Original article

Dysfunctional default mode network and executive control network in people with Internet gaming disorder: Independent component analysis under a probability discounting task

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ABSTRACT

Background: The present study identified the neural mechanism of risky decision-making in Internet gaming disorder (IGD) under a probability discounting task.

Methods: Independent component analysis was used on the functional magnetic resonance imaging data from 19 IGD subjects (22.2 ± 3.08 years) and 21 healthy controls (HC, 22.8 ± 3.5 years).

Results: For the behavioral results, IGD subjects prefer the risky to the fixed options and showed shorter reaction time compared to HC. For the imaging results, the IGD subjects showed higher task-related activity in default mode network (DMN) and less engagement in the executive control network (ECN) than HC when making the risky decisions. Also, we found the activities of DMN correlate negatively with the reaction time and the ECN correlate positively with the probability discounting rates.

Conclusions: The results suggest that people with IGD show altered modulation in DMN and deficit in executive control function, which might be the reason for why the IGD subjects continue to play online games despite the potential negative consequences.

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1. Introduction

Internet gaming disorder (IGD) has increasingly raised widespread public health concerns and has been the spotlight of scientific research [1–3]. In 2013, the DSM-5 committee generated criteria for IGD. The IGD has been included in the section III of the DSM-5 [4,5]. Although there are no monetary rewards in IGD, it is similar to pathological gambling on the psychological, behavioral, and conceptual levels, and thus is also considered as problematic [6]. Given the similarities between IGD and pathological gambling, IGD has been regarded as a non-financial form of pathological gambling [7]. Previous studies demonstrated that subjects with IGD have higher rates of irritability, lower mood and more social, financial, marital, and/or professional difficulties than a control group without IGD [8]. Additionally, adolescents with IGD showed higher social phobias, anxiety, and depression, and poorer school performance than healthy controls (HC) [9].

IGD may share characteristics with substance use disorder and the clinical presentations of IGD resemble the symptoms of substance use disorder [10]. Previous studies have indicated that subjects with substance use disorders or pathological gambling problems showed higher impulsivity and had deficit in decision-making. In particular, they were prone to choose greater propensity for risk-taking under a risk decision circumstance than controls without any addictions [11–14]. Analogously, we infer that subjects with IGD would show an elevated level impulsivity, and impairments in decision-making. The present study is set to explore the features of risky decision-making in IGD.

Probability discounting (PD) is a paradigm to examine the decision-making features under risky circumstances. It measures the trade-off between probabilities and reward magnitudes. In PD task, participants are provided with a choice between a large amount of money with a low probability of acquisition and a small amount of money with a high and fixed probability of acquisition. Choosing the larger amount of money with lower probability of acquisition indicate greater subjective value for probabilistic rewards, which reflects the tendency to take risk. Although most people would prefer the fixed one to avoid the risk of getting...
nothing in the end [12], pathological gamblers and drug addictive subjects are more likely to choose the larger amount of money with lower probability of acquisition [12,15]. Therefore, we hypothesized that IGD subjects would also prefer the large money with low probability rather than the certain small money rewards, which resembles the risk seeking feature of pathological gamblers and drug addicts.

Most of previous studies on IGD were based on general linear modelling (GLM) of the time series of blood oxygenation level dependent (BOLD) [16]. In the present study, we used a new data-driven technique named independent component analysis (ICA) to extract signals of interest and not of interest without the prior information about the task. Different from the traditional model-based GLM, which requires a design matrix and the assumption of regional hemodynamic responses, ICA disintegrates the time series into explanatory variables with one single assumption that the variables are independent. So far, there has been no research applying ICA to investigate the IGD’s risk decision-making in PD task. Thus, an important goal of the current study was to examine the neural mechanism of risk-taking in IGD subjects under a PD task using ICA approaches. Based on previous studies on the IGD and the probability discounting, we aimed to expand previous studies by investigating the alternative brain regions and brain functional connectivity networks in IGD.

2. Materials and method

2.1. Participants

This research was approved by the Human Investigations Committee of Zhejiang Normal University. All participants agreed to participate the study by signing an informed consent. All participants were right-handed males. Only males were included because they showed higher IGD tendency than women. Participants were categorized into two groups based on their scores on Young’s online Internet addiction test (IAT) [17] and the nine DSM-5 criteria for IGD. There was no significant difference in age between two groups (19 IGD subjects: 22.2 ± 3.08 years; 21 HC subjects: 22.8 ± 2.35 years; t (38) = 0.69, P > 0.05). No participant reported previous experience with illicit drugs (e.g., cocaine, marijuana) or gambling. All participants were free from psychiatric/neurological disorder, which was confirmed by their scores on questionnaires (e.g., the MINI-International Neuropsychiatric Interview questionnaire and Sensation Seeking Scale-V [SSS-V]). All participants were medication free and were instructed not to use any drugs, including coffee on the day of scanning.

Young’s online Internet addiction test (IAT) [17] and the nine DSM-5 criteria for IGD [18] were used to identify subjects with IGD. Young’s IAT has been proved to be a valid and reliable instrument that can be used in classifying IAD [19,20]. Young’s IAT consists of 20 items associated with online Internet use measuring psychological dependence, compulsive use, withdrawal, and related problems in school, work, sleep, family or time management. For each item, participants were asked to respond on a scale from 1 = “Rarely” to 5 = “Always”, or “Does not Apply”. Scores over 50 indicate occasional or frequent Internet-related problems and scores over 80 indicate severe Internet addiction disorder (www.netaddiction.net). Referring to Young’s criteria, we used the cut-off scores of 50 to classify IAD subjects. Individuals with IAD were also answer the following question: ‘do you spend most of your online time playing online games (> 80%)’ (Yes, No)?’. Only those who respond with ‘Yes’ were recruited in the IGD group. In the current study, the IAT score of IGD group (64 ± 9.78) is much higher than the HC group (31 ± 11.96, t(38) = -9.4, P < 0.001). In addition, the DSM-5 criteria for IGD contain nine items with each item reflecting a DSM-5 criterion. The IGD subjects met five criteria at least.

2.2. Task and procedure

PD task can assess risky decision-making directly. Discounting means the devaluation of an outcome when the outcome is obtained probabilistically. In general, people discount the value of a monetary reward when the reward accompanies with a low probability of acquisition [12,15]. Each item of the PD task contains a large but probabilistic monetary reward against a small but certain one. For instance, 21 Yuan with 60% chances against 10 Yuan for sure. There is a hyperbolic function used to describe the probabilistic outcomes [21]:

\[ V = A/(1 + hO), \quad O = (1 - P)/P \]

(1)

The V is the subjective value of an option, the A is monetary reward. The P represents the reward probability, the O represents the odds against receiving the money, and the h is a subject-specific discounting constant. Furthermore, the h values reflect the degree of probability discounting. The indifference points are the points at which the subjective value of a probabilistic option is equivalent to that of other certain options, which is used to plot the rate of probability discounting curves. Notably, smaller values of h indicate greater risk seeking, whereas larger h values indicate greater risk aversion.

Firstly, participants completed an informed consent form and the Matters of Attention of functional magnetic resonance imaging (fMRI). Secondly, they were provided with a sample of PD task. All subjects were informed that their choices in the task were very important for us to count the reward that they would receive at the end of the experiment. In particular, they were informed that they would be paid after the experiment according to their choice in a randomly selected trial of the task. If the subject chose the certain money in that trial, he would receive the money in cash. If the subject chooses the probabilistic money, he could select a card from many cards, including two colors (red and black) reflexing the probability of receiving the money. Finally, they completed the PD task in the fMRI scanner. During the task, participants were told to make choices among a range of probabilities and amounts with each of which involving a fixed but small amount of money and a probabilistic but larger amount of money (i.e. 10 Yuan 100% against 21 Yuan 60% (Fig. 1)). The probabilistic choices are composed of nine different probability values: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and nine different amounts of money: 11, 12.5, 14, 17, 20, 25, 33, 50 and 100 Yuan. The whole task consisted of 81 trials and took approximately 15 minutes. The stimuli were presented and behavioral data were collected using the E-prime software (Psychology Software Tools, Inc.).

2.3. Behavioral data analysis

There were three primary steps to analysis the behavior data of PD. Firstly, in order to determine each subject’s best-fit-h value from Eq (1), a non-linear curve-fitting program was applied to those data in Origin 7.0. Secondly, a log 10 transformation of the h values was performed. The log transformation was needed for these data because they were non-normal [22,23] while the resultant distribution of values was normal. The third step was to perform an independent sample t-test to examine the different probability discounting value (h value) of HC and IGD subjects. Four subjects (two IGD, two HC) were excluded because they consistently chose the certain option for most trials, therefore, no curve could be fitted. But their imaging data were still useful and were included in the fMRI analysis.
2.4. Image acquisition and pre-processing

Functional MRI was performed on a 3 T system (Siemens Trio) with a gradient-echo EPI T2 sensitive pulse sequence in 33 slices (interleaved sequence, 3 mm thickness, TR = 2000 ms, TE = 30, flip angle 90°, field of view 220 x 220 mm², matrix 64 x 64). Stimuli were presented via the Invivo synchronous system (Invivo Company, www.invivocorp.com/) via a monitor in the head coil.

Imaging analysis was performed using SPM5 (http://www.fil.ion.ucl.ac.uk/spm). Images were slice-time, reoriented, and realigned to the first volume. Then, T1-co-registered volumes were normalized to an SPM EPI template and smoothed using an 8 mm FWHM Gaussian kernel spatially. Two subjects (one IGD, one HC) were eliminated because their head motion coefficients exceeded the criteria (head motion > 2.5 mm and 2.5 degree).

2.5. Independent component analysis

A group spatial ICA was applied to the preprocessed fMRI data within a toolbox (GIFT v2.0) implemented in Matlab (http://icatb.sourceforge.net). The group ICA can reveal spatio-temporal associations within human brain. The default component number was 20, which splits the fMRI data into a final set of spatially independent and temporally coherent functional networks (FNs). The fMRI data were reduced through two principal component analysis (PCA) stages [24]. Then, a spatial ICA was conducted to estimate the 20 mutually independent components using the infomax algorithm, which is a stochastic process [25]. ICASSO algorithm [26] was performed to remedy the problem, which repeated the ICA analysis multiple times and then output a final set of independent components, providing a measurement of the consistency between different ICA runs. In the present study, we designated ICASSO to rerun ICA analysis for 100 iterations. Eventually, a single ICA time course and an independent functional spatial map (representing brain regions included in the network) for every subject were obtained.

2.6. Component selection

There were two steps to sort the ICA components of interest. In the first step, each ICA component spatial map was correlated with prior probabilistic maps of cerebral spinal fluid (CSF), gray matter and white matter within a standardized brain space provided by the MNI templates in SPM5. If the spatial correlation of white matter and CSF was greater than $r^2 = 0.025$, and smaller than $r^2 = 0.05$ for gray matter, then the component was considered to be artefactual and was discarded. Thus, this analysis found noise-related components that represented eyeball movement, head motion, ventricle activity, and other signal artefacts [27].

The second stage was to select the task-related components from remaining components based on the first analysis. A multiple temporal regression was performed on the ICA time courses with the GLM design matrix to estimate the association between the experimental paradigm and the independent components. The GLM design matrix represented a combination of task onsets convolved with a canonical hemodynamic response function. It was constructed in SPM5, which included all conditions (fix selection, probability selection, and missed selection) and 6 head movement parameters. The temporal regression resulted in a set of beta weights for each subject and each condition (probability and certain). The beta weights represented the degree of synchrony between the component and corresponding time courses, and indicated the engagement of the FNs during specific task conditions [28]. Positive and negative beta weights represented positive and negative correlation with the specific task condition respectively. An increase or decrease in beta weight under one task condition than another indicated an increase or decrease in task-relevant activity in the component. Then, these beta weights for the remaining components were examined with an independent one-sample t-test ($P < 0.05$) for IGD and HC group separately under each task condition. The beta weight of components that differed significantly from zero indicated a significant association with that condition, whereas components that did not show significant difference were regarded as non-task-related and then discarded.

2.7. Between-group comparison of components

Components that survived the two selection criterion were subjected to between-group task-related activity comparison analysis. To complete this comparison, an independent two-sample t-test ($P < 0.05$) on the beta weights of each remaining component between the HC and IGD group was performed. It was completed in the GIFT toolbox.

2.8. Correlations between behavioral performance and brain activities

The beta weights depicted the brain task-related activities of each component. We analyzed the correlation between behavioral performance and the beta weights of each remaining independent component. Firstly, we conducted an outlier analysis and then we entered beta weights of the surviving components into correlation analyses with both the reaction time (RT, the average reaction time of trails during which subjects chose probabilistic larger money minus that of trails during which subjects chose certain smaller money), and the probability discounting rate (the $h$ values). Further, the correlation between beta weights for only IGD group and the addiction severity (participants’ IAT scores) were also examined.

3. Results

3.1. Behavioral performance

We plotted the behavioral performance (i.e., the curve for PD functions) based on the median indifference point values (Fig. 2a). The data were inevitably skewed because of the limits on possible variability imposed by the property of the choice items during the task. Therefore, median values were analyzed in the present study.

![Fig. 1. The timeline of one trial in the probability discounting task in the present study. ¥ is the China’s currency, 1 ¥ is equal to 15.73 cents.](image-url)
[29]. For the median h values, IGD: 2.64, HC: 3.23. Independent sample t-test on the logged h values indicated that the IGD group showed lower h values than the HC, t = 2.12, P = 0.042, d = 0.75 (Fig. 2b). Finally, the data of RT (RT\text{probability} − RT\text{certain}) were subjected to an independent sample t-test, and the result showed that the RT (RT\text{probability} − RT\text{certain}) of IGD is much shorter compared with HC (IGD = 45 ± 115 ms, HC = 150 ± 210 ms), t(1, 30) = 1.92, P = 0.064, d = 0.642. Correlation analysis between the h values and the RT showed that they were positively correlated (r = 0.359, P = 0.037) (Fig. 2c).

3.2. Independent component

Five out of twenty components (components 3, 8, 12, 13, 16 (C3, C8, C12, C13, C16)) passed our selection criteria. These five components had a relatively low spatial correlation with white and cerebral spinal fluid (CSF) and a high correlation with grey and highly correlated with the experimental task (Table 1). Moreover, results from running ICASSO at group level in GIFT showed that these five components displayed no spatial variability between every iteration of ICA analysis.

3.3. Between-group differences

For the remaining components: C3, C8, C12, C13, C16, independent two-sample t-test on the beta weights showed that only C8 and C12 were significantly different under one or two conditions (Table 2). Under the probability condition, C8 was negatively modulated by the condition and the IGD group showed marginally higher task-related activity than HC. For C12, the IGD and HC group were modulated in different directions under the two conditions. To identify which network the two components belong to, we contrasted each component of these brain regions with the fourteen brain networks [30]. Consequently, component 8 was involved in default mode network (DMN) that mainly consist of posterior cingulate cortex (PCC), middle temporal gyrus, precuneus, partial frontal gyrus, and parietal lobe. Component 12 was involved in executive control network (ECN), primarily including inferior frontal gyrus (IFG), precentral gyrus, middle temporal gyrus, and caudate (Fig. 3). In addition, the event-related averages of each surviving component reflect the level of activation over the time course of a typical hemodynamic response, modulated positively or negatively by the task (Fig. 4).

3.4. Correlation analysis results

We analyzed the correlation between task behavioral performance and the beta weights of C8 and C12. There were a significant positive correlation between the beta values (\beta_{\text{probability}} − \beta_{\text{certain}}) of C12 and the logged h values of subjects (r = 0.446, P = 0.008) (Fig. 5a) and a marginally significant negative correlation between the beta values (\beta_{\text{probability}} − \beta_{\text{certain}}) of C8 and the RT (RT_{\text{probability}} − RT_{\text{certain}}) (r = −0.302, P = 0.065) (Fig. 5b). Interestingly, we found that the beta values (\beta_{\text{probability}}) of C12 was negatively correlated with the addiction severity in IGD subjects (C12: r = −0.448, P = 0.082) (Fig. 5c). Although some of these correlations did not reach the statistical significance, the trends are obvious.

4. Discussion

In the present study, we identified two important task-related brain functional networks (DMN and ECN) that showed significant alterations in IGD subjects.

<table>
<thead>
<tr>
<th>Component</th>
<th>Probability</th>
<th>Certain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
<td>IGD</td>
</tr>
<tr>
<td>C3</td>
<td>r = 8.42 (P &lt; 0.000)</td>
<td>r = 9.85 (P &lt; 0.000)</td>
</tr>
<tr>
<td>C8</td>
<td>r = −4.54 (P &lt; 0.000)</td>
<td>t = −2.87 (P = 0.011)</td>
</tr>
<tr>
<td>C12</td>
<td>r = 3.38 (P &lt; 0.003)</td>
<td>t = −0.35 (P = 0.732)</td>
</tr>
<tr>
<td>C13</td>
<td>r = 3.71 (P &lt; 0.001)</td>
<td>t = 1.24 (P = 0.232)</td>
</tr>
<tr>
<td>C16</td>
<td>r = −5.66 (P &lt; 0.000)</td>
<td>t = −3.46 (P &lt; 0.003)</td>
</tr>
</tbody>
</table>

Probability means the probability larger option in the PD task, certain means the certain smaller option in the PD task; HC: healthy controls; IGD: participants with Internet gaming disorder; C: component.

* Components that showed one-sample significant with the task for either IGD subject or HC group were pursued for further analysis (P < 0.05).
Table 2
Components that showed significant differences in two-sample t-tests of beta weights.*

<table>
<thead>
<tr>
<th>Component</th>
<th>Mean ± SD</th>
<th>t-value (HC-IGD)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IGD subjects (n = 18)</td>
<td>HC subjects (n = 20)</td>
<td></td>
</tr>
<tr>
<td>C8</td>
<td>8.17 ± 3.52</td>
<td>8.84 ± 4.69</td>
<td>0.49</td>
</tr>
<tr>
<td>Certain</td>
<td>7.58 ± 3.26</td>
<td>8.56 ± 5.21</td>
<td>0.69</td>
</tr>
<tr>
<td>C12</td>
<td>-1.56 ± 2.30</td>
<td>-3.19 ± 3.11</td>
<td>-1.83</td>
</tr>
<tr>
<td>Certain</td>
<td>-1.83 ± 1.74</td>
<td>-2.96 ± 3.02</td>
<td>-1.39</td>
</tr>
<tr>
<td>C13</td>
<td>-0.17 ± 2.03</td>
<td>1.82 ± 2.41</td>
<td>2.73</td>
</tr>
<tr>
<td>Certain</td>
<td>-1.26 ± 1.88</td>
<td>0.51 ± 2.73</td>
<td>2.30</td>
</tr>
<tr>
<td>C16</td>
<td>0.91 ± 3.10</td>
<td>1.88 ± 2.27</td>
<td>1.12</td>
</tr>
<tr>
<td>Certain</td>
<td>-0.26 ± 3.10</td>
<td>1.11 ± 2.39</td>
<td>1.54</td>
</tr>
<tr>
<td>C12</td>
<td>-2.66 ± 3.26</td>
<td>-3.20 ± 2.53</td>
<td>-0.56</td>
</tr>
<tr>
<td>Certain</td>
<td>-2.26 ± 3.21</td>
<td>-2.97 ± 2.04</td>
<td>-0.83</td>
</tr>
</tbody>
</table>

Components that showed significant difference between IGD group and HC group in beta weights (P < 0.05, FDR corrected). The beta weights of C8 under the probability condition showed marginally significant difference across the two groups, and the beta weights of C12 under both two conditions showed significant difference across the two groups.

4.1. Default mode network

DMN is an acknowledged large-scale brain network including a set of brain regions that demonstrate increased activity during the resting-state. In the present study, the DMN (C8) survived from our two selection criteria, which means that DMN represents hemodynamic change rather than signal artifacts. In addition, the DMN alternation correlates negatively with the PD task, which suggests that the DMN plays a role in risky decision-making. The DMN has been proposed to be included in decision-making [31], and the negative correlations with the two task conditions are consistent with the characteristics of DMN, deactivated when doing tasks [32,33].

In current study, IGD subjects demonstrated higher task-related activity (negative modulation) than HC subjects in the risk condition. Abnormal functions in DMN have been found in other neuropsychiatric disorders (i.e. schizophrenia, attention-deficit hyperactivity disorder, depression, and Alzheimer disease) and drug addiction [34–39]. Besides the imaging results, significant negative correlation was found between the beta weights of DMN and the RT, which indicates that the longer time they spent in making decision, the lower task-related brain activity would be evoked in DMN. The behavioral results showed that IGD subjects were associated with shorter RT, which is consistent with imaging data. Previous studies have demonstrated that the activity in the DMN is reduced during task performance and this reduction typically occurs with increased activity in task-related regions [40,41]. What is more, it was found that the failure to suppress the DMN is related to impaired performance in behavioral tasks [42,43]. Taking the functions of DMN and the features of IGD into account, the disadvantageous risky decision-making in the IGD group may suggest that IGD subjects are prone to make decisions quickly with less attention to the consequence of their choices and thus fail to active the decision-relevant regions.

4.2. Executive control network

Some neuropsychological researches have demonstrated that executive control functions play a key role in decision-making under risk circumstances [44–48]. In the present study, the executive control network (ECN; C12) was found to be highly correlated with the PD task and the beta weights of the ECN were positively correlated with probability discounting rates, which suggests that the lower task-related activity in the ECN is accompanied with less steep rates of discounting. Consistent with the studies mentioned above, these results suggest that the ECN has a strong relationship with risk decision-making.

The ECN have been proved to be embroiled in IGD, such as the IFG and the precentral gyrus [16,49]. Literatures have found that people with IGD or other drug addiction disorders showed impairments in executive control ability [16,50–53]. Notably, in the present study, the beta weights showed that the ECN of the HC group were positively correlated with the risky and fixed conditions, whereas the IGD group showed negative correlations.

![Image](Fig. 3. Illustrating of two independent components (C8, C12) identified from ICA, with regions modulated by the PD task condition.)
with the two conditions. This phenomenon suggests that the IGD subjects did not engage the ECN adequately when making risky decision, they showed less engagement in task than the HC. Executive function is known as an important contributor to inhibit individuals’ desires for pleasant behaviors under unfavorable circumstances [16,54–57]. The less engagement of ECN might be the reason for why IGD subjects failed to control their desire for risky choices. This is consistent with our previous findings that IGD subjects showed higher impulsivity and enhanced reward sensitivity than HC subjects [58,59]. Furthermore, the IGD subjects showed less steep discount of probabilistic rewards than HC subjects. In addition, there was a negative correlation between the beta weights and the addiction severity, which suggests that lower task-related activity in the ECN was accompanied by greater addiction severity. Taken together, we concluded that the IGD subjects showed deficit in the ECN, which leads to a dysregulated carvings for big reward.

5. Conclusions

The present study revealed that IGD subjects showed alteration in the two highly task-related brain networks (DMN and ECN) as compared to HC. Firstly, the results revealed that the IGD subjects show altered modulation in DMN, which might impair their ability to active the decision-relevant brain regions effectively to choose advantageous options. Secondly, less engagement of ECN in IGD subjects suggests that they cannot effectively control their desire to seek rewards, which results in higher risky performance. In sum, the modulation in DMN and executive control deficit might be the reason for why the IGD subjects continue to play online games despite the risks of getting disadvantageous consequences.

Disclosure of interest

The authors declare that they have no competing interest.

Acknowledgements

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Fig. 4. The event-related averages (Z scores) over a window of 20 s of the remaining second component (C8, C12) time course under the probability and certain condition separately. C: component.

Fig. 5. The correlation results between the brain activities and behavioral performance. a: correlation between the beta weights of component 12 in probability minus certain option and the h value; b: correlation between the beta weights of component B in probability minus certain option and RT in probability minus certain option; c: correlation between the beta weights of component 12 in probability and the addiction severity (the IAT scores).


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