Rajeswari *et al.*
BioMedical Engineering OnLine (2025) 24:45
https://doi.org/10.1186/s12938-025-01382-9

BioMedical Engineering OnLine

RESEARCH

Open Access

Music interventions and obstructive sleep apnea: a brain connectivity analysis

J. Rajeswari[1], S. Navaneethan[2], P. Siva Satya Sreedhar[3] and M. Jagannath[4*]

*Correspondence:
jagan.faith@gmail.com

[1] Department of Biomedical Engineering, Agni College of Technology, Chennai, Tamil Nadu, India
[2] Department of Electronics and Communication Engineering, Saveetha Engineering College, Chennai, Tamil Nadu, India
[3] Department of Information Technology, Seshadri Rao Gudlavalleru Engineering College, Krishna District, Andhra Pradesh, India
[4] School of Electronics Engineering, Vellore Institute of Technology (VIT), Chennai 600127, India

Abstract

Background: The blockage in the upper airway that occurs, while sleeping is represented as obstructive sleep apnea (OSA). This seem to be a major issue which cause breathing difficulties also increases the risk of severe complications, such as heart attacks and strokes. Therefore, in this proposed study the impact of OSA using brain connectivity analysis under various conditions such as Neelambari, Kapi, and no music has been investigated. The electroencephalogram (EEG) recordings of twelve subjects were acquired in two different conditions, such as listening to music 1 and 2 (Neelambari and Kapi) and the absence of music. The raw EEG signals were then preprocessed using both bandpass and notch filters. Meanwhile, the EEG sub-bands were obtained using the wavelet packet decomposition (WPD) method. These sub-bands, including delta, theta, alpha, and beta, were used for brain connectivity analysis. This approach provides the visualization of frequency-specific regional brain connectivity patterns by applying Pearson Correlation to the absolute values of the detail coefficients from WPD using a graph theory metric, node strength.

Results: Increased connectivity in the right hemisphere of the brain was observed among the nodes in the frontal and temporal regions (F8, FC6, and T8) when participants listened to Neelambari music (Music 1). In the beta band, the correlation values for Neelambari music ranged from a minimum of 0.943 to a maximum of 0.998. In the delta band, positive correlation values ranged from 0.945 (minimum) to 0.999 (maximum). The alpha and theta bands exhibited moderate correlations, ranging from 0.746 (minimum) to 0.996 (maximum). Compared to Kapi music, Neelambari music showed stronger neural synchronization, evidenced by consistently higher correlation values across all frequency bands. This increased connectivity suggests that Neelambari music may profoundly impact brain dynamics, potentially enhancing cognitive or physiological responses.

Conclusions: In conclusion, it has been analyzed that OSA patients have positive brain connectivity while listening to music 1 (Neelambari).

Keywords: Brain connectivity analysis, Obstructive sleep apnea, Electroencephalogram, Wavelet packet decomposition, Kapi music, Neelambari music

Introduction

The Greek term sleep apnea is classified into three types: obstructive sleep apnea (OSA), central sleep apnea (CSA), and mixed sleep apnea. OSA is a condition in which breathing momentarily stops during sleep, and it is known as the most critical sleep disorder [1]. Tiredness and snoring seem to be the major symptoms of OSA, which occurs during the day after missing a night's sleep. The other symptoms of OSA have an impact on cognitive, emotional, and physical health. The prevalence of cognitive impairments are memory deficiencies, poor executive function, problems with attention and mental control. The emotional problems are also prominent, such as poor emotional regulation and increased anxiety. Sleep fragmentation is another indicator of OSA includes sleep cycles, limits restorative slow-wave sleep, and contributes to fatigue and impaired cognitive performance [2]. In addition, OSA is the cause of anatomical and functional problems in significant brain regions related to emotion and cognition, such as the frontal, temporal, and subcortical. Early prevention is necessary when the aforementioned issue does not interfere with day-to-day activities and increases the risk of neurological disorders such as dementia. Benjafield et al. [3] reported that worldwide estimates of adults with mild to severe OSA are 936 million. Untreated OSA leads the major health issues in the heart, kidney, and metabolism. Polysomnography (PSG), the conventional approach was used to diagnose OSA using the physiological signals, such as electromyogram (EMG), electroencephalogram (EEG), electrooculogram (EOG), electrocardiogram (ECG), airflow, oxygen saturation, and respiratory movement. Another method for diagnosing OSA to reduce the time and cost associated with this conventional PSG approach was validated questionnaires [4].

In addition, positive airway pressure (PAP), a special medical equipment was used for treating all people with OSA. However, when using a PAP device patients may feel nasal congestion, dryness in the pharynx and nose, or ocular irritation from air leaks. As a result, mouth appliances such as the mandibular advancement device may be helpful for patients who cannot endure PAP therapy. A more time and money-consuming alternative therapeutic option for certain patients with OSA may be jaw, palate, or nasal surgery [5–7]. Numerous research studies have established that pleasant music can enhance sleep quality for OSA patients. A study discovered that music did not significantly improve sleep initiation (latency); it considerably reduced time spent in light sleep (stage II) and increased deep sleep in the long-sleep latency group. This implies that sedative music could improve the sleep quality of persons who struggle to fall asleep quickly [8]. According to a meta-analysis, music can successfully enhance sleep quality for people with sleep complaints, regardless of whether they have co-occurring medical issues. That analysis discovered a moderately favorable effect of music-assisted relaxation [9]. Another investigation summarized the possible advantages of background music in promoting sleep quality in young children. It emphasizes that relaxing music can assist youngsters in falling asleep sooner and achieving more profound, more restful sleep.

The study, which looked at the sleep patterns of elementary school-aged children, found that some types of background music can increase sleep duration, minimize night awakenings, and overall sleep quality [10]. Few studies have revealed useful information about how the use of Neelambari and Kapi music can increase sleep quality and cognitive function in people with OSA. The existing literature on music therapy and brain connectivity yields promising outcomes. Most South Indian lullabies are based on Neelambari music, which was the subject of an earlier study by Gitanjali [11] on improving sleep quality. The time-consuming PSG approach was alternated with the introduction of questionnaire-based investigations, and OSA diagnosis accuracy increased. Adalarasu et al. [12] used the Epworth sleepiness scale questionnaire to diagnose patients with sleep disorders. Then, Carnatic music such as Kapi, Kalyani, and Neelamabari were used to detect increased attention and arousal. The improvement was seen by the OSA while listening to Kapi music. For instance, in patients with OSA, the intervention might reduce sleep fragmentation or improve oxygen saturation levels. Studies on brain connectivity in OSA patients have highlighted the regions affected and emphasized the importance of interventions to improve sleep quality.

Cordi et al. [13] propounded that relaxing music improves the low/high-frequency ratio, which describes listening to music before a 90-min nap produced the most significant increases in subjective and objective sleep parameters The specific characteristics of sleep include an improvement in the low/high-frequency power ratio, a reduction in the duration of light sleep at stage N1, and an increase in slow-wave sleep. Although patients with OSA may not always experience sleep deprivation in a clinical sense, they commonly exhibit symptoms, such as fragmented sleep, poor sleep quality, and excessive daytime drowsiness. These findings suggest that relaxing music can positively influence sleep quality by promoting more profound, restorative sleep. Alluri et al. [14] determined the brain networks of musicians and non-musicians using a graphical method. The auditory cortex, emotion, attention, and processing have all been positively correlated with early-trained musicians. While the major hubs of non-musicians are located in the left and parietal hemisphere temporal areas, the sensorimotor regions of the musicians were activated during passive listening to music. Another survey by Melek et al. [15] highlighted how listening to brainwave music designed to promote slow-wave sleep improves synchronization in the delta and theta bands, improving sleep quality. The discussed literature offers insights into leveraging music to enhance sleep quality while highlighting its modulatory effects on brain regions during auditory experiences.

Another key aspect of this study is visualizing changes in brain activity with and without music using regional brain connectivity analysis. Several studies have demonstrated the effectiveness of brain connectivity analysis and transform-based methods for signal decomposition. These approaches have been widely used to examine functional connectivity and network properties across various neurological conditions. Acevedo et al. [16] investigated 6-week yoga practice on participants and applied discrete wavelet transform (DWT) to fMRI time-series data, decomposing the signals into different frequency components. Low-frequency fluctuations in wavelet scale 2 (~ 0.06–0.13 Hz) were extracted to estimate functional connectivity. Finally, the zero-order Pearson correlation was computed between all pairs of regional time-series data, resulting in 415×415 functional connectivity matrices for each participant. Another study investigated the relationship between insomnia and depressive status in postpartum women, leveraging functional near-infrared spectroscopy to examine brain network topological properties by extracting time series data using photodetectors.

Pearson correlation analysis was then applied to these time series data to compute the correlation coefficient between each pair of brain regions, resulting in the correlation coefficient matrix [17]. Seshadri et al. [18] analyzed the distinct functional changes in brain networks of dyslexic children during arithmetic task performance using EEG. Wavelet packet decomposition (WPD) was employed to process the EEG signals, followed by brain connectivity analysis. Brain functional network measures were computed using graph theory methods, including node strength, clustering coefficient, characteristic path length, and small-world properties. Most literature describes traditional methods, such as Fourier transform, short-time Fourier transform, and autoregressive models, which focus only on time-domain signals [19, 20].

On the other hand, wavelet transform (WT) applies to time–frequency analysis for processing signals such as EEG. However, WT processes only approximation coefficients, while its extended version (WPD) processes approximation and detail coefficients [21]. This proposed study employs WPD to extract four EEG frequency sub-bands: delta, theta, alpha, and beta, ensuring high time–frequency localization. Since the WPD detail coefficients offer a reliable, multi-resolution time–frequency representation of EEG data, their absolute values are utilized for brain connectivity estimation. The absolute value represents the strength (or magnitude) of the wavelet packet coefficient, which directly relates to the energy of the EEG signal in a given frequency band. The connectivity metric seems crucial in this analysis, as graph theory is utilized in brain connectivity studies to examine complex brain networks'structural and functional models. It represents the brain as a network, where brain areas and electrode locations serve as nodes, and the connections between them are edges.

The computation of graph features is widely applied to identify abnormalities in brain development and neurological disorders [22]. A recent study proposed an application of graph theory that examines the neural correlates of how music rhythms evoke fear and anger [23]. Statistical dependencies between comparatively shorter and longer non-overlapped EEG segments across the brain have been estimated using Pearson and Spearman Correlation. After that, the relevant brain connection, represented as a graph, is converted into binary integers based on two distinct thresholds (mean and 60%max) [24]. Based on the work above, this study employs the Pearson correlation in brain connectivity studies to measure the functional connectivity between different brain regions. It helps to assess how synchronized two electrode signals are over time, indicating the strength of their functional relationship. The sum of correlation values for each node (electrode) determines its strength in the network. Understanding the neurological effects of OSA and exploring potential interventions motivated this study's investigation of brain connectivity in response to music. The brain connectivity was analyzed to determine whether music influences neural activity and enhances brain function in OSA patients, under different auditory conditions, including Neelambari and Kapi music.

Results

This study utilized 14 electrode positions to construct 196 brain connections based on positive correlations. The coordinates of each electrode were validated using the Brodmann Atlas [25]. Pearson correlation determines the connectivity strength between brain regions by measuring the synchronization between EEG signals from different electrodes. Graph theoretical analysis was conducted to examine the topological characteristics of functional brain connectivity between OSA and healthy individuals under conditions with and without music, using node strength as the primary metric. Initially, Music 1 and Music 2 brain connectivity have been monitored. The left and right hemispheric view of the Neelambari music (1) is illustrated in Fig. 1 for the four bands: delta, beta, theta, and alpha. The mean and standard deviation values of OSA patients while listening to Neelambari music, Kapi music, and in the absence of music are presented in Table 1.

Neelambari music is connected to an emotional event and activates the brain's right hemisphere. When listening to Neelambari music, as shown in Fig. 1a, b, the nodes and edges in the right temporal (T8) and the right frontal (F8 and FC6) of OSA patients were positively more vital. The moderate positive correlation is demonstrated in Fig. 1c, d. From a physiological perspective, the positive correlations observed in brain connectivity suggest that listening to music helps restore or enhance communication between different brain areas.

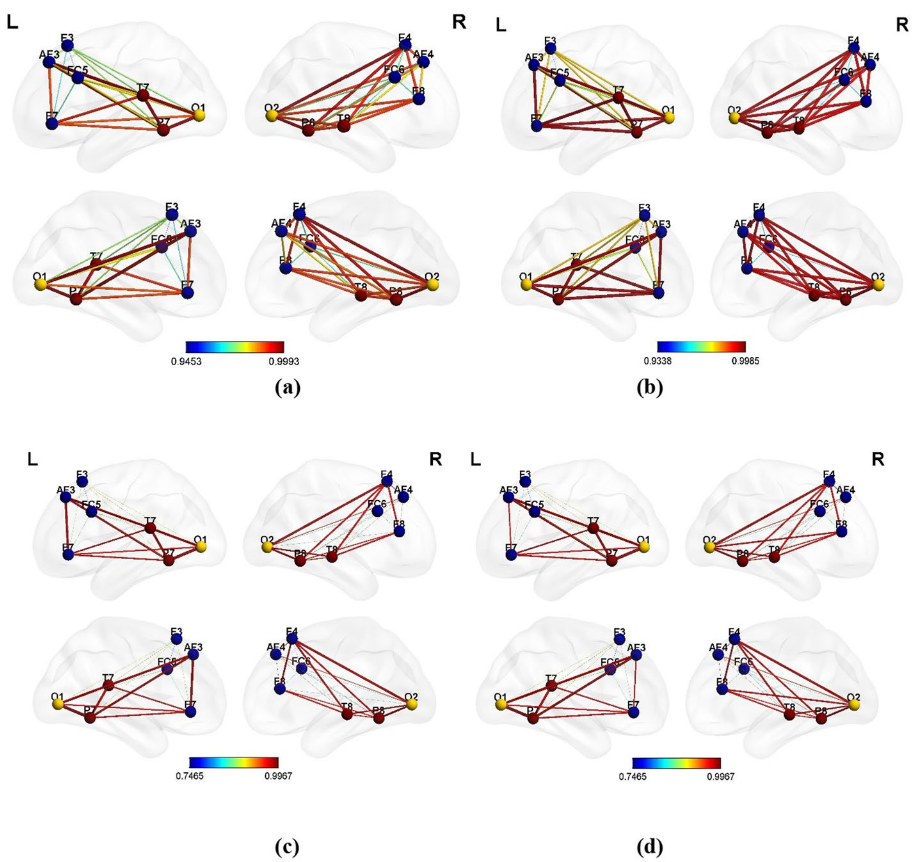

Fig. 1 Left and right hemispheric brain connectivity of obstructive sleep apnea patients during Neelambari music condition: **a** delta, **b** beta, **c** alpha, **d** theta

Table 1 Mean and standard deviation values of OSA patients while listening to Neelambari music, Kapi music, and no music

Band	Neelambari music		Kapi music		No music	
	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Delta	0.984	0.013	0.980	0.019	0.968	0.037
Beta	0.985	0.016	0.984	0.012	0.973	0.028
Theta	0.931	0.062	0.886	0.084	0.888	0.107
Alpha	0.930	0.063	0.912	0.063	0.912	0.082

In individuals with OSA, brain regions often become impaired due to factors, such as oxygen deprivation (hypoxia) and fragmented sleep (frequent awakenings or disrupted sleep stages). These disruptions can negatively affect brain function and connectivity.

In this study, the positive correlations observed imply that music may act as a stimulus that encourages the brain to re-establish or strengthen its neural connectivity, particularly in cognitive and emotional processing areas. Music could serve as a therapeutic tool to compensate for the neural disruptions caused by OSA, improving the overall functionality and synchronization of brain networks, which might otherwise be weakened or impaired due to poor sleep and low oxygen levels during sleep. The 14×14 correlation matrix of OSA patients under the music 1 condition is depicted in Fig. 2. The correlation values depict the connectivity between these electrode positions. The correlation with 14 electrode positions and their brain connectivity was presented in a matrix of the delta and theta bands for OSA subjects.

The Music 2 conditions (Kapi) were then played to analyze the brain connectivity in OSA patients. Kapi music can elicit feelings of devotion, melancholy, and sadness in listeners, because it typically performs at slow and medium rates. Figure 3a, b shows the brain connectivity measures estimated in delta and beta sub-bands. Meanwhile, the brain connectivity patterns for the alpha and theta bands are shown in Fig. 3c, d. It has been noted that there was activation in the frontal lobe (FC5) left hemisphere and (F8) right hemisphere in the delta band while listening to Kapi music. However, the alpha and theta bands showed a low positive correlation.

This study has uncovered compelling implications for OSA treatment. Both music conditions show a positive correlation with the right hemisphere of the brain, with Neelambari demonstrating a stronger positive correlation in delta and beta bands compared to kapi. These findings, visually demonstrated through brain connectivity analysis, make the implications more tangible and open up new possibilities for OSA treatment strategies. Finally, the no-music condition was also analyzed in OSA patients, with moderate brain connectivity compared to the music condition. Figure 4a, b shows the brain connectivity in the delta and beta bands of the no-music condition. The electrode positions F8 and P8 in the delta band and the electrode positions F8, T8, and O2 in the beta band were positively correlated with the brain.

Consequently, the electrode position F8 had a correlation in the alpha band, and the electrode positions F8 and T8 had a moderate positive correlation in theta band,

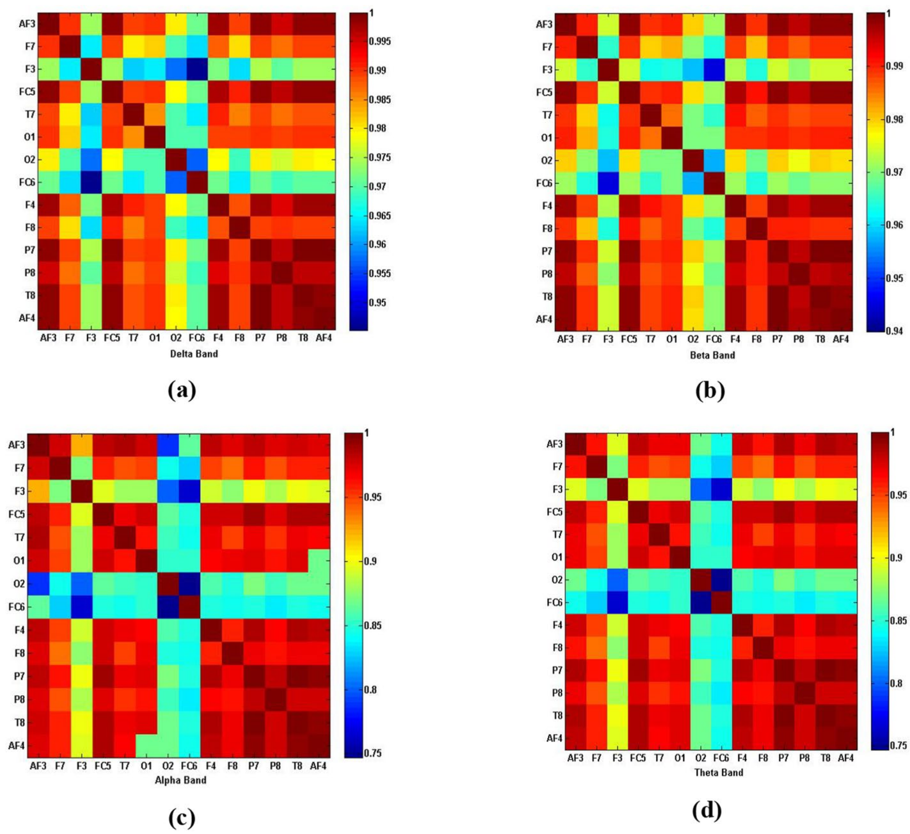

Fig. 2 14 × 14 correlation matrix of obstructive sleep apnea patients during Neelambari music condition: **a** delta band, **b** beta band, **c** alpha band, and **d** theta band

as shown in Fig. 4c, d. Figure 5a–d depicts the correlation matrix 14 ×14 of OSA patients in the no-music condition.

The positive correlation value starts from 0.86 for the delta band and 0.65 for the theta bands. The correlation values represent the brain connectivity among the 14 electrode positions. In addition, it was evident that the no-music condition was moderately connected to Music 1 and Music 2 conditions in OSA patients.

Discussion

The proposed study investigates the influence of Carnatic music on brain connection in OSA patients. A peaceful and enjoyable sleep has been reported to be brought about by the music Neelambari [26]. Raga Chikitsa, an ancient manuscript, talked about raga's therapeutic qualities. A precious collection of ragas that explain how to use various ragas to treat common ailments is allegedly kept at the Thanjavur library [27]. This ancient approach inspired us to use music to monitor brain connectivity in patients with OSA. Music therapy has emerged as a viable intervention for people in vegetative and minimally conscious states, providing a noninvasive way to stimulate brain activity and improve recovery. However, even in the state of diminished awareness condition music can evoke distinct reactions by activating both cortical and subcortical brain regions [28]. It is noted that improvements in sleep quality and emotional well-being using

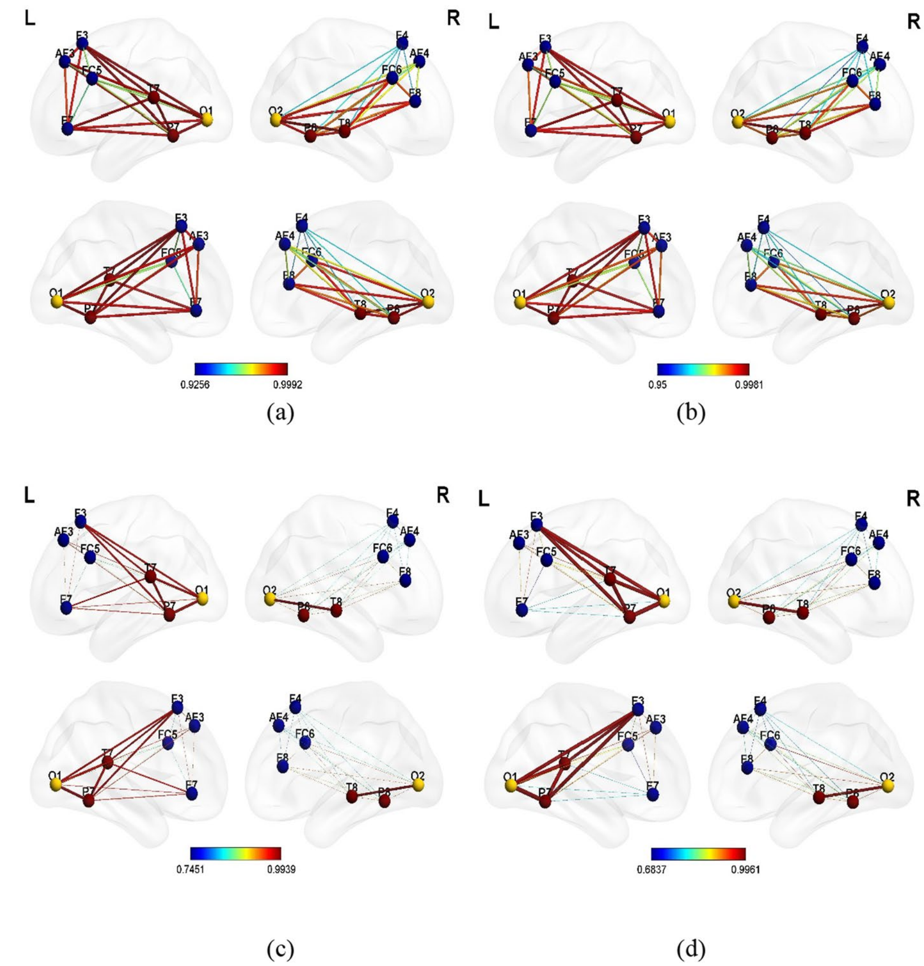

Fig. 3 Left and right hemispheric brain connectivity of obstructive sleep apnea patients during Kapi music condition: **a** delta, **b** beta, **c** alpha, **d** theta

functional connectivity while listening music. The activations of several brain regions using music was reported by another study including the auditory cortex for sound processing, the prefrontal cortex for decision-making and emotional management, and the limbic system for emotional reactions. By stimulating neurotransmitters such as dopamine and serotonin music can induce emotional reactions associated with pleasure and mood regulation [29]. Based on the literature, the therapeutic effect of music was explored on OSA patients experiencing emotional and cognitive disruptions. In a recent research, Lowey et al. [30] propounded a music therapy evidence that may help sleep disorder patients feel more at peace and less anxious. Moreover, they stated that the music's interaction with the limbic system regulates emotions, lowers cortisol levels, and produces improved sleep. The brainwave music has the prominent improvement in slow wave sleep and overall sleep architecture.

Numerous studies have investigated and utilized the brain connectivity analysis between different brain regions. Canessa et al. [6] demonstrated a brain connectivity analysis method to classify OSA patients and normal subjects using non-linear factors, such as variance and energy. They examined the association of OSA with chronic sleep

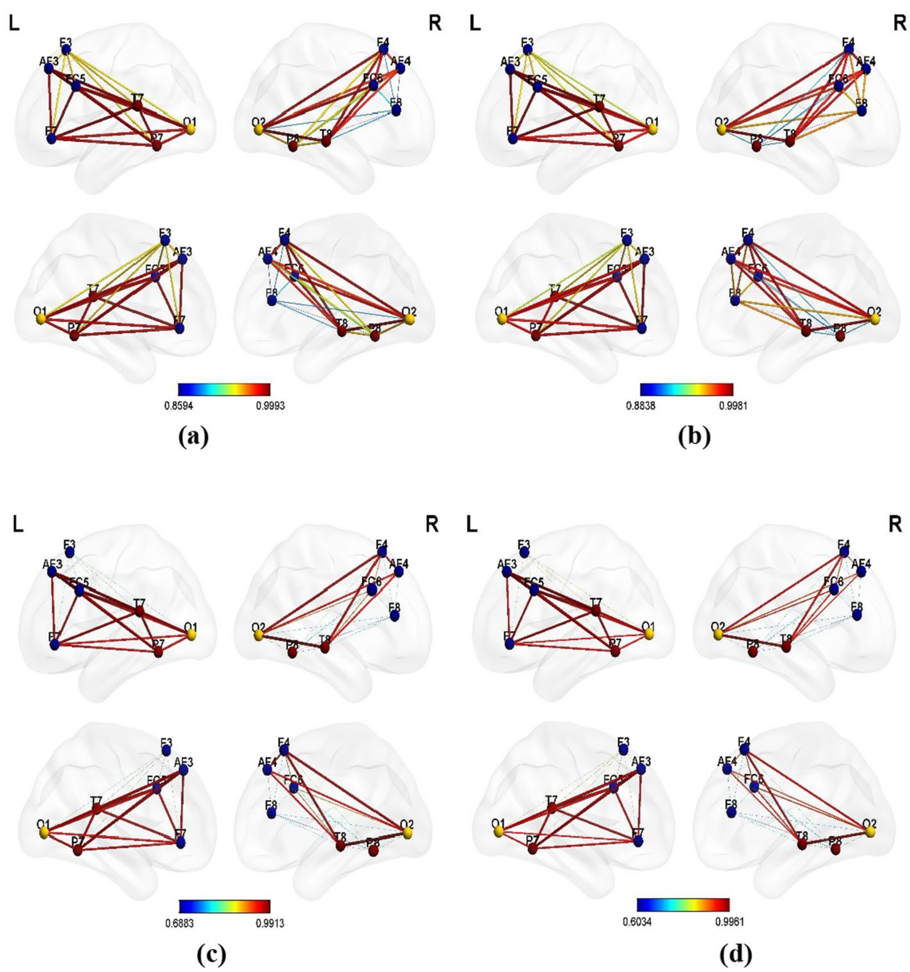

Fig. 4 Left and right hemispheric brain connectivity of obstructive sleep apnea patients during no music condition: **a** delta, **b** beta, **c** alpha, **d** theta

deprivation and intermittent hypoxia that causes structural alterations in the brain regions related to cognition and memory, such as the prefrontal cortex, hippocampus, and thalamus. This approach is reliable with the proposed study in that it investigates the impact of OSA on brain regions related to cognition and memory, thereby supporting the importance of brain connectivity analysis in diagnosing and understanding OSA-related impairments. Torelli et al. [31] analyzed the connection of moderate–severe OSA with significant cognitive impairments, often accompanied by brain tissue damage in regions critical to various cognitive functions. The improvements between healthy individuals and patients with other neurological conditions were monitored using the altered functional connectivity in areas, such as the cerebellum, occipital, limbic, and basal ganglia [32]. Meanwhile, this proposed study discovered alterations in the frontal (F8 and FC5) and temporal (T8) electrode positions during music listening, indicating a shift in brain activity related to cognitive processing and emotional regulation.

Another study investigates how OSA causes microstructural abnormalities in sleep, which contribute to cognitive impairment and increased dementia risk. Sleep fragmentation, a hallmark of OSA, reduces restorative sleep and worsens

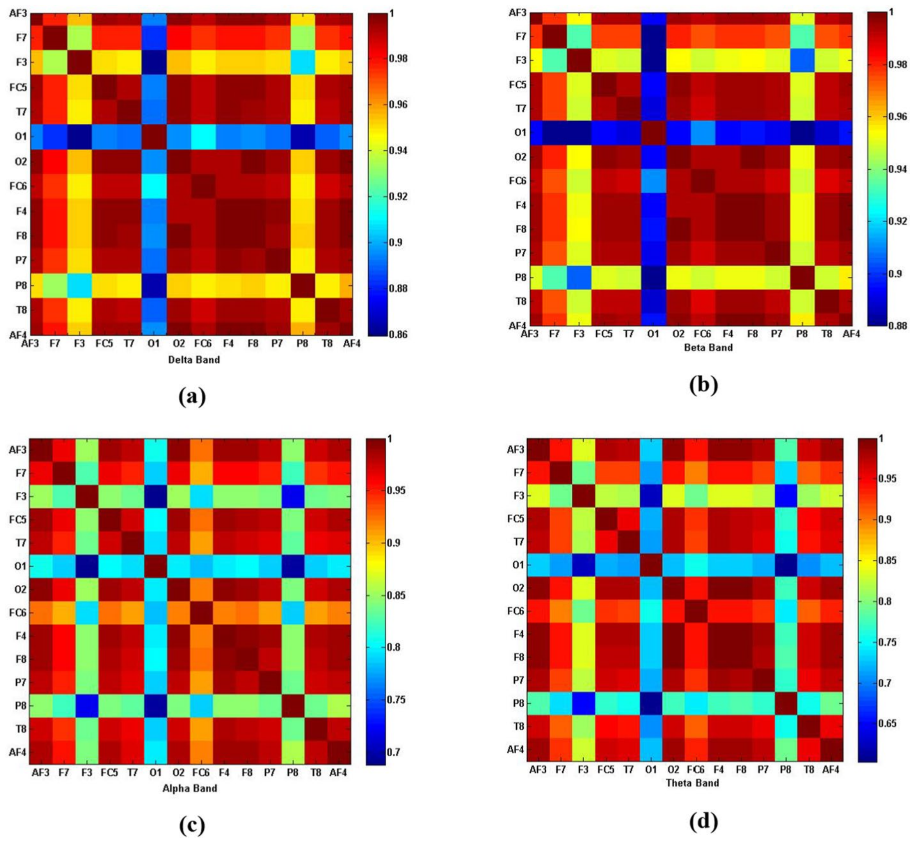

Fig. 5 14 × 14 correlation matrix of obstructive sleep apnea patients during no music condition: **a** delta band, **b** beta band, **c** alpha band, and **d** theta band

the processes required for cognitive function, such as memory consolidation and executive task performance [33]. A method was proposed by Pan et al. [34] to assess the pattern of information flow from posterior to anterior in OSA patients using cortical connectivity. It also examines how OSA impacts the brain's functional connectivity, focusing on effective cortical connection. It detects altered connection patterns, particularly in areas, such as the prefrontal cortex and parietal lobes, essential in cognitive control, attention, and memory. These findings are consistent with the proposed study, showing that OSA impacts brain connectivity, particularly in the frontal and temporal regions.

Previous research has demonstrated music's impact on brain connectivity, emotional regulation, and sleep architecture, further supporting its therapeutic applications. The findings align with contemporary approaches to evaluating brain connectivity in OSA patients, revealing structural and functional abnormalities in critical regions, such as the frontal, temporal, and subcortical areas. Identifying research gaps in OSA patients that are significant for public health, as well as making recommendations for future study. There are limited Carnatic music-based approaches and management algorithms for OSA patients, highlighting the need for more clinical studies that are robust in both quantity and quality to support practical applications. The data set exhibits a notable imbalance in gender distribution, consisting of three female and nine male subjects. This disparity has the potential to restrict the generalizability of the findings, given the well-established differences in brain activity and connectivity associated with gender, as documented in neuroscience literature. Although this study did not specifically examine gender-based differences, subsequent research with a more equitably represented demographic will be conducted to validate and expand upon these findings.

Conclusion

The functional brain connectivity in patients with OSA and healthy controls was analyzed while listening to and without music. Brain connectivity was assessed using the Pearson correlation matrix, and wavelet packet decomposition was employed to identify the EEG sub-bands most strongly associated with different brain regions. The findings revealed that delta and beta band activity in patients with OSA positively correlated with brain connectivity compared to healthy individuals. In addition, patients with OSA demonstrated enhanced functional connectivity in the frontal and temporal brain regions when listening to music. These results highlight the potential of music-based assessments for evaluating functional brain connectivity in patients with OSA. Future studies exploring music-based interventions could contribute to the early detection and monitoring of sleep-related disorders.

Methods

Participant's details and investigational design

The written informed consent of each participant was obtained and documented in compliance with the university's ethical guidelines. Table 2 shows the demographic details of the participants. The authors initially employed self-administered questionnaires (SAQ) [4] to diagnose OSA in conjunction with a control group of healthy subjects, utilizing a standard scaling method. By eliminating redundant questions present in the Berlin Questionnaire (BQ), Sleep Breathing Questionnaire (SBQ), and OSA50 questionnaires, they formulated a comprehensive self-administered questionnaire consisting of 15 distinct questions. The participants were asked to fill out

Table 2 Demographic details of the participants

Participant no	Gender	Group	Age (years)	Music (day 1)	Music (day 2)
1	Male	Sleep apnea	39	Neelambari	Kapi
2	Male	Sleep apnea	31	Kapi	Neelambari
3	Male	Sleep apnea	45	Neelambari	Kapi
4	Male	Sleep apnea	40	Kapi	Neelambari
5	Female	Sleep apnea	25	Neelambari	Kapi
6	Male	Sleep apnea	39	Kapi	Neelambari
7	Male	Normal	36	Neelambari	Kapi
8	Male	Normal	31	Kapi	Neelambari
9	Male	Normal	46	Neelambari	Kapi
10	Female	Normal	24	Kapi	Neelambari
11	Female	Normal	35	Neelambari	Kapi
12	Male	Normal	40	Kapi	Neelambari

the self-administered questionnaire [4]. Based on the scores the participants were split into two groups. The group classified as healthy has a score of less than five, whereas an OSA group has a score of greater than five.

Prior to the experiment, participants were provided with detailed information regarding the signal acquisition procedure. To promote optimal sleep during the recording sessions, participants were advised to refrain from sleeping the night preceding the session. On day 1, subsequent to lunch, participants were instructed to rest in a quiet environment for approximately 20 min without the presence of music. On day 2, the same participant engaged in a music session, which consisted of listening to Music 1 followed by Music 2 (Neelambari and Kapi) for a duration of 25 min. For subsequent participants, the sequence was reversed, with Music 2 (Kapi) presented first, followed by Music 1 (Neelambari). This counterbalanced design was implemented to ensure that the order of music presentation did not affect the outcomes of the study. EEG signals were recorded at 128 Hz using an Emotiv Epoch +headset. This EEG cap features 14 channels distributed based on the 10–20 international system shown in Fig. 6, which includes the following electrode positions: AF3, F7, F3, FC5, T7, O1, O2, FC6, F4, F8, P7, P8, T8, and AF4.

Pre-processing of EEG

Noise and artifacts in the obtained raw EEG signals can make analysis difficult. The fourth-order bandpass filter (0.5–35 Hz) reduces noise by producing a more distinct transition between the passband and stopband. Slow drifts and very low-frequency noise, including baseline wander and motion artifacts, can be reduced with the lower cutoff at 0.5 Hz, while high-frequency noise, such as muscle artifacts (EMG) and outside electromagnetic interference, can be eliminated with the upper cutoff at 35 Hz [35]. In addition, a 50 Hz notch filter was used to remove power line interference in recorded EEG signals.

Extraction of EEG sub-bands

In the extraction process, the EEG signals were separated into frequency bands using the wavelet packet decomposition (WPD) approach following pre-processing. The

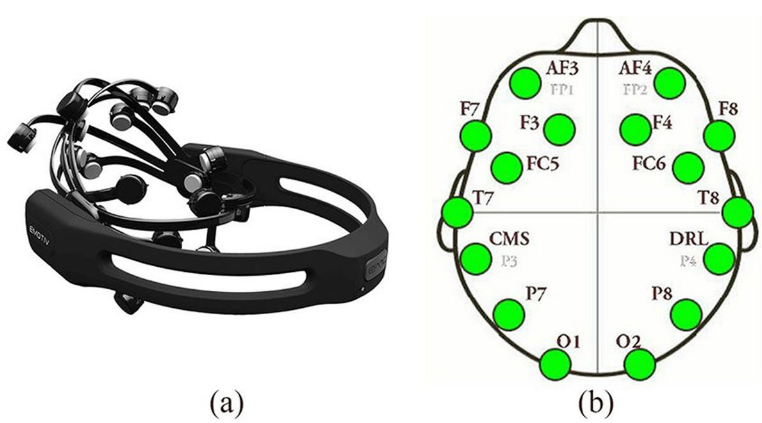

Fig. 6 Emotive epoch +device. **a** Headband. **b** Electrode locations

pre-processed EEG signals were decomposed into five frequency sub-bands: delta (δ) (0.5–4 Hz), theta (θ) (4–8 Hz), alpha (α) (8–16 Hz), beta (β) (16–32 Hz), and gamma (γ) (32–64 Hz) [36]. The WPD method decomposed the low and high-frequency components as approximation and detail wavelet coefficients represented in the following equation:

$$W_d(t) = \sum_k W_j(k)\varphi_{jk}(t) + \sum_k d_j(k)\psi_{jk}(t) \tag{1}$$

where $\phi_{jk}(t)$ is the scaling function, $\psi_{jk}(t)$ are the mother wavelets, $d_j(k)$ are the detail coefficients, $W_j(k)$ are the approximation coefficients, and $W_d(t)$ is the decomposed EEG signal.

A Level 5 decomposition with the Daubechies-4 (db4) wavelet was applied, effectively separating the EEG sub-bands at a sampling frequency of 128 Hz. The WPD decomposes both approximation and detail coefficients at each level.

Estimation of regional brain connectivity levels

After decomposition, the absolute values of the detail wavelet coefficients were computed to prevent phase cancellation and enhance feature stability. Brain connectivity was assessed by calculating pairwise correlations between the absolute detail wavelet coefficients across multiple EEG channels, providing a quantitative measure of regional connectivity within the brain. To investigate the impact of auditory stimuli on subjects with OSA and healthy individuals, connectivity metrics were computed independently for each condition, including no music, Neelambari, and Kapi. MATLAB's BrainNet Viewer package was utilized for visualizing the node-edge representations [25]. In brain networks, nodes represent specific brain regions, while edges define the connectivity between them. Pearson correlation coefficient was used to measure the strength of associations between brain regions across frequency bands, such as delta, theta, alpha, and beta. When Pearson correlation values are used to construct a functional connectivity network, the network becomes inherently weighted, with each edge carrying a distinct significance level. This weighted representation, captured by node strength, ensures that variations in connection strengths are preserved, offering a more accurate depiction of functional relationships between brain regions. Node strength quantifies the overall connectivity of a node by summing the weights of all its connections, serving as a measure of the region's influence and activation level [37]. The mathematical formula of node strength is provided in the following equation:

$$\mathrm{NS}_i = \sum_{j \in G} w_{ij} + \sum_{j \in G} w_{ji} \tag{2}$$

NS_i is the nodal strength of the node, G is the set of all nodes in the network, w_{ij} is the weight of the connection from node i to node j, and w_{ji} is the weight of the connection from node j to node i.

A brain region (node i) exhibits strong connectivity and greater involvement in network communication when NS_i is high. Conversely, a lower NS_i indicates weaker connectivity, suggesting reduced functional participation in the network.

Statistical analysis

Because the random signals are non-stationary, non-parametric approaches were used to analyze the EEG data. The statistical analysis was carried out with the Statistical Package for the Social Sciences (SPSS) version 15.0. The non-parametric Mann–Whitney *U* test was used to compare persons with OSA to those who were healthy. This test was conducted on the EEG sub-bands, such as delta, theta, alpha, and beta across both music and non-music conditions. Significant changes ($p < 0.05$) were observed in the delta and beta bands, particularly in the frontal and temporal lobes.

Acknowledgements

The authors gratefully acknowledge the Vellore Institute of Technology, Chennai, for providing the seed grant that facilitated the purchase of the EMOTIV EPOC+ EEG headset used in this study. They also extend their sincere appreciation to the participants for their patience and cooperation during the signal acquisition process. Lastly, the authors thank the researchers whose work has been cited and referenced, contributing significantly to the foundation of this manuscript.

Author contributions

J&S: resources, methodology, investigation, writing—original. P&M: conceptualization, resources, writing—review and editing, visualization, supervision. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data availability

The authors confirm that the data supporting the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the "Declaration of Helsinki".

Informed consent

Informed consent was obtained prior to performing the procedure, including permission for publication of all photographs and images included herein.

Competing interests

The authors declare no competing interests.

Received: 25 July 2024 Accepted: 8 April 2025
Published online: 22 April 2025

References

1. Rajeswari J, Jagannath M. Brain connectivity analysis-based classification of obstructive sleep apnea using electroencephalogram signals. Sci Rep. 2024;14:5561.
2. Sweed RA, Elghany RARA, Elganady AA, Mohamed EE, Mekky JF, Elshafei MM. Impact of obstructive sleep apnea on cognition, mood, and fatigue: an MRI-based study. Egypt J Bronchol. 2023;17:75.
3. Benjafield AV, Ayas NT, Eastwood PR, Heinzer R, Ip MSM, Morrell MJ, Nunez CM, Patel SR, Penzel T, Pépin J-L, et al. Estimation of the global prevalence and burden of obstructive sleep apnoea: a literature-based analysis. Lancet Respir Med. 2019;7:687–98.
4. Rajeswari J, Jagannath M. Screening of obstructive sleep apnea in an urban population in south India. Obes Med. 2020;18:100220.
5. Castronovo V, Canessa N, Ferini LS, Aloia MS, Consonni M, Marelli S, et al. Brain activation changes before and after PAP treatment in obstructive sleep apnea. Sleep. 2017;32:1161–72.
6. Canessa N, Castronovo V, Cappa SF, Aloia MS, Marelli S, Falini A, et al. Obstructive sleep apnea: brain structural changes and neurocognitive function before and after treatment. Am J Respir Crit Care Med. 2011;183:1419–26.
7. Kim Y, Koo YS, Lee HY, Lee S-Y. Can continuous positive airway pressure reduce the risk of stroke in obstructive sleep apnea patients? A systematic review and meta-analysis. PLoS ONE. 2016;11(1):e0146317.
8. Chen CK, Pei YC, Chen NH, Huang LT, Chou SW, Wu KP, Ko PC, Wong AM, Wu CK. Sedative music facilitates deep sleep in young adults. J Altern Complem Med. 2014;20(4):312–7.
9. De Niet G, Tiemens B, Lendemeijer B, Hutschemaekers G. Music-assisted relaxation to improve sleep quality: meta-analysis. J Adv Nurs. 2009;65(7):1356–64.
10. Tan LP. The effects of background music on quality of sleep in elementary school children. J Music Ther. 2004;41(2):128–50.

11. Gitanjali B. Effect of the karnatic music raga "neelambari" on sleep architecture. Indian J Physiol Pharmacol. 1998;42(1):119–22.
12. Adalarasu K, Jagannath M, Keerthiga N. EEG based neurophysiological responses to music among sleep disorder patients. Int J Recent Sci Res. 2012;3(5):360–5.
13. Cordi MJ, Ackermann S, Rasch B. Effects of relaxing music on healthy sleep. Sci Rep. 2019;9(1):9079.
14. Alluri V, Toiviainen P, Burunat I, Kliuchko M, Vuust P, Brattico E. Connectivity patterns during music listening: evidence for action-based processing in musicians. Hum Brain Mapp. 2017;38(6):2955–70.
15. Melek M, Manshouri N, Kayikcioglu T. Low-cost brain-computer interface using the emotiv EPOC headset based on rotating vanes. Traitement Du Signal. 2020;37:831–7.
16. Acevedo BP, Robert M, Kosik KS, Zarinafsar S, Santander T. Yoga improves older adults' affective functioning and resting-state brain connectivity: evidence from a pilot study. Aging Health Res. 2021;1(3):100018.
17. Chen X, Zhao S, Chen D, Zhang D. The impact of sleep disorders on brain network connectivity in postpartum women: a functional near-infrared spectroscopy-based study. Front Neurol. 2024;15:1487985.
18. Seshadri NPG, Geethanjali B, Singh BK. EEG based functional brain networks analysis in dyslexic children during arithmetic task. Cogn Neurodyn. 2022;16(5):1013–28.
19. Balasubramanian G, Kanagasabai A, Jagannath M, Seshadri NPG. Music induced emotion using wavelet packet decomposition—an EEG study. Biomed Signal Process Control. 2018;42:115–28.
20. Chiarion G, Sparacino L, Antonacci Y, Faes L, Mesin L. Connectivity analysis in EEG data: a tutorial review of the state of the art and emerging trends. Bioengineering (Basel). 2023;10(3):372.
21. Aggarwal S, Chugh N. Signal processing techniques for motor imagery brain computer interface: a review. Array. 2019;100003:1–2.
22. Rubinov M, Sporns O. NeuroImage complex network measures of brain connectivity: uses and interpretations. Neuroimage. 2010;52:1059–69.
23. Kılıç B, Aydın S. Classification of contrasting discrete emotional states indicated by EEG based graph theoretical network measures. Neuroinformatics. 2022;20(4):863–77.
24. Aydın S, Onbaşı L. Graph theoretical brain connectivity measures to investigate neural correlates of music rhythms associated with fear and anger. Cogn Neurodyn. 2024;18:49–66.
25. Mikail R, Olaf S. Complex network measures of brain connectivity: uses and interpretations. Neuroimage. 2010;52(3):1059–69.
26. Charulatha M. RagAlive: neelambari. Int J Creat Media Res. 2021;6:1–4.
27. Prabhuswami H, Lekshmi S, Vaishali RM, Jyoti S, Prakash N. Effect of music therapy on blood pressure among hemodialysis patients at tertiary care hospital. J Pharmaceut Negat Results. 2022;13(7):1–6.
28. O'Kelly J, James L, Palaniappan R, Taborin J, Fachner J, Magee WL. Neurophysiological and behavioral responses to music therapy in vegetative and minimally conscious states. Front Hum Neuroscie. 2013;25(7):884.
29. Trimble M, Hesdorffer D. Music and the brain: the neuroscience of music and musical appreciation. Bjpsych Int. 2017;14(2):28–31.
30. Loewy J. Music therapy as a potential intervention for sleep improvement. Nat Sci Sleep. 2020;12:1–9.
31. Torelli F, Moscufo N, Garreffa G, Placidi F, Romigi A, Zannino S, et al. Cognitive profile and brain morphological changes in obstructive sleep apnea. Neuroimage. 2011;54(2):787–93.
32. Park B, Bumhee P, Jose A, Mary W. A Disrupted functional brain network organization in patients with obstructive sleep apnea. Brain Behav. 2016;6(3):e00441.
33. Marchi NM, Allali G, Heinzer R. Obstructive sleep apnea, cognitive impairment, and dementia: is sleep microstructure an important feature? Sleep. 2024;47:zsae161.
34. Pan Y, Yang J, Zhang T, Wen J, Pang F, Luo Y. Characterization of the abnormal cortical effective connectivity in patients with sleep apnea hypopnea syndrome during sleep. Comput Methods Programs Biomed. 2021;204:106060.
35. Jiang X, Bian GB, Tian Z. Removal of artifacts from EEG signals: a review. Sensors (Basel). 2019;19(5):987.
36. Kong D, Xu L, Li X, Tian X. A new concept for the distributions of wavelet packet decomposition coefficients in detail sub bands. In: Proceedings of IEEE international symposium on instrumentation and control technology (ISICT). 2012.
37. Al-Shargie F, Tariq U, Hassanin O, Mir H, Babiloni F, Al-Nashash H. Brain connectivity analysis under semantic vigilance and enhanced mental states. Brain Sci. 2019;9(12):363.

Publisher's Note