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FULL-LENGTH REPORT

# Neural mechanisms of intertemporal and risky decision-making in individuals with internet use disorder: A perspective from directed functional connectivity

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## ABSTRACT

*Background and aims:* The intertemporal and risk decision-making impairments are vital cognitive mechanisms in internet use disorder (IUD). However, the underlying neural mechanisms for these two decision-making dysfunctions in individuals with IUD remain unclear. *Methods:* This study employed Functional Near-Infrared Spectroscopy (fNIRS) to record changes in blood oxygen concentration in the prefrontal cortex of individuals with IUD during intertemporal and risk decision-making tasks. *Results:* The findings revealed that the intertemporal decision-making deficits in IUD group were primarily associated with reduced activation in the left dorsolateral prefrontal cortex (dlPFC) and orbitofrontal cortex (OFC) and FC from the left dlPFC to the right dlPFC. On the other hand, risk decision-making impairments were linked to decreased OFC activation and weakened functional connectivity from the left dlPFC to the right dlPFC and OFC. *Discussions and Conslusions:* These results suggested that while there were common neural mechanisms underlying intertemporal and risk decision-making impairments in individuals with IUD, specific neural foundations existed for each type of dysfunction.

## KEYWORDS

internet use disorder, intertemporal decision-making, risky decision-making, functional connectivity, OFC, dlPFC

## INTRODUCTION

In daily life, individuals frequently face choices such as opting to receive a smaller immediate reward or a larger delayed reward, or evaluating options with different levels of risk and making choices accordingly (Ko et al., 2017; Li, Guo, & Yu, 2019; Liu et al., 2017). The former is termed as intertemporal decision-making, and the latter is risky decision-making, both of which play pivotal roles in decision-making (Johnson, Bixter, & Luhmann, 2020). According to the Interaction of the Person-Affect-Cognition-Execution (I-PACE) model, Internet Use Disorder (IUD) has an intense relationship with their abnormalities in decision-making (Brand et al., 2019).

IUD is a pattern of behavior characterized by impaired control over internet use, increasing priority given to internet use over other activities to the extent that internet using takes precedence over other interests and daily activities, and continuation or escalation of internet using despite the occurrence of negative consequences (APA, 2013; WHO, 2017; Young, 1998). On the one hand, individuals with IUD are aware of the negative consequences

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of excessive internet use yet struggle to control their usage, displaying impulsive behavior that seeks immediate gratification while disregarding adverse outcomes - a short-sighted behavior indicating intertemporal decision-making abnormalities (Li, Jin, & Guo, 2016; MacKillop et al., 2011). On the other hand, they exhibit excessive impulsivity and insensitivity to outcome feedback. Even with numerous negative consequences from excessive internet use, they continue to indulge in it, revealing risky decision-making abnormalities (He, Zhu, Nie, & Ying, 2017; Nie, Zheng, & Zhang, 2017).

Researchers showed significant interest in studying the cognitive mechanisms of intertemporal and risky decision-making as vital underpinnings of IUD (Li et al., 2019; Liu et al., 2017). Abundant studies found that individuals with IUD tended to prefer immediate choices over delayed ones, showing deficits in delayed gratification (Cheng, Ko, Sun, & Yeh, 2021; Li, 2021; Li et al., 2016, 2019). For example, Li and her colleague found that individuals with IUD discounted delayed gains more deeply than healthy people exhibited their shortsightedness (Li et al., 2016, 2019). Moreover, a substantial body of research confirmed that individuals with IUD preferred risky options (He et al., 2017; Ko et al., 2017; Nie et al., 2017; Yao et al., 2015). For instance, Yao et al. (2015) and Nie et al. (2017) provide evidence for this statement through different paradigms (the cups task and Iowa gambling task), explaining why individuals with IUD continue internet use while there are adverse consequences.

Similar to other addiction disorders, the two types of decision-making impairments in individuals with internet use disorder both fall under motivational dysfunction, sharing certain commonalities (Gueguen, Schweitzer, & Konova, 2021; Zhou, Zhang, Li, Xue, & Zhang-James, 2020). Intertemporal and risky decision-making tasks, measuring individual impulsivity, reflect one's self-control ability (Dong & Potenza, 2014). Moreover, these two types of decision-making also involve value assessment and outcome anticipation (Berns, Laibson, & Loewenstein, 2007; Ko et al., 2017; Peters & Buchel, 2009). Researchers proposed that impairments in intertemporal and risky decision-making among individuals with IUD stemmed from abnormalities in these functions above (Brand et al., 2019; Du et al., 2018; Ko et al., 2017; Zheng et al., 2019).

On the other hand, the two types of decision-making impairments in individuals with IUD also have distinct characteristics. According to the single-process theory, intertemporal delays also carry an element of risk, making delayed and risky options somewhat analogous (Ericson, White, Laibson, & Cohen, 2015). However, despite the inherent risk in both delayed and risky options, individuals with IUD tended to lean towards the immediate option with lower risk in intertemporal decision-making rather than exhibiting risk preference, as seen in risky decision-making (Li et al., 2019; Zheng et al., 2019). This disparity stemmed from the distinct emphasis on functions in different decision tasks (Cheng et al., 2021; Cui, Ye, Sun, Zhang, & He, 2022).

Specifically, intertemporal decision-making primarily assesses an individual's ability to delay gratification, and anomalies in intertemporal decision-making among individuals with IUD might be more closely related to weaker self-control (Cheng et al., 2021; Li et al., 2019). Differently, risky decision-making is intertwined with instrumental learning, where individuals typically learn to avoid such stimuli after negative feedback from choosing risky options. However, individuals with IUD struggle with this type of learning and thus demonstrate risk preference (Ko et al., 2017; Yao et al., 2015). Furthermore, according to the dual-process theory and I-PACE model, individual decision-making is guided by two interactive systems: a reward/emotion system, which is based on associative learning, such as instrumental learning, and a cognitive control system, which is closely correlated with self-control (Brand et al., 2019; Cui et al., 2022; Li et al., 2019). Thus, impairments of the intertemporal decision-making of the IUD group might be more associated with the cognitive control system, and their risky decision-making abnormalities mainly lie in their abnormal reward/emotion system functions.

Taken together, impairments in intertemporal and risky decision-making in individuals with IUD share common characteristics and demonstrate differences, which might manifest in the neural aspect. First, dlPFC, responsible for cognitive control, is a critical brain region for these two types of decision-making (Finger et al., 2010; Ikink, Engelmann, van den Bos, Roelofs, & Figner, 2019; Tannou, Magnin, Comte, Aubry, & Joubert, 2021). Similarly, OFC, which is involved in value evaluation and outcome anticipation, also plays a vital role (Peters & Buchel, 2009; Tannou et al., 2021). Furthermore, previous studies demonstrated that impairments of these two types of decision-making in individuals with IUD were due to aberrant functions in dlPFC and OFC (Liu et al., 2017; Peters & Buchel, 2011; Qi et al., 2015; Wang et al., 2017).

Nevertheless, dlPFC and OFC might not work similarly in impairments of these two types of decision-making in individuals with IUD. The critical difference between intertemporal and risky decision-making is that the former relies on self-control, which belongs to the cognitive control system, and the latter is mainly based on instrumental learning, which is involved in the reward/emotion system. As we know, dlPFC is responsible for self-control (Finger et al., 2010; Ikink et al., 2019; Tannou et al., 2021). Functional connectivity between dlPFC and OFC is associated with instrumental learning (Han et al., 2015; Yucel & Lubman, 2007). Moreover, a transcranial direct current stimulation (tDCS) study revealed that the cognitive control system relied more on the activation of dlPFC, while the reward/emotion system on the interaction of dlPFC and OFC (Nejati, Salehinejad, & Nitsche, 2017). Thus, OFC and dlPFC are not only the common brain region of the two types of decision impairment of individuals with IUD but also might operate differently in each type of impairment.

A addiction-related research review suggested that multidimensional assessments (such as intertemporal decision-making, risky decision-making, loss aversion, and error prediction) could be valuable in differentiating sub-types within a disorder and promoting tailored interventions (Gueguen et al., 2021). Wang, Tian, Zheng, Li, and Liu (2020) classified individuals with internet gaming disorder into two sub-types based on their scores for internet addiction, loss aversion, and inhibitory control, verified the feasibility of this idea. Given the discrepancy in intertemporal and risk decision-making impairments, distinguishing different subtypes of IUD based on the performance or brain activity in these two types of decision-making might also be possible.

However, exploring the neural mechanisms underlying these two types of decision impairments, especially in functional connectivity between brain regions, are insufficient. Furthermore, Existing research has yet to compare the neural mechanisms underlying intertemporal and risky decision-making in individuals with internet use disorder, leaving unclear the specific similarities and differences in the neural bases of these two types of decision-making impairments. Therefore, thoroughly exploring and comparing the similarities and differences in intertemporal and risky decision-making among individuals with IUD is imperative.

This study targeted the OFC and dlPFC as regions of interest (ROI). The non-invasive nature, minimal individual restraint, and high tolerance for motion artifacts make functional Near-Infrared Spectroscopy (fNIRS) an ideal tool for studying cognitive and brain functional impairments (Ieong & Yuan, 2018; Yuan & Ye, 2013). Therefore, this study employed a combination of the Monetary Choice and Risky Decision-Making Task and fNIRS to compare the neural mechanisms underlying impairments in intertemporal and risky decision-making among IUD.

In addition to examining differences in activation levels within brain regions, the study utilized Granger causality values to characterize directed functional connectivity (FC) between brain regions. Granger causality analysis (GCA) depicts the potential causality and interactions between brain regions, portraying directed interactions through predictive relationships among brain region signal changes (Granger, 1969; Hu, Lam, & Yuan, 2019). Hence, compared to undirected FC analysis techniques such as Pearson correlation and wavelet coherence analysis, GCA can more precisely represent the mutual interactions between brain regions.

Research Hypothesis: In terms of behavior, individuals with IUD will exhibit greater preferences for choosing immediate and risky options compared to healthy controls (Ko et al., 2017; Li et al., 2019). Regarding brain activation levels, individuals with IUD will demonstrate reduced activation in one or more regions of interest during both tasks compared to the normal control group (Liu et al., 2017). In terms of functional connectivity, there will be abnormal functional connections between brain regions in individuals with IUD during decision-making (Han et al., 2015; Wang et al., 2016). Furthermore, while there are shared neural bases underlying impairments in intertemporal and risky decision-making in individuals with IUD, there will also be specific neural mechanisms for each type of decision-making deficit.

# METHODS

## Participants

The study employed the Internet Addiction Test (IAT) developed by Young et al. (1999) to screen participants. This questionnaire consists of 20 items, rated on a 5-point scale. Participants are required to select the option that best describes their recent situation. The Chinese version of the IAT ($\alpha$ = 0.83) and the original version ($\alpha$ = 0.91) both demonstrate adequate internal consistency (Cao, Yang, & Yang, 2010; Li et al., 2019). In this study, individuals with an IAT score above 50 were included in the experimental group (IUD Group), while those with scores below 50 were included in the healthy controls (HCs) (Li et al., 2016, 2019).

Using G*Power 3.1 with a moderate effect size of $f = 0.25$ and a statistical power of 1-$\beta$ = 0.8 as parameters, the calculation for a 2 (Group: IUD Group, HCs) $\times$ 2 (Task: Risk Decision-Making, Intertemporal Decision-Making) mixed design required a minimum sample size of $N = 34$. The survey was distributed through various channels such as QQ and WeChat, resulting in the collection of 435 questionnaires. Among these, 32 had incorrect responses in the control questions, resulting in a final collection of 403 valid questionnaires, yielding a valid response rate of 92.64%.

Based on the selection criteria mentioned earlier, 41 participants were included in the experiment. However, two participants withdrew from the experiment due to discomfort, leaving a final dataset of 39 responses. Among these, 19 participants were in the IUD group and 20 participants were in the control group. There were no significant differences in age ($t$ (39) = −1.30, $p$ = 0.203) and gender ratio ($\chi^2$ (1) = 0.67, $p$ = 0.412) between the two groups. The IUD group showed significantly higher IAT scores (74.58 ± 8.15) compared to the HCs (35.70 ± 7.04) ($t$ (39) = 15.98, $p$<0.001). All participants had normal or corrected-to-normal vision, and had no history of color blindness, color weakness, or psychiatric disorders. The experiment received ethical committee approval (Number: CCNU-IRB-202109003), and informed consent was obtained from all participants prior to the experiment. To ensure the authenticity of participants' responses, we told them before the experiment that they would be paid 30 yuan plus or minus a fluctuating amount. This amount resulted from the outcome of a random trial in the risk decision-making divided by 10 (Alvarez, Hafezi, Bonagura, Kleiman, & Konova, 2022; Konova et al., 2020).

## Monetary choice task

The present study utilized the Monetary Choice Task to assess participants' intertemporal decision-making, with the currency amount in the original task converted based on the exchange rate of 1 US dollar equals 6.39 RMB (Kirby, Petry, & Bickel, 1999). The task consisted of 27 paired-choice items grouped into nine discount levels (k1-k9), each comprising three questions. Each question presented an immediate option (e.g., receiving 354.1 RMB today) and a delayed option (e.g., receiving 351.5 RMB after 20 days), with the latter amount being higher than the former. Immediate rewards ranged from 70.3 to 511.3 RMB, while delayed rewards varied from 159.8 to 543.2 RMB, with delay intervals spanning from 1 week to 6 months.

The behavioral dependent variable for intertemporal decision-making was the delay discount rate (k), reflecting an individual's inclination to devalue delayed rewards. A lower k indicates a reduced valuation of future gains and heightened impulsivity (Nejati et al., 2017). The formula $V = A/(1+kD)$ was employed to compute k, where V denotes the subjective value, A stands for the actual value, and D signifies the delay time (Kirby, 1999). Due to the skewed original distribution, we applied a logarithm transformation to k, represented as $k_0$. An independent *t*-test was performed on $k_0$.

## Risky decision-making task

The risky decision-making task was adapted from Ko et al. (2017), containing gain and loss conditions. A risky choice and a safe choice are presented simultaneously in each trial. In the gain condition, three winning probabilities (20%, 33%, 50%) and three amounts of money (20, 30, 50 RMB) make up nine risk options. Accordingly, there are nine risk choices in the loss condition. The safe choice is a 100% gain or loss of 10 RMB.

Risky decision-making performance was assessed through the risk selection ratio, calculated as the number of risky choices divided by the total trial count. An independent *t*-test was conducted the risk selection ratio.

## Experimental procedure

Firstly, participants were guided to take their seats and provided with a brief introduction, including an overview of the tasks, the equipment used, and any relevant instructions for the experimental procedure. After this introduction, participants were informed that their task performance would impact their compensation, ensuring the authenticity of their choices. Once their agreement were obtained, participants were asked to sign the informed consent form. Next, the participants were fitted with a near-infrared electrode cap, and then check the signal quality from each channel. The experiment will commence once all channel signals meet the required standards.

The intertemporal decision-making task began after a 3-min resting data collection period. The task consists of a practice phase with 27 trials and a formal experiment divided into three blocks. Each block will comprise 81 trials, repeating the 27 questions from the task three times. In each trial, a white "+" was displayed in the center of the screen for 500 ms, followed by the simultaneous presentation of immediate and delayed options. After the participant selected, a black screen was presented for 3–5 s. After completing the intertemporal decision-making task, participants will have a 5-min rest before proceeding to the risk decision-making task.

The risk decision-making task was follow a similar pattern, beginning with a practice phase containing 18 trials before moving on to the formal experiment. In the formal experiment, the 18 combinations were randomly repeated ten times, totaling 180 trials distributed across three blocks. Each trial will start with a 500 ms display of a white "+," followed by the simultaneous appearance of the risk and safe wheel. Once participants chose, feedback was presented for 600–1000 ms, followed by a blank screen lasting 2–4 s before the subsequent trial (see Fig. 1).

## fNIRS

***fNIRS devices.*** The experiment employed the NIRSOUT near-infrared device developed by NIRX company to collect brain activity data, with a sampling rate of 7.81Hz. The setup included eight light sources and seven detectors, forming 20 channels (refer to Fig. 2). The distance between the light

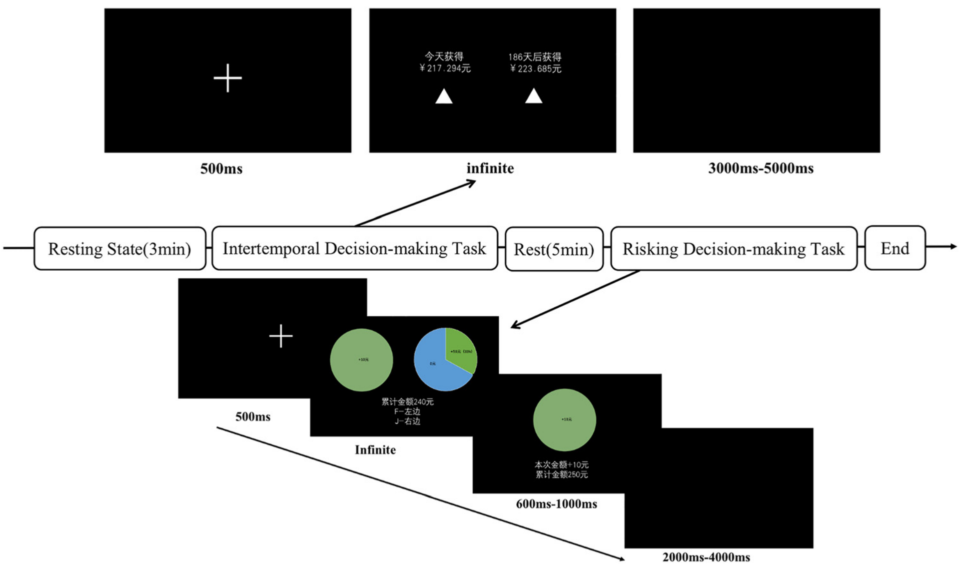


*Fig. 1.* Experimental procedure

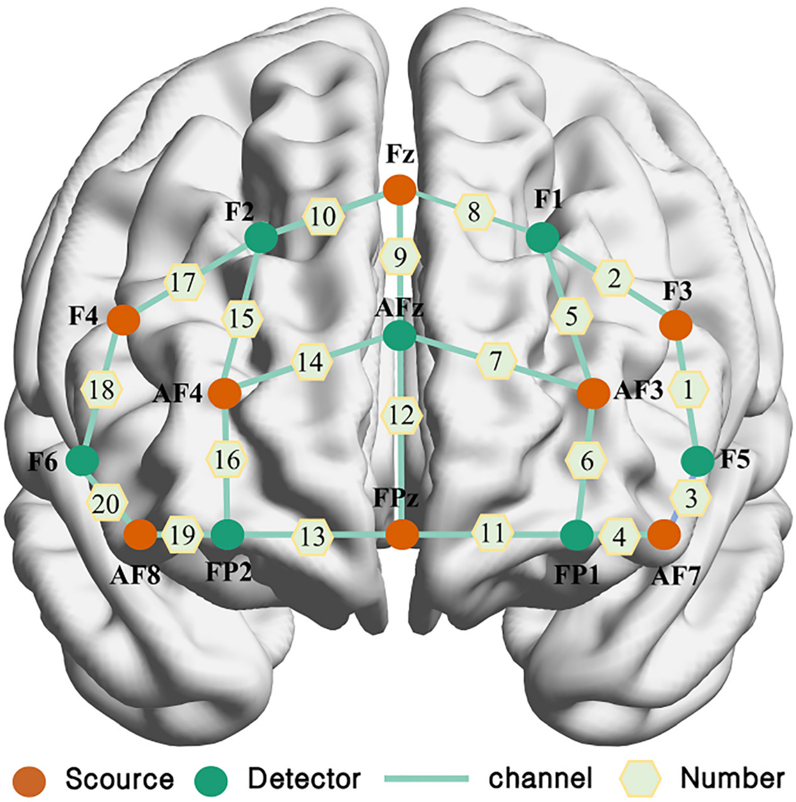


*Fig. 2.* Channel layout

sources and detectors was 3 cm. The coordinates for each optode were acquired through the NIRSite software. The average coordinates of the light sources and detectors were taken as the coordinates for each channel. The corresponding brain regions and coverage for each channel were determined using the NIRS_SPM software (Ye, Tak, Jang, Jung, & Jang, 2009).

Taking into account previous research and the corresponding Brodmann areas for each channel, the target brain regions for this study were identified as follows: the OFC (channels 4, 11, 13, 19), the left dlPFC (channels 1, 2, 3, 5), and the right dlPFC (channels 15, 17, 18, 20) (Zhang et al., 2020).

***fNIRS data processing.*** First, the near-infrared data was preprocessed using the Nirslab software. The following steps were undertaken: (1) converting raw data to optical density data; (2) replacing values from channels with a coefficient of variation (CV) greater than 15% with missing values (NA); (3) using the software's discontinuous and spike features to eliminate motion artifacts from the signals; (4) applying bandpass filtering within the frequency range of 0.01–0.2 Hz to remove physiological signals (Piper et al., 2014); (5) converting optical density signals to concentration signals for △HbO and △Hb using the modified Beer-Lambert law; (6) calculating the effect size $\beta$ values for the activation levels of each channel using the general linear model (GLM). Due to △HbO's sensitivity to brain activity, only △HbO was subjected to statistical analysis in subsequent steps (Strangman, Culver, Thompson, & Boas, 2002).

For each participant, the $\beta$ values for each channel were Fisher Z transformed, and the mean of the Z values corresponding to each ROI's channels was computed to derive the respective brain activation effect size. Independent-sample *t*-tests were conducted on the activation levels of each ROI. Permutation testing is commonly employed for multiple comparison correction. This study used the Coin package in R for precise permutation testing to reduce the risk of false positives (Hothorn, Hornik, van de Wiel, & Zeileis, 2008; Singh, Clowney, Okamoto, Cole, & Dan, 2008).

The study employed Granger causality analysis (GCA) to explore the directed functional connectivity between brain regions during tasks. Initially, the time series of brain activation for each channel during the formal experiment was standardized, subtracting the overall mean and dividing by the standard deviation at each sampling point to remove inter-channel signal differences. Subsequently, the GCA values for each channel pair were calculated using the HERMES toolbox in MATLAB (Niso et al., 2013). Similar to the calculation of ROI activation levels, Fisher Z transformation was applied to the inter-channel GCA values before computing the values for each ROI. Similar to the ROI activation analysis, statistical testing of ROI GCA values underwent permutation testing for multiple comparison corrections.

## Correlation analysis

Pearson correlation analysis was utilized to investigate the potential associations between addiction symptoms (measured by IAT scores), behavioral performance (represented by k0 or risk selection ratio), and brain activity (characterized by the $\beta$ values of △HbO or GCA values). This approach aimed to unveil potential relationships among addiction severity, behavioral tendencies, and brain responses.

### Ethics

The study was approved by the Ethics Committee of Central China Normal University, and all subjects signed informed consent before the experiment.

## RESULT

### Behavioral results

The delay discount rate of the IUD group (−3.85 ± 1.19) was higher than that of HCs (−6.02 ± 1.10) (t (37) = 5.91, $p$ < 0.001, $d$ = 1.89), indicating that compared with HCs, individuals with IUD were more inclined to choose the smaller immediate option (Fig. 3a). The frequency of choosing the risky option in the IUD group (gain: 0.65 ± 0.18; loss: 0.51 ± 0.24) was also significantly higher than that in HCs (gain: 0.52 ± 0.17; loss: 0.37 ± 0.24) (gain: t (37) = 2.31, $p$ = 0.013, $d$ = 0.74; loss: t (37) = 1.86, $p$ = 0.035, $d$ = 0.60) for both domains, suggesting that individuals with IUD preferred the risky option more than HCs (Fig. 3b and c).

### fNIRS results

The fNIRS results were displayed in Table 1. Specifically, the IUD group manifested lower activation of the OFC and left dlPFC in the intertemporal decision-making (Fig. 4a, b, and d), and less △HbO increase of the OFC in the risky decision-making, compared to HCs (Fig. 4c and e). In intertemporal decision-making, individuals with IUD displayed weaker functional connectivities (FCs) from the left dlPFC to the OFC and right dlPFC than HCs. In risky decision-making, except FCs from the left dlPFC to the OFC and right dlPFC, the FCs of individuals with IUD from the right dlPFC to the OFC reduced compared with that of HCs. Moreover, HCs exhibited positive correlations of three directed FCs mentioned above during risky decision-making, while FCs of individuals with IUD were on the contrary (Fig. 5).

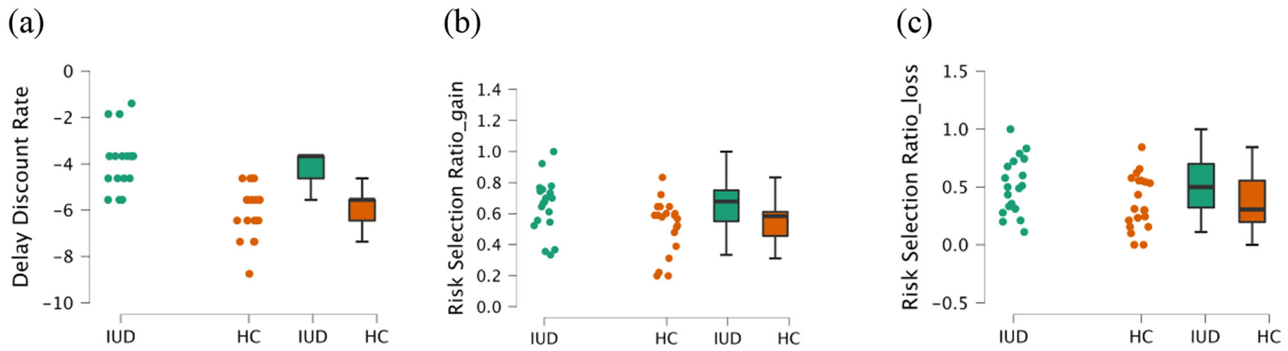


*Fig. 3.* Gorup difference in delay discount rate and risk selection ratio in two domains
*Note*: IUD indicate Internet use disorder group, HC represent healthy control.

*Table 1.* Group difference in brain activity

| | Dependent variables | HC(M±SD) | IUD (M±SD) | *t*-test |
|---|---|---|---|---|
| Intertemporal Decison-making | L-dlPFC | 58.86 ± 64.75 | −19.42 ± 41.37 | $t$ (36) = 4.38, $p$<0.001, $d$ = 1.37 |
| | OFC | 43.91 ± 67.72 | −27.12 ± 65.83 | $t$ (37) = 3.32, $p$ = 0.001, $d$ = 1.06 |
| | L-dlPFC→OFC | 0.945 ± 0.56 | 0.55 ± 0.41 | $t$ (37) = 2.56, $p$ = 0.015, $d$ = 0.82 |
| | L-dlPFC→R-dlPFC | 0.75 ± 0.50 | 0.41 ± 0.45 | $t$ (37) = 2.17, $p$ = 0.037, $d$ = 0.70 |
| Risky Decision-making | OFC | 34.09 ± 26.09 | 0.87 ± 43.45 | $t$ (37) = 2.91, $p$ = 0.005, $d$ = 0.93 |
| | L-dlPFC→OFC | 0.65 ± 0.32 | −0.44 ± 1.38 | $t$ (36) = 3.36, $p$<0.001, $d$ = 1.15 |
| | L-dlPFC→R-dlPFC | 0.61 ± 0.62 | −0.04 ± 1.22 | $t$ (37) = 2.12, $p$ = 0.039, $d$ = 0.68 |
| | R-dlPFC→OFC | 0.27 ± 0.22 | −0.24 ± 1.03 | $t$ (36) = 2.09, $p$ = 0.031, $d$ = 0.76 |

*Note*: HC: healthy control; IUD: Internet use disorder; L-dlPFC: activation in the left dlPFC; OFC: activation in the OFC; L-dlPFC→OFC: FC from the left dlPFC to the OFC; L-dlPFC→R-dlPFC: FC from the left dlPFC to the right dlPFC; R-dlPFC→OFC: FC from the right dlPFC to the OFC. In intertemporal decision-making, a singular value (absolute value of the standard score greater than three) of the activation in the left dlPFC in the IUD group was removed. In risk decision-making, a singular value was removed in the connectivity from both the left and right dlPFC to the OFC in the HC group.

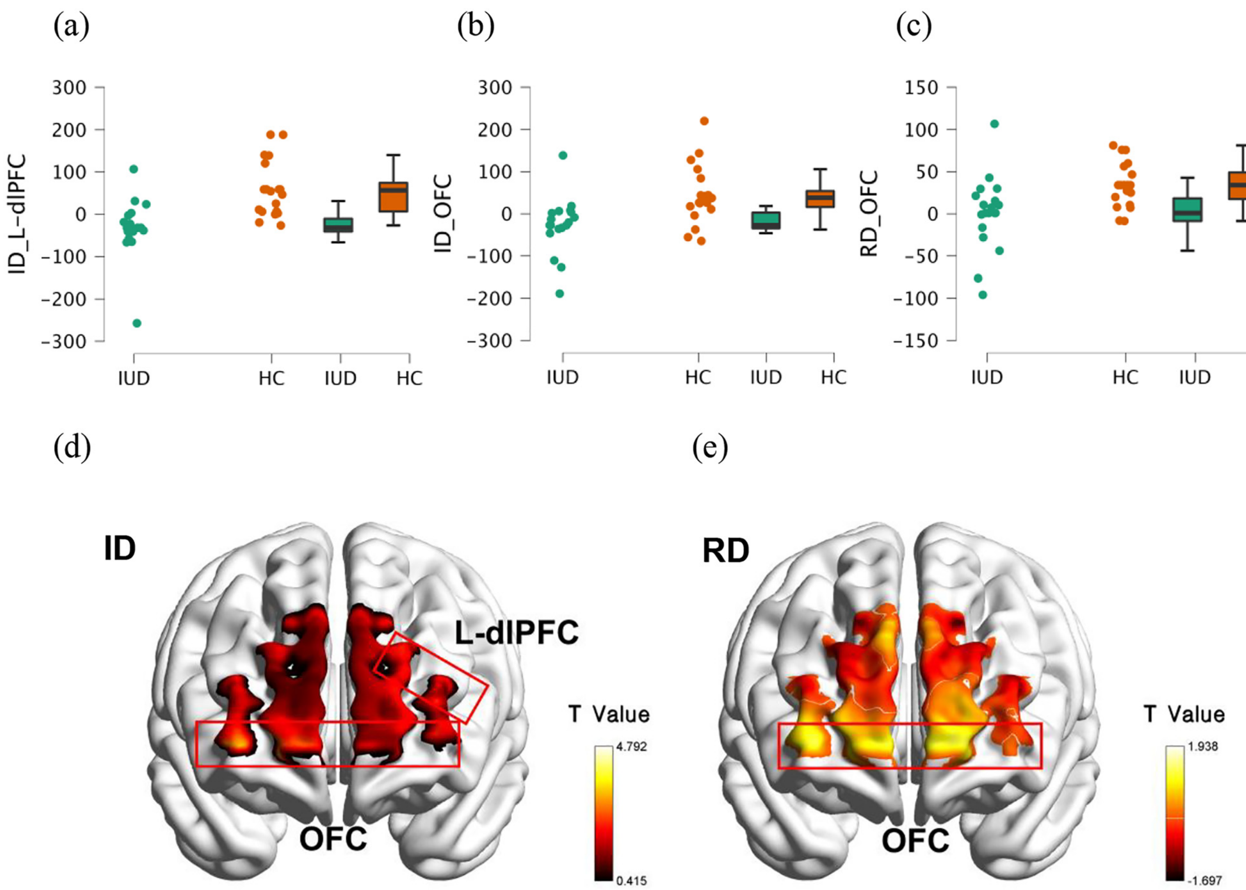


*Fig. 4.* Group difference in brain activation during intertemporal and risky decision-makings

*Note*: ID_L-dlPFC represents activation of the left dlPFC in intertemporal decision-making; ID_OFC and RD_OFC represent activation of the OFC in intertemporal and risky decision-makings; ID represents intertemporal decision-making; RD represents risky decision-making.

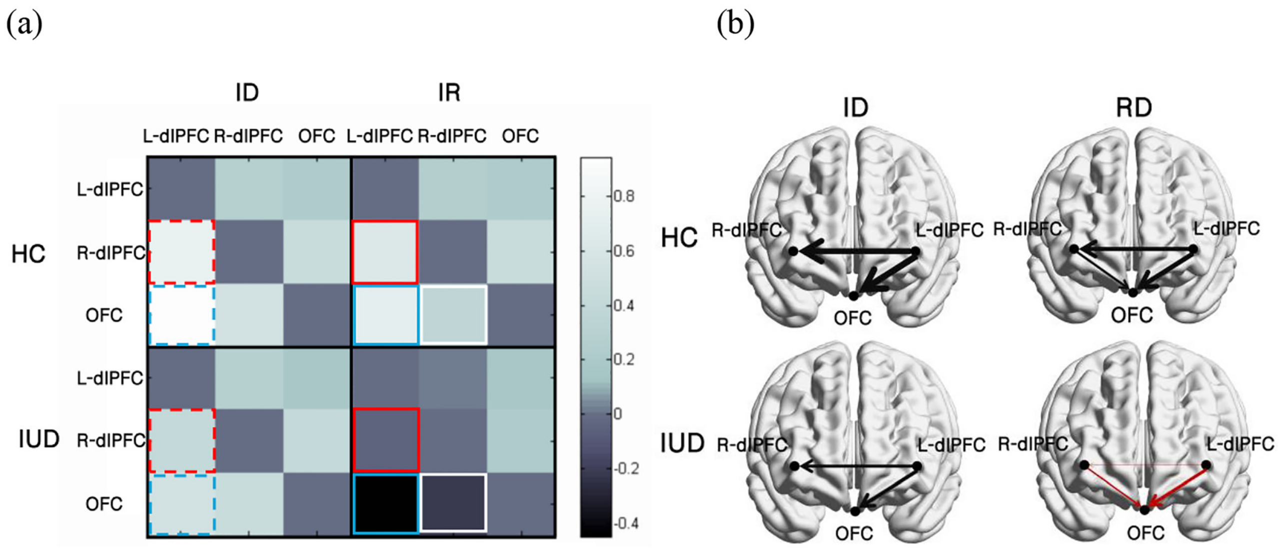


*Fig. 5.* Group difference in functional connectivity during intertemporal and risky decision-makings

*Note*: (a) The direction of FC is columns to rows. For instance, The squares in the second row of the first column represent FC from the left dlPFC to the right dlPFC. Lighter squares represent larger GCA values. FCs that differed significantly between groups have been marked with the same marks in both groups. (b) Arrows point out FC's direction. The thicker the line is, the stronger the FC. Black indicates positive FC, while red indicates negative FC.

### Correlation analysis results

In the intertemporal decision-making, the IAT score had a positive relationship with delay discount rate and negative relationships with activation in the OFC and left dlPFC and FC from the L-dlPFC to OFC. The delay discount rate negatively correlated to activation in the OFC and left dlPFC and FC from the left dlPFC to the right dlPFC (see Fig. 6a).

In the risky decision-making, the IAT score had a positive relationship with the risk selection ratio and a negative relationship with activation in the OFC. It was also positively associated with FC from bilateral dlPFC to the OFC and FC from the left dlPFC to the right dlPFC. The risk selection ratio negatively correlated to activation in OFC and FCs from the left dlPFC to the right dlPFC and OFC (see Fig. 6b).

## DISCUSSION

This study detected the activity of the PFC in individuals with IUD during intertemporal and risky decision-making through fNIRS. It aimed to explore the common or specific neural mechanisms in intertemporal and risky decision-making impairments in individuals with IUD. We compared bilateral dlPFC and OFC activation and directed FCs among these brain areas between IUD group and HCs. Correlation analysis was taken to investigate the relationship between IAT score, behavioral performance, and brain activity. Results showed that: Less activation in the OFC and reduced FC from the left dlPFC and right dlPFC were the general neural basis for the two decision-making impairments; Low activation in the left dlPFC had a more intense relationship with intertemporal decision-making impairment; Risky decision-making disorder was more reliant on the regulation of the left dlPFC to OFC.

### The neural basis in the intertemporal decision-making impairment

In line with previous research findings, individuals with IUD exhibited a greater tendency to opt for immediate choices, reflecting a weakened capacity for delayed gratification. This behavior was attributed to their compromised self-control, diminished value assessment, and altered anticipation of future outcomes (Du & Lv, 2018; Ko et al., 2017; Li et al., 2019; Nie, Zhang, Chen, & Li, 2016). The decreased activation observed in the OFC and left dlPFC in the IUD group, as compared to HCs, and its positive correlation with both IAT scores and the rate of delay discounting, validate this interpretation (Wang et al., 2017).

The left dlPFC played an executive control role in many cognitive activities, which was associated with intertemporal decision-making disorder in people addicted to cigarettes, cocaine, and alcohol (Amlung, Sweet, Acker, Brown, & MacKillop, 2012; Hayashi, Ko, Strafella, & Dagher, 2013; Wesley et al., 2014). In addition to self-control, the OFC was involved in value evaluation and future expectations (Glascher et al., 2012; Ikink et al., 2019; Peters & Buchel, 2011).

Furthermore, the reduced positive FC from the left dlPFC to the right dlPFC in the IUD group (compared to HCs) also underscored their compromised self-control (Cheng, Pan, Hu, & Hu, 2019). The correlation between this FC and behavioral performance further highlights the influence of self-control on intertemporal decision-making. The OFC served a dual role as a component of the executive system and a key player in the reward system (Ikink et al., 2019; Tang, Liu, & Yang, 2022). Consequently, the weakened FC between the left dlPFC and OFC signifies an aberrant interaction between these systems in individuals with IUD, in line with the statement of the Interaction of Person-Affect- Cognition-Execution (I-PACE) model (Brand et al., 2019).

### The neural basis in the risky decision-making impairment

The inclination of individuals with IUD toward risky choices in this study aligned with earlier research findings (Dong & Potenza, 2016; Ko et al., 2017). Generally, individuals receive negative feedback for selecting risky options. Typically, such experiences lead to a behavior change where individuals avoid risky choices, a phenomenon termed as instrumental learning. However, the unusual aspect of individuals with IUD is their persistence in choosing risky options even after encountering adverse outcomes, indicating a reduced sensitivity to reward and punishment compared to normal individuals (Han et al., 2015).

Therefore, the reduced activation of the orbitofrontal cortex (OFC) in individuals with Internet addiction may indicate their inability to effectively engage the OFC region for flexible reinforcement learning (Berlin, 2004). The underlying cause of this difference lied in the activation of the DLPFC, which consumed the top-down control resources of the OFC, manifested as a negative functional connectivity between bilateral dlPFC and OFC (Xu, Sirois, Zhang, Yu, & Feng, 2021). A comparative study involving individuals addicted to alcohol and online games also revealed a negative correlation between dlPFC and OFC during the resting state (Han et al., 2015).

Furthermore, individuals with IUD exhibited weakened FC from the L-dlPFC to the R-dlPFC, while the control group displayed positive FC from the L-dlPFC to the R-dlPFC. This outcome suggested that impaired risky decision-making in individuals with IUD was also linked to compromised executive control (Liu et al., 2017). The OFC activation level and the FC from the L-dlPFC to the right dlPFC and OFC showed a negative correlation with IAT scores and the ratio of risky choices, which provided further evidence for the explanations mentioned earlier.

### General and specific neural basis of two decision-making impairments

The study results underscored the shared neural underpinnings behind intertemporal and risky decision-making deficits in individuals with IUD, including reduced

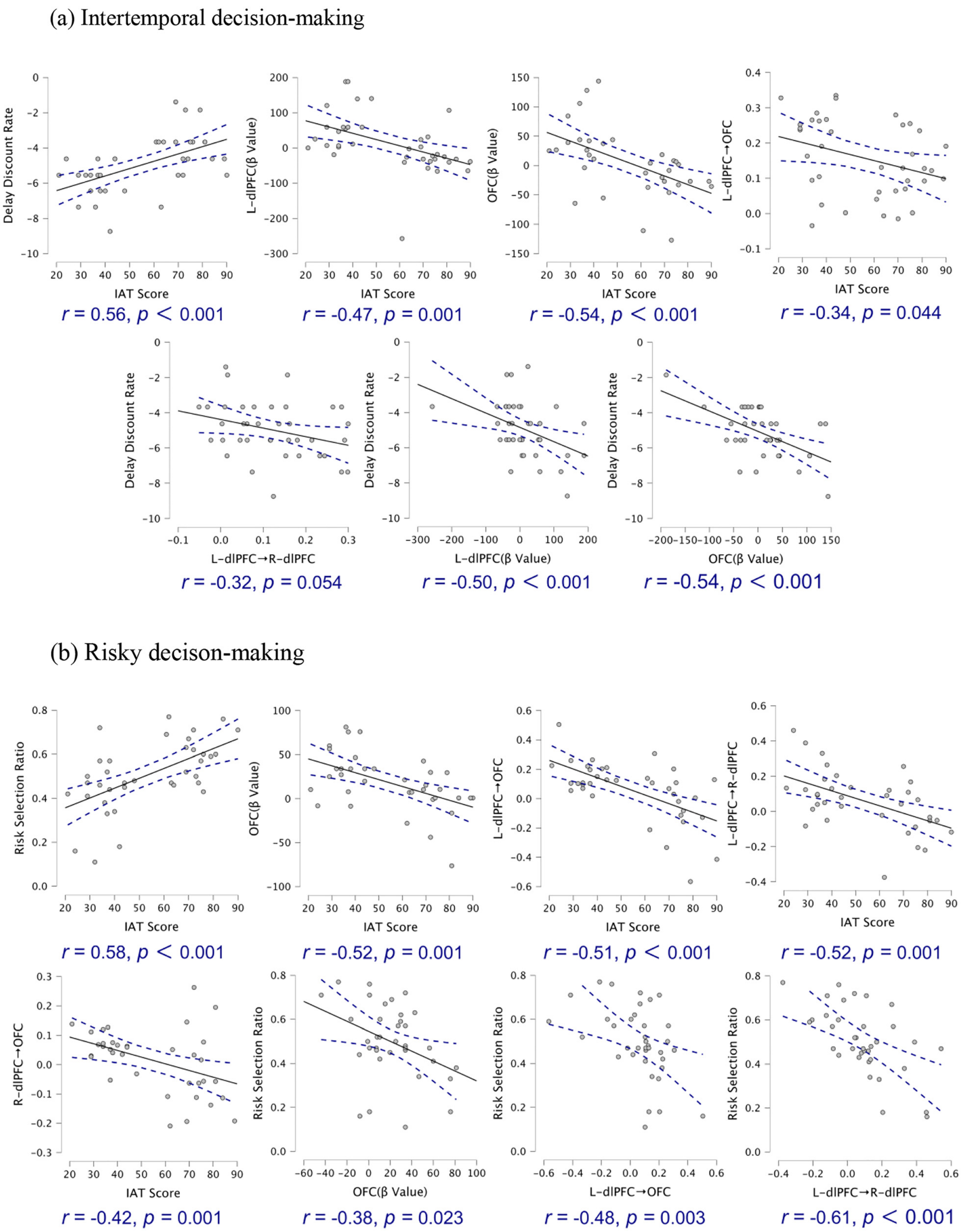


*Fig. 6.* Relationships between IAT score, brain activity and behavioral performance

*Note*: The dashed blue line represents the 95% confidence interval. The singular values were analyzed and excluded using confidence ellipse detection.

activation in the OFC and weakened FC from the left dlPFC to the right dlPFC. These outcomes corroborated earlier studies and indicated that the observed decision-making abnormalities in the IUD group were linked to compromised self-control and disrupted reward processing (Ikink et al., 2019; Tang et al., 2022). The FC patterns from the left dlPFC to other brain regions in individuals with IUD during both decision-making tasks highlighted that their impairments in intertemporal and risky decision-making were associated with the modulation of the left dlPFC with other brain areas (Han et al., 2015; Hayashi et al., 2013).

These two decision-making abnormalities also had their distinct neural underpinnings. Specifically, in the intertemporal decision-making task, individuals with Internet addiction exhibited lower activation in the OFC andL-dlPFC than HCs. However, the intergroup differences in brain activation were only evident in the risky decision-making task in the OFC. This suggested that the L-dlPFC might be a specific brain region related to the intertemporal decision-making impairment in individuals with IUD, which was more closely associated with delayed gratification (Hayashi et al., 2013). Figner et al. (2010) discovered that stimulating the L-dlPFC, rather than the R-dlPFC, led individuals to become more foresighted and make choices more oriented toward delayed outcomes. Subsequent studies validated the impact of the L-dlPFC on intertemporal decision-making within various frameworks (gain or loss) (He et al., 2016; Shen et al., 2023; Xiong et al., 2019). Moreover, the FC from the left dlPFC to the OFC was correlated with behavioral performance exclusively in the risky decision-making task, indicating that risky decision-making was more influenced by the top-down regulation from L-dlPFC to OFC, as this regulation was closely associated with instrumental learning (Han et al., 2015; Yucel & Lubman, 2007).

According to the dual-process theory and I-PACE model, individual decision-making relies on the interaction between the cognitive control system (related to self-control) and the reward/emotion system (related to associate learning) (Brand et al., 2019; Cui et al., 2022; Li et al., 2019). As mentioned before, impairments of intertemporal decision-making in individuals with IUD mainly demonstrated their reduced self-control, while risky decision-making abnormalities manifested their dysfunction in instrumental learning (Cheng et al., 2021; Ko et al., 2017; Li et al., 2019; Yao et al., 2015). Thus, their intertemporal decision-making impairment depended more on the cognitive control system, while their aberrant risky decision-making is more influenced by the reward/emotion system. There is evidence that the cold processing system relied more on the activation in the left dlPFC, while the hot processing system depended more on the interaction of the left dlPFC and OFC (Nejati et al., 2017). Therefore, the impaired intertemporal decision-making in individuals with IUD appeared to be closely related to the reduced activation of the L-dlPFC. The risky decision-making deficits might be more connected to the abnormal functional connectivity from L-dlPFC to OFC.

### Contribution and limitation

This study elucidated the neurophysiological mechanisms underlying the impairments in intertemporal and risky decision-making functions among individuals with IUD. By uncovering the similarities and differences between these two types of decision-making deficits, this research contributed to a deeper understanding of the mechanisms underlying IUD. The findings of this study had significant implications for both diagnosis and the development of intervention strategies using techniques such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS). Moreover, these results can serve as valuable indicators for assessing the effectiveness of interventions. This holds great importance for theoretical research and clinical interventions in IUD.

Indeed, there are limitations in this study. Both the intertemporal and risky decision-making tasks employed natural rewards in the form of money. However, the decision-making performance of individuals with IUD regarding money could not reflect their decision-making behavior concerning internet use and other natural rewards (Brand et al., 2019; Yang et al., 2021). Additionally, the tasks used in this study were relatively simplistic compared to the complex decision-making scenarios encountered in real life (Yang et al., 2021). Therefore, future research should explore the decision-making performance of individuals with IUD concerning addiction-related stimuli or other rewards. Incorporating a temporal dimension into risky decision-making or introducing risk factors into intertemporal decision-making could better simulate real-world decision-making contexts, thereby enhancing the ecological validity of research findings (Zhou, Li, Zhang, Li, & Liang, 2019). In addition, although previous research often used questionnaires such as the IAT to clarify the IUD group and the normal population, the IUD group recruited in this way was not a clinical sample, affecting the study's validity. In future research, employing more rigorous methods, such as diagnosing combining IAT and the criteria outlined in DSM-V and ICD-11, is advisable.

## CONCLUSION

This study investigated the brain activity of intertemporal and risky decision-making in IUD group. We found that the decision-making abnormalities of individuals of IUD were related to the activity changes in the PFC, and the neural mechanisms of the two types of decision-making impairments shared common brain mechanism and had specific neural bases. On the one hand, impairments of intertemporal and risky decision-making in individuals with IUD were related to the difficulty in investing cognitive resources to activate the OFC and reduced FC from the left dlPFC to the right dlPFC. On the other hand, intertemporal decision-making impairment in IUD group was more tightly associated with the reduced activation of the left dlPFC. The risky decision-making disorder might be more related to the abnormal FC from the left dlPFC to the OFC.

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*Conflicts of interest:* The authors have no conflict of interest to report.

*Data availability:* The raw data of this study will be made available by authors, without any reservation.

## REFERENCES

Alvarez, E. E., Hafezi, S., Bonagura, D., Kleiman, E. M., & Konova, A. B. (2022). A proof-of-concept ecological momentary assessment study of day-level dynamics in value-based decision-making in opioid addiction. *Frontiers in Psychiatry*, *13*. https://doi.org/10.3389/fpsyt.2022.817979.

Amlung, M., Sweet, L. H., Acker, J., Brown, C. L., & MacKillop, J. (2012). Dissociable brain signatures of choice conflict and immediate reward preferences in alcohol use disorders. *Addiction Biology*, *19*(4), 743–753. https://doi.org/10.1111/adb.12017.

APA (2013). *Diagnostic and statistical manual of mental disorders(DSM-5®)*. Arlington, VA: American Psychiatric Pub.

Berlin, H. A. (2004). Impulsivity, time perception, emotion and reinforcement sensitivity in patients with orbitofrontal cortex lesions. *Brain*, *127*(5), 1108–1126. https://doi.org/10.1093/brain/awh135.

Berns, G. S., Laibson, D., & Loewenstein, G. (2007). Intertemporal choice–toward an integrative framework. *Trends in Cognitive Sciences*, *11*(11), 482–488. https://doi.org/10.1016/j.tics.2007.08.011.

Brand, M., Wegmann, E., Stark, R., Müller, A., Wölfling, K., Robbins, T. W., & Potenza, M. N. (2019). The Interaction of Person-Affect-Cognition-Execution (I-PACE) model for addictive behaviors: Update, generalization to addictive behaviors beyond Internet-use disorders, and specification of the process character of addictive behaviors. *Neuroscience and Biobehavioral Reviews*, *104*, 1–10. https://doi.org/10.1016/j.neubiorev.2019.06.032.

Cao, J. Q., Yang, J. W., & Yang, J. (2010). Reliability and validity of internet addiction impairment indexes. *Chinese General Practice*, *34*, 033.

Cheng, Y.-S., Ko, H.-C., Sun, C.-K., & Yeh, P.-Y. (2021). The relationship between delay discounting and internet addiction: A systematic review and meta-analysis. *Addictive Behaviors*, *114*, 106751. https://doi.org/10.1016/j.addbeh.2020.106751.

Cheng, X., Pan, Y., Hu, Y., & Hu, Y. (2019). Coordination elicits synchronous brain activity between Co-actors: Frequency ratio matters. *Frontiers in Neuroscience*, *13*. https://doi.org/10.3389/fnins.2019.01071.

Cui, L. D., Ye, M., Sun, L. Y., Zhang, S. M., & He, G. B. (2022). Common and distinct neural correlates of intertemporal and risky decision-making: Meta-analytical evidence for the dual-system theory. *Neuroscience and Biobehavioral Reviews*, *141*(2022), 104851. https://doi.org/10.1016/j.neubiorev.2022.104851.

Dong, G., & Potenza, M. N. (2014). A cognitive-behavioral model of Internet gaming disorder: Theoretical underpinnings and clinical implications. *Journal of Psychiatric Research*, *58*, 7–11. https://doi.org/10.1016/j.jpsychires.2014.07.005.

Dong, G., & Potenza, M. N. (2016). Risk-taking and risky decision-making in Internet gaming disorder: Implications regarding online gaming in the setting of negative consequences. *Journal of Psychiatric Research*, *73*, 1–8. https://doi.org/10.1016/j.jpsychires.2015.11.011.

Du, G., & Lv, H. C. (2018). Relationship between adolescents' future expectation and internet addiction: Based on latent class analysis. *Chinese Journal of School Health*, *39*(12), 1835–1840. https://doi.org/10.16835/jcnki.1000–9817201812020.

Ericson, K. M. M., White, J. M., Laibson, D. I., & Cohen, J. D. (2015). Money earlier or later? Simple heuristics explain intertemporal choices better than delay discounting does. *Psychological Science*, *26*(6), 826–833. https://doi.org/10.1177/0956797615572232.

Figner, B., Knoch, D., Johnson, E. J., Krosch, A. R., Lisanby, S. H., Fehr, E., & Weber, E. U. (2010). Lateral prefrontal cortex and self-control in intertemporal choice. *Nature Neuroscience*, *13*(5), 538–539. https://doi.org/10.1038/nn.2516.

Glascher, J., Adolphs, R., Damasio, H., Bechara, A., Rudrauf, D., Calamia, M., … Tranel, D. (2012). Lesion mapping of cognitive control and value-based decision making in the prefrontal cortex. *Proceedings of the National Academy of Sciences*, *109*(36), 14681–14686. https://doi.org/10.1073/pnas.1206608109.

Granger, C. W. J. (1969). Investigating causal relations by econometric models and cross-spectral methods. *Econometrica*. https://doi.org/10.2307/1912791.

Gueguen, M. C., Schweitzer, E. M., & Konova, A. B. (2021). Computational theory-driven studies of reinforcement learning and decision-making in addiction: What have we learned? *Current Opinion in Behavioral Sciences*, *38*, 40–48. https://doi.org/10.1016/j.cobeha.2020.08.007.

Han, J. W., Han, D. H., Bolo, N., Kim, B., Kim, B. N., & Renshaw, P. F. (2015). Differences in functional connectivity between alcohol dependence and internet gaming disorder. *Addictive Behaviors*, *41*, 12–19. https://doi.org/10.1016/j.addbeh.2014.09.006.

Hayashi, T., Ko, J. H., Strafella, A. P., & Dagher, A. (2013). Dorsolateral prefrontal and orbitofrontal cortex interactions during self-control of cigarette craving. *Proceedings of the National Academy of Sciences*, *110*(11), 4422–4427. https://doi.org/10.1073/pnas.1212185110.

He, J. B., Zhu, P. P., Nie, Y. F., & Ying, S. Y. (2017). The influence of personality on internet addiction and its psychological mechanisms: A review. *Chinese Journal of Clinical Psychology*, *25*(2), 221–224+236. https://doi.org/10.16128/j.cnki.1005-3611.2017.02.006.

He, Q., Chen, M., Chen, C., Xue, G., Feng, T., & Bechara, A. (2016). Anodal stimulation of the left DLPFC increases IGT scores and decreases delay discounting rate in healthy males. *Frontiers in Psychology*, *7*, 1421. https://doi.org/10.3389/fpsyg.2016.01421.

Hothorn, T., Hornik, K., van de Wiel, M. A., & Zeileis, A. (2008). Implementing a class of permutation tests: The coin package. *Journal of Statistical Software*, *28*(8), 1–23.

Hu, Z. S., Lam, K. F., & Yuan, Z. (2019). Effective connectivity of the fronto-parietal network during the tangram task in a natural environment. *Neuroscience*, *422*, 202–211. https://doi.org/10.1016/j.neuroscience.2019.09.021.

Ieong, H. F., & Yuan, Z. (2018). Emotion recognition and its relation to prefrontal function and network in heroin plus nicotine dependence: A pilot study. *Neurophotonics*, *5*, 1. https://doi.org/10.1117/1.NPh.5.2.025011.

Ikink, I., Engelmann, J. B., van den Bos, W., Roelofs, K., & Figner, B. (2019). Time ambiguity during intertemporal decision-making is aversive, impacting choice and neural value coding. *NeuroImage*, *185*, 236–244. https://doi.org/10.1016/j.neuroimage.2018.10.008.

Johnson, K. L., Bixter, M. T., & Luhmann, C. C. (2020). Delay discounting and risky choice: Meta-analytic evidence regarding single-process theories. *Judgment and Decision Making*, *15*(3), 381–400. https://doi.org/10.1017/S193029750000718X.

Kirby, K. N., Petry, N. M., & Bickel, W. K. (1999). Heroin addicts have higher discount rates for delayed rewards than non-drug-using controls. *Journal of Experimental Psychology: General*, *128*(1), 78–87. https://doi.org/10.1037/0096-3445.128.1.78.

Ko, C.-H., Wang, P.-W., Liu, T.-L., Chen, C.-S., Yen, C.-F., & Yen, J.-Y. (2017). The adaptive decision-making, risky decision, and decision-making style of Internet gaming disorder. *European Psychiatry*, *44*, 189–197. https://doi.org/10.1016/j.eurpsy.2017.05.020.

Konova, A. B., Lopez-Guzman, S., Urmanche, A., Ross, S., Louie, K., Rotrosen, J., & Glimcher, P. W. (2020). Computational markers of risky decision-making for identification of temporal windows of vulnerability to opioid use in a real-world clinical setting. *JAMA Psychiatry*, *77*(4), 368–377. https://doi.org/10.1016/j.cobeha.2020.08.007.

Li, H. X. (2021). Working memory depletion affects intertemporal choice among internet addicts and healthy controls. *Frontiers in Psychology*, 675059. https://doi.org/10.3389/fpsyg.2021.675059.

Li, H. X., Guo, Y. F., & Yu, Q. L. (2019). Self-control makes the difference: The psychological mechanism of dual processing model on internet addicts' unusual behavior in intertemporal choice. *Computers in Human Behavior*, *101*, 95–103. https://doi.org/10.1016/j.chb.2019.07.010.

Li, H. X., Jin, S. H., & Guo, Y. F. (2016). How do construal levels affect the intertemporal choices of Internet addicts. *Computers in Human Behavior*, *60*(2016), 173–178. https://doi.org/10.1016/j.chb.2016.02.016.

Liu, L., Xue, G., Potenza, M. N., Zhang, J.-T., Yao, Y.-W., Xia, C.-C., … Fang, X.-Y. (2017). Dissociable neural processes during risky decision-making in individuals with Internet-gaming disorder. *NeuroImage: Clinical*, *14*, 741–749. https://doi.org/10.1016/j.nicl.2017.03.010.

MacKillop, J., Amlung, M. T., Few, L. R., Ray, L. A., Sweet, L. H., & Munafò, M. R. (2011). Delayed reward discounting and addictive behavior: A meta-analysis. *Psychopharmacology*, *216*(3), 305–321. https://doi.org/10.1007/s00213-011-2229-0.

Nejati, V., Salehinejad, M. A., & Nitsche, M. A. (2017). Interaction of the left dorsolateral prefrontal cortex (l-DLPFC) and right orbitofrontal cortex (OFC) in hot and cold executive functions: Evidence from transcranial direct current stimulation (tDCS). *Neuroscience*, *10*(42). https://doi.org/10.1016/j.neuroscience.2017.10.042.

Nie, J., Zhang, W., Chen, J., & Li, W. (2016). Impaired inhibition and working memory in response to internet-related words among adolescents with internet addiction: A comparison with attention-deficit/hyperactivity disorder. *Psychiatry research*, *236*, 28–34. http://dx.doi.org/10.1016/j.psychres.2016.01.004.

Nie, J., Zheng, L. N., & Zhang, W. (2017). Impact of risk situation with rewards and punishment on decision-making in internet addicts. *Chinese Journal of Clinical Psychology*, *24*(4), 601–604+617. https://doi.org/10.16128/j.cnki.1005-3611.2016.04.005.

Niso, G., Bruña, R., Pereda, E., Gutiérrez, R., Bajo, R., Maestú, F., & Del-Pozo, F. (2013). HERMES: towards an integrated toolbox to characterize functional and effective brain connectivity. *Neuroinformatics*, *11*, 405–434. https://doi.org/10.1007/s12021-013-9186-1.

Peters, J., & Buchel, C. (2009). Overlapping and distinct neural systems code for subjective value during intertemporal and risky decision making. *Journal of Neuroscience*, *29*(50), 15727–15734. https://doi.org/10.1523/JNEUROSCI.3489-09.2009.

Peters, J., & Buchel, C. (2011). The neural mechanisms of inter-temporal decision- making: Understanding variability. *Trends in Cognitive Sciences*, *15*, 227–239. https://doi.org/10.1016/j.tics.2011.03.002.

Piper, S. K., Krueger, A., Koch, S. P., Mehnert, J., Habermehl, C., Steinbrink, J., … Schmitz, C. H. (2014). A wearable multi-channel fNIRS system for brain imaging in freely moving subjects. *Neuroimage*, *85*, 64–71. https://doi.org/10.1016/j.neuroimage.2013.06.062.

Qi, X., Du, X., Yang, Y., Du, G., Gao, P., Zhang, Y., … Zhang, Q. (2015). Decreased modulation by the risk level on the brain activation during decision making in adolescents with internet gaming disorder. *Frontiers in Behavioral Neuroscience*, 00296. https://doi.org/10.3389/fnbeh.2015.00296.

Shen, B., Yin, Y., Wang, J., Zhou, X., McClure, S. M., & Li, J. (2023). High-defifinition tDCS alters impulsivity in a baseline-dependent manner. *Neuroimage*, *143*, 343–352. https://doi.org/10.1016/j.neuroimage.2016.09.006.

Singh, A. K., Clowney, L., Okamoto, M., Cole, J. B., & Dan, I. (2008). Scope of resampling-based tests in fnirs neuroimaging data analysis. *Stata Sinica*, *18*(4), 1519–1534.

Strangman, G., Culver, J. P., Thompson, J. H., & Boas, D. A. (2002). A quantitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activation. *Neuroimage*, *17*, 719–731. https://doi.org/10.1006/nimg.2002.1227.

Tang, L., Liu, Y. L., & Yang, Y. K. (2022). The cognitive processes and neural bases of prosocial behavior. *Psychological Development and Education*, *38*(3), 437–446. https://doi.org/10.16187/j.cnki.issn1001-4918.2022.03.15.

Tannou, T., Magnin, E., Comte, A., Aubry, R., & Joubert, S. (2021). Neural activation in risky decision-making tasks in healthy older adults: A meta-analysis of fMRI data. *Brain Sciences*, *11*(8), 1043. https://doi.org/10.3390/brainsci11081043.

Wang, Y., Hu, Y., Xu, J., Zhou, H., Lin, X., Du, X., & Dong, G. (2017). Dysfunctional prefrontal function is associated with impulsivity in people with internet gaming disorder during a delay discounting task. *Frontiers in Psychiatry*, *8*, 287. https://doi.org/10.3389/fpsyt.2017.00287.

Wang, L. X., Tian, M. Q., Zheng, Y., Li, Q., & Liu, X. (2020). Reduced loss aversion and inhibitory control in adolescents with internet gaming disorder. *Psychology of Addictive Behaviors*, *34*(3). https://doi.org/10.1037/adb0000549.

Wang, Y., Wu, L., Zhou, H., Lin, X., Zhang, Y., Du, X., & Dong, G. (2016). Impaired executive control and reward circuit in internet gaming addicts under a delay discounting task: Independent component analysis. *European Archives of Psychiatry and Clinical Neuroscience*, *267*(3), 245–255. https://doi.org/10.1007/s00406-016-0721-6.

Wesley, M. J., Lohrenz, T., Koffarnus, M. N., McClure, S. M., De La Garza, R., Salas, R., … Montague, P. R. (2014). Choosing money over drugs: The neural underpinnings of difficult choice in chronic cocaine users. *Journal of Addiction*, *2014*, 1–14. https://doi.org/10.1155/2014/189853.

WHO (2017). *ICD-11 Beta Draft - mortality and morbidity statistics*. [Internet]. Available from: http://id.who.int/icd/entity/1448597234.

Xiong, G., Li, X., Dong, Z., Cai, S., Huang, J., & Li, Q. (2019). Modulating activity in the prefrontal cortex changes intertemporal choice for loss: A transcranial direct current stimulation study. *Frontiers in Human Neuroscience*, 00167. https://doi.org/10.3389/fnhum.2019.00167.

Xu, T., Sirois, F. M., Zhang, L., Yu, Z., & Feng, T. (2021). Neural basis responsible for self-control association with procrastination: Right MFC and bilateral OFC functional connectivity with left dlPFC. *Journal of Research in Personality*, *91*, 104064. https://doi.org/10.1016/j.jrp.2021.104064.

Yang, L., Zhang, Y., Zhang, J. X., Liu, P. C., Yang, Y. H., Liu, W. X., & Chen, K. L. (2021). The promotion effect of monetary reward on the updating function of working memory of heroin abstainers is weakened. *Journal of Psychological Science*, *44*(2), 391–397. https://doi.org/10.16719/j.cnki.1671-6981.20210219.

Yao, Y. W., Wang, L. J., Yip, S. W., Chen, P.-R., Li, S., Xu, J., … Fang, X. Y. (2015). Impaired decision-making under risk is associated with gaming-specific inhibition deficits among college students with Internet gaming disorder. *Psychiatry Research*, *229*(1–2), 302–309. https://doi.org/10.1016/j.psychres.2015.07.004.

Ye, J. C., Tak, S. H., Jang, K. E., Jung, J. W., & Jang, J. D. (2009). NIRS-SPM: Statistical parametric mapping for near-infrared spectroscopy. *Neuroimage*, *44*, 428–447. https://doi.org/10.1016/j.neuroimage.2008.08.036.

Young, K. S. (1998). Internet addiction: The emergence of a new clinical disorder. *Cyber Psychology & Behavior*, *1*(3), 237–244.

Yuan, Z., & Ye, J. (2013). Fusion of fNIRS and fMRI data: Identifying when and where hemodynamic signals are changing in human brains. *Frontiers in Human Neuroscience*, *7*. https://doi.org/10.3389/fnhum.2013.00676.

Yucel, M., & Lubman, D. I. (2007). Neurocognitive and neuroimaging evidence of behavioural dysregulation in human drug addiction: Implications for diagnosis, treatment and prevention. *Drug and Alcohol Review*, *26*, 33–39. https://doi.org/10.1080/09595230601036978.

Zhang, D. D., Wang, J., Zhao, J., Chen, S. M., Huang, D. L., & Gao, Q. F. (2020). Impact of depression on cooperation: An fNIRS hyperscanning study. *Acta Psychologica Sinica*, *52*(5), 609–622. https://doi.org/10.3724/SP.J.1041.2020.00609.

Zheng, H., Hu, Y., Wang, Z., Wang, M., Du, X., & Dong, G. (2019). Meta-analyses of the functional neural alterations in subjects with Internet gaming disorder: Similarities and differences across different paradigms. *Progress in Neuro-Psychopharmacology and Biological Psychiatry*, 109656. https://doi.org/10.1016/j.pnpbp.2019.109656.

Zhou, L., Li, A. M., Zhang, L., Li, S., & Liang, Z. Y. (2019). Similarity in processes of risky choice and intertemporal choice: The case of certainty effect and immediacy effect. *Acta Psychologica Sinica*, *51*(3), 337–352. https://doi.org/10.3724/SP.J.1041.2019.00337.

Zhou, B., Zhang, W., Li, Y., Xue, J., & Zhang-James, Y. (2020). Motivational but not executive dysfunction in attention deficit/hyperactivity disorder predicts internet addiction: Evidence from a longitudinal study. *Psychiatry Research*, *285*, 112814. https://doi.org/10.1016/j.psychres.2020.112814.