



Research Paper

Altered EEG Power Spectrum and Coherence in Students With Borderline Personality Disorder



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ABSTRACT

Background: The complicated mental illness known as borderline personality disorder (BPD) is characterized by impulsivity, emotional instability, and interpersonal challenges. Measurement of brain electrical activity using electroencephalography (EEG) can yield helpful biomarkers for a range of psychiatric conditions.

Objectives: The present study utilizes comprehensive EEG analysis to identify distinct neural patterns in BPD, providing insights and potential biomarkers for diagnosing and understanding BPD.

Materials & Methods: In a cross-sectional study conducted on students of Guilan University (Iran), 534 students were evaluated through the Millon clinical multiaxial inventory from September 2018 to September 2020. Fourteen students were recruited into this case-control study: Seven students with BPD and seven healthy controls. EEG recording was performed by a standard 21-channel device. The EEG signals were processed with the EEGLAB toolbox in the MATLAB environment. The absolute and relative powers were calculated using the fast Fourier transform function. The power spectral density (PSD) and the coherence between different channels were evaluated, too. The statistical analysis was performed using GraphPad Prism software.

Results: The results showed a significant increase in the delta band range, mainly in the frontotemporal region, and a reduction in the power of the alpha band in students with BPD. The frontal brain region of BPD patients also showed reduced alpha band coherence.

Conclusion: Students with BPD exhibit distinct EEG patterns, including increased delta band power and reduced alpha band power and coherence. These findings suggest potential EEG biomarkers for BPD, highlighting the utility of EEG in understanding this complex disorder.

Keywords: Borderline personality disorder, Quantitative electroencephalogram, Biomarkers, Delta rhythm, Alpha rhythm

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Highlights

- Students with borderline personality disorder show higher relative delta band power.
- Borderline personality disorder patients exhibit lower relative alpha band power.
- The coherence in the alpha band range is decreased in students with borderline personality disorder.

Introduction

Personality disorder is a durable, unconventional, and inflexible pattern of a person's inner experiences and behavior. It results from a complex interaction between the individual's genetics and the environment. It stands as one of the most challenging conditions for psychiatric treatment [1]. Borderline personality disorder (BPD) is one of the most common and resistant of these disorders in the diagnostic and statistical manual of mental disorders fifth edition (DSM-5). The disorder is characterized by instability in interpersonal relationships, self-concept, emotions and impulsivity. Serious problems in the field of identity, emotional regulation, intentional self-injury, attempted suicide, and chronic feelings of emptiness are among the most characteristic features of this disorder [2]. Despite the destructiveness and significant disability due to this disorder, researchers have not reached a consensus to understand and manage it. Although the leading cause of this disorder has remained unknown [3], according to researchers, it is rooted in factors such as inheritance [4], brain abnormalities [5], and early life experiences [6]. BPD arises from a complex interaction of environmental, anatomical, functional, genetic and epigenetic factors [7].

To better comprehend this enigmatic disorder, it is essential to combine research from other disciplines, such as psychology, biology, neurology and so on [8]. Studies in this field have risen over the past two decades due to the advancement of imaging techniques in neurobiology that allow for the non-invasive evaluation of brain changes in individuals with various mental disorders [9]. Evidence supporting the heritability of BPD is what spurred the first wave of neuroscience research in this area [7]. Studies on twins show that BPD is inherited, and genes account for more than 60% of the diversity in how this condition manifests. Also, several symptoms of the disorder, such as impulsivity and emotional dysregulation, may have genetic roots [10]. On the other hand, some researchers assert the existence of quasi-epileptic episodes as a result of clinical observations of borderline

traits. This claim significantly influenced investigations directed toward neurological issues and brain signals [11]. These studies led to the emergence of neurobiological models, such as the local network inhibition model and the Jacksonian model, explaining BPD symptoms' pathophysiology [12].

According to studies, BPD could be a subtype of bipolar disorder (BD) because the diagnostic standards for the two disorders are similar [13]. In addition, structural neuroimaging investigations have revealed some overlapping alterations, ie, the prefrontal cortex volume is shown to have decreased in both illnesses [14]. However, distinguishing changes have also been found. Amygdala and hippocampal volume are higher or normal in BD patients compared to BPD patients, who show a decrease in these brain regions' volume [15]. Since different behavioral and psychological processes can change functional patterns of the brain [16], one of the most informative methods for the study of neurobiology is the evaluation of EEG abnormalities, which can differentiate neuro-psychiatry patients from healthy populations [17]. EEG studies on borderline patients also show inconsistent results. Some researchers reported no EEG patterns particular to BPD [18, 19]. Others found that BPD patients have more epileptiform EEG abnormalities [20]. Flasbeck reported a correlation between BPD patients' alexithymia scores and right frontal EEG asymmetry [19]. Others claim that although individuals with severe depressive illness show more right cortical activity, those with BPD show higher left cortical activation. Patients with BPD show an EEG asymmetry after a social rejection test [21]. In the present study, we compared the relative power and coherence in different frequency bands in the resting state EEGs of seven students with BPD to those of healthy students.

Materials and Methods

Study subjects

Participants were enrolled from September 2018 to September 2020 at Guilan University, Rasht City, Iran.

A total of 455 students (aged between 18 and 24, 215 female and 240 males, not married) completed the mil-lon clinical multi-axial inventory-III (MCMI-III), an assessment of DSM-V-related personality disorders and clinical syndromes (constituted the early sample). The sample was recruited from undergraduate students of all faculties, excluding medical, according to the sample share calculated for each faculty. Both groups of subjects were ascertained to have no unstable medical or neurological conditions or substance dependency and drug usage for at least one month before the study and no history of significant head injury. The Research Ethics Committee at Guilan University approved the study.

In Iran, the MCMI-III questionnaire was standardized, and the correlation between the raw scores of the first implementation and its retest was reported as 0.98 to 0.82. The reliability of the test was calculated through the internal consistency method and the α coefficient of the scales ranged from 0.87 to 0.98 [22]. In the research conducted by Sarabi and Sadeghi [23] on the diagnostic validity of this test, BPD has the highest sensitivity (0.51) and the highest positive predictive power (0.95). Regarding the validity percentage of personality disorder scales, the highest detection rate of coordination in the clinical group is also related to this disorder, with a value of 0.60.

Subgrouping of BPD students

The symptoms of BPD were assessed in two steps. Those who scored above 70 on the BPD scale of MCMI-III were recruited as the primary BPD group. Then, they were interviewed by a psychologist with sufficient training and experience in administering personality disorder scales using structured clinical interviews for DSM-5 personality disorder. After these two psychopathology ratings, BPD participants were sub-grouped. The healthy control (HC) group was recruited after the Mil-lon inventory assessment and diagnosed with no high score in any of the 24 clinical or personality scales. At last, 14 students (BPD group=7, HC group=7, age average=22 y, right-handed) were recruited into the EEG analysis study.

EEG recording

After collecting their data, all patients were provided comfortable seats in a dimly lit, quiet room, including age, sex, marital status and other information. The distance between the nasion and inion was initially measured to determine the appropriate size of the EEG cap. The EEG recordings were carried out at a resting state,

with eyes closed, for 5 minutes, with minimal muscular activity. The 10-20 International EEG system was then used with a 21-channel cap to put the electrodes on the scalp. Electro-gel was used to lower the electrode impedance. To start the recordings, an impedance of less than 20 k Ω was required. The ground electrode was placed on the left wrist, and the average of all channels was used as the standard reference for all analyses. The brain signals were delivered to a 24-channel EEG recording system (Negar Andishgan Ltd., Tehran, Iran). EEG signals were recorded at a sampling rate of 250 Hz. A bandpass filter at 0.5–60 Hz and a notch filter at 50 Hz were applied.

Quantitative EEG analysis

In the recording software environment, 60 seconds of artifact-free epochs were manually chosen for artifact removal. The analyses were performed in the MATLAB 2019a (MathWorks Inc., Massachusetts, USA) environment with the aid of the EEGLAB toolbox (Swartz Center for Computational Neuroscience, San Diego, US). An automatic artifact rejection technique based on artifact subspace reconstruction (ASR) was used to reject the bad recording channels. A bandpass filter of 0.5 – 45 Hz was applied; the sampling frequency was reduced to 125 Hz and the signals were re-referenced to the average of all recording channels. The absolute and relative powers were calculated using the fast Fourier transform function. The power spectral density (PSD) of each frequency band was calculated for each subject using the pwelch method. For the analysis of PSD, a Hanning window with 50% overlap was utilized. Delta (0.5–3.5 Hz), theta (4.0–7.5 Hz), alpha (8–12 Hz), beta1 (12.5–20 Hz), beta2 (21–30 Hz), and gamma (30–45 Hz) waves were estimated as different frequency bands. The relative power was calculated by dividing the PSD in each band range by the sum of PSDs from all bands. The coherence between channels was evaluated using the mscohere function. Finally, the PSD and coherence traces were depicted in the MATLAB software, version R2021b.

Statistical analysis

All statistical analyses were performed using Graph-Pad Prism software, version 9.0. The distribution of data was assessed using the Shapiro-Wilk test. In the case of normal distribution, a two-way analysis of variance (ANOVA) was performed to determine the presence of a significant difference between BPD patients and HC in different frequency bands. Multiple comparisons were made using Tukey post hoc analysis. The Friedmann test was done for FP2, F3, F4, C3, C4, T6, P4 and Pz chan-

nels, which did not pass the normality test. The significance of alterations in the coherence in each frequency band was determined by the Mann-Whitney U test.

Results

Higher relative delta band power of students With BPD in the frontoparietal regions

The results of two-way ANOVA, or equivalent non-parametric test, revealed a significant difference between students with and without BPD in FP1 ($F_{(5, 72)}=5.45$, $P=0.0003$), FP2 ($F_{(5, 72)}=3.9$, $P=0.0034$), F7 ($F_{(5, 72)}=5.48$, $P=0.0002$), F8 ($F_{(5, 72)}=3.67$, $P=0.0051$), C3 ($F_{(5, 72)}=3.45$, $P=0.0074$), T5 ($F_{(5, 72)}=7.07$, $P\leq 0.0001$), P3 ($F_{(5, 72)}=8.62$, $P\leq 0.0001$) and O1 ($F_{(5, 72)}=6.11$, $P\leq 0.0001$) channels. As shown in Figure 1, based on the Tukey post hoc test, the delta relative power increased in FP1 ($P=0.0011$), FP2 ($P=0.0101$), F7 ($P=0.0041$), and F8 ($P=0.0078$) channels of BPD patients compared to HC subjects. Figure 2 shows increased delta power in C3 ($P=0.0089$) and P3 ($P\leq 0.0001$) channels, while Figure 3 demonstrates elevated relative delta power in T5 ($P\leq 0.0001$) and O1 ($P=0.0002$) channels of BPD patients.

Lower relative alpha band power of patients with BPD in the frontocentral brain regions

According to the Tukey post hoc test results, the relative alpha band power was significantly lower in the frontal EEG channels of students suffering from BPD. As depicted in Figure 1, the F7 ($P=0.0032$), F4 ($P=0.0006$), and Fz ($P=0.0087$) electrodes recorded lower alpha power in the BPD group. Figure 2 shows diminished relative alpha power in C4 ($P\leq 0.0001$), Cz ($P=0.0101$), and P4 ($P=0.002$) channels, while alteration in T4 alpha power ($P=0.0027$) is depicted in Figure 3.

Higher relative gamma band power of students suffering BPD in the right central region

The right central brain region (C4) was the only brain zone with a significant difference between students with and without BPD in the gamma-band range. As shown in Figure 2, BPD patients' relative gamma-band power was higher in the C4 ($P=0.0045$) channel.

Figure 4H summarizes the overall alterations (significance level of $P\leq 0.01$) observed in all relative band powers in different brain regions of BPD patients. (Figures 4A, 4B, and 4C), presents sample PSD traces in the brain's frontal region. (Figures 4D and 4G), shows the

PSD of other brain regions. The arrows indicate the alterations observed in students with BPD or HC subjects.

The coherence decrease in the alpha band range in patients with BPD in the frontal and temporal brain region

The coherence between the corresponding electrodes of the two brain hemispheres as well as the electrodes of the central regions was calculated in the MATLAB environment. The bar graphs in Figure 5 show a significant decrease in the alpha-band range in students with BPD.

The results of the Mann-Whitney U test revealed that the coherence level between FP1 and FP2 electrodes decreased significantly ($P=0.0023$) in students with BPD as compared to HC students. A similar decline in the coherence level was observed between F7-F8 ($P=0.0087$), Fz-Cz ($P=0.0071$), and T3-T4 ($P=0.0043$) channels of BPD patients.

Figure 6E summarizes the main coherence alterations observed in the alpha band range in the frontal and temporal brain regions of BPD patients. (Figures 6A, 6B, 6C, and 6D), illustrates the average coherence traces of students with and without BPD in the FP1-FP2, F7-F8, Fz-Cz, and T3-T4 channels.

Discussion

The results of the quantitative EEG analysis suggest an increased delta band power in students with BPD compared to healthy students. Different studies have repeatedly demonstrated that individuals with BPD show alterations in EEG band power and coherence. According to Pop-Jordanova et al. theta and delta band coherence and frequencies were considerably lower in these patients [24]. On the other hand, the most common pathological EEG abnormality observed in BPD patients is diffuse slowing of the EEG signal. Snyder et al. found that borderline individuals' EEGs had higher rates of slow-wave activity. They also detected that EEG traces of BPD patients showed fusing, a mixing of wave frequencies seen in the electroencephalogram, much more frequently than seen in depressed and healthy individuals [25].

Similarly, De la Fuente et al. demonstrated that more than 40% of BPD patients exhibited anomalous tracings. In particular, intermittent rhythmic delta and theta activity were the predominant features of all aberrant EEG recordings. Traces showed random or semi-rhythmic theta in all cases and random or semi-rhythmic delta in 80% of cases. They reported no focal or epileptiform

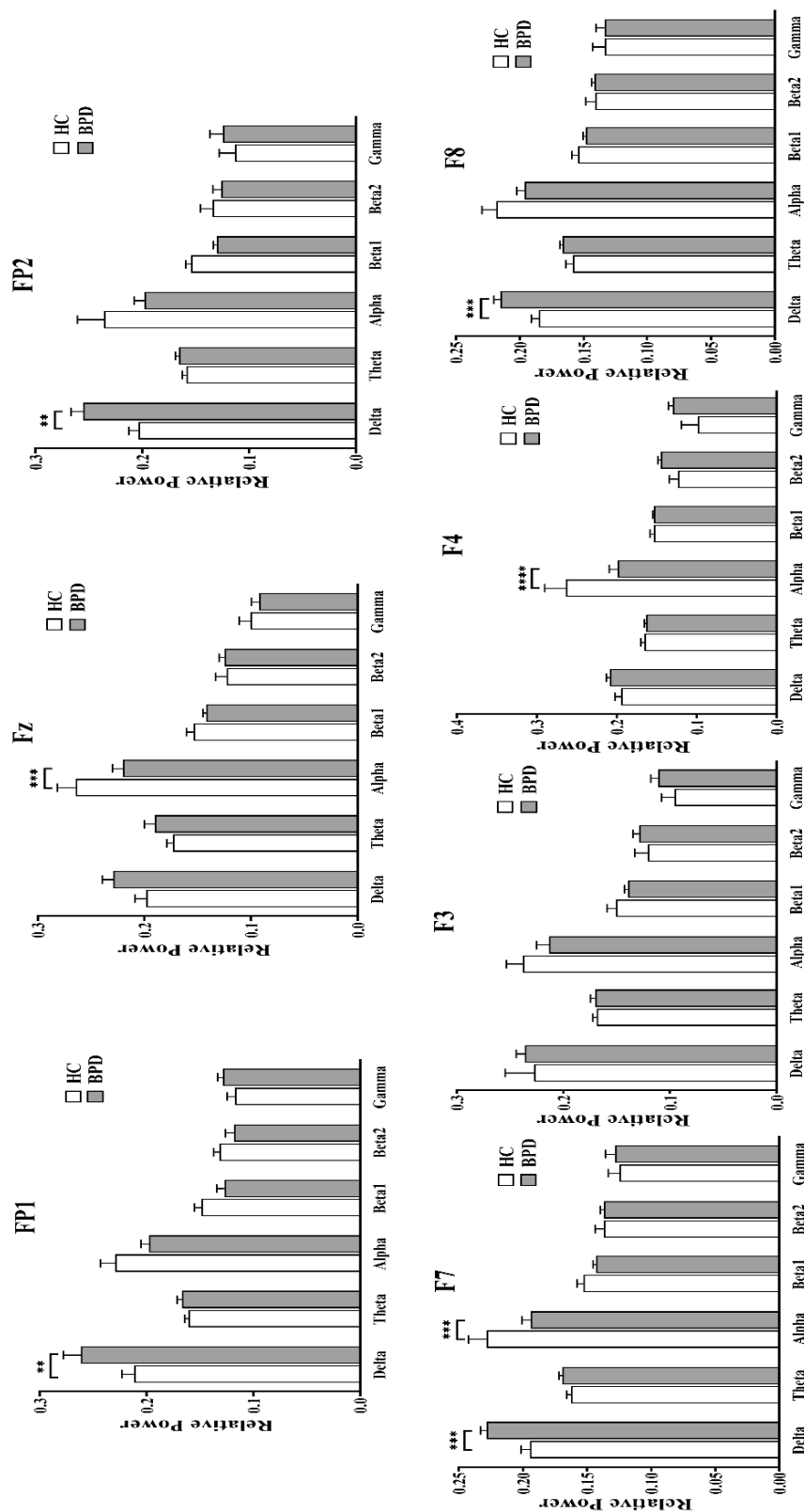


Figure 1. The differences in the relative powers of various eeg bands in the frontal brain regions of students with BPD and HC

Note: Graph titles show the standard EEG electrode names. The results are shown as Mean±SEM based on the Tukey post hoc test; **P≤0.01, ***P≤0.001.

FP: Prefrontal; F: Frontal.

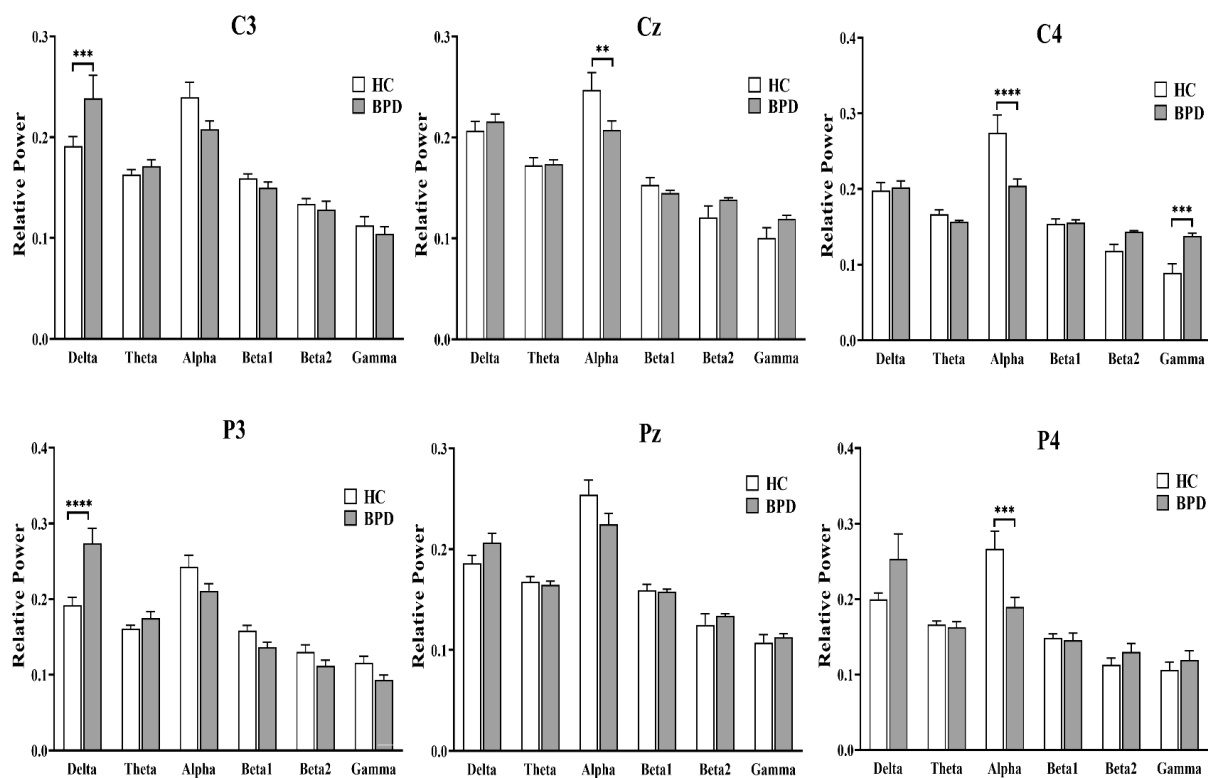


Figure 2. Comparing the relative powers of various EEG bands in the central (C) and parietal (P) brain areas

Note: Graph titles show the standard EEG electrode names. The results are shown as Mean±SEM based on the Tukey post hoc test; * $P\leq 0.01$, ** $P\leq 0.001$, *** $P\leq 0.0001$.

features [26]. Tebartz Van Elst et al. further confirmed this finding, reporting a significantly higher prevalence of intermittent rhythmic delta and theta activity in BPD patients (14.6%) compared to healthy individuals (3.9%) [27]. The present study shows no significant alteration in the theta band range, which may be attributed to the age range of the participants or the small study sample size. Arikan et al. reported that although the absolute power did not differ in patients with BD and BPD, they revealed a significant increase in the absolute delta band power of BPD patients in frontal, parietal and temporal regions in comparison to HCs [28], which is in line with the results of the present study. Numerous sensory, cognitive, and perceptual processes are known to be linked to the delta band [29]. Increased frontal delta activity is associated with focusing on various tasks, like mental calculations and semantic tasks. Extended delta oscillations prevent transmissions that could interfere with mental activities by adjusting the activity of the networks that need to be inactive during tasks [30], which suggests they may have a greater tendency to focus on tasks that require intense concentration. It could potentially explain why patients with BPD might obsessively focus on unpleasant memories, specific people, and events or intensify their behav-

ioral response to social or interpersonal stressors, leading to emotional hyperarousal [7].

The present study observed a significant reduction in the relative alpha band power in the F4, F7, Fz, C4, Cz, P4 and T4 channels. Similarly, in a recent study, Deiber et al. emphasized an increased delta and decreased alpha band power in BPD patients compared to healthy individuals. However, the lowest alpha band activity was observed in the posterior and central brain regions of BPD patients [31]. On the other hand, Arikan et al. [28] reported increased alpha band power mainly in the parietal and temporal brain regions of BD and BPD patients. Although Flasbeck et al. did not detect any significant alterations in alpha power in BPD patients compared to HCs, they revealed lower right frontal alpha power in BPD patients with alexithymia [19]. As alpha waves are associated with relaxation and mental alertness, lower alpha band power in BPD students suggests a state of increased arousal or vigilance [32]. Given the canonical role of alpha-band oscillations for attention and perceptual processes by aiding in selecting relevant data, lower frontal and parietal alpha waves may cause attention impairment in BPD patients [33].

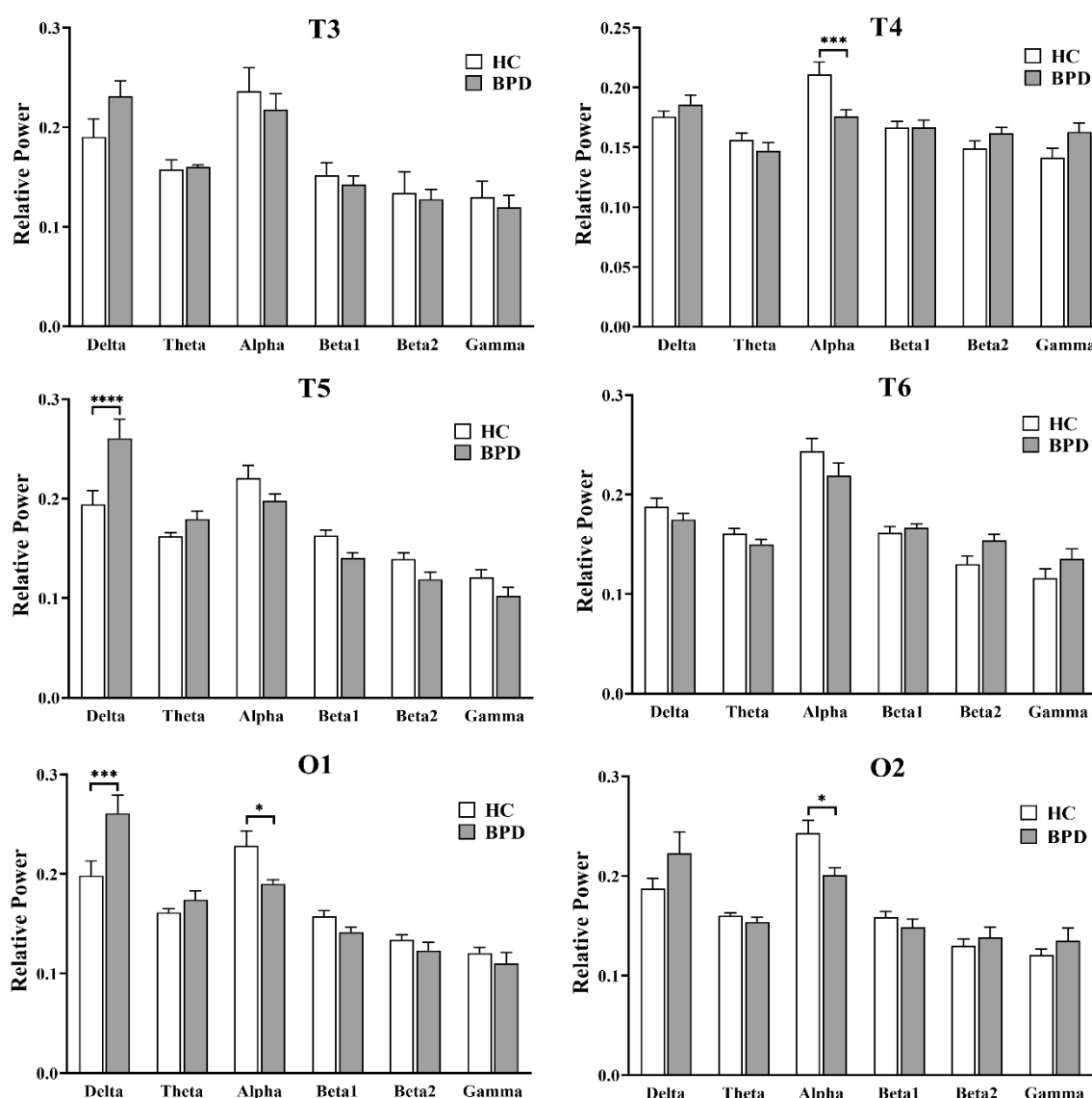


Figure 3. Alterations in the EEG band relative power in the temporal (T) and occipital (O) regions of the brain



Note: The results are shown as Mean $\pm$ SEM based on the Tukey post hoc test; * $P\leq 0.05$, *** $P\leq 0.001$, **** $P\leq 0.0001$.

Additionally, cognitive flexibility—the capacity to switch between tasks or concepts—is mediated by alpha waves. It is supposed that impaired cognitive flexibility in patients with BPD could be attributed to diminished alpha band power [34]. In the present study, an increase in the delta band range was also observed in the left occipital region, which is not reported elsewhere. This alteration may be attributed to the deficits in cognitive control and emotional regulation in BPD patients.

The findings of this study suggest an impairment in interhemispheric and intra-hemispheric connectivity in the alpha band range in patients with BPD. This finding could contribute to the emotional dysregulation and

impulsive behavior that are characteristic of BPD. Previous studies have also shown alterations in the coherence. Pop-Jordanova et al. reported a decrease in the central and frontal coherence in the theta band range. In contrast, the delta coherence was augmented in the frontal and posterior regions and attenuated in the central regions. They did not find any alterations in alpha band coherence [24]. On the other hand, Deiber et al. reported a reduced relative alpha power, specifically at parietal electrodes, indicating a decrease in this frequency band associated with relaxation and cortical inactivity. Similarly, a decreased posterior alpha power was observed, indicating cortical hyperactivation, which may be consistent with symptoms of elevated arousal and vigilance

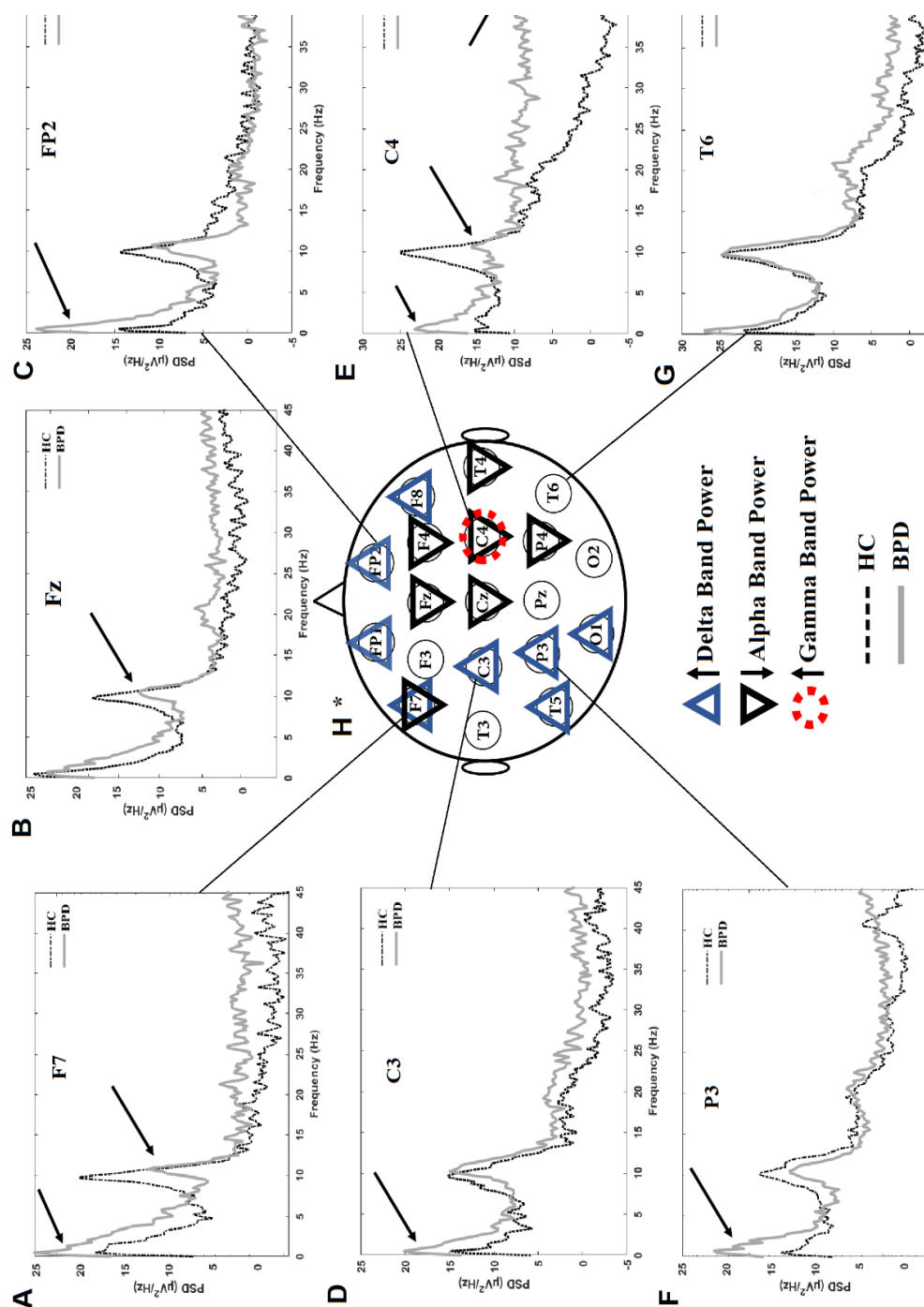


Figure 4. Individual PSD of BPD patients (black dashed line) and healthy students (gray line)

Note: Increased delta and decreased alpha band power in the frontal (A-C) and central (D and E) regions are shown by arrows. In the C4 electrode, increased gamma power is also demonstrated (E). The PSD traces of P3 electrodes depicted in F suggest an elevation in the delta band power. A schematic demonstration of all significant alterations in BPD patients is illustrated in Figure 4H; * $P \leq 0.01$, *** $P \leq 0.001$.

FP: Prefrontal; F: Frontal.

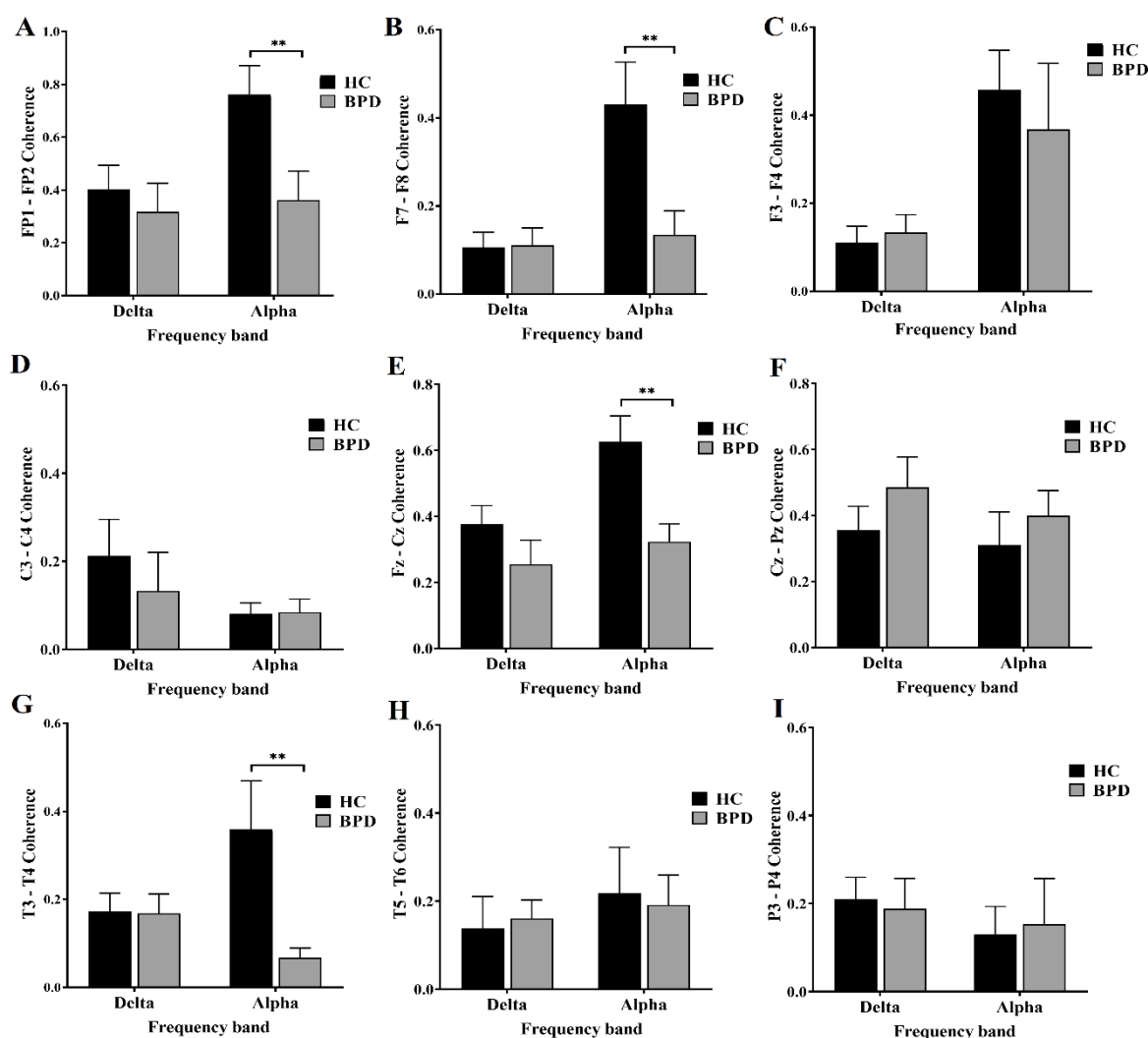


Figure 5. The coherence between the corresponding electrodes of the two brain hemispheres in the delta and alpha band ranges

Note: The coherences in prefrontal (A), frontal (B and C), central (D-F), temporal (E and G) and parietal (H) brain regions of students with and without BPD are shown as Mean ± SEM.

[31]. BPD patients exhibit dysfunction in frontal-parietal activity or connectivity within the cortical midline system. This system is crucial for self-processing, and its disruption can impact various aspects of self-perception and emotional regulation. Furthermore, BPD causes potential alterations in Inter-hemispheric connectivity, influencing the integration of cognitive and emotional processes across the brain's hemispheres [35].

The findings of the present study have implications for the treatment of BPD. Accordingly, neurofeedback (NF) therapy may play a role in using EEG data to train the brain to improve connectivity. Neurofeedback is effective in treating other conditions, such as attention-deficit/hyperactivity disorder and anxiety disorder [36]. Accord-

ing to research by Zachringer et al. applying NF to BPD patients can ameliorate their emotional and affective instability. At the same time, real-time functional magnetic resonance imaging revealed that their amygdala blood oxygen-dependent response was downregulated [37].

It is important to note that this study has some limitations. The sample size was small, and the study only included university students with BPD. Further research is needed to determine if these findings are generalizable to other populations with BPD. Additionally, the study did not investigate the relationship between EEG characteristics and specific symptoms of BPD. Future studies could explore this relationship to understand better the cognitive processes involved in BPD.

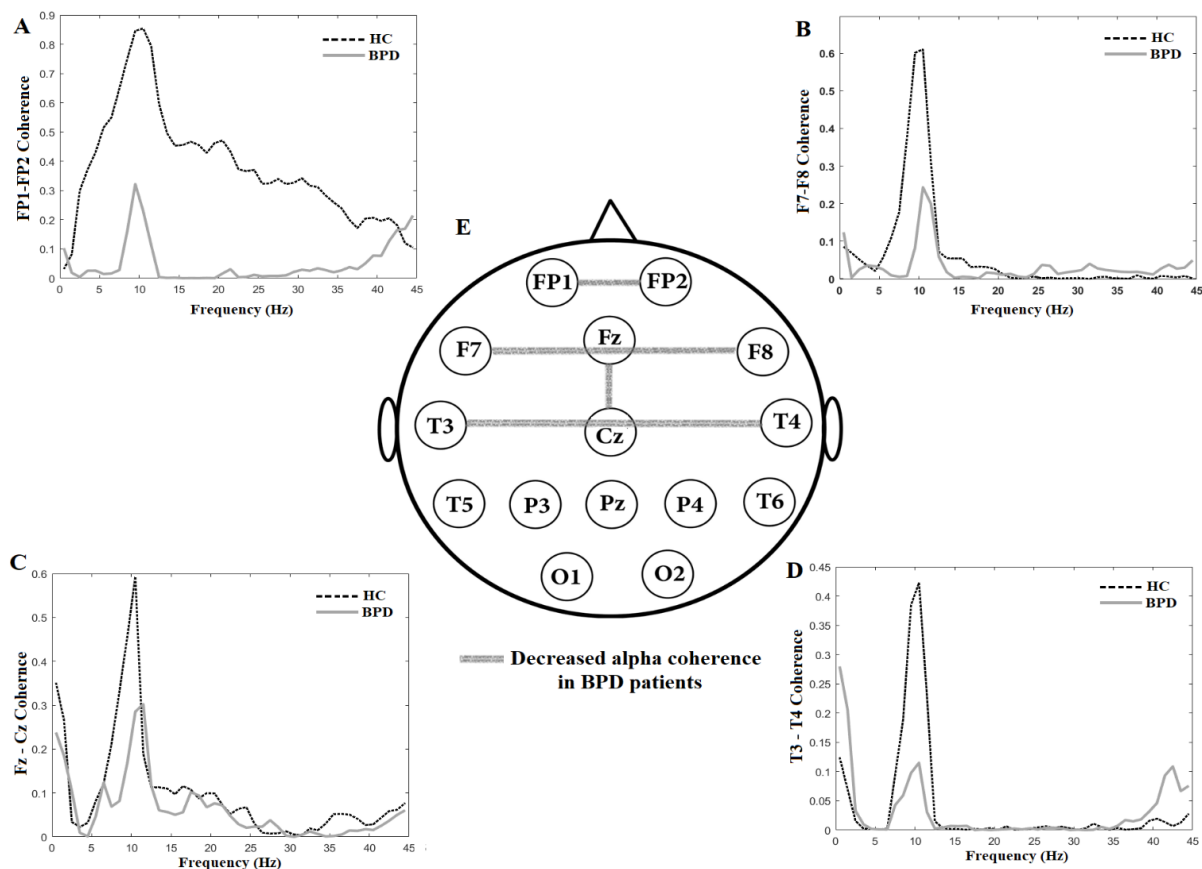


Figure 6. Sample traces of the coherence in the whole frequency band range



Note: The overall coherence level in the prefrontal (A), frontal (B), central (C), and temporal (D) brain regions are compared in students with (gray line) and without BPD (black dashed line).

Conclusion

The results of this study indicate significant differences in brain rhythms between patients with BPD and HCs. Patients with BPD showed a decrease in the power of the alpha band and an increase in the delta band, particularly in the frontotemporal region. The frontal brain region of BPD patients also showed reduced alpha band coherence. These findings suggest an abnormality in the connectivity between brain regions regulating emotion and behavior in BPD. This abnormality, especially in the frontal and temporal brain regions, may play a pivotal role in the development of BPD.

Ethical Considerations

Compliance with ethical guidelines

All ethics procedures performed in this study were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments. Informed

consent was obtained from all participants, ensuring they grasped the study's purpose, procedures, and potential risks and benefits. Participants' privacy and data confidentiality were strictly maintained, with all EEG recordings and related information anonymized. Participants were also informed of their right to withdraw from the study at any time. The study design and procedures were reviewed and approved by the University of Guilan to ensure adherence to ethical guidelines.

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Authors contributions

Conceptualization, study design, data analysis and interpretation: Kambiz Rohampour and Sajjad Rezaei; Data collection: Ameneh Azarmi; Writing the original

draft: Ameneh Azarmi and Kambiz Rohampour; Review & editing: All authors.

Conflict of interest

The authors declared no conflict of interest.

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