero-phase butterworth filter. The fast fourier transform was performed to convert the signal from the time domain to the frequency domain. The absolute power of the theta activity was also used for statistical analysis, which was performed by the Matlab software, version R2019a and the EEGLAB toolbox. The cortical areas and their associated channels are shown in Table 2.

## Statistical analysis

The data were analyzed using SPSS software, version 24. Before performing any other statistical tests, the data were assumed to be normal according to the Kolmogorov-Smirnov test ($P>0.05$). The chi-square test was used to compare the number (frequency) of the two experimental and control groups. The independent t-test was also used to examine the differences between the two groups in terms of mean age. The dependent t-test was also used to compare the Mean+SD of the absolute power of theta activity in the experimental and control groups as well as to find significant differences between the electrodes in different blocks and also compared them to the pre-test.

## Research tools

### Insomnia severity index

ISI is a standard inventory that measures the severity of insomnia in the past 2 weeks and has 5 questions. The minimum and maximum scores are also between 0 and

**Table 1.** Research blocks and how to record data

| Before Intervention 5 min | Pure Theta Binaural Beat | | | After Intervention |
|---|---|---|---|---|
| | 1st 5 min | 2nd 5 min | 3rd 5 min | |
| Block 1 | Block 2 | Block 3 | Block 4 | Block 5 |
| | White noise without binaural beat | | | |

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**Table 2.** Cortical areas of the brain and its associated channels (in 5 min)

| Cortical Areas | Channels |
|---|---|
| Prefrontsl | Fp1, Fp2, F7, F8 |
| Frontal | F3, Fz, F4 |
| Central | C3, Cz, C4 |
| Temporal | T3, T4, T5, T6 |
| Parietal | P3, Pz, P4 |
| Occipital | O1, O2 |

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28 (Yazdi et al., 2012). A score of 0 to 7 indicates no significant insomnia, 8 to 14 below the clinical threshold, 15 to 21 moderate clinical insomnia, and a score of 22 to 28 indicates severe clinical insomnia. This test was first presented and used by Morin et al. Its construct validity was 0.72 and its reliability with the Cronbach α method was 0.74 and 0.78 (Bastien et al., 2001; Yazdi et al., 2012).

### Electroencephalography

EEG is a physiological way of recording the electrical activity produced by the brain. It is done by placing electrodes on the surface of the scalp. EEG signals which were used in this study were produced from 19 active electrodes based on the 10-20 system overhead with a sampling frequency of 512 Hz (Seifiala et al., 2018).

## 3. Results

Out of 31 participants, 15 were female. According to Table 3, no significant difference was observed between the mean age of men and women who participated in this study. There was also no significant difference between the two groups regarding the mean age and frequency of male and female participants (P>0.05). Meanwhile, no significant difference was detected between the two groups in terms of severity of insomnia (P>0.05).

Table 4 presents the comparison of the absolute power of theta activity in the experimental and control groups. According to this table, the absolute power of theta activity in the experimental group who received theta binaural beat was significantly higher in the last block, compared to the first block, in all brain lobes (P<0.05). The largest changes in theta activity were in the temporal and parietal lobes, and the least was in the prefrontal lobe. In the control group, none of the brain lobes showed significant differences in the last block compared to the first block.

Table 5 shows the exact position of the electrodes that showed a significant difference in the experimental group compared to the first block (pre-test) based on the mean of the absolute power of theta activity. This table clearly shows specific areas of the brain that have undergone

**Table 3.** Demographic characteristics of the participants

| Parameters | | Mean/No. (%) | | P |
|---|---|---|---|---|
| | | Experimental | Control | |
| Age (y) | | 26.88±3.01 | 27.01±2.97 | 0.24 |
| Male | | 26.24±3.44 | 26.58±3.37 | 0.44 |
| Female | | 27.87±2.04 | 28.03±2.15 | 0.10 |
| Gender | Male | 8(50) | 8(53.33) | 0.09 |
| | Female | 8(50) | 7(46.67) | |
| Insomnia severity | | 17.24±1.44 | 17.19±1.19 | 0.14 |

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**Table 4.** Comparison of Mean+SD of absolute power of theta activity in experimental and control groups

| Brain Area | Experimental | | | Control | | |
|---|---|---|---|---|---|---|
| | Mean±SD | | P | Mean±SD | | P |
| | Pre-test | Post-test | | Pre-test | Post-test | |
| Prefrontal | 5.3349±1.7339 | 6.0704±1.0231 | 0.0122 | 5.6542±1.6959 | 5.2314±1.6959 | 0.1192 |
| Frontal | 6.7862±1.5935 | 8.5423±1.222 | 0.0101 | 6.6956±1.5828 | 6.6399±1.4725 | 0.2611 |
| Central | 6.4475±1.5699 | 8.8912±1.9761 | 0.0078 | 6.0998±1.5003 | 6.1294±1.4974 | 0.1831 |
| Temporal | 6.9985±1.0955 | 9.9238±2.0988 | 0.0038 | 6.7684±1.1645 | 6.7998±1.1998 | 0.1715 |
| Parietal | 6.7999±1.2979 | 9.4329±2.1249 | 0.0048 | 6.7819±1.1995 | 6.8015±1.1872 | 0.2110 |
| Occipital | 6.2241±1.5565 | 7.2453±1.2987 | 0.0119 | 6.3999±1.3997 | 6.4798±1.4476 | 0.0912 |

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significant changes in the absolute power of theta activity in each brain lobe and block of research. Accordingly, the third block of the study showed the most changes in the levels of the electrodes, while in the second block, none of the electrodes showed any significant difference.

## 4. Discussion

This study aimed to investigate the efficacy of theta binaural beat in altering the pattern of the absolute power of theta activity in primary insomniacs. The findings of this study indicated the theta binaural beat's effect on all brain lobes compared to the pre-test (block 1), along with altering the absolute power of theta activity. However, white noise did not affect any of the brain lobes. Seifiala et al. (2018) investigated the cumulative effects of binaural beats of theta on brain power and functional connectivity in healthy subjects through an EEG (Seifiala et al., 2018). According to their findings, although the relative power of theta activity changes in parietal, temporal, and occipital lobes was significant; however, it was not in anterior, frontal, and central areas. No significant changes were observed in the absolute power of different frequency bands in any parts of the brain in healthy subjects. These results are not in line with the present study. Some of the most important factors that explain this conflict in findings are the differences in the design of intervention protocol, statistical community, and binaural beat music which was used in two studies. On one hand, the 7-Hz binaural beat which was used in Seifiala et al. research was combined with 10% pink noise and presented to participants at different times. On the other hand, the statistical population of the two studies was also different, which should have an important impact.

As previously mentioned, the pattern of brain waves in primary insomniacs was different from healthy subjects. Corsi-Cabrera et al. in 2016 showed that primary insomniacs experience more arousal in the anterior and posterior brain regions, which was distinctly different from healthy subjects (Corsi-Cabrera et al., 2016). The present study strongly showed that although the degree of changes in the absolute power of theta activity was not the same in different regions, primary insomniacs

**Table 5.** Cortical positions that showed a significant difference (P<0.05) in the absolute power of theta activity in the experimental group in each block compared to the pre-test based on the dependent t-test (block 1)

| Research Blocks | Electrode Positions |
|---|---|
| 2 | - |
| 3 | Fp1, Fp2, F3, F4, F7, Fz, C3, Cz, P3, P4, Pz, O1, O2 |
| 4 | Fp1, Fp2, F3, F4, F7, Fz, Cz, P3, P4, Pz, O1, O2 |
| 5 | Fp2, F7, F3, F4, Fz, Cz, P4, O2 |

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were significantly influenced by theta binaural beats in all areas of the brain. This inequality of effect is a confirmation of the hypothesis that different areas of the brain are affected by different frequencies (Laufs et al., 2003). Meanwhile, the efficacy of theta binaural beats on primary insomniacs is differentiated from healthy subjects (Seifiala et al., 2018).

The effect of theta binaural beat on temporal and parietal areas was higher than other brain segments, whereas the prefrontal and occipital regions had the least significant changes in the absolute power of theta activity. Also, the electrode's significant changes in the absolute power of theta activity compared to the first block of research (pre-test) confirm this result. On the other hand, a study by Wołyńczyk-Gmaj and Szelenberger investigated wake EEG in insomnia patients and found that the density of beta waves in different brain areas was higher than in good sleepers (Wołyńczyk-Gmaj & Szelenberger, 2011). Beta waves are at a frequency of at least 16 Hz and are responsible for thinking concentration, and processing of information, and are in high exact density when insomniacs want to go to sleep [Sleep-onset] (Fernandez-Mendoza et al., 2019; Lamarche & Ogilvie, 1997). In good sleepers, while falling asleep, the frequencies of the brain waves gradually decrease, thereby passing through the surface of theta waves to the delta (Guerrero & Achermann, 2019). Theoretically, primary insomniacs tend to process and concentrate on everyday information when trying to calm their attention, achieve deep relaxation and day-dreaming (Carciofo et al., 2017; Nie et al., 2015). In the present study, it has been shown that theta binaural beat can alter the pattern of brain waves in these areas in line with the major activity of beta waves.

## 5. Conclusion

Based on the data obtained from EEG in primary insomniacs and considering the limitations, the present study has two major implications: 1) Theta binaural beat through entrainment can alter the absolute power of theta activity in primary insomniacs; 2) The theta binaural beat can probably affect information processing and relaxation when people try to sleep (sleep-onset).

### Study limitations

Following, the limitations of the study are explained. Since the study participants were primary insomniacs and were taking medication at the time of diagnosis, the type and dose of the medication were not controlled. In future studies, it is recommended that primary insomniacs be screened for the same type and dose of the medication. The small sample size was another limitation; therefore, to generalize the findings of this study, it is recommended to use a larger sample size in future studies. Due to the high cost of data recording, the analysis of the least valid and reliable sample size was used. Yet, it was not possible to investigate changes in subcortical tissue and function through sophisticated brain imaging modalities, such as positron emission tomography, polysomnography, or functional magnetic resonance imaging.

## Ethical Considerations

### Compliance with ethical guidelines

This study was a randomized controlled trial with control and experimental groups. The participants were informed about the research process and conditions and completed the informed consent form. All research data were kept confidential and the results were debriefed for the subjects at the end. Finally, after completing the intervention process in two groups, the binaural beat music at different frequencies was made available to all participants. This study was approved by the Ethics Committee of Kermanshah University of Medical Sciences (Code: IR.KUMS.REC.1397.771) and Iranian Registry of Clinical Trials (Code: IRCT20180205038630N3).

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### Authors' contributions

All authors contributed equally to preparing this article.

### Conflict of interest

The authors declared no conflict of interest.

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## References

Abeln, V., Kleinert, J., Strüder, H. K., & Schneider, S. (2014). Brainwave entrainment for better sleep and post-sleep state of young elite soccer players-A pilot study. *European Journal of Sport Science, 14*(5), 393-402. [DOI:10.1080/17461391.2013.819384] [PMID]

Seifiala, T. S., Ahmadi-Pajouh, M. A., & Nasrabadi, A. M. (2018). Cumulative effects of theta binaural beats on brain power and functional connectivity. *Biomedical Signal Processing and Control, 42*, 242-252. [DOI:10.1016/j.bspc.2018.01.022]

Appleton, S. L., Vakulin, A., D'Rozario, A., Vincent, A. D., Teare, A., & Martin, S. A., et al. (2019). Quantitative electroencephalography measures in rapid eye movement and nonrapid eye movement sleep are associated with apnea-hypopnea index and nocturnal hypoxemia in men. *Sleep, 42*(7), zsz092. [DOI:10.1093/sleep/zsz092] [PMID]

Guha, M. (2013). Diagnostic and statistical manual of mental disorders (DSM-5®). *Reference Reviews, 28*(3), 36-37. [DOI:10.1108/RR-10-2013-0256]

Bastien, C. H., Vallières, A., & Morin, C. M. (2001). Validation of the Insomnia Severity Index as an outcome measure for insomnia research. *Sleep Medicine, 2*(4), 297-307. [DOI:10.1016/S1389-9457(00)00065-4] [PMID]

Beauchene, C., Abaid, N., Moran, R., Diana, R. A., & Leonessa, A. (2017). The effect of binaural beats on verbal working memory and cortical connectivity. *Journal of Neural Engineering, 14*(2), 026014. [DOI:10.1088/1741-2552/aa5d67] [PMID]

Carciofo, R., Song, N., Du, F., Wang, M. M., & Zhang, K. (2017). Metacognitive beliefs mediate the relationship between mind wandering and negative affect. *Personality and Individual Differences, 107*, 78-87. [DOI:10.1016/j.paid.2016.11.033]

Carter, B., & Mancini, R. (2003). *Op Amps for everyone*. Amsterdam: Elsevier Science. [Link]

Cervena, K., Espa, F., Perogamvros, L., Perrig, S., Merica, H., & Ibanez, V. (2014). Spectral analysis of the sleep onset period in primary insomnia. *Clinical Neurophysiology, 125*(5), 979-987. [DOI:10.1016/j.clinph.2013.10.010] [PMID]

Chakalov, I., Paraskevopoulos, E., Wollbrink, A., & Pantev, C. (2014). Mismatch negativity to acoustical illusion of beat: How and where the change detection takes place? *Neuroimage, 100*, 337-346. [DOI:10.1016/j.neuroimage.2014.06.026] [PMID]

Christensen, J. A. E., Wassing, R., Wei, Y., Ramautar, J. R., Lakbila-Kamal, O., & Jennum, P. J., et al. (2019). Data-driven analysis of EEG reveals concomitant superficial sleep during deep sleep in insomnia disorder. *Frontiers in Neuroscience, 13*, 598. [DOI:10.3389/fnins.2019.00598] [PMID] [PMCID]

Colzato, L. S., Barone, H., Sellaro, R., & Hommel, B. (2017). More attentional focusing through binaural beats: Evidence from the global-local task. *Psychological Research, 81*(1), 271-277. [DOI:10.1007/s00426-015-0727-0] [PMID] [PMCID]

Corsi-Cabrera, M., Rojas-Ramos, O. A., & del Río-Portilla, Y. (2016). Waking EEG signs of non-restoring sleep in primary insomnia patients. *Clinical Neurophysiology, 127*(3), 1813-1821. [DOI:10.1016/j.clinph.2015.08.023] [PMID]

Coull, J. T., Jones, M. E., Egan, T. D., Frith, C. D., & Maze, M. (2004). Attentional effects of noradrenaline vary with arousal level: selective activation of thalamic pulvinar in humans. *Neuroimage, 22*(1), 315-322. [DOI:10.1016/j.neuroimage.2003.12.022] [PMID]

Davidson, R. A., & Smith, B. D. (1991). Caffeine and novelty: Effects on electrodermal activity and performance. *Physiology & Behavior, 49*(6), 1169-1175. [DOI:10.1016/0031-9384(91)90346-P] [PMID]

de Zambotti, M., Covassin, N., De Min Tona, G., Sarlo, M., & Stegagno, L. (2011). Sleep onset and cardiovascular activity in primary insomnia. *Journal of Sleep Research, 20*(2), 318-325. [DOI:10.1111/j.1365-2869.2010.00871.x] [PMID]

Draganova, R., Ross, B., Wollbrink, A., & Pantev, C. (2008). Cortical steady-state responses to central and peripheral auditory beats. *Cerebral Cortex, 18*(5), 1193-1200. [DOI:10.1093/cercor/bhm153] [PMID]

Fernandez-Mendoza, J., Li, Y., Fang, J., Calhoun, S. L., Vgontzas, A. N., & Liao, D., et al. (2019). Childhood high-frequency EEG activity during sleep is associated with incident insomnia symptoms in adolescence. *Journal of Child Psychology and Psychiatry, 60*(7), 742-751. [DOI:10.1111/jcpp.12945] [PMID] [PMCID]

Figueredo-Rodríguez, P., del Río-Portilla, Y., Sánchez-Romero, J. I., Pérez-Ortiz, A., & Corsi-Cabrera, M. (2009). Frontal alpha activity in primary insomniacs with sleep onset difficulties. *Salud Mental, 32*(1), 59-67. [Link]

Finelli, L. A., Baumann, H., Borbély, A. A., & Achermann, P. (2000). Dual electroencephalogram markers of human sleep homeostasis: Correlation between theta activity in waking and slow-wave activity in sleep. *Neuroscience, 101*(3), 523-529. [DOI:10.1016/S0306-4522(00)00409-7] [PMID]

Garcia-Argibay, M., Santed, M. A., & Reales, J. M. (2017). Binaural auditory beats affect long-term memory. *Psychological Research, 83*(6), 1124–1136. [DOI:10.1007/s00426-017-0959-2] [PMID]

Fernandez Guerrero, A., & Achermann, P. (2018). Brain dynamics during the sleep onset transition: An EEG source localization study. *Neurobiology of Sleep and Circadian Rhythms, 6*, 24-34. [DOI:10.1016/j.nbscr.2018.11.001] [PMID] [PMCID]

Hancock, K. E., Chung, Y., McKinney, M. F., & Delgutte, B. (2017). Temporal envelope coding by inferior colliculus neurons with cochlear implant stimulation. *Journal of the Association for Research in Otolaryngology, 18*(6), 771-788. [DOI:10.1007/s10162-017-0638-4] [PMID] [PMCID]

Knyazev, G. G. (2012). EEG delta oscillations as a correlate of basic homeostatic and motivational processes. *Neuroscience & Biobehavioral Reviews, 36*(1), 677-695. [DOI:10.1016/j.neubiorev.2011.10.002] [PMID]

Kwan, Y., Baek, C., Chung, S., Kim, T. H., & Choi, S. (2018). Resting-state quantitative EEG characteristics of insomniac patients with depression. *International Journal of Psychophysiology, 124*, 26-32. [DOI:10.1016/j.ijpsycho.2018.01.005] [PMID]

Lamarche, C. H., & Ogilvie, R. D. (1997). Electrophysiological changes during the sleep onset period of psychophysiological insomniacs. Psychiatric insomniacs, and normal sleepers. *Sleep, 20*(9), 726-733. [DOI:10.1093/sleep/20.9.726]

Laufs, H., Krakow, K., Sterzer, P., Eger, E., Beyerle, A., & Salek-Haddadi, A., et al. (2003). Electroencephalographic signatures of attentional and cognitive default modes in spontaneous brain activity fluctuations at rest. *Proceedings of the National Academy of Sciences of the United States of America, 100*(19), 11053–11058. [DOI:10.1073/pnas.1831638100] [PMID] [PMCID]

Lee-Harris, G., Timmers, R., Humberstone, N., & Blackburn, D. (2018). Music for relaxation: A comparison across two age groups. *Journal of Music Therapy, 55*(4), 439-462. [DOI:10.1093/jmt/thy016] [PMID]

Light, G. A., Williams, L. E., Minow, F., Sprock, J., Rissling, A., & Sharp, R., et al. (2010). Electroencephalography (EEG) and event-related potentials (ERPs) with human participants. *Current Protocols in Neuroscience, Chapter 6,* Unit–6.25.24. [PMID] [PMCID]

Maes, J., Verbraecken, J., Willemen, M., De Volder, I., van Gastel, A., & Michiels, N., et al. (2014). Sleep misperception, EEG characteristics and autonomic nervous system activity in primary insomnia: A retrospective study on polysomnographic data. *International Journal of Psychophysiology, 91*(3), 163-171. [DOI:10.1016/j.ijpsycho.2013.10.012] [PMID]

Magezi, D. A., & Krumbholz, K. (2010). Evidence for opponent-channel coding of interaural time differences in human auditory cortex. *Journal of Neurophysiology, 104*(4), 1997-2007. [DOI:10.1152/jn.00424.2009] [PMID] [PMCID]

Makeig, S., & Jung, T. P. (1996). Tonic, phasic, and transient EEG correlates of auditory awareness in drowsiness. *Brain Research. Cognitive Brain Research, 4*(1), 15–25. [DOI:10.1016/0926-6410(95)00042-9] [PMID]

McCloskey, S., Jeffries, B., Koprinska, I., Miller, C. B., & Grunstein, R. R. (2019). Data-driven cluster analysis of insomnia disorder with physiology-based qEEG variables. *Knowledge-Based Systems, 183,* 104863 [DOI:10.1016/j.knosys.2019.07.034]

Morin, A. K., Jarvis, C. I., & Lynch, A. M. (2007). Therapeutic options for sleep-maintenance and sleep-onset insomnia. *Pharmacotherapy, 27*(1), 89–110. [DOI:10.1592/phco.27.1.89] [PMID]

Murat, Z. H., Taib, M. N., Kadir, R. S. S. A., Jahidin, A. H., Lias, S., & Isa, R. M. (2011). *Comparison between the left and the right brainwaves for delta and theta frequency band after horizontal rotation intervention.* Paper presented at: 2011 Third International Conference on Computational Intelligence, Communication Systems and Networks, Bali, Indonesia, 26-28 July 2011. [DOI:10.1109/CICSyN.2011.83]

Nie, X., Shao, Y., Liu, S. Y., Li, H. J., Wan, A. L., & Nie, S., et al. (2015). Functional connectivity of paired default mode network subregions in primary insomnia. *Neuropsychiatric Disease and Treatment, 11,* 3085–3093. [DOI:10.2147/NDT.S95224] [PMID] [PMCID]

Ohayon, M. M., Riemann, D., Morin, C., & Reynolds, C. F., 3rd (2012). Hierarchy of insomnia criteria based on daytime consequences. *Sleep Medicine, 13*(1), 52-57. [DOI:10.1016/j.sleep.2011.06.010] [PMID] [PMCID]

Oster, G. (1973). Auditory beats in the brain. *Scientific American, 229*(4), 94-102. [DOI:10.1038/scientificamerican1073-94] [PMID]

Perales, F. J., Sanchez, M., & Ramis, S. (2019). *A mood modulation using virtual reality and binaural sounds.* Proceedings of the XX International Conference on Human Computer Interaction, New York, USA. [Link]

Perrier, J., Clochon, P., Bertran, F., Couque, C., Bulla, J., & Denise, P., et al. (2015). Specific EEG sleep pattern in the prefrontal cortex in primary insomnia. *PloS One, 10*(1), e0116864. [DOI:10.1371/journal.pone.0116864] [PMID] [PMCID]

Perrin, S. L., Jay, S. M., Vincent, G. E., Sprajcer, M., Lack, L., & Ferguson, S. A., et al. (2019). Waking qEEG to assess psychophysiological stress and alertness during simulated on-call conditions. *International Journal of Psychophysiology, 141,* 93-100. [DOI:10.1016/j.ijpsycho.2019.04.001] [PMID]

Pratt, H., Starr, A., Michalewski, H. J., Dimitrijevic, A., Bleich, N., & Mittelman, N. (2010). A comparison of auditory evoked potentials to acoustic beats and to binaural beats. *Hearing Research, 262*(1-2), 34-44. [DOI:10.1016/j.heares.2010.01.013] [PMID]

Schroeck, J. L., Ford, J., Conway, E. L., Kurtzhalts, K. E., Gee, M. E., & Vollmer, K. A., et al. (2016). Review of safety and efficacy of sleep medicines in older adults. *Clinical Therapeutics, 38*(11), 2340-2372. [DOI:10.1016/j.clinthera.2016.09.010] [PMID]

Schwarz, D. W., & Taylor, P. (2005). Human auditory steady state responses to binaural and monaural beats. *Clinical Neurophysiology, 116*(3), 658-668. [DOI:10.1016/j.clinph.2004.09.014] [PMID]

Sharma, S., Rewadkar, S., Pawar, H., Deokar, V., & Lomte, V. M. (2017). *Survey on binaural beats and background music for increased focus and relaxation.* Paper presented at: 2017 International Conference on Emerging Trends & Innovation in ICT (ICEI), Pune, India, 03-05 February 2017. [Link]

Shekar, L., Suryavanshi, C. A., & Nayak, K. R. (2018). Effect of alpha and gamma binaural beats on reaction time and short-term memory. *National Journal of Physiology, Pharmacy and Pharmacology, 8*(6), 829-833. [DOI:10.5455/njppp.2018.8.1246506022018]

Stein, M. L. (2012). *Interpolation of spatial data: Some theory for kriging.* New York: Springer. [Link]

Tang, H. J., McCurry, S. M., Riegel, B., Pike, K. C., & Vitiello, M. V. (2019). Open-loop audiovisual stimulation induces delta EEG activity in older adults with osteoarthritis pain and insomnia. *Biological Research for Nursing, 21*(3), 307-317. [DOI:10.1177/1099800419833781] [PMID] [PMCID]

Terzano, M. G., Parrino, L., Fioriti, G., Farolfi, A., Spaggiari, M. C., & Anelli, S., et al.(1988). Variations of cyclic alternating pattern rate and homeostasis of sleep organization: A controlled study on the effects of white noise and zolpidem. *Pharmacology Biochemistry and Behavior, 29*(4), 827-829. [DOI:10.1016/0091-3057(88)90218-3] [PMID]

Thatcher, R. W.(2009). EEG evaluation of traumatic brain injury and EEG biofeedback treatment. *Introduction to Quantitative EEG and Neurofeedback (Second Edition),* 269-294 [DOI:10.1016/B978-0-12-374534-7.00011-3]

Tononi, G. (2010). Information integration: Its relevance to brain function and consciousness. *Archives Italiennes de Biologie, 148*(3), 299-322. [PMID]

Turow, G., & Lane, J. D. (2012). Binaural beat stimulation: Altering Vigilance and mood states. In J. Berger, & G. Turow (Eds.), *Music, science, and the rhythmic brain: Cultural and clinical implications* (pp. 131-145). New York: Routledge. [Link]

Vernon, D. (2009). *Human potential: Exploring techniques used to enhance human performance*. Oxfordshire: Taylor & Francis. [Link]

Wołyńczyk-Gmaj, D., & Szelenberger, W. (2011). Waking EEG in primary insomnia. *Acta Neurobiol Exp, 71*, 387-392. [Link]

Yazdi, Z., Sadeghniiat-Haghighi, K., Zohal, M. A., & Elmizadeh, K. (2012). Validity and reliability of the Iranian version of the Insomnia Severity Index. *The Malaysian Journal of Medical Sciences, 19*(4), 31-36. [Link]