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Research Article

# Gender difference in network relationship between inter-temporal decisions and prefrontal activation levels in internet gaming disorder

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## Abstract

**Background:** Impulsivity and decision-making are key factors in addiction. However, little is known about how gender and time sensitivity affect impulsivity in internet gaming disorder (IGD).

**Objective:** To investigate the gender difference of impulsive decision-making and relevant brain responses in IGD.

**Methods:** We conducted a functional magnetic resonance imaging (fMRI) study with 123 participants, including 59 IGD individuals (26 females) and 64 matched recreational game users (RGUs, 23 females). Participants performed a delay-discounting task during fMRI scanning. We examined gender-by-group effects on behavioral and neural measures to explore the preference for immediate over delayed rewards and the associated brain activity. We also investigated the network correlations between addiction severity and behavioral and neural measures, and analyzed the mediating role of brain activity in the link between delay discounting parameters and IGD severity.

**Results:** We found significant gender-by-group interactions. The imaging results revealed gender-by-group interactions in the dorsolateral prefrontal cortex, medial frontal gyrus, and inferior frontal gyrus (IFG). *Post hoc* analysis indicated that, for females, RGUs showed higher activity than IGD individuals in these brain regions, while for males IGD individuals exhibited higher activity than RGUs. The activation in the left IFG mediated the relation between Internet Addiction Test score and discount rate in females. In males, the activation in the right dlPFC mediated the relation between IAT score and time sensitivity.

**Discussion:** Our findings imply that male IGD participants demonstrate impaired intertemporal decisions associated with neural dysfunction. Influencing factors for impulsive decision-making in IGD diverge between males (time sensitivity) and females (discount rate). These findings augment our comprehension of the neural underpinnings of gender differences in IGD and bear significant implications for devising effective intervention strategies for treating people with IGD.

**Keywords:** internet gaming disorder; delay discounting; discount rate; time sensitivity

## Introduction

Internet gaming disorder (IGD) refers to the phenomenon in which players cannot control their cravings for playing games, which leads to various dysfunctions (Dong and Potenza, 2014; Zheng *et al.*, 2019). Based on DSM-5 (in section 3, as a disorder that warrants further study) and the 11th Revision of the International Classification of Diseases (ICD, www.who.int) criteria, the global prevalence is estimated to range between 0.5 and 6%, which is a large group of individuals (Petry *et al.*, 2014). Current addiction theory suggests that impulsivity is a risk factor in the development and relapse of addiction (Volkow *et al.*, 2012), such as IGD, Impulsivity is broadly classified into two types: "waiting impulsivity," which refers to the preference for immediate gratification over long-term rewards, and "stopping impulsivity," which refers to motor or response dis-inhibition (Dalley *et al.*, 2011). Waiting impulsivity is characterized by rapid and unplanned responses without considering the future consequences of such behavior (Evenden, 1999), which is commonly associated with impaired cognitive control and may influence various aspects of addiction, including compulsive drug-seeking, drug-using, and relapse (Czapla *et al.*, 2016). Higher impulsivity is often associated with disadvantageous decision-making and severe symptoms of IGD (Lin *et al.*, 2015; Dong *et al.*, 2019), which may be influenced by factors such as time sensitivity and gender (Becker and Chartoff, 2019).

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In measuring "waiting impulsivity," the delayed-discounting paradigm is commonly used, involving a choice between smaller, immediately available rewards and larger rewards that are available after a delay (McHugh and Balaratnasingam, 2018). Researchers believe that this paradigm can help understand the dimensions of behavior and determine treatment targets under the Research Domain Criteria (RDoC) framework (Lempert *et al.*, 2019). Evidence suggests that higher impulsive delayed reward discounting in the paradigms can predict future engagement in addiction, such as the transition from habitual to compulsive addictive behaviors (Audrain-McGovern *et al.*, 2009; Fernie *et al.*, 2013) and relapse (MacKillop and Kahler, 2009). Studies of delayed-discounting paradigms have also been associated with the valuation, prospection, and execution control functions of the brain (Peters and Büchel, 2011). Prior meta-analyses indicate that individuals suffering from online gaming addiction exhibit higher discounting rates in monetary delayed discounting tasks (Yan *et al.*, 2021). Moreover, task-state magnetic resonance imaging (MRI) reveals heightened discounting rates in the orbitofrontal cortex (OFC) (Zhang *et al.*, 2023; Dong *et al.*, 2021c), dorsolateral prefrontal cortex (dlPFC) (Wang *et al.*, 2017a), and other regions of the prefrontal cortex during a delayed discounting task. Independent component analyses further reveal task abnormalities within the executive control system and basal ganglia network that may play a role in IGD (Wang *et al.*, 2017b; Wang et al., 2020).

However, previous research has mainly focused on immediate gratification preferences, neglecting time sensitivity in addiction (Zhang *et al.*, 2019). To fill this research gap, this study proposes to measure time sensitivity and explore its neural mechanisms. The impulsivity of humans is adjusted by time sensitivity, and at a certain point in time, there will be an obvious turn (Zeng *et al.*, 2022). For instance, patients become more impatient with options after a few weeks and show higher impulsivity than options available earlier. The constant sensitivity model, which incorporates two parameters, discount rate ($k$) and time sensitivity ($s$), can help isolate and measure the time-sensitive components of the paradigms (Ebert and Prelec, 2007). The internal clock that regulates time sensitivity is based on the dopamine system in the striatal-frontal pathway (Petter *et al.*, 2016), which also controls how future rewards are viewed based on their subjective value and is considered the hub for addictive behaviors (Picazio *et al.*, 2018). To describe the relationship between typical neural mechanism related to time sensitivity, we use network analysis from psychology science. Symptom networks (Borsboom and Cramer, 2013) are a new method of explaining the relationships between symptoms and can reveal how different symptoms interact to maintain overall disease status. This method is particularly effective when displaying cross-modal content and can control collinearity problems through partial correlation correction.

Gender differences also play a pivotal role in addictive behaviors. It has been reported that females are biologically protected from addictive behavior and addiction development (Rungnirundorn *et al.*, 2017). However, studies have shown that the prevalence of lifetime drug or alcohol abuse disorder among females in the USA is 30.4%, lower than that of males (48.3%) (Grant *et al.*, 2016). Additionally, some evidence suggests that males tend to make more impulsive decisions than females in health control, as proposed by evolutionary psychologists (Silverman, 2003). Nevertheless, findings on gender differences in inter-temporal decision-making across various substance addictions have been inconsistent. For instance, male amphetamine addicts showed higher delay discounting than females, while male alcohol-dependent individuals exhibited lower delay discounting than females (Myerson *et al.*, 2015) (Vassileva *et al.*, 2016). The neural mechanisms underlying the effects of gender have been preliminarily explored, including the frontal-striatal pathway for dopamine and serotonin, which is also related to addiction processes (Robbins *et al.*, 2019). Nonetheless, neurological evidence on gender differences in impulsivity decision-making, particularly time sensitivity, in behavioral addiction is still lacking.

This study aims to describe and explain different patterns of impulsive decision-making behavior and associated brain activation in different genders. To achieve this, we adopt a delayed-discounting paradigm and computational modeling to investigate whether gender differences affect impulsivity in behavioral addiction in a representative group of behavioral addiction (IGD group) and explore the related neural circuits. Our previous studies have demonstrated that male IGD individuals have a higher discount rate and lower activation in the inferior frontal gyrus (IFG), whereas their activation in the middle frontal gyrus (MFG) is higher than that of male recreational game users (RGUs) (Wang *et al.*, 2017c). Thus, our study proposed three main hypotheses, (i) the IGD group has a tendency to perform more impulsively in delayed discounting tasks and may be related to prefrontal activation; (ii) women have lower discounting rates and different activity in many of the brain regions involved in the delayed discounting paradigm, including the striatum and the prefrontal lobes, when compared to men; and (iii) there is an interaction between gender and group, as evidenced by the fact that in both male and female gamers parameters of the delayed discounting paradigm have a more pronounced positive correlation with specific brain region activation and the severity of online gaming addiction.

## Materials and Methods

### Participants

A total of 126 participants, who were all right-handed and had no difficulty in naming colors, were recruited through advertisements in Shanghai, China. Prior to participation, all participants were informed that their involvement was voluntary and that they could withdraw from the study at any time. Written informed consent was obtained from all participants. Three participants in the delay discounting task (DDT) have been excluded from imaging data analysis because of the large head motion, and their behavioral data were also excluded. The remaining data of 123 participants (59 IGD participants (26 females), 64 RGU (23 females)) were included in the data analysis. No significant differences in age ($P = 0.708$, $\eta^2 = 0.001$), education ($P = 0.721$, $\eta^2 = 0.001$), gender ($\chi^2$ test, $P = 0.26$) were found between the IGD and RGU groups. Significant differences were observed in Young's Internet Addiction Test (IAT) score ($F = 137.340$, $P = 0.002$, $\eta^2 = 0.508$). More details are shown in Table 1. This study was approved by the Human Investigations Committee of Hangzhou Normal University.

All participants were selected based on a modified IAT (Young, 1996), the nine-item diagnostic criteria in the DSM-5 (Petry *et al.*, 2014), time, and frequency of gaming (minimum 14 hours per week during the last 2 years). We modify all the descriptions about "network usage" in the original IAT questionnaire to "network games." The modified version IAT has been repeatedly used and proven to be appropriate for grouping in research over the past 10 years (Dong *et al.*, 2017). IGD scored higher than 50 on the modified IAT, reported more than five DSM-5 criteria as an important component of our study, and most of the time spent online is

**Table 1:** Demographics and clinical characteristics of all participants.

| | Female IGD | Female RGU | Male IGD | Male RGU | *P* value | | |
|---|---|---|---|---|---|---|---|
| | *n* = 26 | *n* = 23 | *n* = 33 | *n* = 41 | Sex | Group | Interaction |
| Demographics | | | | | | | |
| Age (year), M ± SD | 21.67 ± 1.42 | 21.45 ± 2.08 | 22.32 ± 2.61 | 22.22 ± 2.69 | 0.103 | 0.708 | 0.889 |
| Years of education, M ± SD | 14.68 ± 1.41 | 14.44 ± 2.10 | 15.05 ± 2.64 | 14.96 ± 2.64 | 0.302 | 0.721 | 0.874 |
| Clinical characteristics (M ± SD) | | | | | | | |
| IAT | 63 ± 7.87 | 45.3 ± 12.18 | 64.12 ± 11.2 | 34.6 ± 11.56 | 0.019 | <0.001 | 0.004 |
| DSM, | 5.62 ± 1.30 | 2.74 ± 1.10 | 5.8 ± 1.38 | 1.8 ± 1.47 | 0.198 | <0.001 | 0.057 |
| Gaming time (hours/week) | 16.5 ± 9.23 | 13.48 ± 7.68 | 18.40 ± 9.27 | 16.8 ± 11.41 | 0.217 | 0.274 | 0.736 |
| Gaming history (year) | 3.65 ± 0.80 | 3.52 ± 0.73 | 3.8 ± 0.56 | 3.55 ± 1.10 | 0.638 | 0.304 | 0.750 |
| craving | 53.65 ± 15.35 | 42.17 ± 17.10 | 56.93 ± 18.42 | 43.85 ± 10.43 | 0.474 | 0.001 | 0.817 |
| POMS | 66.58 ± 39.2 | 41.68 ± 32.0 | 60.94 ± 34.2 | 31.60 ± 22.37 | 0.181 | <0.001 | 0.705 |
| UCLA | 44.7 ± 10.01 | 40.35 ± 9.73 | 44.53 ± 8.05 | 38.46 ± 8.27 | 0.536 | 0.002 | 0.273 |
| SSSV | 59.15 ± 3.15 | 59.61 ± 2.92 | 52.66 ± 17.8 | 45.24 ± 24.43 | 0.001 | 0.272 | 0.215 |

Abbreviations: M, mean; SD, standard deviation; DSM, number of DSM-5 item; POMS, Profile of Mood States; UCLA, UCLA loneliness scale; SSSV, The sensation seeking scale V.

spent playing games (i.e. >80% of the online time). RGU scored lower than 50 on modified IAT, reported less than four DSM-5 criteria, and also reported no feelings of cravings or urges to play an online game, taking a "take it or leave it" attitude (Dong *et al.*, 2017). When there is inconsistency between the results supported by two scales, the DSM diagnostic suggestion will be used as the final grouping basis. All the participants also finished the University of California Loneliness Scale (UCLA) and Profile of Mood States (POMS). Craving for online games was measured by a self-report containing 10 items ranging from none at all, to a very strong sense of thirst, with a total score ranging from 0 to 100 (Dong *et al.*, 2017).

Each participant underwent the MINI-international Neuropsychiatric Interview (MINI) with an experienced psychiatrist for ∼15 minutes. Exclusion criteria also included the history of neurological diseases, brain surgery, brain injury, and mental illness (depression, schizophrenia, drug abuse, and other behavioral addiction). Depression was further assessed using the Beck Depression Scale Chinese translation II. Anyone with a score of more than five was excluded from the study. Before the scan, all participants were medication-free and did not use any substances (e.g. alcohol, nicotine, and caffeine).

## Task and procedure

The duration of DDT for each participant was ∼15 minutes. Participants first practiced 20 trials outside of the scanner to familiarize themselves with the task and then completed the DDT in the scanner. During the task, participants were required to choose between a small fixed reward immediately (10 Yuan) and a larger amount reward with a specified delay time (e.g. 12 Yuan after 7 days, $1 equal to 6.8 Yuan). The number of delayed rewards ranged from 12 to 200. The time delay varied between 6 hours, 3 days, 7 days, 30 days, and 90 days. There were for two blocks, 36 trials per block were randomly presented in E-prime v.2.0 (Psychology Software Tools).

All participants received a guaranteed 50 Yuan (∼$7) for their participation with an additional reward (ranging from 12 to 50 Yuan) depending on their choices in the task. To motivate the participants to respond thoughtfully, we use the "incentive-compatible approach" in which the experimenter randomly selects one trial in the task and compensates the participants according to their choices, either immediately or after a delay (Fig. 1A).

## Behavioral data analysis

We used both the model fit and area under the indifference curve (AUC) to calculate an individual's discount rate.

At first, the constant sensitivity (CS) model (Ebert and Prelec, 2007) have proven two parameters discount rate ($k$) and time sensitivity ($s$) of to fit DDT data in:

$$SV = A \times \exp(-(k \times d)^s) \quad (1)$$

$A$ is the amount of the delayed reward, SV is the subjective value of $A$, $d$ is the delay time (for immediate rewards, $d = 0$ and $SV = A$), and $k$ is a free parameter that indicates the steepness of the discount curve. This implies that the decline in value per day is steepest for short-term delays and gradually becomes less steep as the delays are prolonged (Kable and Glimcher, 2010). It ranges from 0 to 1, when $k$ is close to 1, the discount is steeper. A larger $k$ value indicates a stronger preference for a smaller/faster reward, in other words, more impulsivity, while a smaller $k$ value indicates a less steep (lighter) discount for the delayed reward resulting in less impulsivity. The parameter $s$ measures the time sensitivity between the delay time and subjective value in the temporal dimension. It ranges from 1 to 10, when $s << 1$, the discount of all future rewards is steeper, which means "present-future dichotomy." When $s >> 1$, the discount of all future rewards is lighter, which means all later options are discounted to a similar level. When $s = 1$, the CS model becomes the exponential model (Mazur and Coe, 1987). More details are given in the Supplementary Data.

## Imaging data analysis

Data were acquired on a 3.0-Tesla Siemens Prisma scanner with a 20-channel head coil at the Shanghai Key Laboratory of Magnetic Resonance (East China Normal University, Shanghai, China). The fMRI images were acquired using an echo-planar imaging pulse sequence with the following parameters: Repetition time = 2000 ms, echo time = 30 ms, flip angle = 90°, number of slices = 33, transverse orientation, field of view = 220 × 220 $mm^2$, matrix size = 64 × 64, slice thickness = 3 mm, and total volumes = 390. The structural images were acquired using a T1-weighted three-dimensional spoiled gradient-recalled sequence with the following parameters: repetition time = 2530 ms, echo time 2.34 ms, inversion time = flip angle = 7°, number of slices = 192, field of view = 256 × 256 $mm^2$, matrix size = 256 × 256, slice thickness = 1 mm. During the scanning, form pads were used to minimize head

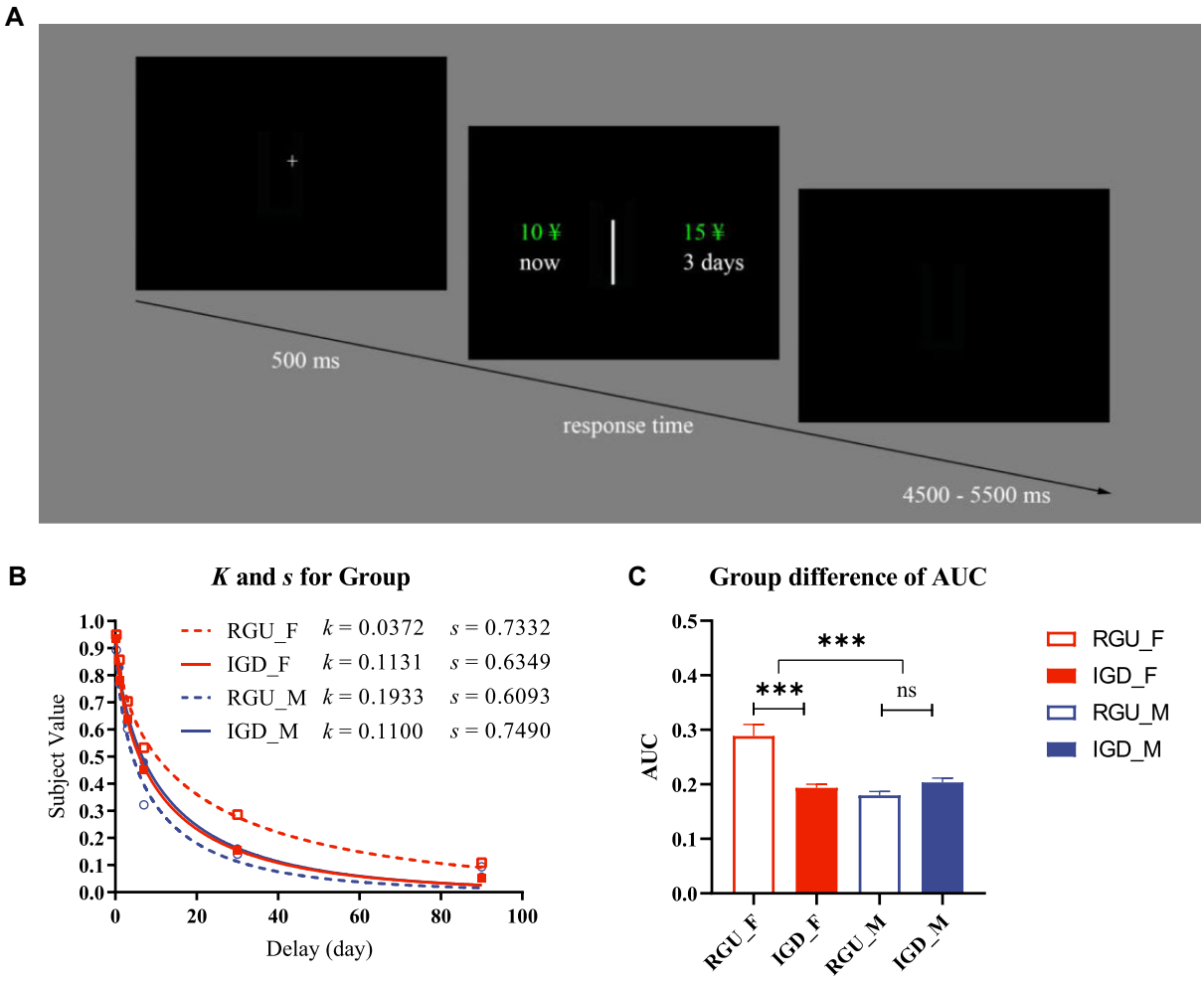


**Figure 1:** The delay discounting rate ($k$) and AUC of group and gender. (**A**) The delay discounting task produce in fMRI. (**B**) delay discounting rate for IGD Female (IGD_F), the RGU Female (RGU_F), IGD Male (IGD_M), and RGU Male (RGU_M); IGD have a higher $k$ than RGU. (**C**) The AUC for IGD_F, RGU_F, IGD_M, and RGU_M. RGU_Fs' AUC is greater than RGU_Ms (***$P < 0.001$).

motion. Stimuli were presented with SA-9900 (Sinorad Company, http://www.sinorad.com/).

Imaging was preprocessed by statistical parameter mapping (SPM12) software (Wellcome Trust Department of Cognitive Neurology, London) and consisted of correcting for slice time, being reoriented, and then carrying out realignment of the first volume. Then, T1-coregistered volumes (the alignment functional images with the anatomical images of each participant using the T1-weighted images as a reference) were normalized to an SPM T1 template. Resampled to 3 × 3 × 3 isotropic voxels, normalized to the standard Montreal Neurological (MNI) space, spatially smoothed using a 4 mm full-width at half-maximum Gaussian filter, and performed using a 1/120 Hz high-pass temporal bandpass filtering. Participants with maximum 2.5-mm head motions were excluded, three participants have been excluded from imaging data analysis because of their larger head motions.

Individual participant general linear model analysis was performed by NeuroElf v.1.1 (http://neuroelf.net). The starting point of each stimulus (choice viewing) was modeled using a $\delta$ function that was convoluted with the synthetic hemodynamic response function and modulated for the duration of the stimulus (4000 ms). The mean brain activity during the stimulus period was defined as the parameter estimate for this stimulus (image viewing) regression. Head motion parameters and a high-pass filter for 128 seconds were included as regressions of no interest.

Group random-effects analysis was performed by NeuroElf v.1.1. For choice viewing, the obtained parameter estimates for the group [IGD, HC] × gender [man, female] × choice [delay, immediate] mixed analysis of (co-) variance (A(C)NOVA), which can help us understand the main effect of group and gender, and the interaction of group and gender. Whole-brain analysis was conducted for the imaging data, and results were reported in the standard MNI space. For the follow-up whole-brain analysis, significant voxels were identified using a joint height ($P = 0.0005$) and extent ($k = 21$) (Zorlu *et al.*, 2013) threshold determined by AlphaSim, using smoothness parameters estimated from the residuals of the statistical map (8.8 mm). Despite this strict thresholding, some clusters were still very large, so subgroups containing 20 or more voxels were also reported.

## Correlation analysis

Correlation analysis between behavioral performance and brain activity was used to test our hypothesis that the correlation between IGD severity (IAT scores), log $k$/$s$ value, AUC, reaction time, and a beta value of region of interest (ROI) was calculated by Jamovi v.1.2. We defined brain regions with significant immediate and delayed group and sex interactions for ROI. For each ROI, a representative beta value is obtained by averaging the signals of all voxels within this ROI. For original significant $\alpha = 0.05$, we use

Bonferroni correction for multiple testing $\alpha' \approx \alpha/m$. For ROI with gender∗ group interactions, those that survived after multiple correlation comparisons with one of the IAT and DDT parameters (log *s* or log *r*) we incorporated further into the network analysis.

## Network construction and comparison

We used the Glasso network approach to estimate the network. We used the quickNet R package for analysis, which integrates qgraph, bootnet, and NCT. We calculated four interrelated centrality indices: strength, closeness, betweenness, and expected influence. Strength was used as the primary centrality index because it has received the most support as a stable and reliable measure of centrality. Closeness represents the reciprocal of the sum of shortest paths between a given node and other nodes. Betweenness represents the number of times a node acts as a bridge in communication processes among other nodes (i.e. how often it appears on shortest paths between pairs of other nodes). Expected influence represents the percentage of variance in a given node that can be predicted by its neighboring edges (both positive and negative). More details are provided in the Supplementary Data.

# Results

## Behavioral performance

To estimate the discounting rate (*k*) and time sensitivity (*s*) of the participants, we use the CS model. The delayed discount value (*k*) of female RGU (0.0327), female IGD (0.1131), male RGU (0.1903), and male IGD (0.1100), the time-sensitivity value (*s*) of female RGU (0.7332), female IGD (0.6349), male RGU (0.6093), and male IGD (0.7490) is well fitted the discounting function by Equation (1). For discount rate *k*, the log (*k*) of IGD (mean = −0.729 ± SD = 0.203) was significantly higher than that of the RGU ($F_{1121} = 12.269$; $P < 0.001$; $\eta^2 = 0.0092$, −0.871 ± 0.273). That indicates that the IGD discount the reward more steeply than RGU (Fig. 1B). There was not any main effect of gender in log (*k*) ($F_{1121} = 0.265$; $P = 0.607$; $\eta^2 = 0.002$). There was no interaction of group ∗ gender in log (*k*) ($F_{1121} = 2.056$; $P = 0.154$; $\eta^2 = 0.015$) (Fig. 1B). For the time-sensitivity value (*s*), there is no main effect of group ($F_{1121} = 0.006$; $P = 0.937$; $\eta^2 = 0.0001$) and gender ($F_{1121} = 1.334$; $P = 0.25$; $\eta^2 = 0.011$) (Fig. 1B). We found significant interaction of group ∗ gender in log (*s*) ($F_{1121} = 4.119$; $P = 0.045$; $\eta^2 = 0.033$). The *post hoc* did not show any simple effects.

The AUC is a simple indicator for the DDT, the two-way ANOVA (group [IGD, RGU] ∗ gender [male, female]) show a significant main effect of group ($F_{1119} = 10.9735$; $P = 0.00122$; $\eta^2 = 0.0844$), gender ($F_{1119} = 21.2760$; $P < 0.001$; $\eta^2 = 0.1517$), and interaction of group and gender ($F_{1119} = 30.5668$; $P < 0.001$; $\eta^2 = 0.2044$). AUC of IGD (0.1992 ± 0.040) was significantly smaller than that of the RGU (0.2189 ± 0.0877), AUC of the female group (0.2382 ± 0.0869) was significantly larger than that of the male group (0.1904 ± 0.0466). The *post hoc* analysis shown simple effects that the AUC in female RGU group (0.2886 ± 0.101) was significantly larger than the male RGU group (0.1798 ± 0.0459, $t_{1119} = 7.1946$, $P < 0.001$, Cohen's $d = 1.8743$), the female IGD group (0.1937 ± 0.0331, $t_{1119} = 5.7085$, $P < 0.001$, Cohen's $d = 1.6341$), and the male IGD group (0.2035 ± 0.0447, $t_{119} = 5.3924$, $P < 0.001$, Cohen's $d = 1.4647$). These results indicated the IGD discounted the rewards steeper than RGU, and the female RGU discounted the rewards steeper than male RGU (Fig. 1C) (Supplementary Table S1).

## Imaging results

### *Main effect of group*

IGD and RGU elicited a significantly different pattern of brain activations for both immediate and delayed choices (including choice immediate and delay). IGD elicited greater activates than RGU in the right medial frontal gyrus (MFG, $x = 12$, $y = 66$, $z = -3$, $k = 22$, $t = 3.805$) (Supplementary Table S2).

### *Main effect of gender*

Male and female participants show significantly different patterns of brain activation during delayed choices. Compared with female participants, male participants have larger beta value in the bilateral dlPFC, and lower beta value in several other brain regions, including regions involved in delayed choices such as the bilateral caudate, precentral gyrus, postcentral gyrus, insula, and cingulate (Supplementary Table S3).

### *Gender-by-group effects*

Brain regions identified by the group ∗ gender interactions were observed in bilateral dlPFC, bilateral MFG, left IFG, left cuneus, left middle occipital gyrus, and right lingual gyrus (Table 2). The beta values of all the regions shown gender-by-group interactions during delay choice were extracted. The female IGD was significantly lower than the female RGU, and the male IGD was significantly greater than the male RGU for all interactions' regions ($P < 0.001$) (Figs 2A and 3A). These results indicated that male and female IGD have opposite brain activates patterns.

## Correlation results

To further test the separate brain active hypothesis, the correlations analysis showed that two separate effects in the female and male groups. For the female group, the discount rate (log *k*) was positively correlated with the brain activities in left IFG ($r = 0.4255$, $P < 0.001$, Fig. 2B) after multiple correct ($\alpha' \approx \alpha/10$), and the severity (IAT score) of IGD was positively correlated with the brain activates in left IFG ($r = 0.3556$, $P < 0.05$, Fig. 2C) and log (*k*) ($r = 0.3109$, $P < 0.001$, Fig. 2D). For the male group, the time sensitivity (log *s*) was positively correlated with the brain activities in right dlPFC ($r = 0.2832$, $P < 0.05$, Fig. 3B), and the severity (IAT score) of IGD was positively correlated with the brain activates in right dlPFC ($r = 0.4182$, $P < 0.001$, Fig. 3C) and log *s*) ($r = 0.2660$, $P < 0.05$, Fig. 3D).

## Network compare

Figure 3A and B show the behavior parameters, brain activity and severity of IGD network in males and females. From the centrality index, the left IFG activity (Betweenness = 3.00, Closeness = 0.0748, Strength = 0.70, Expected Influence = 0.70) is in a central position in the male network; there is a positive connection with IAT and log *s* (Fig. 4C); dlPFC activity (Betweenness = 3.00, Closeness = 0.0529, Strength = 1.06, Expected Influence = 0.0780) is in a central position in the female network, and there is a negative connection with IAT and *r*-log (Fig. 4D). Network tables show that almost all connections have significant differences between the two groups. In the male network, most connections are significantly higher than those in the female network, especially between the log *s* and IAT scores (0.19), while only the connection between log *r* and IAT scores in the female network is significantly higher (−0.14) than that in the male

**Table 2:** Gender-by-group interaction effect in the current study.

| | MNI coordinates *x*, *y*, *z* | Voxel number | Maximum *F* | BA | |
|---|---|---|---|---|---|
| IFG | −56, 43, 3 | 121 | 29.97 | BA 45 | LH |
| **IFG** | **−60, 21, 21** | **24** | **22.01** | **BA 9** | **LH** |
| IFG | −36, 24, −12 | 23 | 17.39 | BA 47 | LH |
| MFG | −43, 29, 37 | 34 | 23.00 | BA 9 | LH |
| MFG | 48, 55, −1 | 25 | 19.51 | BA 10 | RH |
| dlPFC | −15, 17, 52 | 25 | 23.33 | BA 6 | LH |
| **dlPFC** | **26, 36, 44** | **68** | **22.18** | **BA 8** | **RH** |
| Inferior parietal lobule | 54, −57, 42 | 23 | 17.06 | BA 39 | RH |
| Cuneus | −10, −91, 6 | 31 | 21.22 | BA 17 | LH |
| Middle occipital gyrus | −49, −72, −9 | 26 | 18.81 | BA 19 | LH |
| Lingual gyrus | 18, −60, −4, | 61 | 23.41 | BA 18 | RH |

The surviving clusters that had cluster $P < 0.05$, voxel $P < 0.0005$, and voxel number >21 were reported in this table. LH, left hemisphere; RH, right hemisphere. Bold regions are two brain regions pass the following multiple correct of correlation between brain activation and behavior parameters.

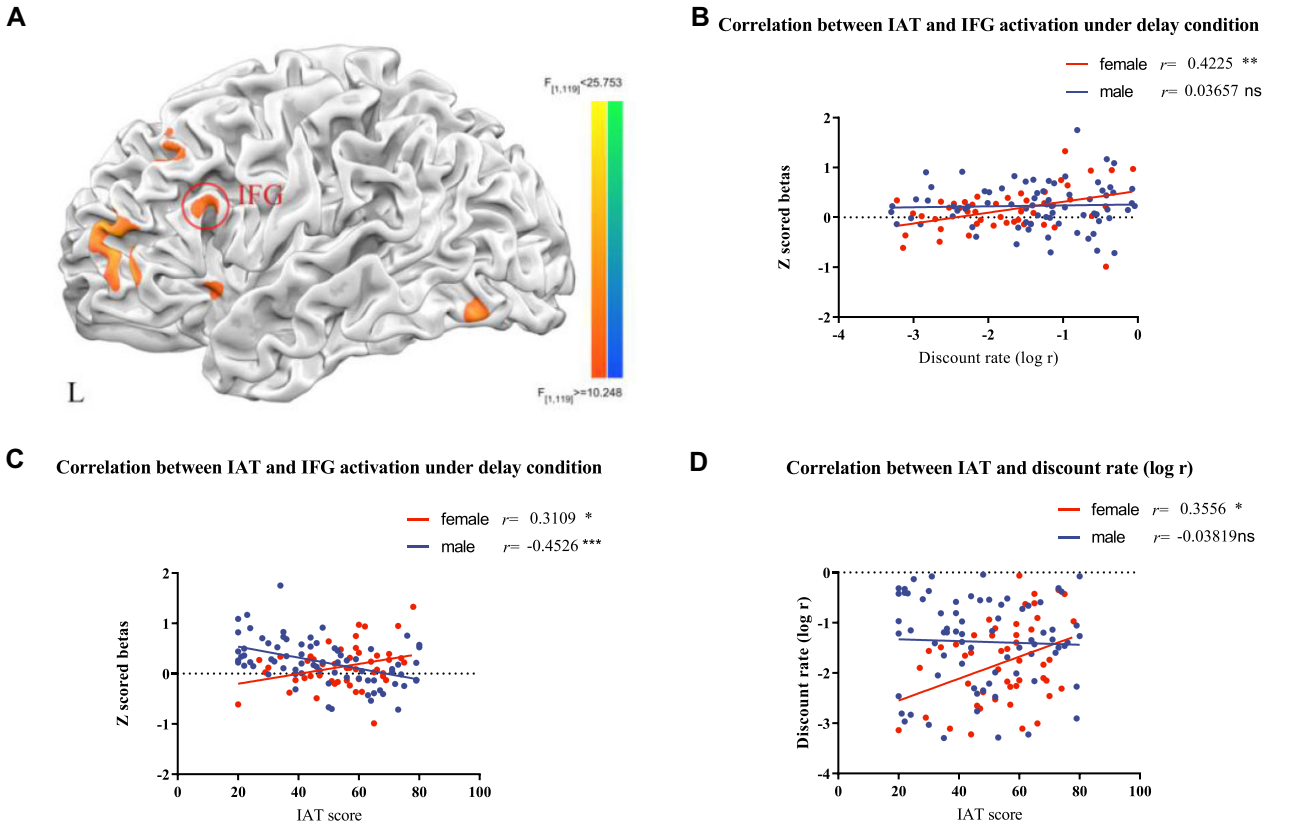


**Figure 2:** The correlation between activity of left IFG during delay choice and severity of IGD. (**A**) the activity of the left IFG (x = −60, y = 21, z = 21) of group by gender during delay choice. (**B**) The positive correlation between the activity of the left IFG and discount rate (log *r*) in females, not males. (**C**) The positive correlation between the activity of the left IFG and Young's IAT in females, and negative correlation in males. (**D**) The positive correlation between log *r* and IAT scores in females, not males (*$P < 0.01$, **$P < 0.001$, ***$P < 0.0001$).

network. These connection results can support mediation analysis again, and we present the relevant methods and processes in the Supplementary Data.

## Discussion

In this study, we used task fMRI and network analysis to explore the relationship between online game addiction and impulsive decision-making neural circuits, with a special emphasis on the role of gender. Our results were consistent with our research hypotheses: (i) IGD patients exhibited more impulsive decision-making and this was modulated by neural activity in the MFG. (ii) Women showed a higher rate of temporal discounting than men and had higher activation in the striatum and insula and lower activation in the dorsal lateral prefrontal cortex. (iii) In women, the severity of addiction was correlated with the rate of discounting and was associated with the activation of the left IFG; whereas in men, the severity of addiction was correlated with time sensitivity and was associated with the activation of the right dlPFC. These findings suggest that the neural mechanisms underlying temporal discounting in online game addiction differ between males and females.

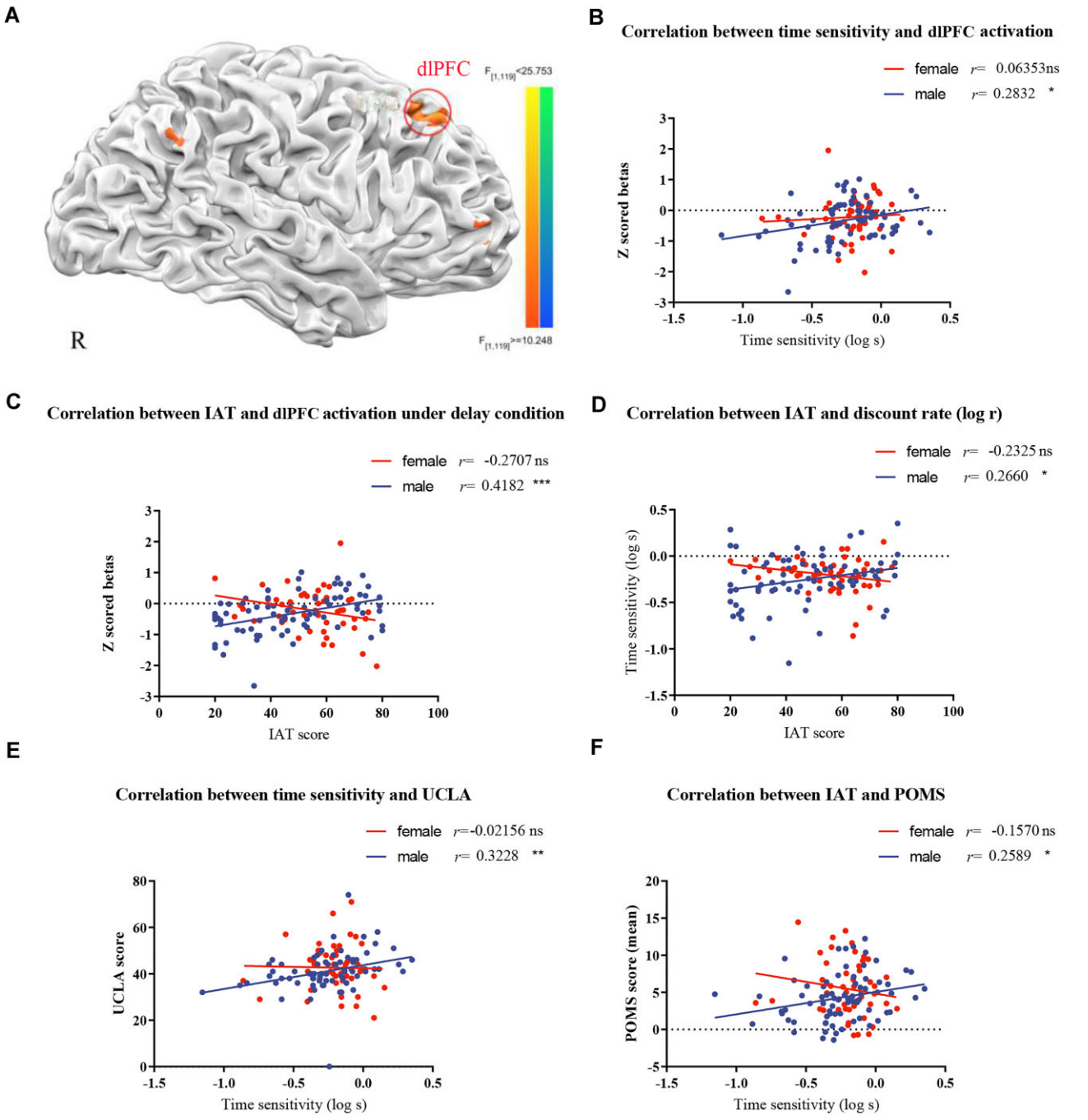


**Figure 3:** The correlation between activity of dlPFC during delay choice and severity of IGD. (**A**) The activity of the right dlPFC (x = 26, y = 36, z = 44) of group by gender during delay choice. (**B**) The positive correlation between the activity of the right dlPFC and time sensitivity (log s) in males, not females. (**C**) The positive correlation between the activity of the right dlPFC and IAT score in males, not females. (**D**) The positive correlation between log *s* and IAT scores in males, not females. (**E**) The positive correlation between UCLA scores and log *s* in males, not females. (**F**) The positive correlation between POMS scores and log *s* in males, not females (*$P < 0.01$, **$P < 0.001$, ***$P < 0.0001$).

## Group difference during delay choices

The discounting rates in IGD were significantly higher than that of RGU, which was consistent with previous research results (Wang *et al.*, 2017c). The IGD group showed a larger beta value in the right MFG during the delayed choice than RGU. Previous studies have found that IGD is associated with hypo-activation in the bilateral IFG and left dlPFC during delayed-choice tasks (Dong *et al.*, 2021a; Wang *et al.*, 2017a). The medial MFG includes the dlPFC, which was functionally connected to the MFG and medial posterior cingulate (Jasinska *et al.*, 2014), and the lateral cluster of MFG has negative functional connectivity to the dorsal anterior cingulate cortex (Val-Laillet *et al.*, 2015). These were known as the key regions of the executive control brain network (Wesley and Bickel, 2014). In the current study, the results indicate that impaired executive control networks play an important role in impulsiveness decision-making in IGD (Wang *et al.*, 2016), such as that in gambling disorder (Chamberlain *et al.*, 2017). In the meantime, the MFG has been consistently recognized as a potential target brain region for intervening in delayed discounting (Cho *et al.*, 2015).

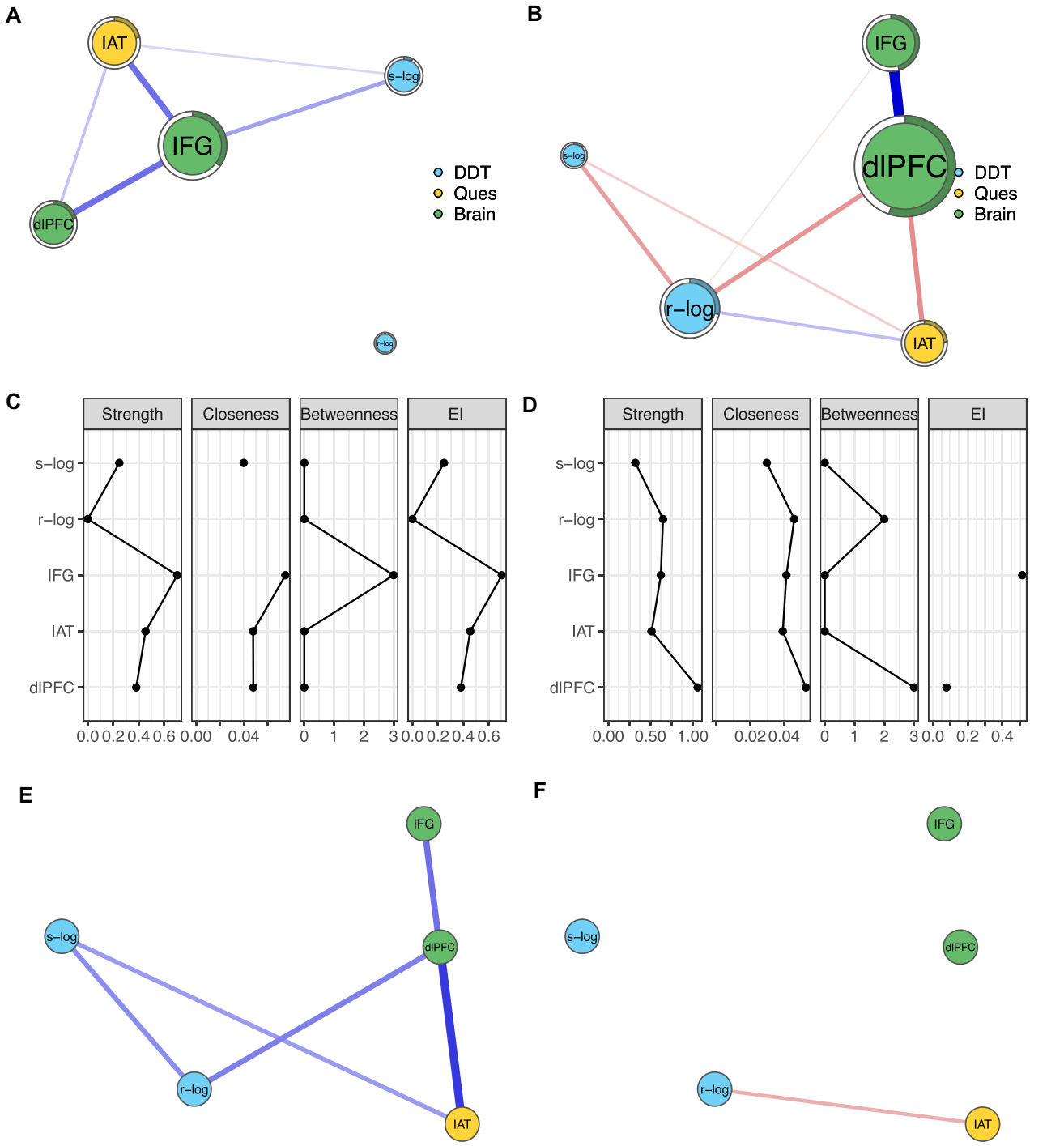


**Figure 4:** Results of symptom network construction and comparison. (**A**) Symptom network for male, nodes represent subscales while edges represent connections between them with blue indicating positive correlation and red indicating negative correlation; edge thickness represents strength of correlation; circles outside nodes represent expected influence (EI). (**B**) Symptom network for female. (**C**) Centrality for male network with points representing specific values and lines having no actual meaning. EI = Expected Influence. (**D**) Centrality for female network. (**E**) Positive edges that decreased in connection strength from male to female, represented in blue with line thickness indicating degree of change. (**F**) Negative edges that increased in connection strength from male to female, represented in red.

## Gender differences during delay choices

We observed significant gender differences in behavioral and neuroimaging results, especially the valuation network and the executive control network. First, there were hypo-activities in the bilateral caudate and thalamus for males rather than females under delay choices, suggesting that female players showed higher brain activity during reward sensory integration processing. This is also reflected in the fact that female players scored higher on the sensation seeking scale than males (Table 1). This higher brain activity and sensation seeking behavior in female players may reflect a greater sensitivity to rewards, which could contribute to their higher discount rate (Vargas *et al.*, 2019). Second, we found that, compared to males, females have hyper-activities in

bilateral IFG, MFG, dlPFC, inferior parietal lobule, superior parietal lobule, and precuneus, while there was hypo-activity in the dlPFC. These brain regions were reported to be part of the executive network, which underlies complex reasoning and working memory functions. This gender difference was also found by us in a previous cue-elicited cravings task, and dlPFC was also the node that found the existence of an interaction (Dong *et al.*, 2018). These differences in brain activity might suggest that female players have a more active executive control network, which could contribute to their less impulsive decision-making and therefore lower time sensitivity. Meanwhile, it was suggested that these cognitive functions might be necessary to optimally evaluate costs and benefits when executing many decision-making tasks (Wesley and Bickel, 2014). Gender has some protective power against the impulsivity of addiction, and significant recovery of GMV was observed in stimulant-dependent women after prolonged fasting, but not in men (Regner *et al.*, 2015). This study also showed a significant correlation between impulsivity and prefrontal gray matter volume only in women. This hypo-activity in males could be indicative of a less active executive control network, which may underlie their higher time sensitivity. In general, our results indicate that females had different brain activity patterns related to DDT from males. These differences might reflect the underlying neural mechanisms and psychological processes that contribute to the gender differences in time sensitivity and discount rate observed in IGD individuals.

## Gender-by-group effect during delayed choices

For the behavioral performance, there were group-by-gender interactions observed in both time-sensitivity and AUC during delayed choices. Females with RGU exhibited higher time-sensitivity values, which indicate a more sufficient time-sensitivity for optimal decision-making, than their male counterparts. However, in the IGD group, females had lower time-sensitivity values than males. The lower values represent insufficient time-sensitivity for optimal decision, corroborating previous studies that focused on discounting rates. The impact of impulsivity on time perception provides a possible explanation as impulsive people often display a preference for immediate rewards over delayed but larger rewards (Wittmann and Paulus, 2016). Previous research suggests that poor time perception might lead individuals to overestimate the duration of the delay time and thereby underestimate the value of the delayed reward (Wittmann and Paulus, 2008). Therefore, our results may indicate that, like substance addiction (Zhang *et al.*, 2019), behavioral addiction also affects an individual's time perception ability.

Moreover, females with RGU exhibited a higher AUC, indicative of less impulsive decision-making, than males with RGU. However, there were no gender differences in AUC among individuals with IGD. This finding suggested that in RGU, females had lower impulse decision-making than males, while the impulse decisions of females and males in IGD were comparable. Interestingly, males with more impulsive decision-making were found to be at a higher risk of developing addiction (Wang *et al.*, 2017a), and females might exhibit more impulsive decisions as a result of IGD.

In terms of brain activity during DDT, we found that males and females exhibited opposite patterns. Specifically, females with RGU had hyperactivity in several brain areas compared to those with IGD. However, males with IGD showed hyperactivity in the same areas compared to those with RGU. These findings echoed previous research suggesting that the impact of IGD on males and females may differ both in functional and structural defects (Wang *et al.*, 2019a, b).

The relationship between brain regions affected by the group-gender interaction during delay choice and the IAT score also revealed gender differences. Previous studies found gender differences in decision-making under high working memory load in substance-dependent individuals and healthy controls (Fridberg *et al.*, 2013). For instance, males tend to have higher discount rates for sexual outcomes than monetary ones during DDT, a trend not observed in females (Johnson and Bruner, 2013). Additionally, the relationship between impulsive decision-making and IGD differed between males and females. We found a positive correlation between the severity of IGD and the discount rate in females, but not in males (Fig. 2D). Other research has shown that higher impulsive decision-making in males was associated with increased risk-taking behaviors such as more cannabis use (Crane *et al.*, 2013), more caffeinated alcoholic beverage consumption (Amlung *et al.*, 2013), higher rates of sexual risk-taking (Black *et al.*, 2015), and decreased risk of alcohol abuse (Stoltenberg *et al.*, 2008) than females.

These results indicate that females and males have different behavioral performance and neurological mechanisms for IGD, and that impulsive decision-making could be a stable marker of the transformation from RGU to IGD only for males. It also implies that the sequence of impulsive decision-making and IGD on males and females may be inconsistent, and the moderating effects of resilience between behavioral inhibition/activation systems and internet addiction only emerged in females (Nam *et al.*, 2018).

## Network comparison

We observed that gender played a role in the association between addiction and impulsivity, and similar studies have found that moderated mediation effect of gender (Su *et al.*, 2019). Network analysis and the following mediation analysis revealed that the bidirectional relationship between IAT scores and discount rate (log $k$) for females was partially mediated by the connection between hyperactivations in the left IFG. Consistent with previous fMRI and transcranial magnetic stimulation studies, the left IFG is critical for value-based decision-making and is modulated explicitly in response to cues predicting devalued outcomes (Howard *et al.*, 2020). Furthermore, higher left IFG activation leads to a stronger sense of reward for addicts, driving them to seek smaller and faster rewards (Lopez *et al.*, 2014). The left IFG plays a key role in the fronto-striatal circuit involving executive control and reward information evaluation, and it is significantly related to the severity of IGD, as measured by IAT scores (Dong *et al.*, 2021b). Therefore, the left IFG may interfere with the value decision-making process of IGD by affecting its activation and making addicts have a stronger preference for smaller and faster rewards. This connection is only found in females, which may be related to the previous finding that the IFG is more activated in female IGD when making decisions than in males (Zhang *et al.*, 2020).

Furthermore, in males, the bidirectional relationship between IAT scores and time sensitivity (log $s$) was partially mediated by the connection between hyperactivations in the right dlPFC. The dlPFC is mainly involved in attention, working memory, and time perception as part of the frontostriatal loop, and more robust activation makes individuals more sensitive to time perception (Mitchell *et al.*, 2018; Wegrzyn *et al.*, 2017). After continuous rewards, participants with IGD show higher dlPFC

activations, indicating that higher dlPFC activation is associated with a higher order of severity (Dong *et al.*, 2013). This connection is only found in males, which may be because male participants have a larger beta value in the dlPFC than females and are more strongly correlated with high impulsivity (Sun *et al.*, 2019). Therefore, addiction severity affects time sensitivity by affecting the activation and function of the dlPFC in male IGD.

## Limitations

Several limitations should be acknowledged. First, the sample size of females and males is not well-balanced, with an overrepresentation of male RGUs. This imbalance has precluded a thorough examination of gender-specific changes in addiction, which warrants further investigation. Future studies should strive to recruit a more diverse and representative sample, as well as specifically probe into the differential evolution of addiction patterns across genders. Additionally, the IGD and RGU groups had different game time, which could be addressed by collecting more data or by controlling for this factor in the analysis. Second, although delay discounting is a widely used behavioral measure of time sensitivity, it is not a direct measurement of this construct. Future studies could incorporate other paradigms to directly measure time sensitivity. Third, self-reported impulsivity could provide a different perspective on cognitive impulsivity, which was not measured in this study. Fourth, paternal history of addiction was not controlled for and may have confounded our results. Finally, we did not control for the risk-taking propensity of the IGD group, which could be assessed in future studies using probabilistic delay tasks. To enhance our understanding of addiction, the research focus should incorporate more comprehensive aspects, including gender-specific changes and risk-taking propensity, in future investigations.

## Conclusion

The study found gender differences in impulsive decision-making in individuals with IGD, with females showing a higher sense of reward and males being more sensitive to time. Impulsive decision-making is a stable marker of shifting from recreational gaming use to IGD, but the influence mechanisms differ between males and females.

## Supplementary Data

Supplementary data are available at *Psychoradiology Journal* online.

## Author Contributions

Hui Zheng (Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft), Weiran Zhou (Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing), Min Wang (Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft) Hao-hao Dong (Investigation, Validation, Visualization, Writing – review & editing), Chunlei Lu (Supervision, Validation, Visualization, Writing – review & editing), Jia-lin Zhang (Resources, Software, Validation, Writing – original draft), Xue-feng Ma (Writing – original draft, Writing – review & editing), Yanbo Hu (Writing – original draft, Writing – review & editing), and Guang-Heng Dong (Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing)

## Conflict of Interest

The authors declare that no conflict of interests exist.

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## Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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