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Multimodal analysis of cortical activation in young male adults with internet gaming disorder: A resting state EEG-fNIRS study

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ABSTRACT

Background: Internet gaming disorder (IGD) has become increasingly prevalent worldwide and is recognized as a significant public health concern because of its negative consequences on individuals mental and physical health, social relationships, academic performance and overall well-being. While research on IGD has gained significant momentum in the past decade, the neural substrates underlying this disorder remains unclear. This study aims to investigate resting-state cortical activation in male subjects with IGD using a concurrent functional near infrared spectroscopy (fNIRS) and electroencephalography (EEG) hybrid system.
Methods: Twenty-two male individuals with IGD (18–23 years old) and twenty-two male healthy, age-matched healthy controls were included in the study. Mean oxygenation of the prefrontal cortex (PFC) and whole head neural activity were measured using fNIRS and EEG respectively, during eyes-open and eyes-closed conditions at the resting state. EEG signals were decomposed into distinct frequency sub-bands with wavelet transform, followed by the analysis of the power spectral density within each band. Mean oxygenation of PFC is measured using a multichannel fNIRS system.
Results: Results revealed that the individuals with IGD had significantly higher beta power in the frontal region compared to the control group. Individuals with IGD showed significantly increased PFC oxygenation compared to healthy controls. Additionally, both frontal beta power and PFC oxygenation were significantly correlated with IGD severity. However, there were no significant correlations observed between oxygenation and beta powers.
Conclusion: This study is the first to examine resting-state cortical activation using multimodal EEG-fNIRS system in young adults with IGD. Moreover, it provides an important contribution to the understanding of the underlying neural mechanisms of IGD and offer new insights for the diagnosis and intervention of the disorder using multimodal EEG-fNIRS system. Further studies should aim to replicate the findings of this study using a larger and more culturally diverse sample to support the neurophysiological basis of IGD.

1. Introduction

Internet Gaming Disorder (IGD) has emerged as a significant global public health concern due to its increasing prevalence and associated negative outcomes. A review and meta-analytic research on IGD revealed that the global prevalence of IGD among adolescents is 9.9% (Gao et al., 2022), reaching up to 27.5% depending on the population and location (Mihara and Higuchi, 2017). In terms of gender, the studies

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show that the prevalence of IGD among males is significantly higher than that among females (Meng et al., 2022). IGD is characterized by excessive or uncontrolled use of internet-based games, resulting in substantial challenges in daily functioning (Kuss and Griffiths, 2012). It is defined as a potential mental disorder and is currently included in the 5th edition of the Diagnostic and Statistical Manual of Mental Disorder (DSM-V) as a condition requiring further research (American Psychiatric Association, 2013). In 2022, the statement "Gaming disorder, predominantly online" was added as a subtype of Gaming Disorder in the International Classification of Diseases, 11th Revision (ICD-11) by the World Health Organization (2022). Understanding the neural substrates of any mental disorder including addiction is essential for accurate diagnosis, effective treatment and prevention strategies (Weinstein and Lejoyeux, 2020). The National Institute of Mental Health advocates the use of Research Domain Criteria (RDoC) which may support classifying mental disorders based on neurobiological measures (National Institute of Mental Health, 2011).

Over the last decade, an increasing number of neuroimaging studies have revealed neurobiological differences between individuals with IGD and healthy controls (HCs). Kuss et al. (2018) reviewed the neurobiological correlates of IGD studied via various neuroimaging techniques and indicated that IGD is associated with reduced inhibitory control, emotional dysregulation, visual and hearing impairments, decreased prefrontal cortex (PFC) functioning and impaired working memory capacity. Electroencephalography (EEG) has been widely used to investigate neural correlates of addictive behaviors including IGD (Yao et al., 2017). Although there are several studies on IGD subjects that have investigated spectral analysis of resting-state EEG, the findings are not consistent and require further research. Burleigh et al. (2020) reviewed resting-state EEG studies and found that individuals with gaming disorder (GD) showed decreased absolute beta power and increased delta and theta activity. Choi et al. (2013) observed lower absolute beta power in internet addiction subjects compared to healthy controls. Hong et al. (2022) indicated that IGD subjects who play a single game exhibit increased beta power compared to healthy controls. They demonstrated that sub-band powers vary depending on game usage patterns and genre. Functional magnetic resonance imaging (fMRI) is another commonly used technique to investigate brain functions in IGD. A meta-analysis of resting state fMRI studies revealed increased brain activity in frontal areas among individuals with IGD compared to healthy controls (Yao et al., 2017).

Similar to fMRI, an emerging non-invasive, optic based method, namely the functional near-infrared spectroscopy (fNIRS) can monitor changes in the cerebral oxygenation related to the neural activity via neurovascular coupling but in a wearable and cost-effective way. fNIRS measures the regional changes in hemodynamic response in the brain, and is widely utilized to investigate various brain disorders including schizophrenia (Eken et al., 2022) depression (Wu et al., 2022), attention deficit hyperactivity disorder (Dolu et al., 2019; Güven et al., 2020), anxiety (Wu et al., 2024) and neurodevelopmental disorders (Ehlis et al., 2014). To date, fNIRS has been rarely utilized to investigate neural correlates of substance use disorder and behavioral addiction. These studies are focused on PFC due to its association with addiction (Weinstein and Lejoyeux, 2020). Carollo et al. (2022) reviewed fNIRS addiction studies and suggested that combining fNIRS with other neuroimaging methods may enhance the ability to predict patients' prognosis and treatment response in clinical practice.

Recently integration of neuroimaging techniques with complementary spatial and temporal resolutions is commonly employed to obtain a more comprehensive information on the underlying cognitive functioning. One such promising method is multimodal EEG-fNIRS which combines two efficient and complementary systems while taking advantage of their portability, cost-effectiveness and non-invasive nature. EEG provides excellent temporal resolution by measuring neural activations and fNIRS offers good spatial resolution by measuring changes in regional cerebral hemodynamics. When integrated, these modalities provide complementary information about the brain function, offering a more comprehensive understanding of neurovascular coupling and cognitive processes (Li et al., 2022). There are several multimodal resting state EEG-fNIRS studies that show relationship between EEG patterns and hemodynamic response. Keles et al. (2016) showed the utility of resting state EEG-fNIRS in tracking neurovascular coupling in cortex.

To the best of our knowledge there are no previous studies that have investigated resting-state fNIRS in IGDs. In this study we aimed to combine EEG and fNIRS modalities in order to provide new insights into IGD. For this purpose, simultaneous resting-state quantitative EEG (qEEG) and fNIRS were analyzed i) to investigate group differences between EEG sub-band powers ii) to examine group differences in PFC oxygenation, and iii) to investigate the relationship of IGD severity and EEG/fNIRS patterns. Based on previous EEG and fMRI studies we hypothesized that i) individuals with IGD would show increased oxygenation in PFC as compared to healthy controls (Meng et al., 2015; Weinstein and Lejoyeux, 2020), ii) there would be a correlation between IGD severity and EEG sub-band powers (Son et al., 2015), as well as IGD severity and PFC oxygenation (Cho et al., 2022), and iii) EEG beta sub-band power would be significantly lower in the IGD group compared to HCs (Burleigh et al., 2020; Kuss et al., 2018; Son et al., 2015).

2. Methods

2.1. Participants

A total of 44 male university students participated in the study, comprising 22 individuals with IGD (mean age 20.86 $\pm$ 1.52) and 22 healthy controls (mean age 20.68 $\pm$ 1.64). Participants were recruited from universities through advertisements and underwent clinical assessments conducted by an experienced psychiatrist. The general inclusion criteria were as follows: (1) male university students age between 18 and 23 years, (2) normal hearing and visual functions, (3) absence of any substance dependence (nicotine, cocaine, alcohol, etc.) according to DSM-V criteria, and (4) absence of any current neurological and Axis 1 psychiatric disorders. The exclusion criteria included: (1) history of a neurological, metabolic, endocrinological, or any other systemic disorder, (2) presence of intellectual disability, and (3) presence of any psychotic disorders, mood disorders, and trauma-related disorders. All participants were medication naïve. Individuals with IGD were diagnosed by an experienced psychiatrist according to DSM-V criteria and Young's Internet Addiction Test (IAT) (Young, 2009). Participants with IGD had IAT scores of at least 50 and met at least five of the DSM-V criteria specified for IGD (Petry and O'Brien, 2013). DSM-V score of participants were calculated with Internet Game Disorder Scale Short Form (IGDSF-9) (Pontes and Griffiths, 2015). As all participants were native Turkish speakers, the Turkish version of IGDSF-9 was used (Evren et al., 2018). The mean IAT score of individuals with IGD was 63.36 $\pm$ 9.74. Their average daily duration spent playing online internet games was 5.82 $\pm$ 2.48 h. The mean IAT score of HCs was 36.5 $\pm$ 8.37. They were playing online internet games for less than 2 h per day and 12 h per week. HCs' mean time spent using internet games per day was 1.20 $\pm$ 1.22 h. All participants in the study had easy access to a computer. Depression, anxiety and impulsivity levels of participants were assessed using the Beck Depression Inventory (BDI; Beck et al., 1961), the Beck Anxiety Inventory (BAI; Beck et al., 1988), and the Barratt Impulsiveness Scale-11 (BIS-11; Patton et al., 1995). BAI score ranged between 0 and 63. In this study, we used standardized cut off values of anxiety (0–7: minimal, 8–15: mild, 16–25: moderate, 26–63: severe). According to these scales all participants scored between 0 and 25 and had mild to moderate anxiety.

Demographic and clinical characteristics of the participants are presented in Table 1. The research was approved by the ethical committee of Erciyes University and written informed consent was obtained

Table 1
Demographic and clinical characteristics of the participants.

Variables	IGD $N = (22)$	HC $N = (22)$	t	*p*
Demographic Data				
Age[a]	20.86 ± 1.52	20.68 ± 1.64	0.381	0.705
Education in Years[a]	14.04 ± 1.29	13.91 ± 1.34	0.344	0.733
Game Usage in a day (h)[b]	5.82 ± 2.48	1.20 ± 1.22	5.403 (z)	0.000[s]
Clinical Data				
IGDSF-9[a]	29.45 ± 5.33	13.68 ± 3.51	11.58	0.000[s]
Young IAT[a]	63.36 ± 9.74	36.5 ± 8.37	9.904	0.000[s]
BDI[b]	11.45 ± 6.63	8.73 ± 6.92	1.767 (z)	0.077
BAI[b]	10.82 ± 7.85	6.77 ± 7.50	1.754 (z)	0.079
BIS 11[a]	69.59 ± 6.32	67.64 ± 6.56	1.006	0.320

[a] Groups were compared with Student's t-tests.
[b] Mann-Whitney test for their variables, IGD: Internet Gaming Disorder, HC: Healthy Control, BAI: Beck's anxiety inventory; BDI-II: Beck's depression inventory II; IAT: Internet addiction test, IGDSF-9: internet game disorder scale short form; s: statistically significant.

from all subjects prior to participation.

2.2. Procedures

After clinical assessment, the participants were referred to the Erciyes University, Clinical Engineering Research and Implementation Center for data acquisition. The records were obtained in a sound-shielded Faraday-caged physiological signal recording room. During the recording sessions, participants were seated in a comfortable chair, and instructed to relax their minds, avoiding movement as much as possible. A 4-min eyes open and 2-min eyes closed resting state data were recorded from each participant. During the eyes-open condition, participants were instructed to look at a fixation cross displayed on a black screen positioned at a distance of 130 cm. EEG and fNIRS were simultaneously recorded. Electrooculography (EOG) was also recorded simultaneously to eliminate eye movements from EEG. Fig. 1 provides an overview of the recording setup. A detailed description of multimodal EEG/fNIRS measurement is presented below.

2.3. EEG data acquisition and analysis

EEG data were recorded using an Ag/AgCl electrode cap (Electro-Cap International, Inc.) and EBNeuro BE-Light amplifier system. Electrodes were placed at standard locations according to the international 10–20 system, on 17 sites including F3, F4, Fz, F7, F8, T3, C3, Cz, T4, C4, T5, P3, O1, Pz, T6, P4 and O2. Additionally, three electrodes were used to record EOG signals; one was positioned above nasion, and the remaining two located below the outer canthus of the left and right eyes (Liu et al., 2017; Schlögl et al., 2007). The reference and ground electrodes were placed on left mastoid and right mastoid, respectively. The electrode impedances were maintained below 10 kΩ and the sampling rate was 512 Hz. EEG processing was performed using EEGLab v2023.1 within the MATLAB environment (Matlab, 2022a; Mathworks Inc., Natick, MA). Raw EEG signals were band-pass filtered with a zero-phase finite

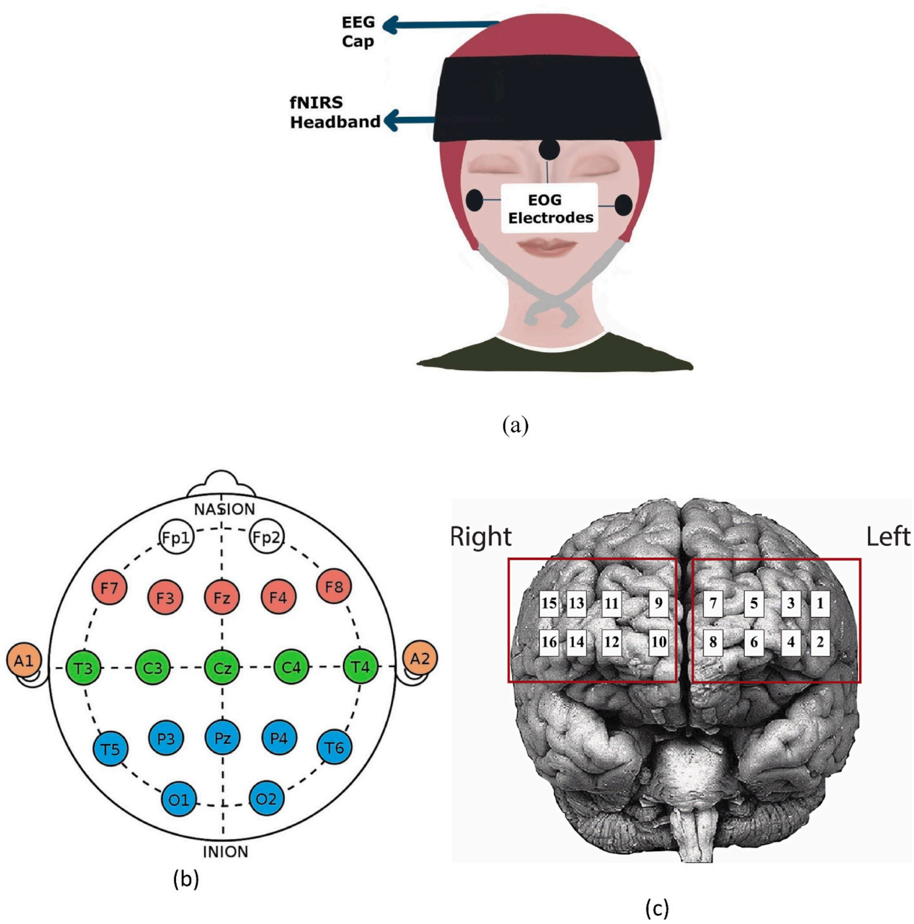

Fig. 1. (a) Experimental design. EEG, fNIRS and EOG signals were simultaneously recorded (Liu et al., 2017) (b) EEG montage: Fp1 and Fp2 channels were covered with fNIRS sensor. Seventeen EEG channels were obtained from marked locations with red circles representing the frontal region, green circles the central region and blue circles the posterior region, A1 and A2 correspond to left and right mastoid for reference and ground electrode, respectively (c) The channel positions of fNIRS measurement area. The right PFC includes optodes 9–16 and the left PFC includes optodes 1–7, Brain surface image is sourced from University of Washington, Digital Anatomist Project.

impulse response (FIR) filter within the frequency range of 0.5–60 Hz. Additionally, a second-order notch filter was applied to eliminate 50 Hz power line noise. Independent component analysis was utilized to remove artifacts related to eye movements and blinks (Jung et al., 2000). EEG signals were decomposed into five frequency bands using a four level dB5 (Daubechies 5) wavelet function: Delta (<4 Hz), theta (4–7.5 Hz) alpha (7.5–12.5 Hz), beta (12.5–30 Hz) and gamma (30–40 Hz). Subsequently, these sub-bands of each channel were assessed for further analysis. The brain activity at 17 electrode sites was categorized into five regions by averaging within each region: Frontal (F3, F4, Fz, F7, F8), Parietal (P3, Pz, P4) Temporal (T3, T4, T5, T6), Central (T3, C3, Cz, T4, C4) and Posterior (T5, P3, O1, Pz, T6, P4 and O2). In addition, frontal EEG signals were classified into left (F3, F7) and right (F4, F8) to assess the variability in absolute power between the two hemispheres. The power spectral density (PSD) of each channel was estimated using Welch's method which is described in detail below.

2.3.1. Power spectral density

PSD is a widely used method for EEG signal analysis representing the distribution of the signal frequency components. There are two main types of methods for estimating PSD: parametric and non-parametric. Parametric methods, such as autoregressive and moving average models, involve building a model for the signal with certain assumptions and then estimating PSD based on the fitted model. On the other hand, non-parametric methods (e.g., periodogram, Welch) directly estimate the spectrum from the data without making explicit assumptions about the underlying signal model. One common non-parametric method for estimating PSD is the periodogram which involves applying the Fourier transform to EEG recordings. However, the periodogram method has some drawbacks including high variance and resolution of the spectrum estimation. The Welch method is an improved form of the periodogram. In this method, the signal is divided into overlapping segments and the periodogram of each segment is computed separately. These individual periodograms are then averaged to reduce variance (Welch, 1967). The periodogram $P_i(f)$ for the i-th segment is computed as:

$$P_i(f) = \frac{1}{M}\left|\sum_{n=0}^{M-1} x_i(n)w(n).e^{-j2\pi fn}\right|^2 \tag{1}$$

Here, M represents the length of the window, and $w(n)$ denotes the windowing function. By averaging periodograms we compute the Welch's PSD as follows:

$$S_W(f) = \frac{1}{L}\sum_{i=0}^{L-1} P_i(f) \tag{2}$$

where L is the length of the signal.

In this study, Welch's method was employed to estimate PSD values using a Hamming window with 50% overlap. We further computed the total area under the PSD curves (Altıntop et al., 2023). PSD was calculated for each sub-band of each channel, resulting in 85 PSD values for each participant (17 × 5 = 85). Subsequently, we averaged the PSD values for each sub-band within the defined region and performed statistical comparisons between the IGD and HC groups.

2.4. fNIRS data acquisition and analysis

fNIRS is a noninvasive neuroimaging technique that measures the regional changes of oxygenated (HbO) and deoxygenated hemoglobin (HbR) related to neural activity (Yücel et al., 2017). By exploiting the distinct absorption characteristics of HbO and HbR at different wavelengths of near-infrared light, fNIRS enables the detection of changes in brain activation (Ayaz et al., 2022). In this study, fNIRS data were collected using a multi-channel continuous-wave optical brain imaging system, Biopac fNIRS Model 203c (fNIR Devices, LLC, Potomac, MD, USA). The sensor is equipped with 4 light sources and 10 photodetectors positioned 2.5 cm apart from the source and together with 2 short-separation detectors. The configuration provides 16 channels (plus two short channels) that cover the PFC. The sampling rate was 10 Hz and the NIR light wavelengths were at 730 nm and 850 nm for the spectroscopic separation of HbR and HbO. Data processing was performed using fnirSoft Professional (Version 4.11) (Ayaz et al., 2012). Raw fNIRS intensity measurements were filtered with a low-pass filter (cut-off frequency 0.1 Hz) using a finite impulse response (FIR) filter employing a Hamming window (order: 100), to eliminate physiological noise (Hall et al., 2023). Saturated channels were identified and excluded from the study. Concentration changes of HbO and HbR were calculated using the modified Beer-Lambert Law (Cope and Delpy, 1988). Compared to HbR, HbO is a more sensitive and reliable marker of cerebral blood flow changes (Fishburn et al., 2014). Besides, it has an acceptable high reproducibility, as well as higher signal-to- noise ratio in comparison with the HbR signal. Thus, in this study we evaluated HbO values. Baseline correction of HbO signals was conducted using data from the 10 s preceding eyes-closed condition. The mean HbO values during the eyes-closed condition were computed for each channel. Subsequently, three regions of interest were defined as: 1) all channels in the PFC (CH1 to CH16), 2) left PFC channels (CH1 to CH8) and 3) right PFC channels (CH9 to CH16), allowing for the evaluation of hemispheric differences. Average HbO values were calculated for each region and used in statistical comparisons to assess differences between individuals with IGD and HCs.

2.5. Statistical analysis

All statistical analyses were conducted using SPSS 21.0. Data normality was assessed using the Shapiro-Wilk test and parametric and non-parametric methods were employed for the analysis based on the distribution of the data. The statistical analyses consisted of six steps: 1) comparison of each sub-band's absolute powers in the defined regions (frontal, frontal right, frontal left, parietal, temporal, central, posterior) between the groups, 2) comparison of the mean HbO values for defined three regions (frontal, frontal right, frontal left) to investigate group differences, 3) correlation analysis of HbO values and frontal beta powers, 4) correlation analysis of IGD severity and EEG powers, 5) correlation analysis of IGD severity and mean HbO values, and 6) exploration of group differences for clinical variables (depression, anxiety and impulsivity scores).

We performed separate t-tests for the comparison of each region. The correlation analysis that investigates the relationship between IGD severity and EEG/fNIRS variables were conducted for only IGD group. The correlation analyses were performed with Pearson's correlation method. All analyses were conducted with a statistical significance threshold set at <0.05.

3. Results

3.1. Demographic and clinical test- scales

As seen in Table 1, groups did not show any significant difference for age, education in years, BDI, BAI, and BAS-11 variables. However, we found statistically significant differences between groups for online game usage, IGDSF-9 and IAT variables.

3.2. EEG results

The PSD of each channel is estimated using the Welch's method as previously described. The mean of the PSD values of the channels from frontal, parietal, temporal, central and posterior region were compared with Student's t-test to evaluate differences between the IGDs and HCs. The statistical test results are shown in Table 2. Results revealed that compared to the control group, IGD participants had significantly higher absolute power in the beta frequency band activity in the frontal region

Table 2
EEG Power of EEG Sub-Band (The Power values correspond to the total area under the PSD curves).

EEG Region	Freq. Bands	IGD (N = 22)		HC (N = 22)		t	p
		Mean	STD	Mean	STD		
Frontal	Gamma	334.35	514.62	134.83	120.98	1.77	0.084
	Beta	1215.24	1931.06	378.23	178.93	2.02	0.049^{s}
	Alfa	1675.57	1603.70	1285.85	874.55	1.00	0.323
	Teta	1267.19	1793.03	1084.52	897.22	0.43	0.671
	Delta	1591.05	2654.93	1505.60	2033.65	0.12	0.905
Frontal Left	Gamma	178.44	146.70	132.06	130.78	1.11	0.275
	Beta	466.20	205.96	338.91	178.56	2.19	0.034^{s}
	Alfa	1060.35	805.01	1096.48	791.02	−0.15	0.881
	Teta	675.34	705.02	920.57	841.23	−1.05	0.301
	Delta	996.43	1963.14	1052.26	1169.65	−0.12	0.909
Frontal Right	Gamma	331.09	667.91	149.07	140.97	1.25	0.218
	Beta	895.19	1658.59	415.13	220.86	1.35	0.186
	Alfa	1673.95	2089.55	1311.50	839.12	0.76	0.454
	Teta	1209.00	2271.94	1168.60	1022.76	0.08	0.940
	Delta	1471.86	2830.83	2148.16	4766.13	−0.57	0.570
Parietal	Gamma	156.40	122.04	125.90	141.22	0.77	0.448
	Beta	647.20	314.26	499.24	288.96	1.63	0.112
	Alfa	2783.52	2346.04	2684.00	2165.91	0.15	0.884
	Teta	711.14	725.59	1065.74	1121.48	−1.25	0.220
	Delta	999.41	2033.07	1015.71	979.07	−0.03	0.973
Central	Gamma	467.39	887.89	268.92	583.53	0.88	0.386
	Beta	1097.26	1969.34	663.88	1309.70	0.86	0.395
	Alfa	1841.96	2364.67	1593.53	1527.94	0.41	0.681
	Teta	1185.71	2012.33	1133.27	1391.28	0.10	0.920
	Delta	1474.33	2644.94	1173.09	1299.86	0.48	0.634
Temporal	Gamma	576.69	1222.72	300.45	728.37	0.91	0.368
	Beta	1247.04	2547.92	700.16	1647.45	0.85	0.403
	Alfa	2127.15	3364.95	1392.48	1775.28	0.91	0.370
	Teta	1286.41	2705.02	969.42	1604.07	0.47	0.639
	Delta	1626.43	3235.61	1093.74	1531.35	0.70	0.489
Posterior	Gamma	188.68	151.19	124.81	119.67	1.55	0.128
	Beta	1047.53	2173.51	405.87	246.99	1.38	0.176
	Alfa	2148.03	1879.85	1946.86	1668.88	0.38	0.709
	Teta	627.75	734.00	818.89	845.84	−0.80	0.428
	Delta	956.62	2038.70	879.16	927.88	0.16	0.872

especially in left hemisphere. We found no significant differences between groups for any of the other bands in any of the seven regions ($p > 0.05$) Nevertheless, we observed that across most of the regions the sub-band powers of the IGDs were greater than HCs (Table 2). The boxplot of power observed in each EEG band are shown in Fig. 2. These plots show the standard deviation were greater for IGD group than HCs in high frequency bands. Fig. 3 depicts the scalp topography of the EEG band powers for the IGD and HC group.

3.2.1. *Association between EEG activity and IGD severity*

Pearson correlations between EEG band powers and IGD severity variables were assessed in the IGD group. We observed a positive correlation between EEG beta power in the frontal region and scores on both the IAT and IGDSF-9 (IAT: $r = 0.394$, $p = 0.008$; IGDSF-9: $r = 0.384$, 0.01). There was no significant correlation between IGD severity and band powers in central and posterior regions, as shown in Table 3.

3.3. *fNIRS results*

The average HbO levels of fNIRS regions were compared for eyes closed condition. The PFC oxygenation was significantly higher in IGD group compared to HCs ($t = 2.32, p = 0.025$). We evaluated the right and left channels separately to investigate hemispheric differences and found that there was a significance in left PFC ($t = 2.46, p = 0.018$), but not in the right PFC ($t = 2.007$, $p = 0.051$) between IGD and HCs. The hemodynamic responses of the defined regions are presented in Table 4.

3.3.1. *Association between fNIRS findings and IGD severity*

We examined the relationship between PFC activation and IAT and IGDSF-9 scores to investigate whether HbO values were associated with IGD severity. As seen in Table 5, a significantly positive correlation was observed between HbO values in PFC, particularly on the left side and IAT scores. IGDSF-9 scores were significantly correlated with left frontal HbO values. However, we found no significant correlation with the right frontal HbO values. Furthermore, we observed no significant correlation between fNIRS HbO values and EEG band powers ($p>0.05$).

4. Discussion

4.1. *Overview*

Despite IGD studies advancing rapidly over the last decade particularly after the inclusion of IGD in the DSM-V, comprehensive understanding of its underlying mechanisms remains a critical area of research. The current study investigated resting state multimodal EEG-fNIRS activities in order to explore differences between individuals with IGD and HCs. To the best of our knowledge, this is the first study combining EEG-fNIRS to investigate neural functioning in IGD. As hypothesized, participants with IGD showed increased activation in Dorsolateral PFC, and a significant correlation was found between the severity of IGD and both electrophysiological and hemodynamic patterns. However, contrary to our hypothesis that EEG beta band power would be lower in IGD, it was observed to be higher in IGD group as compared to the healthy controls.

4.2. *Electrophysiological findings*

EEG has been widely used to investigate brain functions, particularly inhibitory control and executive functions, in individuals with IGD (Yu et al., 2024). Several studies have examined resting-state EEG patterns,

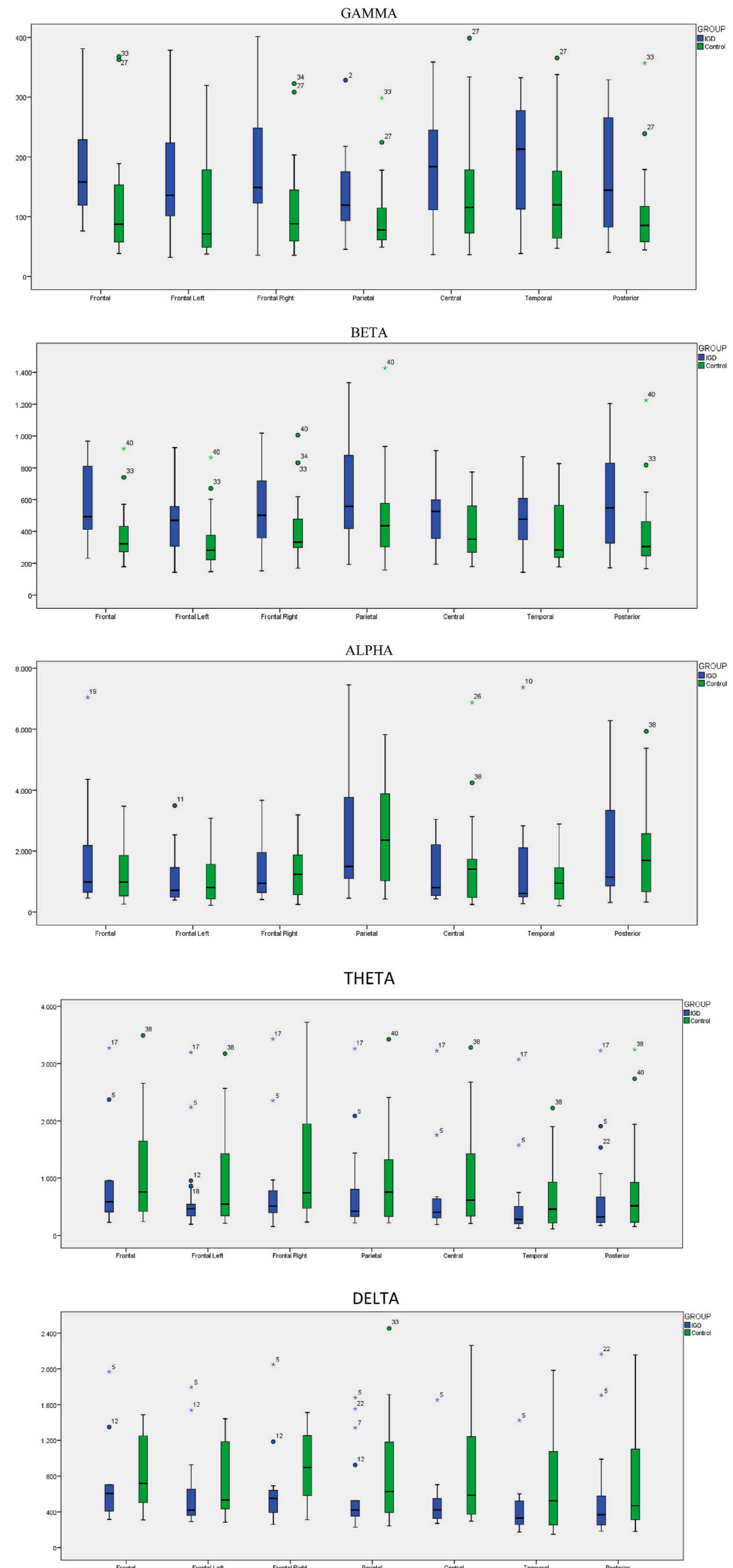

Fig. 2. Boxplot of PSD values for each sub-band.

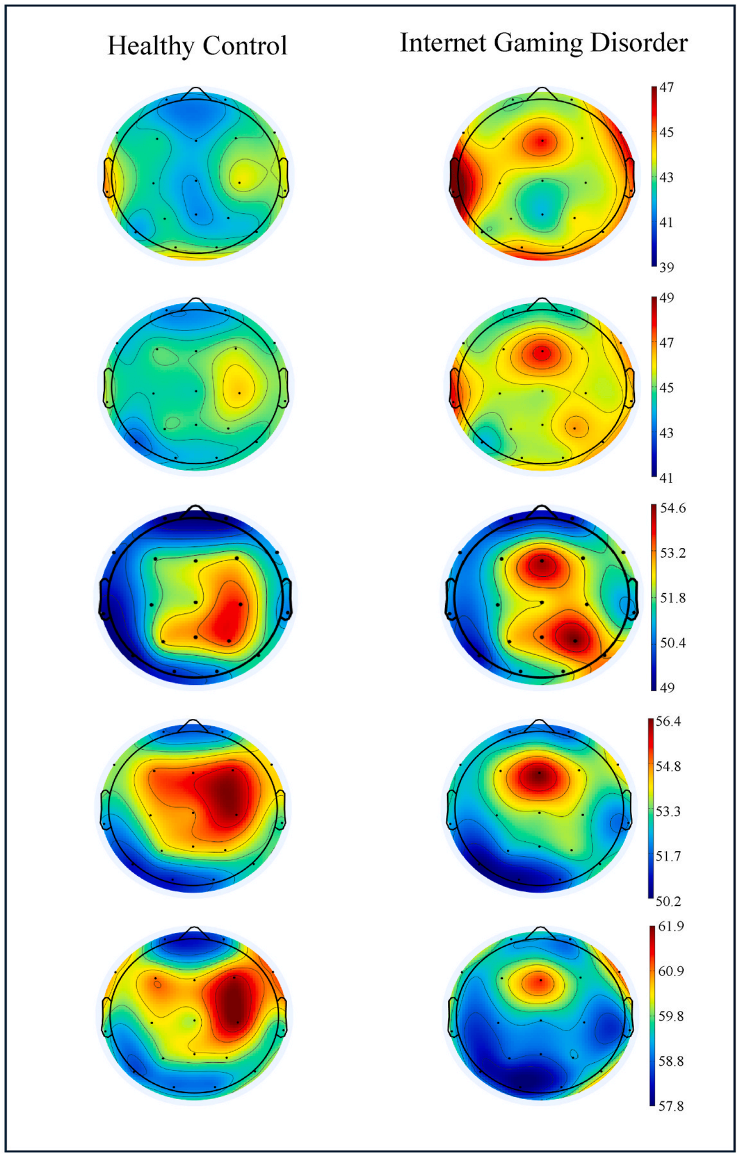

Fig. 3. The topology map of absolute power (μV^2) of IGD and HC at the five frequency bands. The internet game disorder group showed increased beta power in the frontal region compared to the healthy controls.

Table 3
Pearson correlations between PSD variables and IGD severity.

EEG Region	Freq.Bands	IAT		IGDSF-9	
		Corr.	p-value	Corr.	p-value
Frontal	Gamma	0.210	0.717	0.230	0.134
	Beta	0.394	0.008^{s}	0.384	0.010^{s}
	Alfa	0.155	0.316	0.209	0.172
	Teta	0.133	0.391	0.136	0.377
	Delta	0.036	0.814	0.068	0.661
Central	Gamma	0.171	0.268	0.105	0.497
	Beta	0.185	0.230	0.123	0.426
	Alfa	0.140	0.365	0.092	0.552
	Teta	0.127	0.410	0.055	0.721
	Delta	0.201	0.191	0.146	0.346
Posterior	Gamma	0.145	0.346	0.098	0.525
	Beta	0.139	0.369	0.088	0.571
	Alfa	0.149	0.334	,101	0.513
	Teta	0.037	0.812	−0.052	0.735
	Delta	0.144	0.352	0.114	0.460

Table 4
Prefrontal cortex oxygenation of groups.

fNIRS Region	IGD		HC		t	p
	Mean	STD	Mean	STD		
Total Frontal (CH1-CH16)	1.657	1.454	0.737	1.156	2.32	0.025^{s}
Left PFC (CH1-CH8)	1.654	1.526	0.631	1.204	2.46	0.018^{s}
Right PFC (CH9-CH16)	1.662	1.497	0.833	1.229	2.007	0.051

*HbO values are presented in mM mm units; s: statistically significant.

focusing on the PSD of individuals with IGD. However, the results have shown inconsistency. Burleigh et al. (2020) reviewed resting state qEEG studies in gaming disorder and internet addiction. They found that individuals with gaming disorder exhibited increased slow wave activity and reduced high wave activity, whereas internet addiction individuals showed increased gamma activity and reduced beta and delta activity. Contrary to their findings, we found that the beta power in the frontal region was higher in IGD group compared to healthy controls. Burleigh et al. (2020) reviewed only ten studies and five of them utilized PSD

Table 5
Correlation Between PFC Activation and IAT and IGDSF-9 scores in IGD Participants.

fNIRS Region	IAT		IGDSF-9	
	Corr.	p-value	Corr	p-value
Frontal (CH1-CH16)	0.368	0.014[s]	0.301	0.047[s]
Left PFC (CH1-CH8)	0.399	0.007[s]	0.339	0.024[s]
Right PFC (CH9-CH16)	0.312	0.039[s]	0.243	0.113

*s: statistically significant.

analysis. They compared individuals with gaming disorder, internet addiction and healthy controls. Although gaming disorder, internet addiction and IGD have similar cognitive and behavioral traits, they can be distinguished in qEEG by their distinct neurophysiological characteristics (Burleigh et al., 2020; Griffiths, 2018). Hong et al. (2022) revealed that neurophysiological networks in IGD vary based on patterns of game usage and genre. In qEEG analyses they found individuals who played single game showed higher beta power compared with those who played multiple games and controls. Most of the participants of our study were single users and our results are in line with this study showing increased beta activity in frontal region compared to the controls. Recently, Park et al. (2023) showed that IGDs exhibited increased resting state frontal beta and gamma intrahemispheric coherence compared to controls. Son et al. (2015) found decreased high frequency and increased low frequency power in IGD individuals. Similarly, Kim et al. (2017) demonstrated increased slow wave activity in IGD group compared to healthy controls. We did not find any significant differences between groups in low frequency band powers (theta, delta). The inconsistency between the results of these prior studies could be due to the fact that IGD has been defined with different terms prior to its inclusion in DSM-V such as gaming disorder (Danielsen et al., 2024), video game addiction (Limone et al., 2023), mobile game addiction (Wang et al., 2019) and pathological gaming (Jeon et al., 2022). IGD has also been evaluated under different descriptive terms; such as internet addiction, problematic internet users, and pathological internet use. The criteria for IGD can vary for each label. Another possible reason for such variation is that IGD diagnosis criteria can also change in different populations and regions. Because its high prevalence, most of the studies were conducted in the Asia region with excessive users. Further studies are needed with different populations to confirm these results. In this current study, IGD subjects were playing online internet games excessively and they were all diagnosed by an experienced psychiatrist according to IAT and DSM-V scores. We observed a statistical difference only in the beta band power between the groups, with higher values found in the IGD group. Increased beta power in PFC is linked to cognitive effort in managing psychological distress related to self-disgust or negative emotions (Li et al., 2017). Beta power also related to some psychiatric disorders such as anxiety and depression that are comorbid with IGD (Burkauskas et al., 2022). In this study, we also compared depression, anxiety and impulsivity states of groups using BDI, BAI and BIS-11 scores, respectively. Even though IGD group scored higher in all of these scales, there was no significant difference between groups for BDI (Mann-Whitney, $z = 1.767$; $p = 0.077$), for BAI (Mann-Whitney, $z = 1.754$; $p = 0.079$) and for BIS-11 scales (Student's *t*-test, $t = 1.006$ $p = 0.320$). This is maybe because of the small sample size. We also investigated whether EEG sub-band powers were correlated with BDI, BAI and BIS-11 scores and we found a significant negative correlation only between left frontal gamma activity and BDI scores ($r = -0.31$, $p = 0.041$). There was no significant correlation between the EEG findings and the BIS-11 and BAI scores of participants.

4.3. Hemodynamic activity findings

The research and clinical application of fNIRS in psychiatry have been steadily rising due to its superiorities compared to other neuroimaging techniques. (Li et al., 2023). Recently several studies utilized fNIRS to evaluate brain function of individuals with addiction to substances (e.g. alcohol, drug) and behaviors such as gambling. Surprisingly, there is only one fNIRS study that has investigated brain functions in IGD (Cho et al., 2022). In this study they showed that during real time internet gaming, IGD group indicated higher activation of the PFC following positive events. To the best of our knowledge this is the first fNIRS study to examine resting state brain activation in IGD. The combined use of EEG and fNIRS system offers advantages in terms of temporal resolution, convenience, portability, cost-effectiveness, tolerance to motion, and participant comfort compared to fMRI. We found that during the resting state condition, IGD group showed significantly higher activation in PFC, particularly at left side compared to the HCs. Our results were consistent with previous fMRI studies indicating increased activation in PFC (Weinstein and Lejoyeux, 2020) There have been many task-related and resting-state fMRI studies investigating brain functions of IGD. However, the underlying neural mechanisms are still unclear due to the inconsistent results which may arise from methodological differences, low sample sizes, and differences in region of interest (Wager et al., 2009). Resting state fMRI studies have shown brain abnormalities in IGD group especially in PFC that plays an important role in reward system regulation and executive functions (Liu et al., 2023; Weinstein et al., 2017). Meng et al. (2015) conducted a meta-analysis that included various tasks and found that compared to HCs, IGDs showed hyperactivation in multiple brain regions. Zheng et al. (2019) reviewed task-related fMRI studies and observed that the activation of brain region between IGD and HC groups depend on the task. In this study we aimed to utilize a task-independent resting state experiment that reflects baseline brain functions. Additionally, we conducted correlation analysis between hemodynamic response and BDI, BAI, and BIS-11 scores of participants and did not find any significant association. The results suggest that fNIRS can be a valuable tool in investigating neural correlates of IGD.

4.4. The severity of internet gaming disorder

Despite the growing number of IGD studies there are few studies that have investigated the relationship between neural activity patterns and IGD severity. In this current study we examined whether mean HbO values and EEG sub-band powers associated with the severity of IGD. We utilized IAT and IGDSF-9 scores to identify the severity of IGD. As seen in Table 5, there was a significantly positive correlation between the HbO values in PFC particularly in the left side and IAT scores. IGDSF-9 scores were significantly correlated with the left frontal HbO values but we found no significant correlation with the right HbO values. To the best of our knowledge, the present study is the first to examine correlations between fNIRS patterns and IGD severity. Our findings indicate a positive correlation between the severity of IGD and hyperactivation in the left PFC. Previous resting state fMRI studies have shown that fMRI patterns are positively correlated with IGD severity, particularly in the areas related to reward, inhibition and executive functions (Niu et al., 2023; Ye et al., 2022). We found a significant positive correlation between frontal beta band power and both IAT and IGDSF-9 scores. There was no significant correlation between IGD severity and gamma, alpha, theta and delta band activation. Kim et al. (2017) showed positive correlation between delta power and IGD scores. Similar to our results, Choi et al. (2013) demonstrated that resting state EEG frontal beta and gamma activities were significantly associated with the severity of internet addiction. However, Son et al. (2015) found no significant correlation between the IGD severity and qEEG. The diversity between the results may be due to the differences in IGD diagnosis. Further studies are needed to confirm these results.

5. Limitations

The current study has some limitations that should be considered.

First the sample size was small. Because racial and socioeconomic differences can result in variability in neuroimaging results (Goldfarb and Brown, 2022), we recruited participants from the same racial background and similar socioeconomic profiles. However, this approach limited the generalizability of our findings to a broader, more diverse population. Second, we included only male young adults due to high prevalence of IGD in this demographic. Research indicates that there can be significant gender-related differences in the context of neuroimaging results and behavioral outcomes (Dong et al., 2019; Dong and Potenza, 2022). In a review, Marraudino et al. (2022) have shown that IGD is strongly dimorphic by sex for both its psychological features and the involvement of different brain areas. Therefore, by focusing on a single gender, we aimed to reduce gender related variability and ensure more precise and reliable results for this preliminary study. However, since the female population of gamers are steadily increasing, it has become important to investigate this group as well. Thus, including both genders and different age groups in future studies is crucial for a complete understanding of the IGD. Thirdly, although we evaluated whole head electrophysiological data, we could only investigate hemodynamic response in PFC. However, it is well-known that frontal areas are associated with addiction as shown in many prior studies. Additionally, while we demonstrated that individuals with IGD were more anxious and scored higher in BAI and BDI, there was no significant correlation between groups. This is could be due to the small sample size. Further investigations with a larger study population are necessary to examine the relationship of IGD with depression and anxiety.

6. Conclusion

Over the past decade, IGD has emerged as a growing mental health concern worldwide. Since its inclusion in the DSM-V as a mental disorder warranting further studies, there has been an increased number of investigations into the neural substrates of IGD. However, the results of these studies are inconsistent, and the underlying neural mechanisms remain unclear. In this present study, we utilized multimodal EEG-fNIRS system to investigate brain activity of individuals with IGD for the first time. This hybrid system provided a comprehensive understanding of neural processes involved in IGD. The results suggested that IGD participants exhibited significantly higher absolute power in beta-band activity in the frontal region. Furthermore, IGD participants showed significantly increased PFC oxygenation compared to healthy controls. Moreover, we observed significant correlations between both beta power and oxygenation in the frontal region and the severity of IGD. The results suggest that resting-state multimodal EEG-fNIRS system can be a valuable tool to aid the clinicians in supporting the diagnosis of IGD, which currently relies on the interview-based evaluations. In support of utilizing Research Domain Criteria (RDoC) for diagnosing mental disorder (National Institute of Mental Health, 2011), the current study can provide an important contribution to the understanding of the neural mechanisms of IGD and offer new insights for the intervention and treatment of the disorder. The large-scale IGD prevalence studies have shown that the disorder is steadily increasing worldwide and we expect IGD will continue to increase in severity over the next decade, especially because of easy access, advancement and wide spread adoption to new technologies such as Virtual Reality and mobile games. Longitudinal studies are needed to understand effects of chronic addiction on brain functions. Further studies should aim to replicate the findings of this study using a larger and more culturally diverse sample to support the neurophysiological basis of IGD.

CRediT authorship contribution statement

Miray Altınkaynak: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Demet Yeşilbaş:** Writing – review & editing, Visualization, Software, Investigation, Data curation. **Turgay Batbat:** Writing – review & editing, Visualization, Software. **Ayşegül Güven:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Elif Uğurgöl:** Writing – review & editing, Formal analysis, Data curation. **Esra Demirci:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Meltem İzzetoğlu:** Writing – review & editing, Supervision, Methodology. **Nazan Dolu:** Writing – review & editing, Validation, Formal analysis.

Declaration of competing interest

Meltem Izzetoglu has a small share in fNIRS Devices, LLC that produced the fNIRS system used in this work. The other authors declare that they have no conflicts of interest to report.

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