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Altered dynamic reconfiguration of brain functional networks during gaming and deprivation in individuals with internet gaming disorder

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FULL-LENGTH REPORT

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ABSTRACT

Background and aims: Based on the Interaction of Person-Affect-Cognition-Execution (I-PACE) model, this study aimed to identify dynamic reconfiguration of the basal ganglia network (BGN), limbic network (LN) and frontal-parietal network (FPN) in individuals with internet gaming disorder (IGD) during a real gaming situation. This approach overcomes the indirectness of experimental task situations in previous studies, providing direct evidence for the underlying neural basis of IGD. *Methods:* Thirty gamers with IGD and 37 gamers with recreational game use (RGU) were scanned during online gaming and immediate deprivation. Two coefficients (recruitment and integration) were calculated using community structure, an emerging method, to represent individual functional segregation and integration of brain networks over time, respectively. *Results:* The IGD group showed greater recruitment of BGN and LN after deprivation of gaming, and greater integration between the inferior frontal gyrus in the FPN and BGN and between the dorsolateral prefrontal cortex in the FPN and LN during deprivation. In contrast, the RGU group exhibited lower recruitment of BGN during deprivation than during gaming, stable recruitment of LN and stable integration between nodes in the FPN and BGN. *Conclusions:* Gamers with RGU always maintain stable cognitive control and emotional regulation and could drop cravings/anticipation for continuing gaming after being interrupted gaming. However, gamers with IGD have stronger craving/anticipation and emotional responses after being interrupted gaming and insufficient control over cravings/anticipation and emotions. These findings help directly explain why gamers with IGD are addicted to gaming, despite having similar gaming experiences to those of gamers with RGU.

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KEYWORDS

internet gaming disorder, recreational game use, real gaming, dynamic reconfiguration, basal ganglia network, frontal-parietal network

INTRODUCTION

Internet gaming disorder (IGD) is a psychiatric condition that manifests as uncontrollable cravings for gaming, leading to excessive and disruptive gaming patterns (APA, 2013). Studies have shown that IGD is associated with multiple negative consequences, including poor academic achievement, strained interpersonal relationships, and oppositional behavior (Brand, Young, Laier, Wölfling, & Potenza, 2016; Paulus, Ohmann, Von Gontard, & Popow, 2018). In 2013, IGD was included as a potential disorder in the Fifth Edition of the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) (APA, 2013). In 2019, gaming disorder was included as a "disorder due to addictive behaviors" in the 11th revision of the International Classification of Diseases (ICD-11) (https://icd.who.int/browse11/l-m/en). Therefore, there is an urgent need for reliable and comprehensive research into IGD to facilitate the effective identification and treatment of this disorder.

Based on a large quantity of empirical findings, the Interaction of Person-Affect-Cognition-Execution (I-PACE) model (updated version) proposed by Brand et al. (2019) highlights that the interaction between personal characteristics (P, e.g., high sensation seeking), affect (A) and cognitive (C) response to external (e.g., gaming stimuli) and internal triggers (e.g., negative or very positive moods), e.g., increased attention and urges to games and feelings of gratification or relief from negative moods, and execution functions (E, e.g., inhibitory control) jointly contributes to addicting to specific behaviors (e.g., IGD). Moreover, this model elaborates the neurobiological mechanisms of addictive behaviors (including IGD) based on numerous neuroimaging findings. In summary, an imbalance in prefrontal-subcortical circuits involved in urge/emotion regulation and cognitive control is particularly relevant to addictive behaviors, such as striatum, dorsolateral prefrontal cortex (DLPFC), anterior cingulate cortex (ACC), insula, amygdala, etc. Consistent with this model, other neurobiological models or reviews similarly emphasize the important roles of altered neural features in prefrontal-subcortical circuits relevant to reward/emotion processing and cognitive control in developing and maintaining addictive behaviors or mental diseases (Antons, Brand, & Potenza, 2020; Bickel et al., 2018; Brand, 2022; Casey, Jones, & Hare, 2008; Dong & Potenza, 2014; Heatherton & Wagner, 2011; Kuss, Pontes, & Griffiths, 2018; McClure & Bickel, 2015; Weinstein, Livny, & Weizman, 2017). Accordingly, the current study focused on the neural alteration in prefrontal-subcortical circuits relevant to reward/emotion processing and regulation and cognitive control in IGD.

Previous studies using functional magnetic resonance imaging (fMRI) have identified alterations in prefrontal-subcortical circuits in IGD under resting-state and experimental tasks related to reward/emotional regulation/cognitive control. For example, studies using resting-state fMRI have found that compared to healthy controls (HCs), IGD participants showed decreased functional connectivity (FC) between the striatum (including the nucleus accumbens (NAcc) and caudate) and DLPFC (Chen et al., 2016); increased FC in the reward network (including the striatum and orbitofrontal cortex (OFC)); decreased FC in the execution control network (ECN) (including several parts of the frontoparietal cortex) in IGD (Dong, Lin, Hu, Xie, & Du, 2015; Dong, Lin, & Potenza, 2015); and a decreased coactivation pattern in the prefrontal-striatal circuit (L. Wang et al., 2023). By applying cue-reactivity tasks, several fMRI studies have found increased activation in fronto-striatal circuits in IGD participants, including the OFC, NAcc, caudate, DLPFC, ACC, insula, inferior frontal gyrus (IFG), middle frontal gyrus (MFG) in IGD participants when they were shown gaming-related stimuli, and the increased activation in most of these regions was associated with a greater craving for gaming (Dong, Wang, Du, & Potenza, 2017; Ko et al., 2009; Ko et al., 2013; Liu et al., 2017; L. Wang et al., 2017; Jintao Zhang et al., 2016). By using an emotion reappraisal task, researchers found that adults participants with IGD showed greater activation in the ACC and insula and stronger FC between the insula and DLPFC than HCs did, which implied their poor downregulation of negative emotions despite putting in more cognitive resources (Jialin Zhang et al., 2020). On the other hand, during the same task, youth participants with IGD showed blunted neural responses in the striatum, insula, DLPFC and ACC and less engagement in fronto-cingulo-parietal network when facing with negative affective pictures and performing emotion regulation, suggesting poor emotion processing and regulation in IGD (Yip et al., 2018). Additionally, IGD participants displayed increased engagement of the dorsomedial prefrontal cortex (dmPFC) during an emotional go/no-go task, implying the inefficient negative emotion regulation in IGD (Shin, Kim, Kim, & Kim, 2021). Z. Wang, Song, et al. (2022) identified decreased FC between anticipation network (including prefrontal cortex and ACC) and negative-affect network (including amygdala) in IGD participants and this negatively correlated with their maladaptive cognitive emotion regulation strategies.

Overall, although previous research has provided a good understanding of the underlying neural mechanism of IGD, there are still some limitations. First, previous studies have mostly examined the neural features of IGD under well-established experimental paradigms and in the resting state. Their conclusions come from the out-of-gaming state of gamers with IGD, preventing their generalization to features and abnormalities of gamers with IGD in the gaming state. Examining the neural features during gaming is necessary for IGD treatment, which can probe directly into the abnormalities associated with addictive behavior and thus contribute to the identification of precise targets for the treatment and prevention of IGD. Second, limited studies have found that gamers with IGD had enhanced craving after immediate deprivation of gaming (Dong, Wang, Wang, Du, & Potenza, 2019), and cue-induced craving-related activation in the lentiform nucleus after immediate deprivation of gaming was associated with the emergence of IGD (Dong et al., 2020). These findings underscore the important role of immediate gaming deprivation in understanding IGD. More studies are needed to reveal the underlying neural basis of IGD in the context of immediate gaming deprivation. Third, most studies on IGD have examined the static features of brain regions and networks; however, the brain is a complex system that undergoes different activities at different time points (Krienen, Yeo, & Buckner, 2014; Lurie et al., 2020; Spreng, Stevens, Chamberlain, Gilmore, & Schacter, 2010). The dynamic changes and features of brain regions and networks are essential clues for understanding mental disorders, including IGD. Accordingly, the current study aimed to probe the dynamic features of brain regions and networks of gamers with IGD under gaming and immediate deprivation of gaming conditions, thus compensating for the limitations of previous studies and providing direct evidence for the neural alterations of IGD.

The emerging graph metric 'community structure' was applied in the current study to depict the dynamic features of brain regions and networks in gamers with IGD. The interactions between brain regions from the same and different predefined brain functional networks continue to change, thus forming different communities over time. Nodes (i.e., brain regions) that have strong and dense interactions with each other are classified into one community, whereas nodes that have sparse interactions with each other are classified into different communities (Newman & Girvan, 2004). Community structure can trace such dynamic functional segregation and integration of brain regions and networks over time through two main coefficients: recruitment and integration. Recruitment refers to the probability that a node is in the same community as other nodes from its own network, representing the compatibility between nodes of one network and the functional stability of this network over time. Integration refers to the probability that a node is in the same community as nodes from other networks, representing the interactivity between nodes from different networks and the interactivity between networks over time (Bassett, Yang, Wymbs, & Grafton, 2015; X. He, Bassett, et al., 2018; Mattar, Cole, Thompson-Schill, & Bassett, 2015). Community structure has been applied to study various neurological and psychiatric disorders, including epilepsy (X. He, Bassett, et al., 2018), major depressive disorder (Y. He, Lim, et al., 2018; Zheng et al., 2018), mania (Shao et al., 2019), autism spectrum disorder (M. Wang, Wang, et al., 2022), and attention deficit hyperactivity disorder (Cui et al., 2021; C. Ding et al., 2022). These discoveries endorse the investigation of dynamic reconfiguration in brain functional networks, which is essential for comprehending the pathophysiological mechanisms of brain diseases.

In sum, the current study aimed to investigate the dynamic reconfiguration of brain regions and networks in gamers with IGD during gaming and immediate deprivation. In particular, gamers with recreational game use (RGU), which refers to gamers who played games recreationally without developing IGD, were recruited as the healthy control group (L. Wang, Zheng, et al., 2022; Z. Zhang et al., 2023). This setting could counteract the potential effects of gaming experience and gaming familiarity on the results of this study, revealing the exact differences between gamers with IGD and gamers with RGU and thus identifying the underlying neural basis for why gamers with IGD are addicted to gaming despite having gaming experience similar to those of gamers with RGU. Given the neurobiological models and neuroimaging studies mentioned above, we mainly focused on networks related to reward processing (basal ganglia network, BGN) (Haber & Knutson, 2010), emotional response and regulation (limbic network, LN) (Catani, Dell'Acqua, & De Schotten, 2013), and cognitive control (frontal-parietal network, FPN) (Nee, 2021). We hypothesized that compared to gamers with RGU, 1) gamers with IGD would show greater recruitment of BGN during both real gaming and deprivation conditions, displaying enhanced reward response to games, and the recruitment of BGN would be correlated with their addiction severity; 2) gamers with IGD would show greater recruitment of LN after deprivation of gaming relative to during gaming, displaying enhanced emotion response (or emotion regulation needs) due to deprivation, and the recruitment of LN would be correlated with their addiction severity; 3) gamers with IGD would show greater integration between FPN and BGN after deprivation of gaming relative to during gaming, displaying taking more cognitive resources to inhibit the strong reward response, and this integration would be correlated with their addiction severity; 4) gamers with IGD would show greater integration between FPN and LN after deprivation of gaming relative to during gaming, displaying taking more cognitive resources to regulate potential negative emotions due to deprivation, and this integration would be correlated with their addiction severity.

METHODS AND PROCEDURES

Participants

Thirty right-handed participants with IGD (19 males, 11 females) and 37 right-handed age-matched participants with RGU (19 males, 18 females) participated in this study (Table 1). The number of males and females was balanced between the IGD and RGU groups ($\chi^2 = 0.969, p = 0.325$). All the participants provided written informed consent in accordance with the Declaration of Helsinki. According to previous studies on IGD (Dong et al., 2021; Tian et al., 2018; L. Wang et al., 2021; L. Wang, Zheng, et al., 2022; Z. Zhang et al., 2023), Young's self-reported internet addiction test (IAT) (Pawlikowski, Altstötter-Gleich, & Brand, 2013) and the nine criteria proposed by the DSM-5 (Petry et al., 2014) were used to assess the participants' internet gaming use during the last year to classify participants with IGD and RGU in the present study. For the DSM-5 criteria, the clinical interview by an experienced psychiatrist was conducted to assess whether the participants met these nine criteria. Participants with IGD were defined as those with self-report scores on the IAT greater than 50 and who met at

Table 1. Demographic information and group differences

Items	IGD (M = 19, F = 11)	RGU (M = 19, F = 18)	t	p
Age (years)	21.10 ± 2.26	21.62 ± 2.15	−0.96	0.34
IAT score	66.77 ± 10.03	39.89 ± 10.58	10.58	<0.001
DSM-5 score	5.83 ± 0.99	2.57 ± 1.30	11.34	<0.001
Gaming history (years)	3.65 ± 0.94	3.84 ± 0.65	−0.97	0.34
Game familiarity	4.38 ± 0.82	4.44 ± 0.70	−0.35	0.73
Education (years)	15.27 ± 2.20	15.43 ± 1.82	−0.34	0.74

Table values: mean ± standard deviation.
Abbreviations: IGD, internet gaming disorder; RGU, recreational game use; M, Male; F, Female; IAT, internet addiction test; DSM-5, the fifth edition of Diagnostic and Statistical Manual of Mental Disorders.

least five of the nine DSM-5 criteria. Participants with RGU were defined as those with self-report scores on the IAT less than 50 and who met fewer than five of the DSM-5 criteria; see Table 1 for the group differences in IAT and DSM-5 scores. All the participants were free of any psychiatric disorders or history confirmed by a structured psychiatric interview (MINI) (Lecrubier et al., 1997). No participants reported illegal drug use, and 44 participants reported no alcohol use or smoking. The alcohol use and smoking status of 23 participants who reported experience of alcohol use and smoking were assessed separately by the Alcohol Use Disorders Identification Test (AUDIT) (Qing Li, Babor, Hao, & Chen, 2011) and the Fagerstrom Test for Nicotine Dependence (FTND) (Huang, Lin, & Wang, 2006). None of the participants were addicted to alcohol or nicotine (FTND score: M±SD = 0.44 ± 1.34; AUDIT score: M±SD = 2.22 ± 2.86), and there was no difference in the FTND or AUDIT score between the two groups (FTND score: t (21) = −0.473, p = 0.641; AUDIT score: t (21) = −0.411, p = 0.685). Additionally, to control for the effect of gaming type on the results, all the participants were loyal players in a popular online game named League of Legends (LOL). Their familiarity with LOL was rated (1-not familiar, 5-very familiar), and it revealed that they were all very familiar with LOL with no difference between the two groups (Table 1).

Procedure: gaming and deprivation

1. Arrival and initial setup: upon arrival at the lab, the participants were informed about the study and its procedures. They then logged into their personal game (LOL) accounts (this was set to make the gaming play during the scan closely resemble the participants' usual LOL experience) on a computer located in the fMRI control room. This computer was connected to the fMRI system, allowing the participants to view the screen via screen mirroring within the scanner.
2. Preparation for scanning: the participants were escorted to the fMRI scanner room, where they laid down and had their heads stabilized using foam pads and MRI-compatible headphones to minimize head motion during scan. Then the participants were instructed to use MRI-compatible mouse and keyboard to play the game, and place them in comfortable and appropriate positions. All the participants were right-handed. They used their right hand to operate the mouse and their left hand to operate the keyboard. The keyboard included 5 number keys, the participants were be told to use the 1–4 keys for game skills, as correspond to the QWER keys in normal keyboards. Additionally, the participants were informed that the game sound would not be audible during the scan due to the noise of fMRI scan. After the experiment, they reported that the absence of game sound had little to no impact on their performance and experience.
3. Scanning procedure: for every participant, the experiment began with a 7-minute resting-state scan to establish their own baseline brain activity. Afterward, the participants played LOL using the mouse and keyboard during fMRI scan. The start of the gaming phase was defined as the time when the participants entered the battle scene. After game play reached 5 min and 20 s, to create a situation of immediate deprivation, the experimenter unplugged the network cable from the computer running the game in the fMRI control room (as the deprivation phase's start), so that the participants experienced an unexpected internet disconnection from online gaming. The participants would notice the game freezing, and the keyboard and mouse malfunctioning, followed by the appearance of a loading progress bar. After about 3 min, a message indicating a connection failure and the imminent exit of game would appear, at which point the scan ended. Specially, to eliminate individual differences in inherent neural mechanisms, data from each participant's own resting-state phase were utilized as the baseline state for the study. Two phases were thus obtained: gaming - rest and deprivation - rest.

Image acquisition

Functional MRI for gaming, deprivation and resting-state phases was performed on a 3T scanner (Siemens Trio) with a gradient-echo EPI T2*-weighted sensitive pulse sequence with the following parameters: 33 slices, 3 mm thickness, interleaved sequence, flip angle = 90°, TR = 2,000 ms, TE = 30 ms, matrix = 64 × 64 and field of view = 220 × 220 mm^2. A real-time game screen was presented to the participants through a screen in the head coil using an Invivo synchronous system (www.invivocorp.com).

Community structure analysis

The whole analysis pipeline is shown in Fig. 1.

Image preprocessing. The DPABI version 5.3 toolbox was used to preprocess the fMRI data (http://rfmri.org/dpabi).

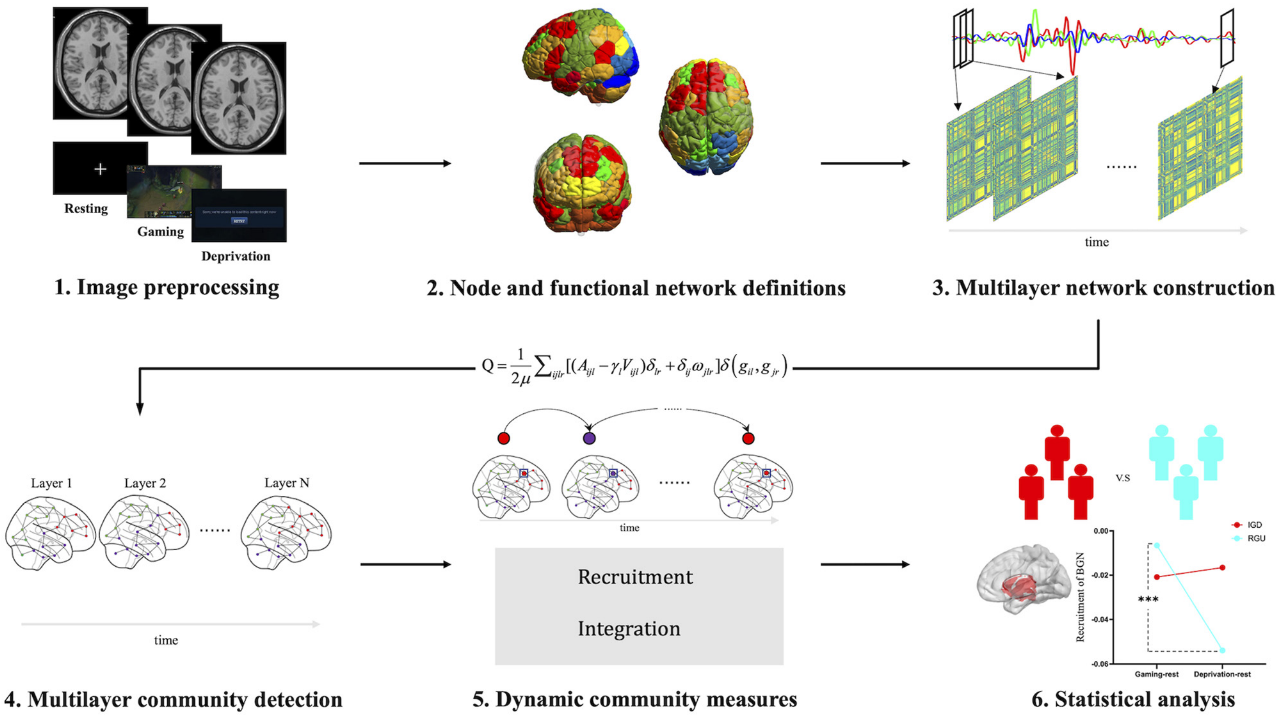

Fig. 1. The whole analytical pipeline of this study
Abbreviations: IGD, internet gaming disorder; RGU, recreational game use; BGN, basal ganglia network. *** indicates $p < 0.001$.

The first 10 volumes of the resting-state data were removed. Time and head movement corrections were applied to all the fMRI data, which were then registered to the corresponding EPI templates and spatially transformed to the standard MNI space with $3 \times 3 \times 3\,mm^3$ voxels. Participants with head movements exceeding 3 mm and 3° were excluded from the current study. A Gaussian kernel with 6 mm FWHM was used to smooth the normalized images. Noisy signals from white matter, cerebrospinal fluid, and head motion parameters (Friston 24) were regressed as covariates to minimize the effects of head motion and irrelevant signals on the images after detrending. Then, the data was filtered within the 0.01–0.1 Hz range to capture low-frequency fluctuations related to intrinsic brain activity while removing high-frequency noise and low-frequency drifts. Finally, we manually inspected each participant's preprocessed brain images to check for any artifacts.

Node and functional network definitions. The 268 brain nodes covering the entire brain from (Shen, Tokoglu, Papademetris, & Constable, 2013) were used in the present study. The 268 brain nodes were assigned to 10 functional networks, namely, the BGN, FPN, LN, medial frontal network, default mode network, motor network, visual networks I and II, visual association network, and cerebellum network (https://bioimagesuiteweb.github.io/webapp/connviewer.html? species=human).

Multilayer network construction. For each of the three phases (gaming, deprivation and resting-state), the whole time-series data of each participant were divided into multiple consecutive time windows of 20 TR (40s) with a step of 1 TR. According to previous research (Gonzalez-Castillo, Hoy, Handwerker, Robinson, & Bandettini, 2013; Leonardi & Van De Ville, 2015; Shirer, Ryali, Rykhlevskaia, Menon, & Greicius, 2012), a 30–60s time window is considered reasonable for studying dynamic functional connectivity based on fMRI. And 1TR step was applied according to (Cai et al., 2024; Patil et al., 2021). For each time window, a 268×268 adjacency matrix was generated using the Gretna toolbox (https://www.nitrc.org/projects/gretna) to indicate the FC between each pair of these brain nodes. All the negative connectivity values were set to 0 since their role in the network remains unclear. Then, for each of the three phases, the adjacency matrices in all the time windows of each participant were linked to generate a multilayer network.

Multilayer community detection. A community refers to a group of nodes that exhibit stronger interconnections with each other than with nodes outside the community (Newman, 2006). Additionally, multilayer communities provide a way to capture changes within a community over time. In our study, we utilized the generalized Louvain community detection algorithm to detect multilayer communities (Mucha, Richardson, Macon, Porter, & Onnela, 2010); this algorithm employs a multilayer modularity quality function Q:

$$Q = \frac{1}{2\mu}\sum_{ijlr}\left[\left(A_{ijl} - \gamma_l V_{ijl}\right)\delta_{lr} + \delta_{ij}\omega_{jlr}\right]\delta\left(g_{il}, g_{jr}\right) \qquad (1)$$

The function considers the edge weight of the network μ, the edge A_{ijl} between nodes i and j at layer l of the multilayer network, the corresponding element V_{ijl} of a null model, the strength of the intralayer and interlayer edges, the community assignments g of nodes across different layers, and the Kronecker delta function δ, where $\delta(g_{il}, g_{jr}) = 1$ if $il = jr$; otherwise, it is 0. In this study, the two parameters were set to the default value of 1, as was done in prior work (He et al., 2019; Rizkallah et al., 2018; Telesford et al., 2016). In addition, despite the orderly nature of the networks we examined, the stochastic nature of the algorithm can sometimes lead to unstable community assignments (Good, De Montjoye, & Clauset, 2010). To ensure the stability of our results, we ran 100 iterations for each participant and calculated the mean, a method employed in previous studies (Y. He, Lim, et al., 2018).

Dynamic community measures. For the multiple community structures detected from the multilayer network during each phase, two main coefficients, i.e., recruitment and integration, were calculated to characterize the dynamic functional segregation and integration among the brain nodes and predefined functional networks over time (Bassett et al., 2015). Recruitment measures the fraction of layers in which a brain node is assigned to the same community as other nodes from the same predefined functional network and is calculated using function (2) below, where *RN i* is the recruitment of node i in network N, m_N is the number of regions in N, and P_{ij} is the module allegiance between node i and node j. Module allegiance quantifies the consistency of community assignments between two nodes across different layers of the multilayer network, ranging from 0 to 1. Integration measures the fraction of layers in which a brain node is assigned to the same community as other nodes from other different networks and is calculated using function (3) below, where *IN i* is the integration of node i in network N, and K is the total number of brain nodes.

$$R_i^N = \frac{1}{m_N} \sum\nolimits_{j \in N} P_{ij} \quad (2)$$

$$I_i^N = \frac{1}{K - m_N} \sum\nolimits_{j \notin N} P_{ij} \quad (3)$$

Statistical analysis

After extracting the recruitment and integration values of each brain node, the values of nodes belonging to the same predefined functional network were averaged for each participant to obtain the recruitment and integration of functional networks of interest. In the present study, given previous findings on IGD, we focused on the dynamic features of the BGN, LN, FPN and their nodes. As shown in Fig. 2, the BGN mainly included the NAcc, caudate, putamen, thalamus and hippocampus. The LN mainly included the insula, ACC, medial prefrontal cortex and partial IFG. The FPN mainly included the DLPFC, superior frontal gyrus (SFG), MFG, IFG and inferior parietal lobe (IPL). Analysis at the brain node level could further locate specific regions with abnormal community reconfiguration in the functional networks of participants with IGD. Accordingly, the recruitment and integration values of each of these 3 functional networks and each of their nodes were separately pooled into a 2 (Groups: IGD and RGU groups) × 2 (Phases: (gaming-rest) and (deprivation-rest)) ANOVA to examine the group-by-phases effect of dynamic features. Following a significant interaction, post-hoc tests were performed to compare the differences between groups across different phases, with the Holm-Bonferroni correction applied to adjust for multiple comparisons (Eichstaedt, Kovatch, & Maroof, 2013; Holm, 1979). Finally, Pearson correlation analyses were performed to evaluate the associations between these dynamic features and addiction severity (IAT and DSM-5 scores).

Ethics

The study procedures were carried out in conformity to the Declaration of Helsinki. The Institutional Review Board of Hangzhou Normal University approved the current study. All participants provided written informed content and the safety screening scale for MRI scan before the study.

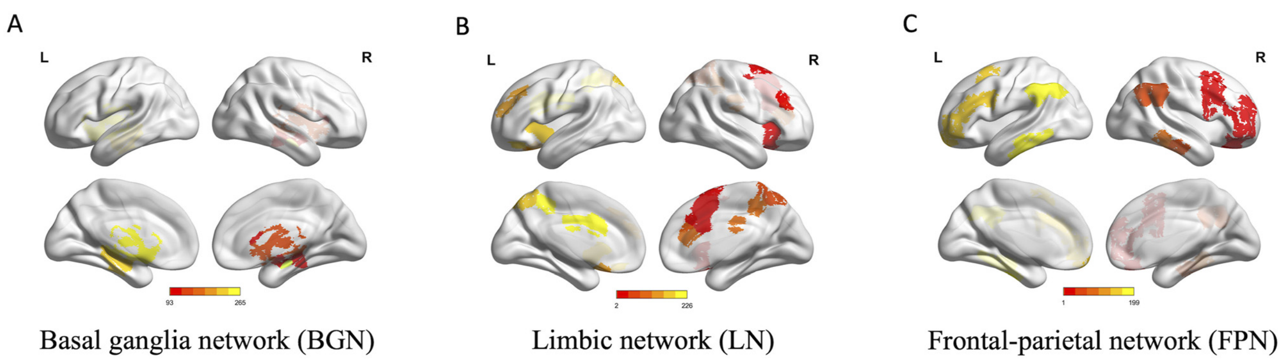

Fig. 2. Brain regions included in the BGN, LN and FPN
The values indicate the numbers of the brain nodes within the networks and do not have any meaning.
Abbreviations: BGN, basal ganglia network; LN, limbic network; FPN, frontal-parietal network; L, left; R, right.

RESULTS

1. The recruitments of the BGN and its nodes

For the recruitment of BGN (Fig. 3A), the interaction effect of Groups × Phases was significant ($F = 9.610$, $p = 0.003$). Partially consistent with the hypothesis 1, post-hoc analysis showed that the RGU group had significantly lower recruitment during the deprivation phase than during the gaming phase, whereas the IGD group exhibited similar recruitment during the gaming and deprivation phases, with a slight upward trend after entering the deprivation phase. The correlational analysis showed that smaller differences between the gaming and deprivation phases of BGN recruitment were associated with greater addiction severity among all the participants (Fig. 3B).

For the recruitment of nodes in the BGN (Table 2), 5 nodes exhibited significant interaction effects of Groups × Phases. Specifically, the interaction effects of the nodes "right caudate", "right NAcc", "left putamen" and "right putamen" were driven by significantly lower recruitment during deprivation than during gaming in the RGU group. Figure 3C shows the post-hoc result for the node "right caudate" as an example. The interaction effect of the node "left caudate" was driven by two significant differences: lower recruitment during deprivation than during gaming in the RGU group and greater recruitment in the IGD group than in the RGU group during deprivation, as shown in Fig. 3D.

Additionally, it should be noted that the negative values for recruitments of BGN and its nodes are because that for each of the phases (gaming and deprivation), each subject's own recruitment under resting-state (as baseline state) was subtracted from their recruitments under gaming/deprivation phase to eliminate individual differences in inherent neural mechanisms, as stated in Procedure: gaming and deprivation. Under resting-state, the participants just needed to keep relax and still without doing anything or facing any stimuli, in which their brain activities may be less variation and stable. In contrast, under gaming phase, the participants needed to operate mouse and keyboard to play games; under deprivation phase, the participants needed to deal with the deprivation situation and regulate possible emotions or craving. The participants' brain activities may be larger variation and unstable under gaming and deprivation phases compared to the activities under resting-state. Accordingly, it is understandable that the dynamic parameters (recruitment) of the networks under resting-state are bigger than the parameters under gaming/deprivation phases. Regardless

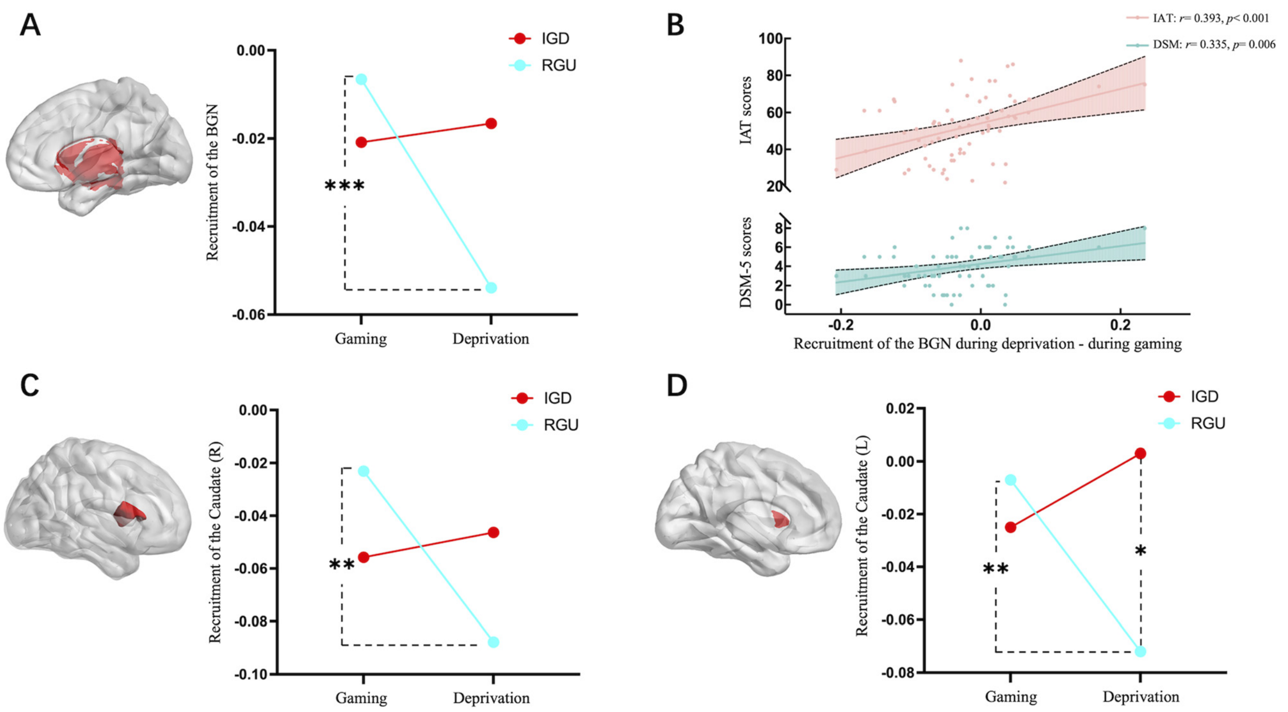

Fig. 3. The recruitments of the BGN and its nodes

(A) Post-hoc results for the recruitment of the BGN.

(B) The change in the recruitment of the BGN from gaming to deprivation (recruitment $_{deprivation}$ - recruitment $_{gaming}$) showed a significant positive correlation with addiction severity (IAT and DSM-5 scores) among all the participants.

(C) Post-hoc results for the recruitment of the node "right caudate" in the BGN.

(D) Post-hoc results for the recruitment of the node "left caudate" in the BGN.

Abbreviations: IGD, internet gaming disorder; RGU, recreational game use; BGN, basal ganglia network; L, left; R, right; IAT, internet addiction test; DSM-5, the fifth edition of diagnostic and statistical manual of mental disorders. * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

of this, we mainly focused on the interaction effect between the groups (IGD vs RGU) and the phases ((gaming-rest) vs (deprivation-rest)) in the dynamic parameters.

2. The recruitments of the LN and its nodes

For the recruitment of the LN (Fig. 4A), the interaction effect of Groups × Phases was significant ($F = 5.328$, $p = 0.024$). Consistent with the hypothesis 2, post-hoc analysis showed that the IGD group had significantly greater recruitment during deprivation than during gaming, and the IGD group had significantly lower recruitment than the RGU group during gaming, whereas the RGU group exhibited similar recruitment during gaming and deprivation. Correlation analysis also revealed that larger differences between the gaming and deprivation phases of LN recruitment were associated with greater addiction severity among all the participants (Fig. 4B).

For the recruitment of the nodes in the LN (Table 2), 3 nodes (i.e., bilateral insula and right ACC) exhibited significant interaction effects of Groups × Phases. Specifically, the interaction effects of nodes “bilateral insula” was driven by two significant differences: greater recruitment during deprivation than during gaming in the IGD group and lower recruitment in the IGD group than in the RGU group during gaming. Figure 4C shows the post-hoc result for the node “left insula” as an example. The interaction effect of the node “right ACC” was driven by lower recruitment in the IGD group than in the RGU group during gaming (Fig. 4D).

3. The integrations of the FPN and its nodes with the BGN

For the integration of the FPN, no significant interaction effect of Groups × Phases was found. Three nodes (i.e., bilateral IFG and left IPL; Table 2) of the FPN had significant interaction effects of Groups × Phases on the integrations with BGN, which were driven by the significantly greater degree of integration during deprivation than during gaming in the IGD group. This is consistent with the hypothesis 3. Figure 5A shows the post-hoc results for the node “left IFG” as an example. The correlation analysis showed that larger differences between the gaming and deprivation phases of the integration of nodes “bilateral IFG” were associated with higher IAT scores among all the participants (Fig. 5B).

4. The integrations of the FPN and its nodes with the LN

Two nodes (i.e., the right DLPFC and left IFG; Table 2) from the FPN exhibited interaction effects of Groups × Phases on the integration with LN. Specifically, the interaction effect of the node “right DLPFC” was driven by two significant differences: greater integration during

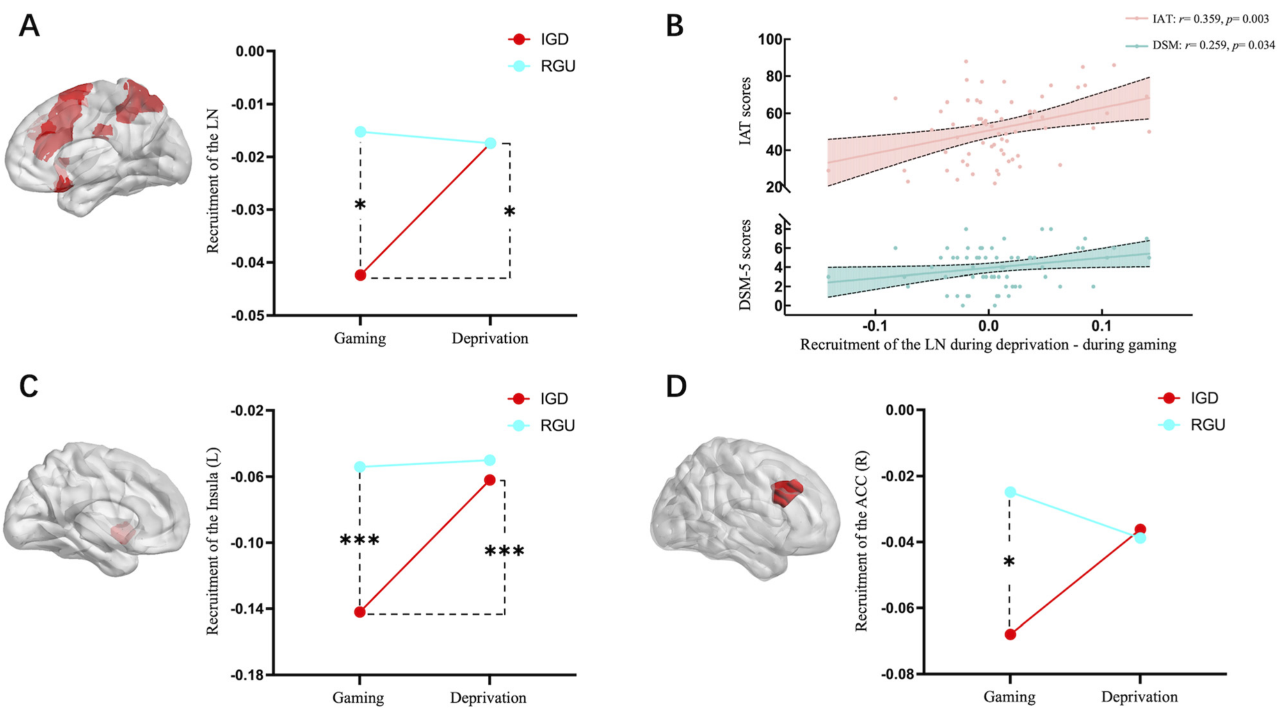

Fig. 4. The recruitments of the LN and its nodes
(A) Post-hoc results for the recruitment of the LN.
(B) The change in the recruitment of the LN from gaming to deprivation (recruitment $_{\text{deprivation}}$ - recruitment $_{\text{gaming}}$) were significantly positively correlated with addiction severity (IAT and DSM-5 scores) among all the participants.
(C) Post-hoc results for the recruitment of the node “left insula” in the LN.
(D) Post-hoc results for the recruitment of the node “right ACC” in the LN.
Abbreviations: IGD, internet gaming disorder; RGU, recreational game use; LN, limbic network; L, left; R, right; IAT, internet addiction test; DSM-5, the fifth edition of diagnostic and statistical manual of mental disorders; ACC, anterior cingulate cortex. * indicates $p < 0.05$; *** indicates $p < 0.001$.

Table 2. Brain nodes with significant interaction effect of Group × Phase ANOVA

Node names	IGD		RGU		F	*p*
	gaming	deprivation	gaming	deprivation		
BGN						
Recruitment						
Caudate (L)	−0.025 ± 0.093	0.003 ± 0.115	−0.007 ± 0.100	−0.072 ± 0.094	11.56	0.001
Caudate (R)	−0.056 ± 0.099	−0.046 ± 0.121	−0.023 ± 0.099	−0.088 ± 0.103	8.446	0.005
Putamen (L)	0.028 ± 0.113	0.018 ± 0.138	0.044 ± 0.101	−0.043 ± 0.108	6.824	0.011
Putamen (R)	0.033 ± 0.106	0.010 ± 0.148	0.045 ± 0.107	−0.046 ± 0.120	5.190	0.026
NAcc (R)	−0.015 ± 0.092	−0.014 ± 0.141	0.019 ± 0.110	−0.040 ± 0.122	4.573	0.036
LN						
Recruitment						
Insula (L)	−0.142 ± 0.089	−0.062 ± 0.102	−0.054 ± 0.082	−0.050 ± 0.097	8.267	0.005
Insula (R)	−0.141 ± 0.098	−0.072 ± 0.100	−0.063 ± 0.082	−0.050 ± 0.082	6.116	0.016
ACC (R)	−0.068 ± 0.059	−0.036 ± 0.075	−0.025 ± 0.058	−0.039 ± 0.057	6.496	0.013
FPN						
Integration with BGN						
IFG (L)	−0.011 ± 0.082	0.043 ± 0.104	0.020 ± 0.102	0.004 ± 0.084	7.492	0.008
IFG (R)	−0.078 ± 0.115	0.015 ± 0.137	−0.021 ± 0.102	0.001 ± 0.104	4.059	0.048
IPL (L)	−0.072 ± 0.121	−0.003 ± 0.137	−0.021 ± 0.098	−0.021 ± 0.106	4.843	0.031
Integration with LN						
DLPFC (R)	−0.124 ± 0.088	−0.066 ± 0.098	−0.046 ± 0.092	−0.046 ± 0.092	4.539	0.037
IFG (L)	−0.078 ± 0.070	−0.041 ± 0.089	−0.012 ± 0.072	−0.031 ± 0.087	5.505	0.022

Table values: mean ± standard deviation.
Abbreviations: IGD, internet gaming disorder; RGU, recreational gaming user; L, left; R, right; BGN, basal ganglia network; NAcc, nucleus accumbens; LN, limbic network; ACC, anterior cingulate cortex; FPN, frontal-parietal network; IFG, inferior frontal gyrus; IPL, inferior parietal lobe; DLPFC, dorsolateral prefrontal cortex.

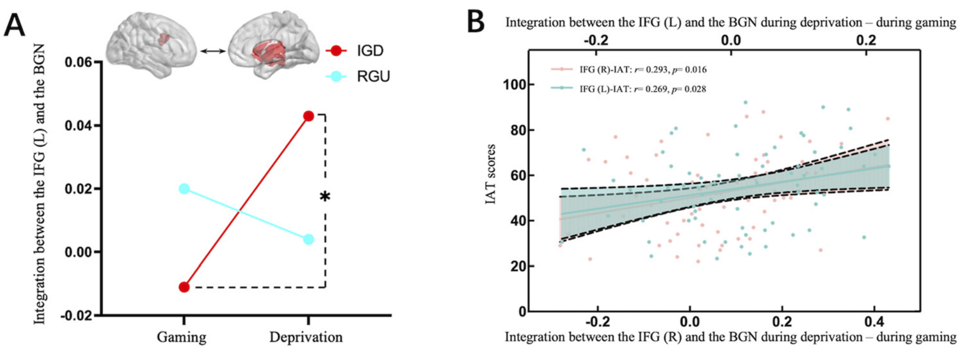

Fig. 5. The integrations of the nodes in the FPN with BGN
(A) Post-hoc results for the integration between the node "left IFG" in the FPN and BGN.
(B) The change in this integration from gaming to deprivation (integration deprivation - integration gaming) showed a significant positive correlation with addiction severity (IAT scores) among all the participants.
Abbreviations: IGD, internet gaming disorder; RGU, recreational game use; IFG, inferior frontal gyrus; L, left; R, right; FPN, frontal-parietal network; BGN, basal ganglia network; IAT, internet addiction test. * indicates $p < 0.05$.

deprivation than during gaming in the IGD group and lower integration in the IGD group than in the RGU group during gaming (Fig. 6A). This is consistent with the hypothesis 4. The interaction effect of the node "left IFG" was driven by significantly lower integration in the IGD group than in the RGU group during gaming (Fig. 6B). The correlation analysis showed that larger differences between the gaming and deprivation phases of the integration of these 2 nodes were associated with greater addiction severity among all the participants (Fig. 6C).

DISCUSSION

Compared to traditional single-layered networks, a time-varying multilayer network has the advantage of modeling multiple interactions of brain regions and functional networks over time. In this study, we employed the multiple community structure detection method and found that, compared to the RGU group, the IGD group exhibited altered dynamic functional segregation and integration in networks related to reward processing (BGN), emotional

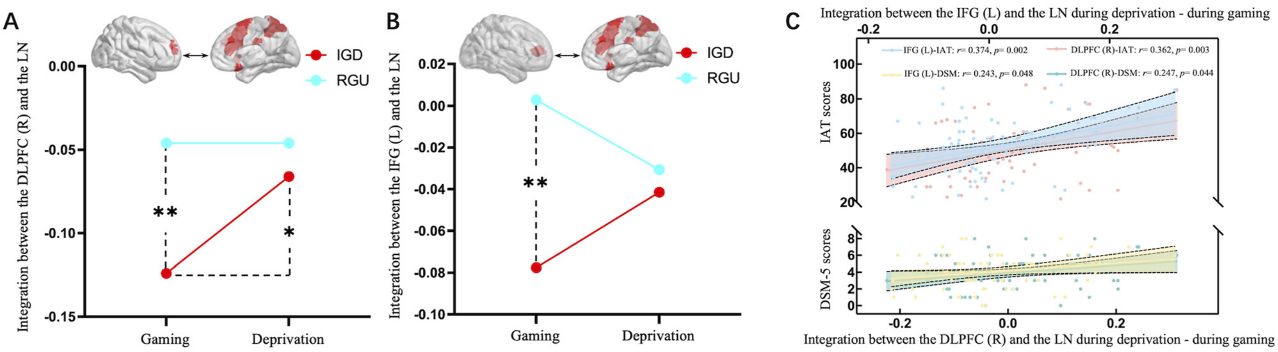

Fig. 6. The integrations of the nodes in the FPN with LN
(A) Post-hoc results for the integration between the node "right DLPFC" in the FPN and LN.
(B) Post-hoc results for the integration between the node "left IFG" in the FPN and LN.
(C) Changes in these two integrations from gaming to deprivation (integration $_{deprivation}$ - integration $_{gaming}$) were significantly positively correlated with addiction severity (IAT and DSM-5 scores) among all the participants.
Abbreviations: IGD, internet gaming disorder; RGU, recreational game use; DLPFC, dorsolateral prefrontal cortex; L, left; R, right; FPN, frontal-parietal network; LN, limbic network; IFG, inferior frontal gyrus; IAT, internet addiction test; DSM-5, the fifth edition of diagnostic and statistical manual of mental disorders. * indicates $p < 0.05$; ** indicates $p < 0.01$.

response and regulation (LN), and cognitive control (FPN) during gaming and immediate deprivation conditions. The detailed results and implications are discussed below.

Stronger craving and anticipation for continuing gaming in the IGD group after immediate deprivation of gaming

The first difference between the IGD and RGU groups was that the RGU group exhibited significantly lower recruitments of BGN and its nodes (i.e., the right caudate, right NAcc, bilateral putamen) after immediate deprivation of gaming; however, the IGD group exhibited similar recruitment of BGN regardless of the phases. Moreover, one brain node in the BGN (i.e., the left caudate) showed significant greater recruitment in the IGD group than in the RGU group after immediate deprivation. The BGN, as the core of the reward circuit, is mainly composed of the striatum and includes the bilateral NAcc, caudate, and putamen. It plays a key role in reward processing and reward-based learning, helping individuals to evaluate and respond to rewarding stimuli (e.g., generating positive feeling like pleasure, enjoyment and gratification during gaming), predict future rewards based on previous experiences and thus reinforce future behaviors (e.g., reinforcing the behavior and craving to keep playing games persistently for prolonged periods based on the generated positive feelings during gaming; or anticipating/craving for continuing gaming to get positive feelings from gaming after being interrupted) (Haber, 2008; Haber & Knutson, 2010; Kawagoe, Takikawa, & Hikosaka, 1998). Moreover, many studies have proven the close relationship between the BGN and cravings for addictive behaviors and substances. Using a cue-craving task, researchers found that activation in the striatum was positively correlated with participants' craving induced by gaming pictures (Dong, Wang, Du, & Potenza, 2018; Ko et al., 2009). An increase in cerebral blood flow in the striatum can predict chronic smokers' abstinence-induced cravings to smoke (Z. Wang et al., 2007). Increased dopamine levels and activation in the striatum were associated with cue-induced craving in cocaine users and methamphetamine users (Grodin, Courtney, & Ray, 2019; Volkow et al., 2008; Wong et al., 2006).

In the present study, recruitment represents the compatibility between the nodes of one network and the functional stability of this network over time. Combined with the functions of the BGN in reward processing, reward-based learning and craving, the current results may imply that during gaming, both the IGD and RGU groups experienced positive feelings and thus reinforced their behavior and craving to keep playing games persistently. After being deprived of gaming, the RGU group could immediately decrease their craving and anticipation for continuing gaming as indicated by the decreased recruitment of the BGN after being unable to play games. However, for the IGD group, they still remained stable and stronger craving and anticipation for continuing gaming than the RGU group after being unable to play games, as indicated by the greater recruitment in the left caudate (a main component of the BGN) than did the RGU group during deprivation. This inference was further supported by the correlational results that a smaller difference between gaming and deprivation in the recruitment of BGN was associated with greater addiction severity among all the participants. Moreover, previous studies also identified that the IGD group exhibited greater activation in the caudate and stronger FC between the striatum and thalamus than did the RGU group when presented with gaming pictures after deprivation of gaming (Dong et al., 2019; Dong, Zheng, et al., 2018). Overall, the current results indicated stronger craving and anticipation for continuing gaming in the IGD group and decreased craving in the RGU group after the participants were unable to play the game. Furthermore, the bilateral caudate, putamen and NAcc are the main neural basis related to the strong craving and anticipation in IGD patients.

Abnormalities in cognitive control over craving and anticipation in the IGD group after immediate deprivation of gaming

The second difference between the IGD and RGU groups was that the RGU group maintained stable integration between the nodes of the FPN (bilateral IFG and left IPL) and the BGN during both the gaming and deprivation phases; however, the IGD group had significantly greater integration after immediate deprivation of gaming. The FPN mainly contains parts of the frontoparietal cortex, including the bilateral IFG, IPL, DLPFC and SFG. It is widely found to be involved in cognitive control, helping individuals select, inhibit and monitor behaviors and thoughts to achieve goals (Nee, 2021). Integration represents the interactivity between nodes from different networks and interactivity between networks over time. Based on the functions of the FPN and BGN, the integration between the nodes of the FPN and BGN indicates the coupling between cognitive control and game craving/reward anticipation and response (Kober et al., 2010). The greater integration after the deprivation of gaming in the IGD group may suggest that they need more cognitive resources to inhibit their strong craving and anticipation for continuing gaming. In contrast, the RGU group always maintained stable cognitive control, which may be the reason why their craving and anticipation for continuing gaming decreased quickly after not being able to play the games (as discussed above). The association between greater addiction severity and greater differences in the integration between gaming and deprivation further support our inference.

Consistent with the current results, previous studies have also revealed abnormalities in cognitive control over craving in IGD patients. Using the cue reactivity tasks, researchers found that the IGD group had greater activation in control-related regions (i.e., the DLPFC and ACC) and craving-related regions (i.e., the striatum and OFC) than did the control group (Dong et al., 2017; Ko et al., 2009), and that greater activation of control-related regions (e.g., the DLPFC and ACC) in the IGD group was associated with greater craving induced by gaming pictures (Ko et al., 2009). Similarly, using the craving-regulation task, a task in which subjects need to downregulate their gaming craving when presented with gaming pictures, researchers found greater activation in the DLPFC and ACC in the IGD group than in the control group. The IGD group needed more cognitive resources to downregulate their craving (Jialin Zhang et al., 2021). Additionally, individuals with IGD displayed abnormal activation related to cognitive control in some classic tasks used to measure cognitive control (e.g., the Stroop task and the go/no-go task); that is, they needed to activate stronger control-related regions to perform like the HCs (W. Ding et al., 2014; Dong, DeVito, Du, & Cui, 2012). Based on these findings, the current results demonstrated abnormal cognitive control over craving/anticipation in the IGD group under real-gaming conditions, which is particularly related to the abnormalities in the coupling between the IFG, IPL and BGN.

Abnormalities in emotional regulation in the IGD group during gaming and immediate deprivation

The third difference between the IGD and RGU groups was that for the recruitment of the LN and integration between the nodes of the FPN (right DLPFC and left IFG) and the LN, the RGU group exhibited stable recruitment and integration during both the gaming and deprivation phases; however, the IGD group had significantly lower recruitment and integration than did the RGU group during gaming, and these two indices significantly increased after immediate deprivation. The LN is mainly composed of the bilateral ACC, insula, and part of the IFG and DLPFC. The LN, often termed the "emotional network", is involved in both emotional and cognitive processes (Catani et al., 2013; Connaughton et al., 2023). Additionally, the prefrontal-limbic neural circuit is suggested to be involved in emotional regulation (Kebets et al., 2021; C. R. Li & Sinha, 2008). The lower recruitment and integration in the IGD group than in the RGU group during gaming might indicate that the IGD group was completely immersed in gaming and allocated few resources to emotional regulation. After they suddenly cannot play the game, they need to increase their emotional resources to inhibit and regulate their deprivation-related emotions, as indicated by their greater recruitment and integration. In contrast, the RGU group always maintained stable emotions and emotional regulation, similar to their cognitive control over craving and anticipation for continuing gaming (as discussed above). The association between greater addiction severity and greater differences in these recruitment and integration tasks between gaming and deprivation could support this inference.

Abnormal emotional regulation in IGD patients has also been proven in previous studies. Research has demonstrated that poor emotional regulation is one of the main risk factors leading individuals to develop IGD (Liang, Zhu, Dai, Li, & Zheng, 2021; Qi Li et al., 2019; Yildiz, 2017). Escape or relief from a negative mood is one of the nine diagnostic criteria proposed by the DSM-5 for IGD, which reflects the poor negative emotional regulation in individuals with IGD (Petry et al., 2014). Using the emotion reappraisal task, researchers found that the IGD group exhibited greater activation in the left ACC and bilateral insula and stronger FC between the insula and DLPFC than did the control group when participants were asked to downregulate the negative emotions induced by negative pictures (Jialin Zhang et al., 2020). The IGD group engaged more cognitive resources but could still not downregulate negative emotional experiences as efficiently as the RGU group, which is consistent with the current results. Other studies also demonstrated difficulties in emotional regulation in IGD patients from fMRI evidence (Z. Wang, Song, et al., 2022; Yan, Gao, Yang, & Yuan, 2022) and ERP evidence (Hou et al., 2019; Jiao, Wang, Peng, & Cui, 2017). Overall, the current results demonstrated abnormal emotional regulation in the IGD group from the perspective of real gaming, which is particularly related to the abnormalities in the LN and the coupling between the DLPFC and IFG and the LN.

Implications based on the I-PACE model

Based on the I-PACE model proposed by Brand, Potenza, and Stark (2022), the interaction between individual predispositions, affective responses, cognitive processing, and executive functions provides a solid framework for interpreting the current findings about IGD. The model suggests that addictive behaviors, including IGD, arise through the interaction of these components, which leads to maladaptive reinforcement of behaviors that persist over time. During the process of developing and maintaining addictive behaviors, addicts gradually develop a sensitized response to addictive cues (e.g., increased craving and cue reactivity induced by cues, and increased attention bias to addictive cues) (Antons et al., 2020), improper emotional regulation (e.g., using gaming to relieve negative emotions) (Jialin Zhang et al., 2020; Koob, 2015) and diminished inhibitory control over urges (Kuss et al., 2018). Moreover, the model highlights that an imbalance in the prefrontal-subcortical circuits underlying emotion and urge regulation related to these main aspects of addictive behaviors. Align with this model, the current study identified altered dynamic interactions between prefrontal cortex (FPN) and subcortical networks (limbic and striatal regions) in gamers with IGD under a real gaming situation. These findings uncover the underlying neural basis for the poor emotion regulation and diminished inhibitory control over enhanced craving in IGD individuals. The current findings further extend the application of the I-PACE model in understanding IGD. Also, other neurobiological models, such as the neural pathway in addiction proposed by Brand (2022), the self-regulation model proposed by Heatherton and Wagner (2011), the adolescent dual-system neurobiological model proposed by Casey and Jones (2010), emphasized the imbalanced between the prefrontal-subcortical circuits in mental diseases and addiction. These models coincide with the I-PACE model and current findings.

Furthermore, combined with the I-PACE model, the current findings may inform the development of targeted therapeutic interventions for IGD. The current study underscores the key neural alterations in IGD, i.e., altered dynamic interactions between FPN and subcortical limbic and striatal networks. The regions in these altered networks, including NAcc, caudate, insula, ACC, IFG, DLPFC, could be targeted for brain stimulation therapy for IGD, e.g., transcranial magnetic stimulation (TMS), transcranial direct current stimulation (tDCS), thus helping to improve their cognitive control over reward processing and emotional regulation. Researchers have identified the effect of tDCS of DLPFC in decreasing IGD individuals' craving (Jeong et al., 2024; Wu et al., 2021). The selection of targets plays a crucial role in the efficacy of brain stimulation therapy. Moreover, the findings regarding gamers with IGD's neural alterations during deprivation of gaming highlight that future behavioral therapy for IGD should focus on the training of emotional regulation and cognitive control over reward processing/craving when they can't play games immediately. Further research is needed to optimize these interventions and validate their efficacy in clinical settings.

Strengths and limitations

This study offers several strengths. First, a key strength is the use of real gaming situation, which improves ecological validity by applying a more naturalistic context. Accordingly, the current findings provide direct and reliable evidence for the neural alterations in gamers with IGD compared to gamers without IGD. Second, the application of the emerging dynamic network analysis method named "community structure" provides deeper insights into the temporal dynamics of brain functional networks involved in IGD. It offers a more nuanced understanding for IGD compared to static approaches, e.g., functional connectivity, regional homogeneity (ReHo), and amplitude of low frequency fluctuation (ALFF). Moreover, consistent with the current findings, researchers have found increased integration between FPN and BGN in individuals with tobacco use disorder; and repetitive TMS over the left DLPFC significantly decreased this integration (S. Li et al., 2024). This study not only demonstrated the efficacy of TMS treatment in reshaping the brain alterations in addicted individuals, but also highlighted the application of dynamic network analysis in understanding addicted individuals, as the current study. More studies are needed to explore the dynamic network reconfiguration in addicted population and thus help understand the similarities and differences between different addicted disorders. Third, the current findings provide reliable evidence for the I-PACE model in understanding IGD. Supporting and extending the model is not only beneficial to future studies on exploring the psychological and neurobiological mechanisms of IGD, but also contributes to clinical practice on the targeted therapeutic interventions for IGD (Brand et al., 2022).

Three limitations should be noted. First, the cross-sectional design of the current study prevents causal conclusions, highlighting the need for longitudinal studies to examine whether the changes in dynamics of brain functional networks are causes or consequences of IGD. Second, the current sample is composed of college students with 18–27 years old, which may limit the generalizability of the current findings to other age groups or cultural contexts. Future studies recruiting samples with broader age and other cultural contexts are needed to examine the current findings. Third, the history of IGD in the RGU participants was not assessed in the current study. Although the RGU participants' gaming use was assessed based on the last year, and we suppose that their potential IGD history had minimal impact on the results, we cannot completely rule out this potential effect. Future studies should consider assessing participants' IGD history to better control for this variable and provide more comprehensive insights into the observed effects.

CONCLUSION

This is the first study to investigate the dynamic functional segregation and integration of brain networks and regions in an IGD population during a real-gaming situation compared to those in an RGU population. This real-gaming situation enables us to explore the direct and true abnormalities associated with addictive behavior. A comparison with the RGU population prevents the potential effects of gaming experience from occurring, thus enabling us to identify the exact abnormalities in the IGD population. We found that the RGU group always held stable cognitive control over craving/anticipation and emotional regulation and immediately dropped their craving and anticipation for continuing gaming after being unable to play games. In contrast, the IGD group held stronger craving/anticipation and emotional responses after being unable to play games, at the meantime, they had abnormal cognitive control and emotional regulation, resulting in insufficient control over craving/anticipation and emotions. The underlying neural features of these abnormalities in the IGD group (e.g., striatum, insula, IFG and DLPFC) identified in this study could lead to important and precise targets for the intervention and prevention of IGD.

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Authors' contribution: ZZ and LW conducted the statistical analysis and wrote the manuscript. LW and GHD collected the research data and modified the manuscript. MW contributed to the data collection and statistical analysis. GM and YQ contributed to the revision of the manuscript. All authors have full access to all data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis. All authors have approved the final manuscript.

Conflict of interest: The authors declare no conflict of interest.

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