Evaluation of Drug Abuse on Brain Function using Power Spectrum Analysis of Electroencephalogram Signals in Methamphetamine, Opioid, Cannabis, and Multi-Drug Abuser Groups

Nasimeh Marvi (PhD Candidate)[1], Javad Haddadnia (PhD)[1*], Mohammad Reza Fayyazi Bordbar (PhD)[2]

[1]Department of Electrical and Computer Engineering, Hakim Sabzevari University, Sabzevar, Iran
[2]Psychiatry and Behavioral Sciences Research Center, Mashhad University of Medical Sciences, Mashhad, Iran

ABSTRACT

Background: The effect of different types of substances on brain function is still challenging; however, many studies have shown the functional and structural damage to the brain under influence of substance abuse.

Objective: This study aimed to quantitatively compare the effect of opioid (Op), methamphetamine (Meth), cannabis (Can), and simultaneous methamphetamine and opioid (Multi-Drug (MD)) abuse on brain function. Furthermore, the impacts of pure Op and Meth abuse were considered with simultaneous substance abuse.

Material and Methods: In this descriptive study, the electroencephalogram (EEG) signal was recorded from 52 participants in the Meth, Op, Can, and MD abusers, and the Healthy Control (HC) groups at rest state. EEG data were analyzed on the frequency domain with electrode-based, cortex-based, and hemisphere-based approaches.

Results: However, the power spectrum in the delta band in the Op group, the gamma band in the Can group, and the gamma and beta bands in the MD group more significantly increased compared to the HC group, the power spectrum values in the Meth group reduced in the alpha, beta, and gamma bands. Moreover, the power spectrum values in the MD group more significantly higher than the Meth and Op groups in the beta and gamma bands.

Conclusion: Since substance abuse in different types caused various changes in frequency components, the different power spectrum bands analysis in abusers can be reasonable to apply as a biomarker to detect the drug types.

Citation: Marvi N, Haddadnia J, Fayyazi Bordbar MR. Evaluation of Drug Abuse on Brain Function using Power Spectrum Analysis of Electroencephalogram Signals in Methamphetamine, Opioid, Cannabis, and Multi-Drug Abuser Groups. *J Biomed Phys Eng*. 2023;13(2):181-192. doi: 10.31661/jbpe.v0i0.2210-1550.

Keywords

Electroencephalography; Cannabis; Opioid-Related Disorders; Power Spectrum Analysis; Methamphetamines

*Corresponding author: Javad Haddadnia
Department of Electrical and Computer Engineering, Hakim Sabzevari University, Sabzevar, Iran
E-mail: haddadnia@hsu.ac.ir

Received: 16 October 2022
Accepted: 12 February 2023

Introduction

According to the report of the United Nations Office on drugs and crime, 585,000 individuals died of substance abuse worldwide in 2017 [1]. Happiness and high energy after using a drug, the drug's availability, and its low cost have led to increasing substance abuse, especially among young individuals. According to the Diagnostic and Statistical Manual of Mental Disorders, the Fifth Edition (DSM-5) [2] report, Opioids (Op), stimulants, cannabis (Can), hallucinogens, and methamphetamines (Meth) are essential drug categories. The investigation of the brain function damage caused by the pure abuse of drugs and the simultaneous use of two or more groups of drugs is favorable.

Excessive drug use activates the brain reward system and enhances some related behaviors. The use of a substance can increase the reward system activity, leading to neglecting normal activities and appearing in some disorders, such as a cluster of cognitive, behavioral, and physiological symptoms [2]. Substance abuse causes damage to brain tissue [3-7] and its function [8-10]. In the electroencephalography (EEG) technique, recording the cortical activity by electrodes placed on the scalp led to providing the appropriate time resolution of brain activity in different mental states. The EEG requires more straightforward recording equipment, which is available and inexpensive, compared to other brain function recording techniques, such as functional magnetic resonance imaging and functional near-infrared spectroscopy.

Regarding the effect of Can on the brain [11, 12], Crane NA et al. [11] examined brain responses during play (external stimuli) and represented that the parameters related to delta and theta bands were not significantly different in Can abusers. In contrast, Imperatori C et al. [12] investigated the changes in delta band connection in the brain connectivity study. Imperatori research results showed that delta band connections between the salient network and the central executive network were increased in Can users. Khajehpour H et al. [10, 13] analyzed functional connectivity in the brain with Graph theory and showed abnormal interregional connection and network hub changes; the graph theory indicators were also reduced in delta and gamma frequency bands. Ahmadlou et al. [14] examined the topology of functional brain connectivity and reported the disruption in brain connectivity of Meth abusers, especially in the gamma band. Newson JJ et al. [15] reviewed frequency band changes studies in mental illnesses such as addiction. According to the findings of the Newson JJ study [15], those who abuse alcohol and opioids had higher beta-band power spectra and lower alpha-band power spectra. Moreover, Minnerly C et al. [16] analyzed the EEG signal power spectrum in different types of drug and alcohol abusers and observed the highest power of the delta band in Op. Also, the energy of the theta and delta bands increased in the Op and Meth groups, and the alpha power spectrum decreased [16].

Therefore, it is needed to study the variation of the power spectrum in different drug abuser groups. The current study aimed to investigate power spectrum changes in Op, Can, Meth, and Multi-Drug (MD) abuser groups compared to the Healthy Control (HC) individuals in various frequency bands and also explore the effect of simultaneous use of two different groups of drugs (Op and Meth) against their net consumption on brain function from the power spectrum viewpoint.

Material and Methods

This descriptive study is conducted as follows.

Participants

The study involved 65 participants in total. After examining the EEG signals by a neurologist, 13 of them showed signs of epileptic seizures in their brain signals and were excluded from the study. A total of 52 men, who were ranging 18-55 years old in the groups of Meth abusers (8; mean age: 35.9±7.5), Can abusers (11; mean age: 34±7.58), Op abusers (12 mean age: 39.58±11.08), MD abuser (10; mean age: 40.66±6.63), and HC group (11; mean age: 34.45±7.25) volunteered to participate based on inclusion criteria: 1) male gender, 2) age range of 18-55 years, 3) drug user based on a urine test, 4) consent to participate in the study, 5) substance dependence criteria based on DSM-5 report [2], 6) at least two years of drug use according to history, 7) no comorbidity, head injury, trauma, epileptic seizures according to history, and lack of criteria for psychological distress according to the DSM5 report [2], 8) Pure consumption of a drug in the Can, Meth, and Op abuse groups and non-use of other drugs, in the MD group concurrently use of Op and Meth while abstaining from of other drugs, 9) Neurologist confirmation of EEG signal health.

The participants, who were daily drug users, were asked not to use drugs on the day of the signal record. A urine test was done before recording the signal. According to the urine test results and the history of participants, the Meth, Op, and Can abuse groups used only one type of pure drug, while the MD group used Op and Meth simultaneously.

EEG Signal Recording

EEG signal was recorded in the sleep clinic of Ibn Sina Hospital Psychiatric Research Center (Mashhad, Iran). The signal was recorded between 10:30-13 AM. Before the recording session, the signal recording process was explained to the research volunteers. Participants in the study received a gift in exchange for their participation after they signed a consent form.

EEG signals were recorded by the Norofax EEG-1200 (Nihon Kohden, Japan) diagnostic and monitoring platform [17]. During the signal recording, participants were asked to lie on a comfortable bed in a dimly lit room and close their eyes. EEG signal based on 10-20 standards from 18 channels (Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T3, T4, T5, T6, Fz, and Pz), with consideration of A1 and A2 electrodes as references located on earlobes, was recorded for 5 min with a 500 Hz the sampling frequency. At the end of the session, referral letters from addiction treatment centers were given to the participants in the study.

Signal Preprocessing

Proper EEG signal preprocessing was essential in correctly analyzing signal changes and designing diagnostic assistance systems. The raw EEG signal was usually mixed with power line interference, motion artifacts, eye movement, and biological signals [18]. The regression methods, empirical mode decomposition, blind source separation, filtering methods, and discrete wavelet transform could eliminate noise and artifacts [19]. The filtering method was more efficient and easily implemented than the above techniques.

A 100-second noise-free continuous segment was considered from the signal. A 6th-order Butterworth filter with a cutoff frequency of 1 to 64 Hz was then applied to the data to remove the high-frequency components. Finally, The EEG data was processed with a 50 Hz notch filter in order to remove power line interference.

Feature Extraction

A 50,000-sample segment is considered from the preprocessed EEG signal. Then, each EEG segment was windowed into 500 sample windows with a 50% overlap. The signal power spectrum in delta (1-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz), and gamma (30-64 Hz) frequency bands was calculated for 18 channels by fast Fourier transform method. The power spectrum of the frequency bands in each window was calculated. The EEG signal was analyzed using the electrode-based, cortex-based, and hemispherical-based approaches [16]. The electrode-based method calculated the EEG signal power spectrum in all frequency bands in 18 channels, leading to the comparison between groups in full detail, the large volume of data, and difficult comparisons. The cortex-based approach divided the brain's surface into six areas: the prefrontal, frontal, central, temporal, parietal, and occipital. The limited data in this approach caused the easier comparison between groups easier. The power spectrum values for each region were obtained as the average power spectrum values of the channels in that region (Table 1). In the hemispherical-based method, the brain was divided into two hemispheres: right and left. Changes in the power spectrum in Pz and Fz channels were ignored. The values obtained from the hemisphere-based analysis were the average power spectrum values in the channels related to each hemisphere (Table 2). Tables 1 and 2 show the division of brain regions and hemispheres.

Statistical Analysis

The Kolmogorov-Smirnov test assessed the normality of data distribution in each group, and the significance of changes in different groups of abusers (Meth, Op, Can, and MD) compared to the HC group was analyzed by t-test. Wilcoxon rank sum analysis was utilized to examine questionnaire data between substance abuse groups and the HC group. The research analysis was performed by MATLAB software version 2018b.

Table 1: Division of electrodes in the cortex-based approach

Region	Channel
Prefrontal	FP1, FP2
Frontal	F3, F4, F7, F8, Fz
Central	C3, C4
Temporal	T3, T4, T5, T6
Parietal	P3, P4, Pz
Occipital	O1, O2

Table 2: Division of electrodes in the hemispherical-based approach

Hemisphere	Channel
Right	FP2, F4, C4, P4, T4, T6, O2
Left	FP1, F3, C3, P3, T3, T5, O1

Results

Evaluation of Psychological Indicators and Sleep Quality

The depression, anxiety, stress scale – 21 (DASS21) [20] and Pittsburgh Sleep Quality Index (PSQI) [21] questionnaires were used to assess psychological symptoms and sleep quality in substance abusers and the HC group. Because substance abusers usually suffer from psychological problems [2] and sleep problems [22], participants were asked to complete the DASS21 and PSQI questionnaires before the EEG data recording session. The demographic information of the research participants and the results of the DASS 21 and PSQI questionnaires are shown in Table 3. The Wilcoxon rank sum test was used to examine the questionnaire data between the substance abuse and HC groups.

The evaluation of the DASS-21 questionnaire revealed that the Meth, Can, and Op groups suffered from moderate, and the MD group suffered from severe depression, anxiety, and stress. Sleep quality assessment by checking PSQI questionnaires showed that the Can and MD groups had poor sleep quality. Meth group answers were not valid in the PSQI questionnaire, while face-to-face interviews with these individuals indicated many sleep problems. The Wilcoxon Rank Sum test examined the significance of the changes in the indexes extracted from the DASS 21 and PSQI questionnaires. Statistical analysis showed that the stress index between the Can and HC groups, and the sleep quality index were significant between the MD and HC groups (*P*-value<0.05).

Power Spectrum Evaluation

Figure 1 shows the mean values of the power spectrum in the delta, theta, alpha, beta, and gamma frequency bands in the Meth, Op,

Table 3: Demographic characteristics of the subjects participating

	Opioid abuser (mean±SD, *P*-value)	Cannabis abuser (mean±SD, *P*-value)	Methamphetamine abuser (mean±SD, *P*-value)	Multi-Drug abuser (mean±SD, *P*-value)	Healthy Control subjects (mean±SD)
Number of participants	12	11	8	10	11
Age (year)	35.12±7.65, _	34±7.58, _	35.9±7.5, _	40.66±6.63, 0.0392	34.45±7.25
Education (years)	9.5±4.4, 0.0232	10.63±2.46, 0.0356	10.37±1.99, _	8.40±1.26, 0.0221	14.36±1.96
Lifetime drug use (year)	8.75±4.30, _	9.27±7.86, _	9±3.68, _	13.70±7.70, _	_
Number of addiction quits	3±2.9, _	1.9±4, _	1.25±1.16, _	3±1.9, _	_
Depression	17.5±10.88, _	17.14±12.37, _	22±12.32, _	36.22±7.96, _	4.33±4.7
Stress	18.5±7, _	17.71±10.74, 0.0162	23.1±10.13, _	36.22±6.81, _	10±8.32
Anxiety	12.25±6. 8, _	15.14±6.20, _	17.09±11.07, _	34.88±7.88, _	2.90±3.14
Pittsburgh Sleep Quality Index	6.83±2.88, _	12.71±2.81, _	-	10.88±2.08, 0.337	5.72±3.43
Marital status (married)	7	7	3	3	8
Number of subjects with a history of cigarette smoking	10	7	7	6	4

SD: Standard deviation

Can, and MD abusers and the HC group in the channel-based analysis.

In the first approach (electrode-based), changes between groups were investigated by analyzing the power spectrum in all channels. The topographic map of t values, depicting the difference between groups, was shown to visualize the results (Figure 2). The areas shown in white in the t-value topography are the channels, with no significant changes.

The second approach (cortex-based approach) divided the brain into prefrontal, frontal, central, temporal, parietal, and occipital regions to study the power spectrum. Figure 3 shows the bar graphs of changes for the mean values of the power spectrum in the cortex regions in the delta, theta, alpha, beta, and gamma frequency bands.

The third approach divided the brain into the right and left hemispheres. Figure 4 shows the average power spectrum in the different frequency bands in the right and left hemispheres.

The Kolmogorov-Smirnov test showed the changes in the power spectrum values for all bands in 18 channels, 6 regions, and 2 hemispheres in all groups with a normal distribution.

Comparing the substance abuse groups with the HC group

Delta band power spectrum analysis showed an increase in the average values of the power spectrum in the Op abuser group with a sig-

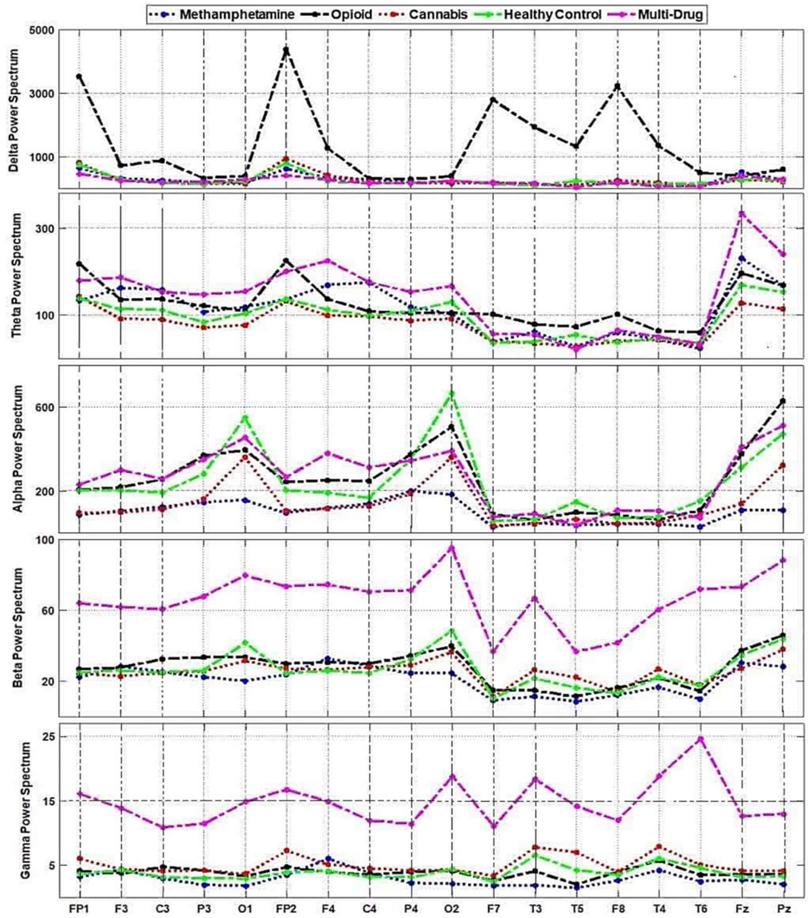

Figure 1: The mean values of the power spectrum in the delta, theta, alpha, beta, and gamma frequency bands in the Methamphetamine, Opioid, Cannabis, and Multi-Drug abusers and the Healthy Control group in the channel-based analysis.

nificant difference from the HC group. Figure 4 confirmed the significance of changes in all regions (except Fz).

Analysis of the power spectrum in the theta band with the electrode-based, cortex-based, and hemispherical-based approaches showed that the mean values of the power spectrum in the theta band in the MD, Op, and Meth abuser groups were higher than in the HC group, which were lower in the Can group than the HC group.

The power spectrum analysis in the alpha band showed that the mean values of the power spectrum in the MD and Op groups in 14 channels, 4 regions, and 2 hemispheres were higher than in the HC group. The mean values of the power spectrum in the Meth and Can groups in all areas were lower than those in the HC group.

Analysis of the power spectrum in the beta band showed that the mean values in the MD group were significantly higher than in the HC group, with a significant difference in the three approaches. The mean values of the power spectrum in the Op group were higher in most channels and areas with a slight difference than in the HC group. The mean values of the power spectrum in the Meth group in 15 channels and 2 hemispheres were lower than in the HC group. The Can group's average power spectrum values were lower than those of the HC group in 13 channels.

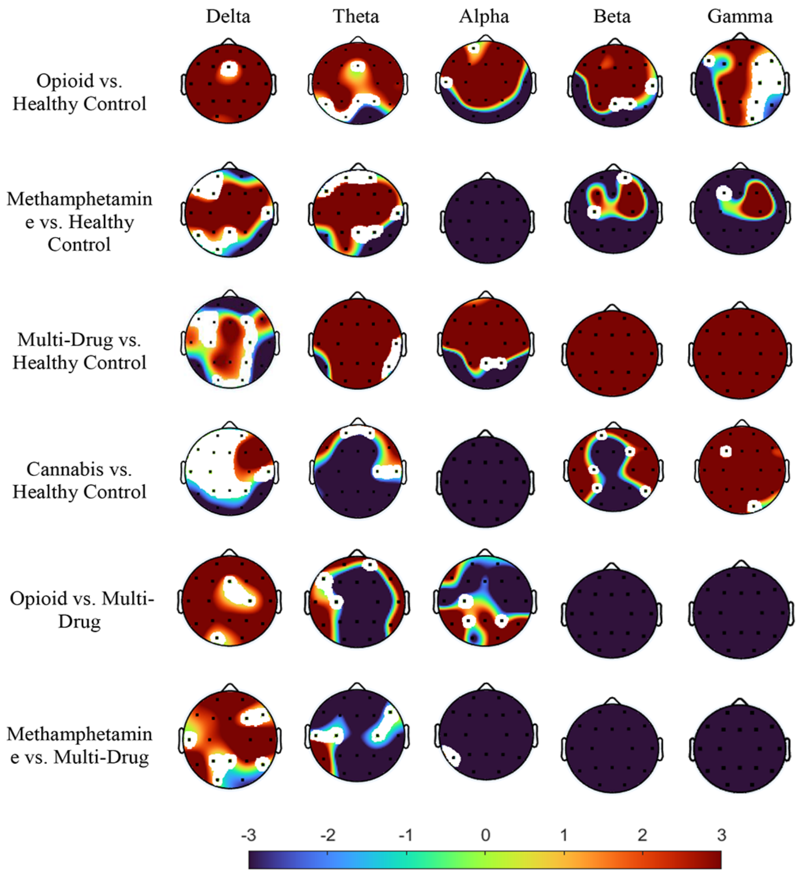

Figure 2: The topographical plot of the t-statistic values of the t-test for comparing groups.

Analysis of the gamma band's power spectrum showed that the MD group's mean values were significantly higher than in the HC group with the electrode-based, cortex-based, and hemispherical-based approaches that these changes were significant everywhere (Figure 4). A notable point in the gamma band was an increase in the power spectrum in the Can group compared to the HC group.

Based on the results, power spectrum values decreased in the Meth group in the alpha, beta, and gamma bands compared to the HC group, leading to sleep problems, which were confirmed during interviews with Meth abusers and a review of the PSQI questionnaire. Reduced power spectrum in the beta and gamma bands led to Meth abusers with daydreaming, depression, and poor cognition.

Comparing the effect of simultaneous use of two drugs with comparing the impact of each of them on the brain

In the delta band, the mean power spectrum in the Op group was significantly higher than in the MD group in the electrode-based, cortex-based, and hemispherical-based approaches. The mean values of the power spectrum in the Meth group with more negligible difference in 14 channels, all areas (except the occipital region), and two hemispheres were higher than in the MD group.

However, the average values of the power spectrum in the Op group more decreased in the theta band compared to the delta band, mean values were still higher in 8 channels and 4 regions than the mean values of the power spectrum in the MD group. In contrast,

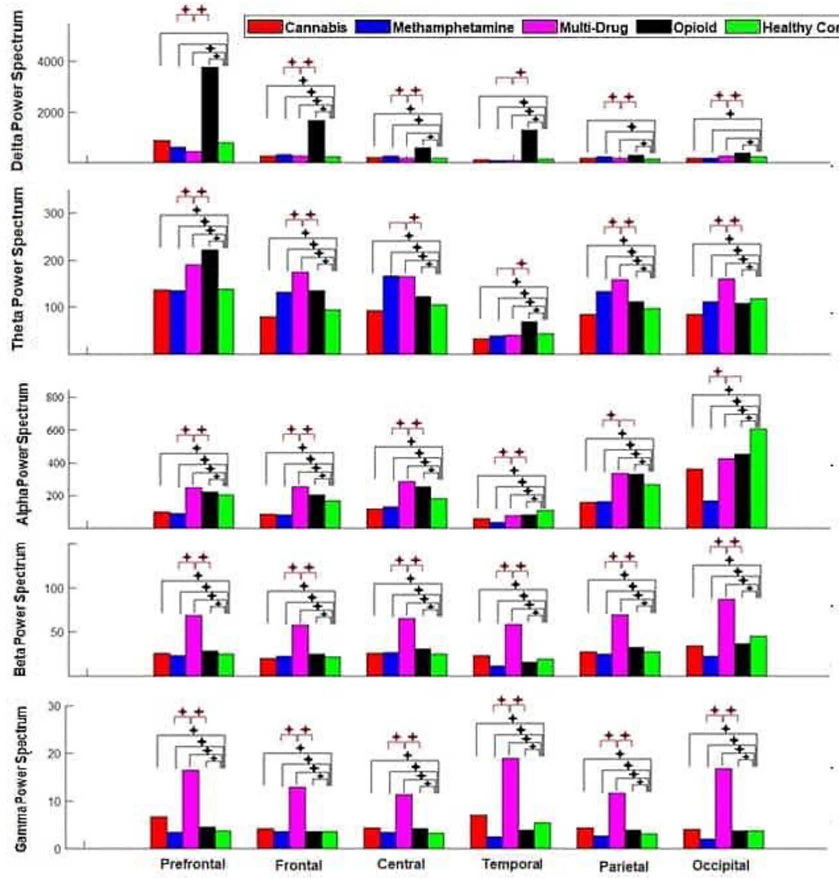

Figure 3: Mean power spectrum values in delta, theta, alpha, beta, and gamma frequency bands in Methamphetamine, Opioid, Cannabis, Multi-Drug, and Healthy Control groups in the cortex-based analysis. The black and red lines show the Significant differences between the abuser groups with the Healthy Control group and the MD group with the Opioids and Meth groups, respectively. (* for $P<0.05$).

the mean values of the power spectrum in the Meth group were lower than the MD group in all channels (except T3 and T5), all regions, and two hemispheres.

In the alpha band, the average power spectrum values of the Op group in 12 channels and all regions (except the occipital area) were lower than the MD group. Also, the power spectrum mean values in the Meth group in all regions were lower than in the MD group according to the electrode-based, cortex-based, and hemispherical-based approaches.

In the beta and gamma bands, the power spectrum mean values in the MD group were more prominent than in the Op and Meth groups by a wide margin, which was significant everywhere (Figure 4).

Discussion

This descriptive study investigated the frequency changes of the delta, theta, alpha, beta, and gamma EEG signal bands in the drug abuser groups (Op, Meth, Can, and MD) against the HC group. The study's primary objectives were to answer the following two questions with a simple power spectrum processing method: 1) What has changed the EEG signal frequency contents in different frequency bands due to the consumption of the substances in the Op, Meth, Can, and MD groups?

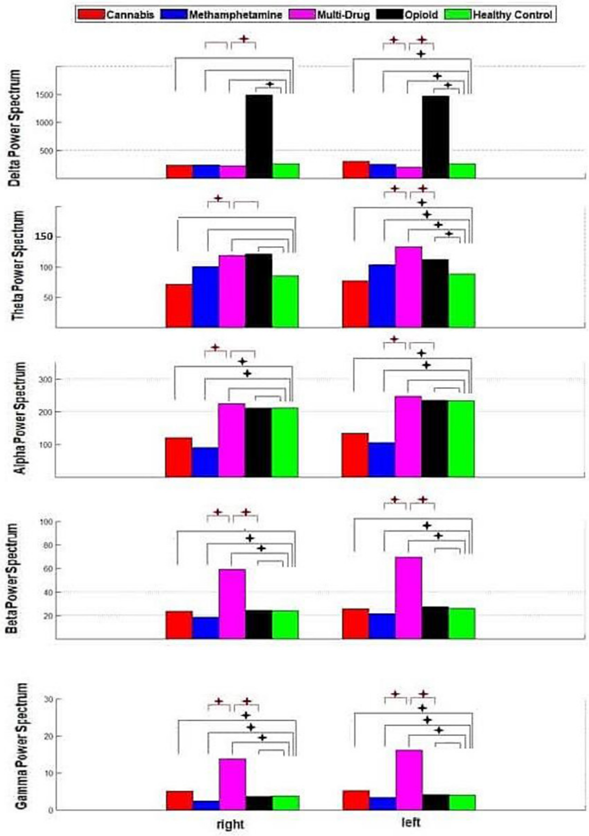

Figure 4: Mean power spectrum values in Delta, Theta, Alpha, Beta, and Gamma frequency bands in Methamphetamine, Opioid, Cannabis, and Multi-Drug groups compared to the Healthy Control group in the hemisphere-based approach. The black and red lines show the Significant differences between the abuser groups with the Healthy Control group and the MD group with the Opioids and Meth groups, respectively. (* for *P*-value<0.05).

2) What changes were made in the frequency contents of the five bands of the EEG signal in the MD group, concurrent Op and Meth users, compared to the abuser groups of pure Meth and Op?

Frequency content analysis was performed using the conventional power spectrum analysis method. To broaden the perspective, we considered three approaches to investigate changes in the EEG signal power spectrum [16]. The study, with three different methods, simplified the analysis and comparison between other groups. Also, the consistency of the electrode-based, cortex-based, and hemispherical-based approaches showed that the results were reliable.

a. Changes in frequency components of EEG signal due to substance abuse

The Op group's power spectrum in the delta band increased when compared to the HC group. The increase in delta band components in the Op compared to the HC group causes learning problems. Minnerly C et al. [16] showed an enhancement in the delta power spectrum in the Op group.

The alpha power spectrum significantly increased in the HC group compared to the substance abuse groups in the occipital region. The decrease in frequency components in the occipital region led to more reduction in consciousness in the substance abuse groups compared to the HC group [16, 23].

The present study showed that the power spectrum in the Can group was lower in the alpha and beta bands than in the HC group but increased significantly in the gamma band. A rise in the power spectrum in the gamma band showed high irritability of Can abusers. The power spectrum in the delta and theta band in the Can group was similar to the HC group. In the analysis of brain behavior in response to external stimuli, Crane NA et al. [11] indicated that the Can group did not exhibit any appreciable change in the delta and theta bands. Lapervote V et al. [24] demonstrated increased brain complexity in acute Can users. Raising the high-frequency band's power spectrum can result in increasing the complexity of the brain.

The power spectrum values in the gamma and beta bands considerably higher in the MD group compared to the HC group, showing high irritability, stress, and anxiety in these individuals, which were confirmed with DASS 21 and PSQI test results.

Yun K et al. [25] demonstrated a reduced brain complexity in Meth abusers that is consistent with a decrease in the beta and gamma bands' power spectrum. Hassan Khajeh pour H et al. [10, 13] also showed a decrease in gamma band connection indices in Meth abusers. Ahmadlou M et al. [14] demonstrated impairment of brain connection topology in gamma-band Meth abusers.

b. Changes in frequency components due to simultaneous abuse of Meth and Op:

In the Delta and Theta bands, the MD group had a lower frequency content than the Op and Meth groups. A lower power spectrum value in MD indicated poor sleep, inability to regenerate and prepare the brain, and poor emotional states in the MD group compared to the Op and Meth groups, which were confirmed with the results of the PSQI and DASS21 tests.

The alpha power spectrum value in the occipital region in the Op group was greater than the MD group, and the MD group was higher than in the Meth group. Reducing the power spectrum value in Meth indicates that the Meth group lost more consciousness than the other groups [23].

In high-frequency bands (beta and gamma), the values of the power spectrum in the MD increased significantly compared to the Meth and Op groups, showing higher anxiety, stress, arousal, and irritability in the MD than in the Meth and Op groups. The results of the DASS21 test showed a noticeable increase in stress, anxiety, and depression in the MD group compared to the Op and Meth groups.

This study had some limitations, as follows: the number of samples in each group was 17 individuals, and the study was conducted with a smaller number of participants due to the prevalence of covid-19 and the difficulty of finding abusers in the community.

Conclusion

The current research investigated the functional brain damage under the influence of Meth, Op, and Can and the simultaneous use of Meth and Op using the power spectrum analysis of EEG signals. Substance abuse caused changes in the frequency components of the EEG signals, depending on the type of drug used. The resulting changes can be introduced as biological indicators. Furthermore, the research findings can be a starting point for designing drug abuse automated diagnostic assist systems.

Authors' Contribution

N. Marvi conceived the idea. J. Haddadnia, and MR. Fayazi Bardbar conceptualized. N. Marvi and J. Haddadnia specified the research method. N. Marvi collected the research data. MR. Fayazi Bardbar supervised the data collection. N. Marvi performed the formal analysis, and software, and wrote the original draft. J. Hadadania and, MR. Fayazi Bardbar validated the research. N. Marvi, J. Hadadania, and, MR. Fayazi Bardbar reviewed and edited the research. All the authors read, modified, and approved the final version of the manuscript.

Ethical Approval

The Behavioral and Psychiatric Sciences Research Center ethics committee of Mashhad University approved this research (Ethic cod: IR.MUMS.MEDICAL.REC.1400.027).

Informed consent

All the participants have written informed consent in the project.

Conflict of Interest

None

References

1. United Nations Office on Drugs and Crime. Data UNODC/ dp-drug-use-prevalence. 2021. Available from: https://dataunodc.un.org/dp-drug-use-prevalence.
2. American Psychiatric Association. Diagnostic and statistical manual of mental disorders. Washington: American Psychiatric Association; 2013.
3. Cox BM. Pharmacology of opioid drugs. In: The Opiate Receptors. Springer; 2011. p. 23-57.
4. Keihani A, Ekhtiari H, Batouli SAH, Shahbabaie A, Sadighi N, et al. Lower Gray Matter Density in the Anterior Cingulate Cortex and Putamen Can

Be Traceable in Chronic Heroin Dependents After Over Three Months of Successful Abstinence. *Iran J Radiol*. 2017;**14**(3):e41858. doi: 10.5812/iranjradiol.41858.

5. Farnia V, Farshchian F, Farshchian N, Alikhani M, Pormehr R, Golshani S, Salemi S. A Voxel-Based Morphometric Brain Study of Patients with Methamphetamine Dependency: A Case Controlled Study. *NeuroQuantology*. 2018;**16**(12):57-62. doi: 10.14704/nq.2018.16.12.1851.
6. Vuletic D, Dupont P, Robertson F, Warwick J, Zeevaart JR, Stein DJ. Methamphetamine dependence with and without psychotic symptoms: A multi-modal brain imaging study. *Neuroimage Clin*. 2018;**20**:1157-62. doi: 10.1016/j.nicl.2018.10.023. PubMed PMID: 30380522. PubMed; PMCID: PMC6205927.
7. Moreno-Alcázar A, Gonzalvo B, Canales-Rodríguez EJ, Blanco L, Bachiller D, Romaguera A, et al. Larger Gray Matter Volume in the Basal Ganglia of Heavy Cannabis Users Detected by Voxel-Based Morphometry and Subcortical Volumetric Analysis. *Front Psychiatry*. 2018;**9**:175. doi: 10.3389/fpsyt.2018.00175. PubMed PMID: 29773998. PubMed PMCID: PMC5943550.
8. Huhn AS, Meyer RE, Harris JD, Ayaz H, Deneke E, Stankoski DM, Bunce SC. Evidence of anhedonia and differential reward processing in prefrontal cortex among post-withdrawal patients with prescription opiate dependence. *Brain Res Bull.* 2016;**123**:102-9. doi: 10.1016/j.brainresbull.2015.12.004. PubMed PMID: 26711857. PubMed PMCID: PMC4893930.
9. Zare Sadeghi A, Jafari AH, Oghabian MA, Salighehrad HR, Batouli SAH, Raminfard S, Ekhtiari H. Changes in Effective Connectivity Network Patterns in Drug Abusers, Treated With Different Methods. *Basic Clin Neurosci*. 2017;**8**(4):285-98. doi: 10.18869/nirp.bcn.8.4.285. PubMed PMID: 29158879. PubMed PMCID: PMC5683686.
10. Khajehpour H, Mohagheghian F, Ekhtiari H, Makkiabadi B, Jafari AH, Eqlimi E, Harirchian MH. Computer-aided classifying and characterizing of methamphetamine use disorder using resting-state EEG. *Cogn Neurodyn*. 2019;**13**(6):519-30. doi: 10.1007/s11571-019-09550-z. PubMed PMID: 31741689. PubMed PMCID: PMC6825232.
11. Crane NA, Funkhouser CJ, Burkhouse KL, Klumpp H, Phan KL, Shankman SA. Cannabis users demonstrate enhanced neural reactivity to reward: An event-related potential and time-frequency EEG study. *Addict Behav*. 2021;**113**:106669. doi: 10.1016/j.addbeh.2020.106669. PubMed PMID: 33035810. PubMed PMCID: PMC7736273.
12. Imperatori C, Massullo C, Carbone GA, Panno A, Giacchini M, Capriotti C, et al. Increased Resting State Triple Network Functional Connectivity in Undergraduate Problematic Cannabis Users: A Preliminary EEG Coherence Study. *Brain Sci*. 2020;**10**(3):136. doi: 10.3390/brainsci10030136. PubMed PMID: 32121183. PubMed PMCID: PMC7139645.
13. Khajehpour H, Makkiabadi B, Ekhtiari H, Bakht S, Noroozi A, Mohagheghian F. Disrupted resting-state brain functional network in methamphetamine abusers: A brain source space study by EEG. *PLoS One*. 2019;**14**(12):e0226249. doi: 10.1371/journal.pone.0226249. PubMed PMID: 31825996. PubMed PMCID: PMC6906079.
14. Ahmadlou M, Ahmadi K, Rezazade M, Azad-Marzabadi E. Global organization of functional brain connectivity in methamphetamine abusers. *Clin Neurophysiol.* 2013;**124**(6):1122-31. doi: 10.1016/j.clinph.2012.12.003. PubMed PMID: 23332777.
15. Newson JJ, Thiagarajan TC. EEG Frequency Bands in Psychiatric Disorders: A Review of Resting State Studies. *Front Hum Neurosci.* 2019;**12**:521. doi: 10.3389/fnhum.2018.00521. PubMed PMID: 30687041. PubMed PMCID: PMC6333694.
16. Minnerly C, Shokry IM, To W, Callanan JJ, Tao R. Characteristic changes in EEG spectral powers of patients with opioid-use disorder as compared with those with methamphetamine- and alcohol-use disorders. *PLoS One*. 2021;**16**(9):e0248794. doi: 10.1371/journal.pone.0248794. PubMed PMID: 34506492. PubMed PMCID: PMC8432824.
17. Nihon Kohden Corporation. EEG system: EEG-1260. 2022. Available: https://us.nihonkohden.com/products/eeg-1200/.
18. De Cheveigné A, Arzounian D. Robust detrending, rereferencing, outlier detection, and inpainting for multichannel data. *Neuroimage.* 2018;**172**:903-12. doi: 10.1016/j.neuroimage.2018.01.035. PubMed PMID: 29448077. PubMed PMCID: PMC5915520.
19. Jiang X, Bian GB, Tian Z. Removal of Artifacts from EEG Signals: A Review. *Sensors (Basel)*. 2019;**19**(5):987. doi: 10.3390/s19050987. PubMed PMID: 30813520. PubMed PMCID: PMC6427454.
20. Salehi M, Darchini-Maragheh E, Payandeh A, Behdani F, Ghasemzadeh Kolagar H. Evaluation of the Correlations between Depression, Anxiety, and Stress as DASS-21 Subscales and High-Risk Behaviors in the Adolescents in Torghabeh and Shandiz Towns, Iran. *Patient Saf Qual Improv*. 2017;**5**(3):584-90 doi: 10.22038/PSJ.2017.9479.

21. Kushkestani M, Parvani M, Nosrani SE, Bathaeezadeh SY. The relationship between drug use, sleep quality and quality of life in dormitory students at Allameh Tabataba'i University, Iran. *Popul Med*. 2020;**2**:1-7. doi: 10.18332/popmed/115799.
22. Du X, Xu W, Li X, Zhou D, Han C. Sleep Disorder in Drug Addiction: Treatment With Transcranial Magnetic Stimulation. *Front Psychiatry*. 2019;**10**:848. doi: 10.3389/fpsyt.2019.00848. PubMed PMID: 31798482. PubMed PMCID: PMC6878723.
23. Moini J, Piran P. Functional and Clinical Neuroanatomy: A Guide for Health Care Professionals. Academic Press; 2020.
24. Laprevote V, Bon L, Krieg J, Schwitzer T, Bourion-Bedes S, Maillard L, Schwan R. Association between increased EEG signal complexity and cannabis dependence. *Eur Neuropsychopharmacol.* 2017;**27**(12):1216-22. doi: 10.1016/j.euroneuro.2017.10.038. PubMed PMID: 29132831.
25. Yun K, Park HK, Kwon DH, Kim YT, Cho SN, Cho HJ, Peterson BS, Jeong J. Decreased cortical complexity in methamphetamine abusers. *Psychiatry Res.* 2012;**201**(3):226-32. doi: 10.1016/j.pscychresns.2011.07.009. PubMed PMID: 22445216.