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Altered resting-state network connectivity in internet gaming disorder

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Abstract

Background The growing popularity of internet gaming among adolescents and young adults has driven an increase in both casual and excessive gaming behavior. Nevertheless, it remains unclear how progressive increases in internet gaming engagement led to changes within and between brain networks. This study aims to investigate these connectivity alterations across varying levels of gaming involvement.

Methods In this cross-sectional study, 231 participants were recruited and classified into three groups according to Diagnostic and Statistical Manual of Mental Disorders (DSM-5) criteria for Internet Gaming Disorder (IGD): IGD group, highly engaged gaming(HEG) group, and lowly engaged gaming (LEG) group. Resting-state fMRI data from 217 participants (143 males, 74 females) were included in the final analysis. Independent component analysis was used to examine differences in intra- and inter-network functional connectivity (FC)across the three groups.

Results No significant differences were found in intra-network FC across the three groups. However, significant inter-network differences between the dorsal attention network(dAN)and the visual network (VN) among the three groups were observed. The HEG group exhibited significantly higher dAN-VN functional network connectivity (FNC) compared to the LEG group. Linear correlation analyses showed no significant correlation between the dAN-VN FNC values and IGD-20T scores.

Conclusion Throughout the development of IGD, increasing levels of engagement are associated with a rise and subsequent decline in FNC of DAN-VN. This pattern may reflect top-down attentional regulation in the early stages of addiction, followed by attentional bias as addiction progresses.

Keywords Internet gaming disorder, Independent component analysis, Dorsal attention network, Visual network, fMRI

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Background

Internet gaming activities has become a prominent aspect of modern social and recreational life [1], with significant cultural and economic impacts. Video games now stand as the leading global cultural entertainment product, with adolescents and young adults representing the primary consumer demographic [2]. In China alone, the gaming market reached a revenue of 265.88 billion yuan in 2023, supported by an expansive user base of 664 million players (http://www.cgigc.com.cn/details.html?id=08dc70a3-deb3-4af9-8043-8b92d80fff2c%26;tp=report). For Chinese youth, internet and gaming exposure is pervasive, with recreational gaming being typical. However, in some cases, this behavior escalates into excessive use and potential addiction [3]. With Asia experiencing a high prevalence of Internet Gaming Disorder (IGD) and China housing one of the world's largest gaming populations, the potential IGD-affected population is substantial [4]. Given these trends, investigating the progressive neural effects of gaming and uncovering the mechanisms behind gaming addiction is crucial.

Resting-state functional connectivity (rs-FC) analysis can identify neural circuit dysfunctions in various neuropsychiatric disorders, including addiction [5]. Changes in rs-FC circuits are less likely to be disrupted by subtle task-based paradigms, and the networks identified remain consistent both between individuals and within individuals over time [6]. While this approach elucidates rs-FC changes between regions, it does not address alterations in intra- and inter- network connectivity [7]. Some scholars argue that a whole-brain approach, as opposed to using a limited number of predefined seed regions, may provide a more comprehensive understanding of the underlying neural mechanisms associated with addiction [5]. A comprehensive understanding of IGD's neurobiological basis thus necessitates research at the network level. In this study, we applied independent component analysis (ICA)—a data-driven technique known for minimizing prior assumptions and enhancing the detection of novel findings in neuroimaging [8].

Studies on IGD employing ICA have predominantly focused on male players or adolescents, which constrains the generalizability of the findings and limits the representativeness of the sample. Furthermore, researchers have highlighted the diversity in criteria used to differentiate between non-problematic, problematic, and addictive gaming behaviors. These behaviors may be better understood as part of a continuous spectrum, which requires consideration of multiple dimensions for a more nuanced understanding [9, 10]. However, previous studies have largely compared addicted gamers to recreational gamers or healthy controls, often overlooking network-level brain changes across the continuum of gaming engagement. To address this, we used DSM-5 criteria for IGD to recruit participants (both males and females) spanning a range of diagnostic criteria, aiming to explore the continuity of intra- and inter- network connectivity alterations as gaming behavior progresses. This continuum-based approach offers the potential for more nuanced insights into the mechanisms driving IGD.

Methods

Participants

A total of 231 participants (156 males, 75 females) were recruited between June 2022 and December 2023 from Wuhan and its surrounding regions, through combined online and offline recruitment. All participants underwent resting-state functional magnetic resonance imaging (rs-fMRI) and high-resolution volumetric imaging at the PET Center of Renmin Hospital of Wuhan University. Prior to the neuroimaging scan, all participants were administered the Chinese version of the Internet Gaming Disorder-20 Test (IGD-20T) to evaluate the severity of their internet gaming addiction [11]. Additionally, participants provided self-reported data on their weekly gaming duration. Based on the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) criteria for IGD, participants were categorized into three groups: the IGD group, the highly engaged gaming (HEG) group, and the lowly engaged gaming (LEG) group. The Clinician Version of structured clinical interview for DSM-5 (SCID-5-CV) were conducted by experienced psychiatrists to screen for psychiatric disorders, and participants reporting any gambling or illicit drug use (e.g., cannabis, heroin) were excluded. Participants were also instructed to refrain from using any substances, including coffee, tea, or alcohol, on the day of the scan.

Participants were assigned to groups based on the nine DSM-5 diagnostic criteria for IGD. Group-specific inclusion criteria were as follows: IGD Group: (1) age > 18 years, (2) meeting at least five DSM-5 IGD criteria, (3) minimum education level of junior high school, (4) right-handedness. HEG Group: same criteria as above, except meeting only three or four DSM-5 IGD criteria. LEG Group: same criteria as above, but meeting no more than two DSM-5 IGD criteria. Exclusion criteria included: (1) severe physical illness, particularly neurological disorders; (2) history of head trauma with > 5 min loss of consciousness; (3) MRI contraindications.

Image acquisition and pre-processing

MRI data were acquired using a 3.0-Tesla GE Signa HDx MRI scanner (General Electric, Brookfield, WI, USA). Participants lay comfortably supine, instructed to close their eyes and remain calm yet awake. Head movement was minimized using a plastic mask and foam padding. High-resolution T1-weighted structural images were obtained using a gradient-echo

sequence with the following parameters: repetition time (TR) = 8.5 ms, echo time (TE) = 3.2 ms, flip angle (FA) = 12°, slice thickness = 1.0 mm, no inter-slice gap, field of view (FOV) = 256 × 256 mm^2, matrix = 256 × 256, voxel size = 1.0 mm^3, and a total of 176 slices. The rs-fMRI data were collected using an echo-planar imaging (EPI) sequence: TR = 2000 ms, TE = 30 ms, FA = 90°, FOV = 220 mm × 220 mm, matrix size = 64 × 64, voxel size = 3.4 mm × 3.4 mm × 4.0 mm, slice thickness = 4.0 mm, no inter-slice gap, 36 slices, with a total of 240 volumes.

Image pre-processing was conducted using Statistical Parametric Mapping (SPM12, http://www.fil.ion.ucl.ac.uk/spm) and DPARSF V5.2 [12]. Initially, DICOM data were converted to NIfTI format. To stabilize magnetization, the first 10 volumes for each functional time series were discarded. Images then underwent slice timing correction and realign, with participants excluded if head displacement exceeded 3 mm or rotation surpassed 3°. We also examined the framewise displacement (FD) of each participant, and those with an FD>0.5 were excluded from further analysis. Each participant's 3D T1-weighted structural image was co-registered with the mean functional image and spatially normalized to the Montreal Neurological Institute (MNI) space, with voxel resampling to 3.0 × 3.0 × 3.0 mm^3. Spatial smoothing was applied with a 6-mm full width at half maximum (FWHM) Gaussian kernel. Fourteen participants (13 males, 1 female) were excluded due to excessive head motion, resulting in a final sample of 98 IGD, 59 HEG, and 60 LEG participants for further analysis (Fig. 1).

Independent component analysis

Group ICA was performed on pre-processed fMRI data using the Group ICA of fMRI Toolbox (GIFT v3.0c) in the Matlab R2016b environment (http://icatb.sourceforge.net). Data reduction was achieved through two stages of principal component analysis (PCA). The optimal number of components was determined as 25 using the minimum description length (MDL) criterion. Spatial ICA was conducted using the Infomax algorithm to estimate these 25 independent components, and ICA stability was enhanced by performing 100 iterations with ICASSO (http://www.cis.hut.fi/projects/ica/icasso). Each participant's independent components (including spatial maps and time series) were obtained by back reconstruction and scaled to Z scores. Ultimately, for each subject, a single ICA time course and an independent functional spatial map were obtained.

Identification and selection of RSNs

Utilizing the graphical user interface (GUI) in the GIFT toolbox, which displays all extracted components, independent components (ICs) linked to cerebrospinal fluid (CSF), motion artifacts, or vascular-induced confounds were excluded from further analysis. To assess the spatial relevance of each IC, the spatial correlation coefficient between the ICs and a pre-defined network template was computed, employing the maximum spatial similarity criterion based on the Stanford Find Laboratory prior network model. The IC exhibiting the highest correlation with the template was identified, and the corresponding brain network was delineated and validated through manual visual inspection. Standardized resting-state

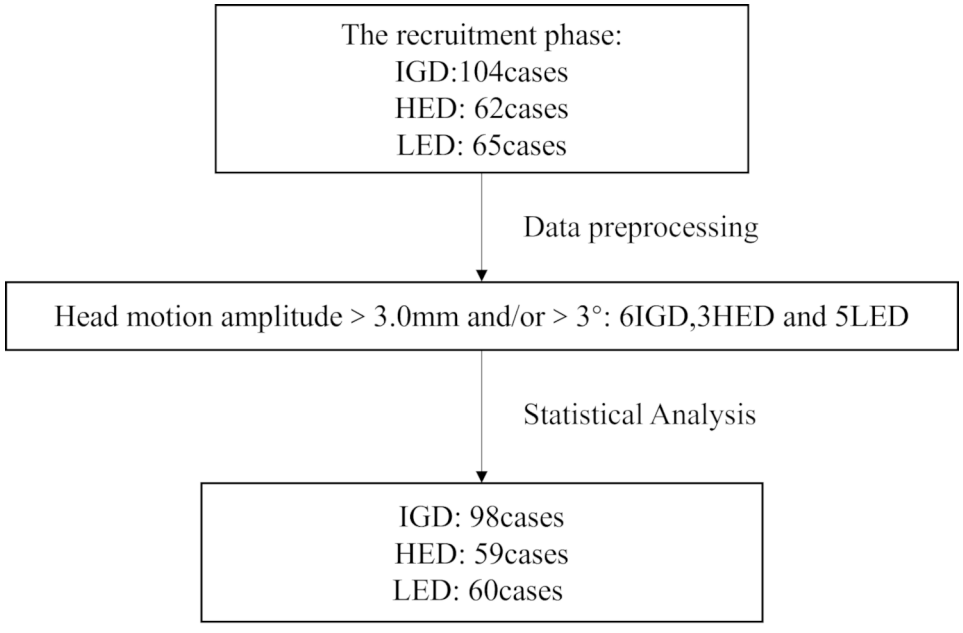

Fig. 1 Flow chart of subject inclusion and exclusion

networks (RSNs) derived from ICA of the Human Connectome Project(HCP) dataset, encompassing 497 participants and supported by extensive empirical research, served as the reference for network identification [13–17]. Additionally, all ICs were subject to a thorough visual inspection by two independent researchers to ensure the validity and appropriateness of the selected RSNs.

Analysis of intra- and inter-network connectivity

For intra-network FC analysis, one-sample t-tests were conducted on each group's RSNs using SPM12 software in the Matlab R2016b environment, generating group-level templates (family-wise error rate [FWE], $p<0.05$) with concurrent sets used as global masks for each network. To assess FC differences across the three groups within each network, One-way analysis of covariance (ANCOVA) (false discovery rate [FDR]-corrected, voxel $p<0.001$, cluster $p<0.05$) was conducted, controlling for age and gender as covariates of no interest. For inter-network functional network connectivity (FNC), time series for selected network components were extracted and completed Fisher r-to-z transformation. Between-group FNC differences were evaluated using one-way ANOVA ($p<0.05$, FDR-corrected), with age and gender eliminated by linear regression.

Statistical analysis

Statistical analyses were performed using SPSS version 23 to evaluate demographic characteristics and clinical scale scores across the three groups. The quantitative data are presented as the mean ± standard deviation ($\bar{x} \pm s$). For continuous variables with equal variances, a one-way ANOVA was conducted to detect group differences, followed by post hoc analysis using the Bonferroni method. In cases of unequal variances, Welch's ANOVA was utilized, with subsequent pairwise comparisons conducted via the Games-Howell test. Categorical variables, such as gender, were analyzed using the Chi-square test. Statistical significance was determined at a threshold of $p<0.05$.

Results

Demographic and clinical characteristics

The demographic characteristics and clinical scale scores for all participants are summarized in Table 1. Statistical analysis revealed no significant differences among the three groups in terms of age, gender distribution, years of education, or mean FD ($p>0.05$). However, significant differences were observed in IGD-20T scores, weekly gaming duration and adherence to DSM-5 criteria for diagnosing internet gaming disorder (DSM-5 score) ($p<0.001$) (Table 1). Regarding weekly gaming duration, post-hoc tests revealed that LEG subjects (LEGs) spent significantly less time compared to both IGD subjects (IGDs) and HEG subjects (HEGs) ($p<0.001$). For the IGD-20T and DSM-5 scores, post-hoc analyses indicated that IGDs scored significantly higher than both HEGs and LEGs ($p<0.001$). Additionally, HEGs scored significantly higher than LEGs on both measures ($p=0.001$ for IGD-20T; $p<0.001$ for DSM-5).

Resting-state networks

ICA identified 25 components, 8 of which align with RSNs. These RSNs include the default mode network (DMN), left and right frontoparietal networks (lFPN, rFPN), dorsal attention network (dAN), salience network (SN), sensorimotor network (SMN), visual network (VN), and auditory network (AUN) (Fig. 2).

Intra-network analysis of the eight networks

There were no significant intra-network FC differences across the three groups for any of the networks.

Inter-network analysis of the eight networks

In terms of inter-network connectivity, significant differences were detected among the groups in dAN-VN functional network connectivity (FNC) ($p<0.05$, FDR-corrected). Notably, the HEG subjects (HEGs) demonstrated higher dAN-VN FNC compared to both the IGD subjects (IGDs) and the LEG subjects (LEGs) ($p<0.05$) (Fig. 3).

Table 1 Demographics and clinical characteristics of the subjects

Item	IGDs($N=98$)	HEGs($N=59$)	LEGs($N=60$)	F/χ2	*p*
Age (years, M ± SD)	23.02 ± 2.81	23.41 ± 3.20	24.03 ± 2.86	2.36	0.10
Sex(male/female)	71/27	38/21	34/26	4.21	0.12
Educations (years, M ± SD)	16.37 ± 2.30	16.61 ± 2.74	16.98 ± 1.77	1.80	0.17
WGD(hours, M ± SD)	28.49 ± 11.03	24.28 ± 12.91	11.63 ± 10.62	41.06	<0.001
mean FD(M ± SD)	0.054 ± 0.023	0.059 ± 0.035	0.063 ± 0.041	1.50	0.23
IGD-20T(M ± SD)	74.37 ± 12.04	65.31 ± 15.49	41.83 ± 17.13	82.83	<0.001
DSM-5 score(M ± SD)	6.00 ± 1.01	3.58 ± 0.50	0.78 ± 0.89	580.39	<0.001

Abbreviations: WGD = weekly gaming duration; mean FD = mean Framewise displacement; IGD-20T = Internet Gaming Disorder-20 Test; IGDs = Internet Gaming Disorder subjects; HEGs = highly engaged gaming subjects; LEGs = lowly engaged gaming subjects

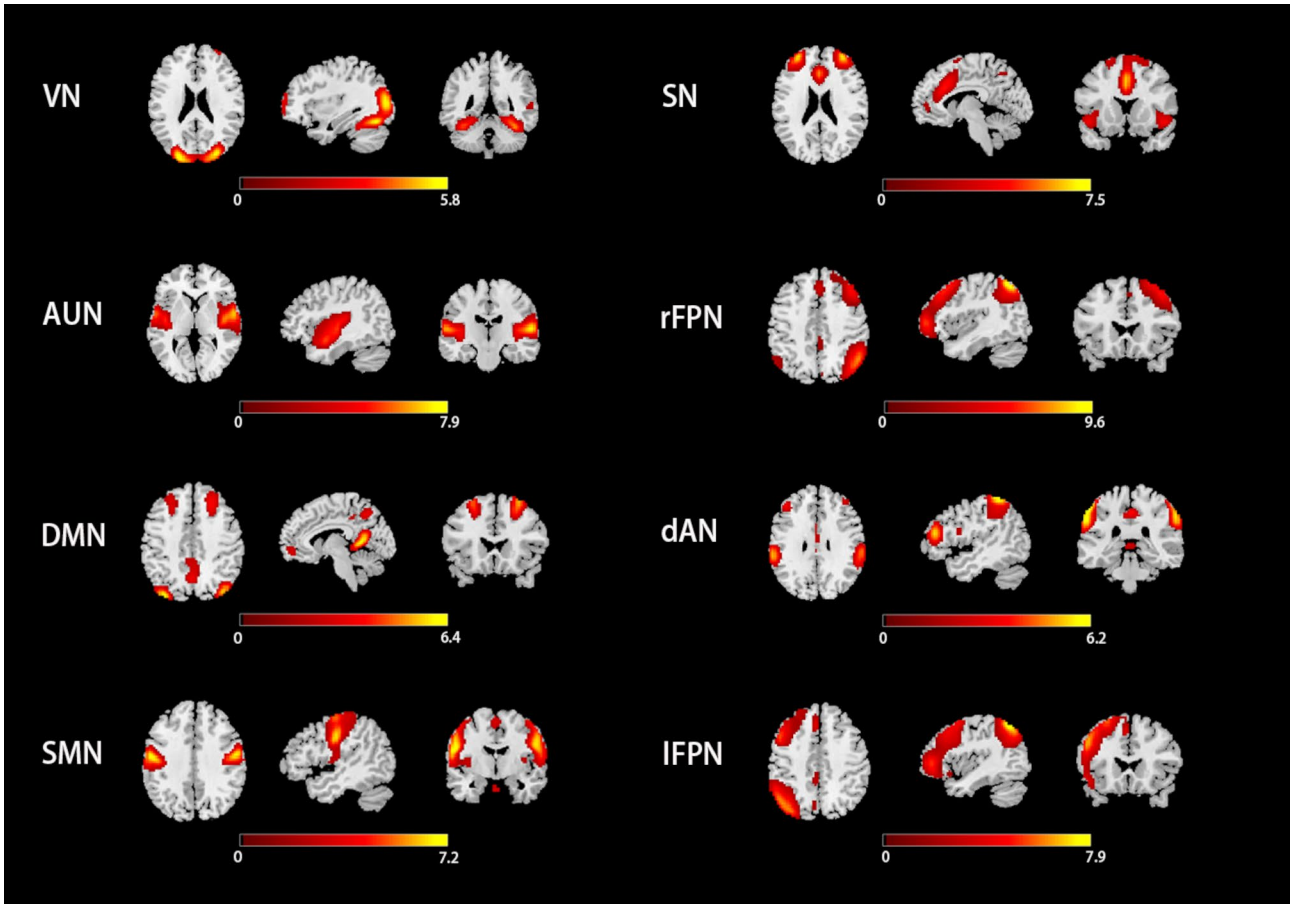

Fig. 2 Spatial maps of eight networks. Abbreviations: VN = visual network, SN = salience network, AUN = auditory network, rFPN = right right frontoparietal networks, DMN = default mode network, dAN = dorsal attention network, SMN = sensorimotor network, and lFPN = left right frontoparietal networks

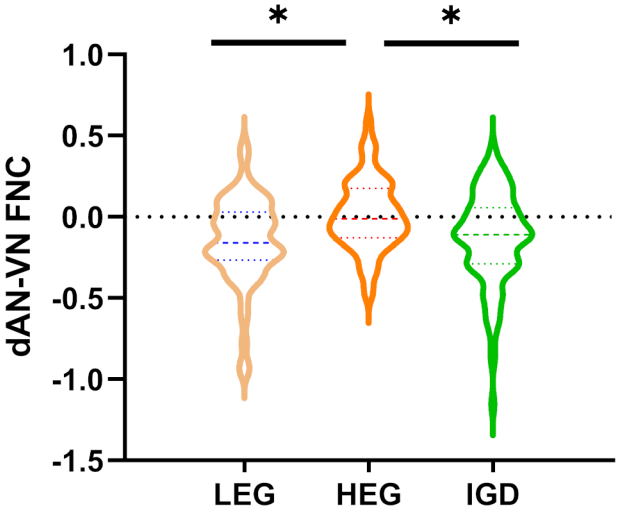

Fig. 3 Inter-network connectivity changes among the groups. Significant differences were detected among the groups in dAN-VN functional network connectivity ($p < 0.05$, FDR-corrected). Notably, the HEGs demonstrated higher dAN-VN FNC compared to both the IGDs and the LEGs ($p < 0.05$)

Correlations between FNC and the severity of IGD

Linear correlation analyses showed no significant correlation between the dAN-VN FNC values and IGD-20T scores.

Discussion

In this experiment, we examined the demographic characteristics, weekly gaming duration, IGD-20T scores, and intra- and inter-network FC among individuals with varying levels of involvement in internet gaming. It was found that the LEG group spent significantly less time gaming per week compared to the other two groups. Regarding the IGD-20T scores, a progressive decrease was observed from the IGD group to the HEG group, and then to the LEG group.

This study applied ICA to examine FC patterns across varying levels of gaming engagement, highlighting an inverted U-shaped trend in FNC between the dAN and VN as involvement progressed from low to high, culminating in addiction. Specifically, FNC initially increased and then declined, while intra-network FC remained stable. This pattern may reflect shifts in top-down

attentional control and the emergence of attentional biases as addiction progressed.

Visual network

Extensive research on addictive disorders underscores the pivotal role of the VN. For instance, studies have shown that the VN can predict post-abstinence craving levels in opioid use disorder [18]. Structural MRI data reveal reductions in VN gray matter volume among adult methamphetamine users compared to controls [19]. Similarly, significant negative correlations have been documented between intra-network FC of the VN and problematic social media and smartphone use [5]. Former heroin-dependent individuals who have abstained for over three years show diminished positive connectivity within the VN and DMN, as well as reduced negative FNC between these networks [20]. These findings collectively emphasize the VN's association with both substance and behavioral addictions. However, in this study, no significant differences in VN intra-network connectivity were observed across the groups, possibly due to the limited variation in gaming engagement among participants and the conservative multiple-comparison correction applied.

Dorsal attention network

The dAN is also integral to the pathophysiology of addictive disorders. Studies on alcohol use disorder, including both resting-state [21] and task-based [22] fMRI research, suggest that dAN plays a crucial role in addiction development and maintenance. Task-based fMRI research on IGD likewise demonstrates altered dAN activation compared to healthy controls [23]. Resting-state ICA study on IGD reports decreased intra-network connectivity in dAN's frontal eye fields and increased connectivity between the dAN and executive control network (ECN) [24].

The dAN is typically involved in top-down attentional control, modulating attentional direction in response to endogenous or exogenous cues [25], and shows sustained activity when attention is directed voluntarily to specific stimulus features [26]. Top-down attentional control is crucial in the development and progression of addictive disorders, including alcohol and tobacco dependence [27, 28]. Studies have also shown that naltrexone may help reduce addictive behaviors by modulating these attentional control mechanisms, providing potential therapeutic benefits [29]. Moreover, studies suggest that aberrant FC involving the dAN is implicated in problematic social media use [30].

FNC between the dAN and VN

Our findings indicated that as levels of gaming engagement intensify, the FNC between the dAN and the VN does not follow a straightforward linear trajectory. Rather, it exhibits an inverted U-shaped pattern, characterized by an initial increase followed by a subsequent decrease. In alignment with the neurophysiological model of attention [31, 32], the dAN orchestrates attentional orientation by modulating sensory cortical activity [26]. Within the framework of this study, we hypothesize that with escalating levels of engagement in the gaming context, the dAN may enhance visual processing through top-down interactions with the VN, thereby facilitating readiness for anticipated stimuli [33].

Scholars have noted that top-down bias signals induced by visual attention can influence neural processing in various ways. Specifically, these influences encompass: the enhancement of neural responses to stimuli of interest; the filtration of irrelevant information through the attenuation of inhibition from proximal distractors; the elevation of baseline activity in the absence of visual stimuli, thereby favoring signals directed toward salient locations; the augmentation of neuronal sensitivity to stimulus contrast, which increases the perceptual prominence of relevant stimuli [32]. We propose that these mechanisms contribute to more rapid and accurate target responses in gaming contexts, thus facilitating improved performance outcomes. Accordingly, we hypothesize that as player engagement escalates—from minimal to extensive involvement, characterized by increased time commitment and practice—the functional connectivity between the visual network and the dorsal attention network is augmented via top-down attentional control. This enhancement is expected to yield significant benefits in players' performance during gameplay.

The transition from the HEG group to the IGD group was not characterized by a continued enhancement of functional connectivity. Instead, there was a notable decrease in the connectivity between the dAN and the VN. This reduction may reflect an underlying attentional bias. Previous research has identified specific attentional processes contributing to this bias in individuals with IGD. Compared to recreational gamers, IGDs exhibit prolonged response times to addiction-related cues relative to neutral targets [34]. Our findings offer indirect corroboration of this phenomenon through fMRI. When considered alongside other results, the researchers concluded that IGD-related attention is impaired in disengaging from addiction-related stimuli, which hinders the initial deployment of attention to these stimuli [34]. This finding may also help explain our results. Furthermore, if the reduced FC between the dAN and the VN represents a specific manifestation of the transition from gaming engagement to addiction, this finding could have significant clinical implications for the diagnosis and management of IGD, given the well-established link between attentional bias and treatment outcomes in substance

use disorders [35]. However, given the current limited evidence, we approach the idea of using this connectivity reduction as a definitive biomarker for IGD with caution.

Limitations

This study has several limitations. First, most IGD participants met only 5–6 DSM-5 criteria, suggesting that the sample may lack individuals who are more severely affected, which could limit the robustness of our findings. Future studies should aim to recruit more severely affected IGD cases. Second, despite efforts to recruit participants from a variety of sources, the majority were university students, which may restrict the generalizability of the results to a broader population. Further research should focus on IGD individuals actively seeking treatment. Third, our interpretation of the results is based on existing literature. Future research could strengthen our interpretations by incorporating surveys on participants' satisfaction with their current gaming performance or their objective gaming achievements.

Conclusion

This study highlights an inverted U-shaped trend in VN-DAN connectivity across the continuum of gaming involvement, suggesting that top-down attentional modulation during the development of addiction gives way to attentional bias in the advanced stages of IGD. These findings offer valuable insights into the neural mechanisms underlying the progression of IGD, which could inform clinical strategies for early diagnosis and intervention.

Abbreviations

DSM-5	Diagnostic and statistical manual of mental disorders
IGD	Internet gaming disorder
HEG	Highly engaged gaming
LEG	Lowly engaged gaming
rs-fMRI	Resting-state functional magnetic resonance imaging
FC	Functional connectivity
dAN	Dorsal attention network
VN	Visual network
FNC	Functional network connectivity
rs-FC	Resting-state functional connectivity
ICA	Independent component analysis
IGD-20T	Internet gaming disorder-20 test
TR	Repetition time
TE	Echo time
FA	Flip angle
FOV	Field of view
SCID-5-CV	Clinician version of structured clinical interview for DSM-5
SPM12	Statistical parametric mapping
MNI	Montreal neurological institute
FWHM	Full width at half maximum
FD	Framewise displacement
GIFT	Group ICA of fMRI toolbox
PCA	Principal component analysis
MDL	Minimum description length
GUI	Graphical user interface
ICs	Independent components
CSF	Cerebrospinal fluid
RSNs	Resting-state networks
DMN	Default mode network
lFPN	Left frontoparietal networks
rFPN	Right frontoparietal networks
SN	Salience network
SMN	Sensorimotor network
AN	Auditory network

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Not applicable.

Author contributions

GG and BR were responsible for the study concept and design. GW supervised the study. JH, MZ, HZ, NT and LB contributed to the acquisition of MRI data. GG, JH, and BR assisted with data analysis and interpretation of findings. GG wrote the first draft of the manuscript. BR, LX, and GW provided critical revision of the manuscript for important intellectual content. All authors reviewed the manuscript.

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Data availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Declarations

Ethics approval and consent to participate

This study adhered to the ethical principles outlined in the Declaration of Helsinki and received approval from the Ethics Committee of Renmin Hospital of Wuhan University (approval number: WDRY2022-K090). All participants received a comprehensive explanation of the study procedures and potential risks before enrollment, and each provided written informed consent.

Consent for publication

Informed consent was obtained from all subjects involved in the study.

Competing interests

The authors declare no competing interests.

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