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Both online and face-to-face mindfulness meditation can change cortical structure in internet gaming disorder

Haohao Dong [a,b], Huabin Wang [b], Xuefeng Xu [b], Xuefeng Ma [b], Haosen Ni [b], Chang Liu [c], Xiaolan Song [d], Guangheng Dong [b,*], Renlai Zhou [a,**]

[a] Department of Psychology, Nanjing University, Nanjing, China
[b] Department of Psychology, Yunnan Normal University, Kunming, China
[c] NuanCun Mindful-Living Mindfulness Center, Hangzhou, China
[d] Center of Mindfulness, School of Psychology, Zhejiang Normal University, Jinhua, China

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ABSTRACT

Background: Mindfulness meditation (MM) has been shown to effectively alleviate symptoms of Internet Gaming Disorder (IGD) and improve neural functioning. However, it remains unclear whether both online and face-to-face MM can enhance cortical structure, a stable and reliable neural biomarker.

Methods: This study included 100 IGD patients randomly assigned to three groups: face-to-face MM (31 participants), online MM (38 participants), or progressive muscle relaxation (PMR) (31 participants). Pre- and post-assessments were conducted after 8 training sessions. Cortical area, volume, thickness, and local gyrification index (LGI) changes were analyzed using FreeSurfer, with group comparisons and seed-based structural covariance analysis.

Results: Both online and face-to-face MM significantly reduced IGD severity. Structural analysis revealed increased cortical thickness in the superior temporal gyrus (face-to-face + online vs. PMR: $t = 4.725$, $p = 0.014$). The face-to-face group also showed significant increases in LGI in the left superior temporal gyrus ($t = 6.030$, $p < 0.001$) and right insula ($t = 3.792$, $p = 0.009$). All results were correlated with reduced IGD severity. Structural covariance further revealed that MM (face-to-face + online) reduced the covariance between the right superior temporal gyrus and both the default mode and sensory networks.

Conclusion: Both online and face-to-face MM reduce IGD severity and enhance cortical structures, such as the superior temporal and the right insula, highlighting potential neuroanatomical targets for IGD treatment.

1. Introduction

Internet Gaming Disorder (IGD) is characterized by the inability to control excessive internet gaming, leading to cognitive control deficits, emotional disturbances, and related neural dysfunctions (Gao et al., 2022; Niu et al., 2022; Yao et al., 2017; Zheng et al., 2019). Individuals with IGD often exhibit significant functional abnormalities in brain regions such as the prefrontal cortex, striatum, superior temporal gyrus, precuneus, cingulate gyrus, and insula, all of which are crucial for reward processing and executive control (Yao et al., 2017; Zheng et al., 2019). Furthermore, reductions in grey matter volume in these areas are commonly observed in IGD patients (Chen et al., 2021; H. Wang et al., 2015; Z. Wang et al., 2018).

Given the severe consequences and increasing prevalence of IGD (Gao et al., 2022), there is growing interest in developing effective treatment strategies (Dong et al., 2024). While cognitive behavioral therapy (CBT) is the widely used intervention, its effectiveness is often limited by high relapse rates (Zajac et al., 2020). In contrast, Mindfulness Meditation (MM) enhances individuals' awareness of both internal and external experiences, helping them approach stress and emotions with acceptance and openness, rather than reacting impulsively or avoiding them (Webb, n.d.). Previous studies have shown that MM significantly reduces IGD symptoms and gaming cravings (Dong et al., 2024; Ni et al., 2024). Neuroimaging research further suggests that MM reduces activation in the insula, putamen, and middle frontal gyrus

* Corresponding author.
** Corresponding author.
E-mail addresses: dh582387540@163.com (H. Dong), 1209317602@qq.com (H. Wang), xxfpsych@163.com (X. Xu), alainfuren@163.com (X. Ma), nhsnsz@163.com (H. Ni), 582387540@qq.com (C. Liu), xlsong@zjnu.cn (X. Song), dongguangheng@ynnu.edu.cn (G. Dong), rlzhou@nju.edu.cn (R. Zhou).

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Glossary

Internet Gaming Disorder (IGD)
Mindfulness Meditation (MM)
Internet Addiction Test (IAT)
Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5)
Five Facet Mindfulness Questionnaire (FFMQ)
Progressive muscle relaxation (PMR)
Local gyrification index (lGI)
Questionnaire for Gaming Urges (Craving)

during cue-reactivity tasks, while enhancing resting-state functional connectivity between executive control and reward-related regions (Ni et al., 2024; Xu et al., 2024).

Although functional imaging provides valuable neurophysiological insights, its lower resolution and poor reproducibility limit its effectiveness (Griffanti et al., 2016). In contrast, structural measures, which underpin brain function (Honey et al., 2007), offer more stable and reliable markers. These measures can visually capture changes in brain anatomy, revealing developmental or pathological conditions (Sowell et al., 2003). Previous studies have shown that mindfulness meditation (MM) induces structural changes in the salience network, particularly in the insula (Siew and Yu, 2023), and the default mode network, with key nodes in the cingulate gyrus and temporoparietal regions (Hölzel et al., 2011). These networks are involved in emotional responses, self-awareness (Kral et al., n.d.), attention regulation, and mind-wandering (Fox et al., 2015). Furthermore, MM has been shown to increase grey matter volume in the insula in opioid-addicted patients, correlating with reduced impulsivity (Wolf et al., 2022). These structural changes suggest that MM may influence IGD neurobiology by altering the insula and temporoparietal regions. However, research on this is limited, and the present study seeks to explore the structural effects of MM on IGD brain morphology.

As noted, the neural effects of MM are reflected not only in individual brain region changes but also in the reorganization of interregional networks. Structural covariance provides a robust framework, indicating that regions with similar morphological features often exhibit concurrent developmental changes. This helps us understand long-term connectivity between different regions (Mo et al., 2024). Structural covariance abnormalities have been observed in various addictive disorders, including cannabis use (Li and Xu, 2024), amphetamine use (Mo et al., 2024), alcohol dependence (Cao et al., 2024), and smoking (W. Wang et al., 2023). Moreover, research has shown disruptions in structural covariance patterns between the default mode network (DMN) and regions involved in attention and reward processing in IGD patients (Chen et al., 2021). Thus, this study further explores MM's impact on structural covariance networks in the IGD brain.

With the development of information technology and the global pandemic experience, MM has increasingly shifted to online platforms. Due to its accessibility, time efficiency, and cost-effectiveness, online MM has gained widespread popularity (Spijkerman et al., 2016; Wahbeh et al., 2014). Research has shown that online MM has a moderate effect in reducing stress, although its effect on alleviating depression and anxiety is more limited (Spijkerman et al., 2016). A comparative study found that both online and face-to-face MM effectively reduced psychological distress in cancer patients, with face-to-face interventions showing slightly better outcomes, although the differences were not statistically significant (Compen et al., 2018). Therefore, this study further explores the differences between face-to-face and online MM programs in terms of their influence on the severity of IGD and the brain structure, providing insights for selecting the most effective intervention approach.

In summary, the goal of this study is to investigate the potential effects of mindfulness meditation (MM), both face-to-face and online, on the brain morphology and structural covariance relationships in individuals with IGD. Based on previous studies, we hypothesize that both face-to-face and online MM may induce morphological changes and modifications in the covariance relationships of brain regions associated with emotions, such as the insula, as well as regions involved in self-awareness and sensory processing, including the default mode network and sensory related networks.

2. Methods

2.1. Ethics

This study follows the ethical guidelines of the World Medical Association and the Declaration of Helsinki. It was approved by the Human Research Ethics Committee of Hangzhou Normal University, China, and registered in the Chinese Clinical Trial Registry (http://www.chictr.org.cn; ChiCTR2300075869). All participants were recruited via advertisements and provided written informed consent.

2.2. Participants

We initially distributed an online screening survey—including the Internet Addiction Test (IAT) and DSM-5 diagnostic criteria—via advertisements. A total of 942 responses were received. Among them, 740 did not meet the criteria for IGD, which aligns with the estimated 10 % prevalence among Chinese adolescents (Gou et al., 2024). An additional 51 individuals declined to participate due to scheduling conflicts or personal reasons.

Participants scoring above 50 on the IAT were subsequently interviewed by a psychiatrist. Those meeting DSM-5 criteria with a symptom count of $\geq$6 (Dong et al., 2020) were considered to have clinically significant IGD and were eligible for inclusion.

Following our previous studies (Ni et al., 2024; Xu et al., 2024), rigorous screening excluded participants with (1) psychiatric or neurological disorders other than IGD; (2) cognitive impairment (MINI) (Lecrubier et al., 1997; Sheehan et al., 1998) or depression (BDI) (Beck et al., 1961); (3) recent surgery, head trauma, or cardiovascular disease; (4) claustrophobia; (5) metal implants/tattoos in the head or neck; (6) substance use disorders in the past year; (7) psychiatric medication use; (8) prior mindfulness training.

The total of 120 participants—college students from Hangzhou, Zhejiang Province—were included and randomly assigned (1:1:1) to face-to-face group, online group, or progressive muscle relaxation (PMR) groups. After exclusions, 31 from the face-to-face group, 38 from the online group, and 31 from the PMR group were analyzed (Fig. 1a). Specifically, in the face-to-face group, 4 participants dropped out, 4 were excluded due to excessive head motion, and 1 due to the FreeSurfer longitudinal processing failure (Fig. 1c). In the online group, 2 participants dropped out. In the PMR group, 6 participants dropped out, 2 were excluded due to head motion, and 1 due to the longitudinal processing failure.

2.3. Behavioral measurements

IGD severity was assessed before and after training using the DSM-5 and IAT, while gaming craving was measured with the modified Tiffany Questionnaire for Smoking (Tiffany and Drobes, 1991). Mindfulness levels were evaluated using the Five Facet Mindfulness Questionnaire (FFMQ) (Baer et al., 2006) (Fig. 1b).

A mixed ANOVA examined the interaction between Group (Offline, Online, PMR) and Time (pre vs. post). Additionally, we analyzed the correlation between changes in IGD severity and mindfulness improvement to assess whether increased mindfulness reduces IGD severity. Statistical analysis was conducted using the bruceR package in

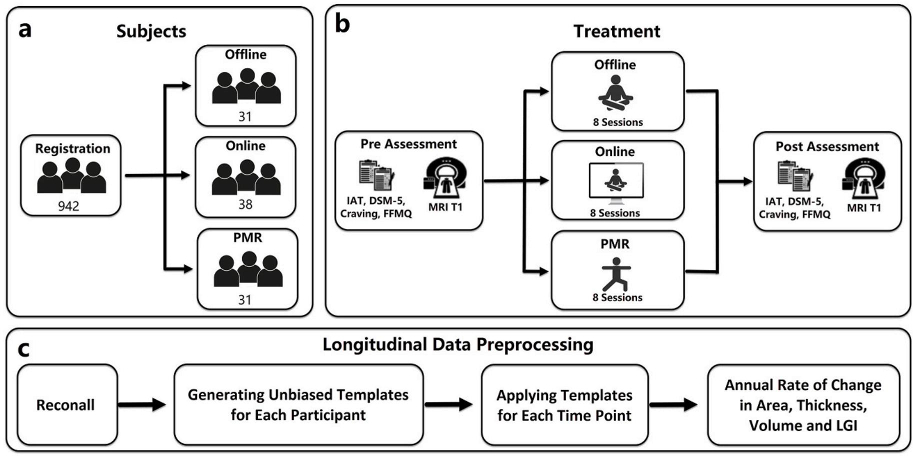

Fig. 1. Schematic diagram of the entire research process a
Participant selection **b:** Pre- and post-Assessment and different treatments. **c:** FreeSurfer Longitudinal Analysis Pipeline. **Offline**: Face-to-face Mindfulness Meditation; **Online**: Online Mindfulness Meditation; **PMR**: Progressive Muscle Relaxation; **IAT**: Internet Addiction Test; **DSM-5**: Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, Text Revision; **Craving**: Questionnaire for Gaming Urges; **FFMQ**: Five Facet Mindfulness Questionnaire; **LGI**: local Gyrification Index.

R (https://cran.r-project.org/web/packages/bruceR/index.html).

2.4. Mindfulness meditation training

The face-to-face (offline) and online MM training was conducted by two professional mindfulness instructors over 8 sessions, each lasting 2.5–3.5 h. To reduce dropout rates, a schedule was adjusted to two sessions per week over 4 weeks, instead of the usual 8-week format. Other procedures followed our previous study (Ni et al., 2024).

The control group participated in progressive muscle relaxation (PMR) with the same schedule as the MM training and received education on body relaxation techniques. PMR was chosen as the control due to its proven effectiveness in reducing anxiety, stress, and improving sleep (Gallego-Gómez et al., 2020; K. Liu et al., 2020). Other procedures were consistent with our previous research (Ni et al., 2024).

2.5. Image acquisition and preprocessing

Structural imaging data were acquired before and after training using a Sigma 3 T scanner (GE HealthCare) with a T1-weighted 3D gradient echo sequence. Scanning parameters included TR = 1700 ms, TE = 3.93 ms, 176 slices, 1.0 mm slice thickness, 0 mm gap, Flip Angle = 15°, TI = 1100 ms, FOV = 240 × 240 mm^2, and resolution = 256 × 256.

Structural images were processed using FreeSurfer (v7.3.2) following a standard longitudinal analysis pipeline (https://surfer.nmr.mgh.harvard.edu/fswiki/FsTutorial/LongitudinalTutorial?highlight=%28Longitu%29). (1) Pre- and post-images were reconstructed (recon-all) into 2D cortical surfaces. (2) An unbiased subject template was generated to improve consistency. (3) Each time point was reprocessed based on this template (Fig. 1c).

Cortical area, thickness, volume (bilateral cerebellum, thalamus, caudate nucleus, putamen, pallidus, hippocampus, amygdala, accumbens), and local gyrification index (lGI) were calculated. The lGI, a cortical folding measure, has shown abnormalities in addiction-related disorders (Schaer et al., 2008; Cao et al., 2025; Cerasa et al., 2014; Hu et al., 2022; Sullivan et al., 2020; Trevisan et al., 2023).

FreeSurfer's longitudinal analysis enhances statistical power by reducing inter-individual variability (Bernal-Rusiel et al., 2013; Reuter et al., 2012; Reuter and Fischl, 2011). Annual change rates were calculated as Rate = (Post - Pre)/(Post time - Pre time) in years.

2.6. Statistical analysis

After calculating annual change rates for cortical morphology, we aligned all participants' data to a standard space and conducted vertex-wise group comparisons using a 10 mm FWHM spatial smoothing kernel. Following FreeSurfer's standard group comparison workflow (https://surfer.nmr.mgh.harvard.edu/fswiki/FsTutorial/GroupAnalysis), a general linear model (GLM) was applied for group-level analysis.

To examine MM-induced cortical changes, we first compared (Online + Offline) vs. PMR, followed by pairwise comparisons (Offline vs. PMR), (Offline vs. Online), and: (Online vs. PMR), controlling for age and gender. To rigorously control for false positives, multiple comparison corrections were applied at several levels. First, a vertex-wise threshold of $p < 0.001$ was used to identify significant cortical points. Second, cluster-level significance was determined using a two-tailed Monte Carlo simulation with a corrected threshold of $p < 0.05$, accounting for spatial autocorrelation (FreeSurfer default method). Third, corrections were applied across both hemispheres to control for bilateral testing. Finally, Bonferroni correction was used to adjust for the three-group comparisons, and only results that survived the adjusted threshold ($p < 0.0166$) were considered statistically significant.

Significant clusters were extracted for Pearson correlation analyses with IGD severity changes (IAT, DSM-5, Craving). All statistical analyses and visualizations were performed using R.

For the significant regions identified, we used them as regions of interest (ROIs) to perform structural covariance analysis. Structural covariance analysis assesses the correlation between morphological indicators of brain regions, based on the assumption that brain regions with similar changes in volume or other metrics are interconnected. Unlike direct connectivity methods such as Diffusion Tensor Imaging (DTI), morphological covariance analysis may reveal that changes in neural connectivity are driven by long-term processes such as neurodevelopment or neurodegeneration. Previous studies have shown abnormal cortical morphological covariance in individuals with substance use disorders (Mo et al., 2024) and IGD (Chen et al., 2021). Thus, MM training may alter structural changes in these regions while also affecting the covariance relationships between these regions and others.

We performed structural covariance analysis using the SurfStat toolbox in MATLAB (https://www.math.mcgill.ca/keith/surfstat/). For each ROI, we fitted a linear interaction model at each surface vertex i (Worsley et al., 2009).

$$Meas_i \sim intercept + \beta_1(Group) + \beta_2(Meas_{seed}) + \beta_3(Age) + \beta_4(gender) + \beta_5(Group^{*}Meas_{seed})$$

In the formula above, * represents the interaction term, $Meas_{seed}$ is the mean value of the seed region, and $beta_3$ and $beta_4$ are the covariates. To control for false positives, we employed a two-stage correction approach (SurfStat toolbox default): first applying a stringent vertex-level threshold ($p < 0.001$), followed by cluster-level False Discovery Rate (FDR) correction ($p < 0.05$, one-tailed).

3. Results

In total, 100 participants were included in the final analysis: 31 in the face-to-face MM group (mean age [SD] = 20.26 [1.88] years; 17 females, 15 males), 38 in the online MM group (mean age [SD] = 21.45 [2.05] years; 18 females, 20 males), and 31 in the PMR group (mean age [SD] = 21.13 [1.52] years; 16 females, 15 males). Detailed information is provided in Table 1.

We found that the groups differed significantly in age (F (2, 97) = 5.468, p = 0.005) and craving scores (F (2, 97) = 5.736, p = 0.004) at baseline. Post hoc tests revealed that the online group had a significantly higher age (vs. PMR: t (97) = 2.950, p = 0.012; vs. offline: t (97) = 2.660, p = 0.027) and higher craving scores (vs. PMR: t (97) = 3.175, p = 0.006; vs. offline: t (97) = 2.479, p = 0.044) compared to the other groups.

3.1. Behavioral measurements

A significant interaction between Group (Offline, Online, or PMR) and Time (pre or post) was observed for all severity measures of IGD (IAT: F (2, 97) = 26.790, $p < 0.001$; DSM-5: F (2, 97) = 37.738, $p < 0.001$; Craving: F (2, 97) = 24.952, $p < 0.001$). Based on the simple effects analysis of pre- and post-measures for each group, participants in all groups showed significant decreases in severity scores of IGD. However, the reduction in the PMR group was smaller (IAT: t (97) = 2.343,p = 0.021, d = .425; DSM-5: t (97) = 2.409, p = 0.018,d = .437; Craving: t (97) = 2.162, p = 0.033,d = .392), while the offline group (IAT: t (97) = 10.401, $p < 0.001$, d = 1.887; DSM-5: t (97) = 10.642, $p <$ 0.001,d = 1.931; Craving: t (97) = 8.523, $p < 0.001$,d = 1.547) and the online group (IAT: t (97) = 12.891, $p < 0.001$, d = 2.113; DSM-5: t (97) = 15.415, $p < 0.001$,d = 2.526; Craving: t (97) = 12.834, $p < 0.001$,d = 2.103) showed greater reductions. Specific data can be found in Fig. 2a–c. Additionally, it is worth noting that the difference between the online and offline groups in post-test scores was not significant (IAT: t (97) = .463, $p > 0.999$; DSM-5: t (97) = 1.386, p = 0.506; Craving: t (97) = .600, $p > 0.999$).

To further clarify whether one treatment was more effective than the others, we conducted pairwise post-hoc comparisons on the change scores (i.e., post-treatment minus pre-treatment) to minimize the potential impact of baseline differences. The results (Bonferroni-corrected for three pairwise comparisons) showed that both the online (t (97) = 6.902, $p < 0.001$) and offline groups (t (97) = 5.697, $p < 0.001$) had significantly greater reductions in IAT scores compared to the PMR group, with no significant difference between the online and offline groups (t (97) = .922, p = 1.000). Similarly, for DSM-5 scores, both the online (t (97) = 8.544, $p < 0.001$) and offline groups (t (97) = 5.821, $p <$ 0.001) outperformed the PMR group, and the difference between online and offline groups was marginally significant (t (97) = 2.435, p = 0.0501). Regarding Craving scores, the online (t (97) = 6.997, $p <$ 0.001) and offline (t (97) = 4.498, $p < 0.001$) groups again showed significantly greater reductions than the PMR group, whereas the online vs. offline comparison was not statistically significant (t (97) = 2.277, p = 0.075).

Although no significant interaction was found in FFMQ scores (F = 1.672, p = 0.193), simple effects analysis revealed that both the offline (t = 4.622, $p < 0.001$, d = .839) and the online groups (t = 4.054, $p <$ 0.001, d = .664) showed significant increases in FFMQ scores, while the PMR group (t = 2.066, p = 0.042, d = .375) also showed a significant increase, but to a smaller extent (Fig. 2d).

Furthermore, we performed a correlation analysis between the improvement in severity scores of IGD (post-test score - pre-test score) and the change in mindfulness levels (post-test score - pre-test score). The results showed that with an increase in mindfulness levels, participants' addiction scores significantly decreased (IAT: r = −.295, p = 0.002; DSM-5: r = −.218, p = 0.028; Craving: r = −.228, p = 0.022).

3.2. Group Differences in Cortical Morphology

First, we found that the mindfulness groups (Offline + Online) exhibited significant increases in thickness at the superior temporal gyrus (t = 4.725, p = 0.014), compared to the PMR group (see Table 2). Furthermore, as IAT and DSM-5 scores decreased, participants showed an increase in the thickness of the superior temporal gyrus (DSM-5: r = −.263, p = 0.007, see Fig. 3a).

Next, the offline group showed significant increases in LGI compared to the PMR group in the left superior temporal gyrus (t = 6.030, p < 0.001) and the right insula (t = 3.792, p = 0.009) (see Table 2). Moreover, as DSM-5 scores decreased, participants exhibited gradual increases in LGI in the left superior temporal gyrus (r = −.310, p = 0.015, see Fig. 3b) and the right insula LGI (r = −.267, p = 0.037, see Fig. 3c).

Finally, we found that, compared to the PMR group, the online group also showed a marginally significant increase in cortical area at the right postcentral gyrus (t = 5.627, p = 0.017, Bonferroni-corrected p = 0.051) (see Table 2). Similarly, we found that as DSM-5 scores decreased, participants showed an increase in the area of the right postcentral gyrus (r = −.296, p = 0.013). Unfortunately, no significant differences were found between the online and face-to-face groups.

3.3. Group Differences in Seed-based structural covariance analysis

We used all significant results as ROIs to perform structural covariance analysis across the whole brain. The results indicated that when using the cortical thickness of the right superior temporal gyrus as a ROI (Fig. 4a), the covariance in the mindfulness group (Offline + Online) was significantly decreased than the PMR group in several brain regions (see Table 3 and Fig. 4). Specifically, the PMR group showed significantly greater structural covariance in the left superior temporal gyrus with the left lateral occipital lobe (t = 4.140, p = 0.016, Fig. 4b), precuneus (t = 4.757, p = 0.006, Fig. 4c), middle temporal gyrus (t = 4.481, p = 0.011, Fig. 4d), posterior cingulate gyrus (t = 5.390, p = 0.004, Fig. 4c), right inferior parietal lobe (t = 4.568, p = 0.010, Fig. 4e), lateral

Table 1
Demographic characteristics of participants.

	Offline	Online	PMR	F	p
No. (F/M)	31 (17/14)	38 (18/20)	31 (16/15)	.388 (FET)	.823
Age	20.258 ± 1.879	21.447 ± 2.049	20.129 ± 1.521	5.468	.005
IAT	70.064 ± 10.779	74.605 ± 10.039	69.612 ± 9.759	2.593	.080
DSM-5	6.935 ± 1.123	7.447 ± .891	7.096 ± .870	2.59	.081
Craving	60.032 ± 14.220	67.500 ± 11.286	57.935 ± 11.893	5.736	.004

Offline: Face-to-face Mindfulness Meditation; **Online:** Online Mindfulness Meditation; **PMR:** Progressive Muscle Relaxation; **FET:** Fisher's exact test; **IAT:** Internet Addiction Test (revised version for IGD); **DSM-5:** Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, Text Revision; **Craving:** Questionnaire for Gaming Urges. **Note:** All F-values have degrees of freedom (2, 97). **Post hoc** tests showed that the online group had significantly higher age (vs. PMR: t (97) = 2.950, p = 0.012; vs. offline: t (97) = 2.66, p = 0.0274) and craving scores (vs. PMR: t (97) = 3.175, p = 0.006; vs. offline: t (97) = 2.479, p = 0.044).

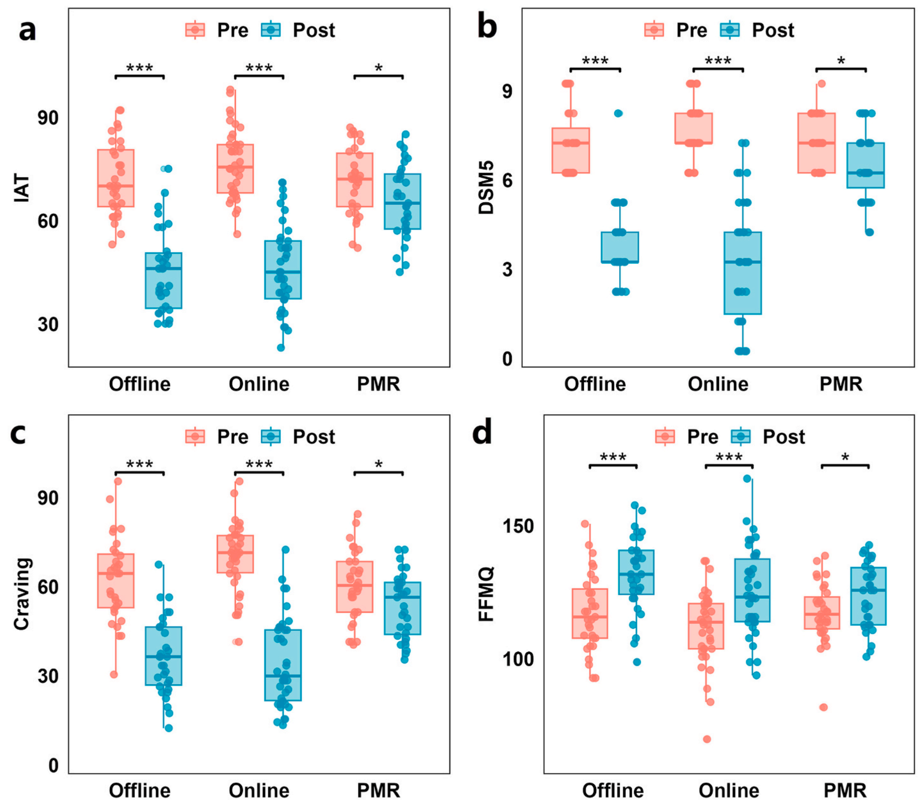

Fig. 2. Pretest and Posttest Assessments of IGD severity. abc
The simple effects analysis of individual IAT, DSM-5, and Craving scores for each group at pre- and post-measurements showed that the PMR group had a smaller decrease (IAT: $t\,(97) = 2.343$, $p = 0.021$, $d = .425$; DSM-5: $t\,(97) = 2.409$, $p = 0.018$, $d = .437$; Craving: $t\,(97) = 2.162$, $p = 0.033$, $d = .392$), while the offline group (IAT: $t\,(97) = 10.401$, $p < 0.001$, $d = 1.887$; DSM-5: $t\,(97) = 10.642$, $p < 0.001$, $d = 1.931$; Craving: $t\,(97) = 8.523$, $p < 0.001$, $d = 1.547$) and online group (IAT: $t\,(97) = 12.891$, $p < 0.001$, $d = 2.113$; DSM-5: $t\,(97) = 15.415$, $p < 0.001$, $d = 2.526$; Craving: $t\,(97) = 12.834$, $p < 0.001$, $d = 2.103$) showed greater reductions. **d** represents the simple effects analysis of individual FFMQ scores for pre- and post-measurements in each group. We found that the offline ($t\,(97) = 4.62$, $p < 0.001$, d = .83) and online ($t\,(97) = 4.05$, $p < 0.001$, $d = .66$) mindfulness groups showed significant and large increases in FFMQ scores, while the PMR group ($t\,(97) = 2.06$, $p = 0.042$, $d = .37$) also showed a significant increase, but to a lesser extent. **IGD**: Internet Gaming Disorder; **Offline**: Face-to-face Mindfulness Meditation; **Online**: Online Mindfulness Meditation; **PMR**: Progressive Muscle Relaxation; **IAT**: Internet Addiction Test; **DSM5**: Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, Text Revision; **Craving**: Questionnaire for Gaming Urges; **FFMQ**: Five Facet Mindfulness Questionnaire.

occipital lobe ($t = 4.177$, $p = 0.016$, Fig. 4b), and precuneus ($t = 4.416$, $p = 0.012$, Fig. 4f). All results were corrected for False Discovery Rate (FDR).

4. Discussion

This study is the first to compare face-to-face and online MM training for IGD and explore their neural mechanisms. Both methods effectively alleviated symptoms and enhanced brain plasticity, particularly in the superior temporal gyrus and insula.

4.1. Behavioral measurements

Our study found that both online and face-to-face MM effectively reduced IGD symptoms, as evidenced by significant improvements in IAT, DSM-5, and Craving scores (Fig. 2). The degree of improvement correlated with MM engagement, indicating that greater participation led to better outcomes.

However, individual differences were more pronounced in the online group (Fig. 2), likely due to the absence of group dynamics and immediate feedback, which are crucial for motivation. While highly motivated individuals benefited from the flexibility of online courses, less motivated participants responded better to the structure of face-to-face training.

Additionally, the PMR group showed modest symptom improvement, suggesting a potential placebo effect. Previous studies have shown that PMR can reduce anxiety and physical discomfort, contributing to lower addictive behaviors (Limsanon and Kalayasiri, 2015; Murphy et al., 2019; L. Wang et al., 2023). This reinforces that MM's effects in our study go beyond general relaxation.

4.2. MM increased the cortical morphological features of IGD

4.2.1. Increased cortical thickness in the superior temporal gyrus

We also found that MM (offline + online) resulted in increased cortical thickness in the right temporal gyrus in individuals with IGD. Additionally, the face-to-face MM group exhibited a significant increase in the Local Gyrification Index (LGI) in the left part of this region. Notably, as participants' cortical area or LGI in the temporal gyrus increased, there was a corresponding decrease in the severity of their IGD, as measured by DSM-5 scores.

The temporal gyrus is part of both the default mode network and the auditory network, and is involved in auditory processing, self-awareness, and emotional recognition. Previous research has reported reductions in cortical thickness and volume in this region in individuals with IGD, which may be linked to impaired decision-making abilities (Z. Wang et al., 2018). Moreover, mindfulness meditation has been shown to enhance activation (Jang et al., 2018) and node efficiency (W. Liu et al., 2022) in the temporal gyrus. MM emphasizes present-moment awareness of bodily sensations and emotions, which heightens awareness of one's internal state—a process closely related to the emotional processing and self-referential functions of the temporal gyrus. Studies

Table 2
Group differences in cortical morphology.

Annot		Group		MNI (X Y Z)			NVts	*t*	*p*
		(Offline + Online) vs	**PMR**						
Thickness	R Superior Temporal	-.090 ± .548	-.516 ± .765	53	-8	-2	296	4.725	.014
		Offline vs	**PMR**						
LGI	L Superior Temporal	.760 ± 1.443	-.393 ± 1.900	-44	-32	2	1633	6.030	.000
LGI	R Insula	.270 ± 1.896	-.800 ± 1.480	34	3	6	1118	3.792	.009
		Online vs	**PMR**						
Area	R Postcentral	.038 ± .136	-.172 ± .282	14	-39	74	228	5.627	.017

NVts: The number of vertices contained in the cluster; **Annot:** Brain region where ROI are located (defined by the DK atlas); **LGI:** local Gyrification Index; **Offline:** Face-to-face Mindfulness Meditation; **Online:** Online Mindfulness Meditation; **PMR:** Progressive Muscle Relaxation; ***t*:** t-value of the peak; ***p*:** Whole-brain correction was applied using Monte Carlo simulation (FreeSurfer default settings; two-tailed; hemisphere-wise correction).Significance thresholds were set at voxel-level $p < 0.001$ and cluster-level $p < 0.05$. For between-group comparisons (three groups), a Bonferroni-corrected threshold of $p < 0.0167$ was used; **a:** The mean and standard deviation of the cortical measurements change rate calculated by FreeSurfer in units of years. The change rate is defined as (Post measure – Pre measure)/(Post time – Pre time). **Note:** All t-values have degrees of freedom 95.

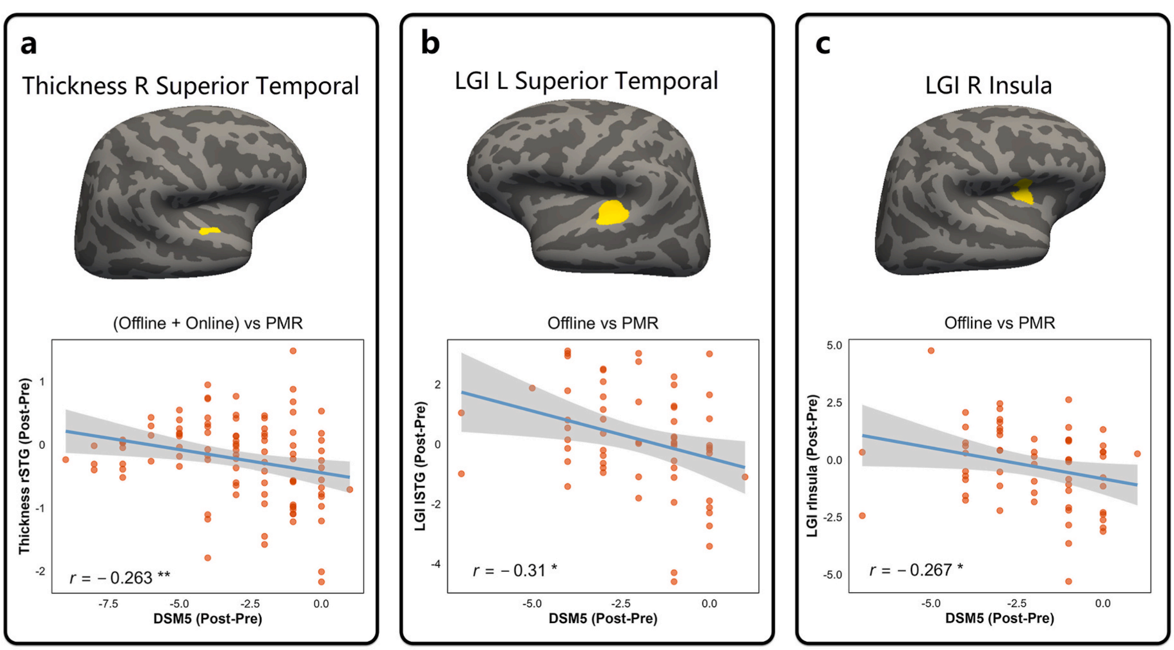

Fig. 3. Group Differences in Cortical Morphology. a shows that the mindfulness group (offline + online) exhibited a significant increase in cortical thickness of right temporal superior gyrus compared to the PMR group (t (95) = 4.725, $p = 0.014$). Additionally, as DSM-5 scores decreased, participants demonstrated an increase in the thickness of right temporal superior gyrus (DSM-5: $r = -.263$, $p = 0.007$). **b** and **c** show that the offline group compared to PMR exhibited significant increases in LGI at the left temporal superior gyrus (t (95) = 6.030, $p < 0.001$) and the right insula (t (95) = 3.792, $p = 0.009$). Furthermore, as DSM-5 scores decreased, participants exhibited gradual increases in the left temporal superior gyrus ($r = -.310$, $p = 0.015$) and the right insula LGI ($r = -.267$, $p = 0.037$). **LGI**: local Gyrification Index; **Offline**: Face-to-face Mindfulness Meditation; **Online**: Online Mindfulness Meditation; **PMR**: Progressive Muscle Relaxation; **IAT**: Internet Addiction Test; **DSM5**: Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, Text Revision.

have indicated that MM can alter sensory-related networks involving regions such as the temporal gyrus and insula (Kilpatrick et al., 2011).

In other words, while IGD may lead to a reduction in cortical thickness at the temporal gyrus, MM appears to enhance the function and structure of this region. Therefore, our results suggest that MM may help alleviate the severity of IGD by promoting increases in cortical

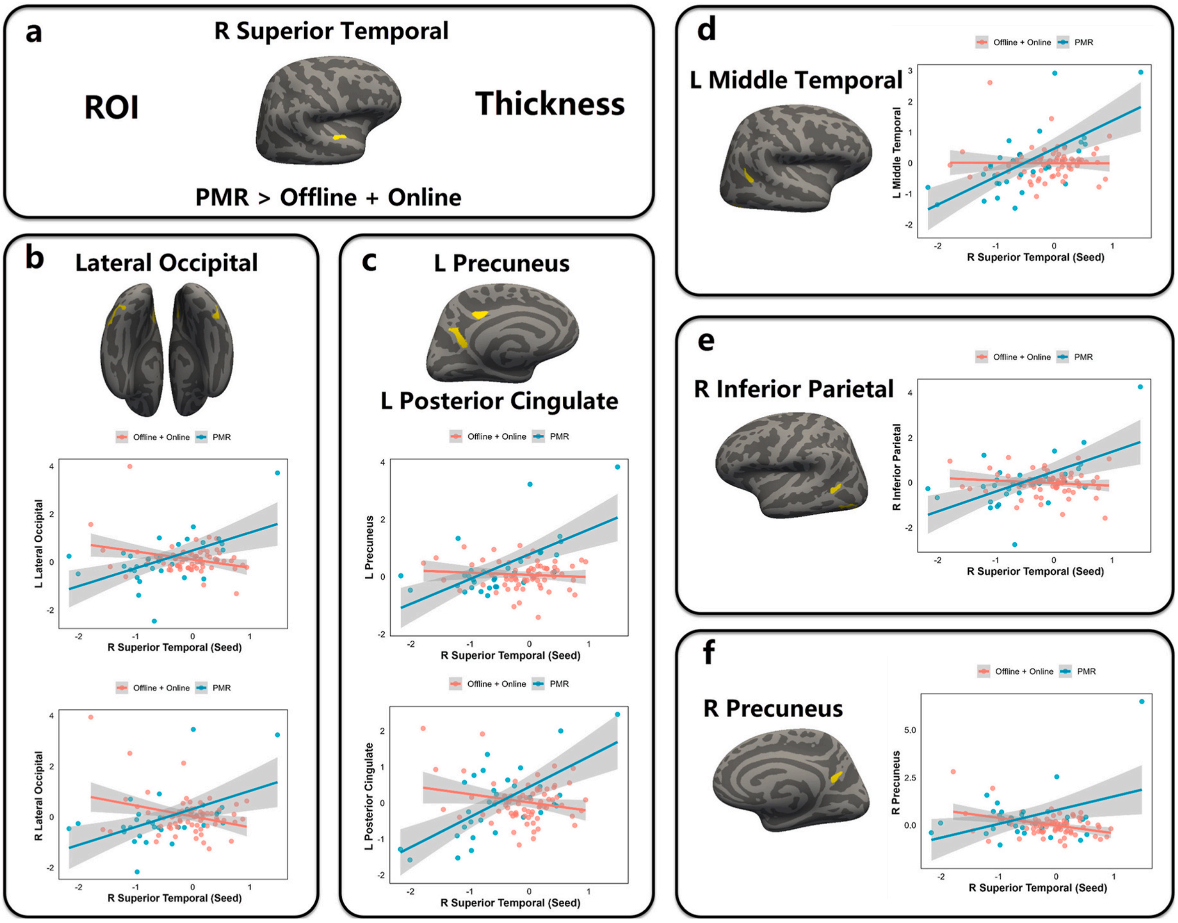

Fig. 4. Group Differences in Seed-Based Structural Covariance Analysis
The results indicated that when using the cortical thickness of the right superior temporal gyrus as a ROI (Fig. 4a), the covariance in the mindfulness group (Offline + Online) was significantly decreased than the PMR group in several brain regions (see Table 3 and Fig. 4). Specifically, the PMR group showed significantly greater structural covariance in the left superior temporal gyrus with the left lateral occipital lobe (t (95) = 4.140, p = 0.016, Fig. 4b), precuneus (t (95) = 4.757, p = 0.006, Fig. 4c), middle temporal gyrus (t (95) = 4.481, p = 0.011, Fig. 4d), posterior cingulate gyrus (t (95) = 5.390, p = 0.004, Fig. 4c), right inferior parietal lobe (t (95) = 4.568, p = 0.010, Fig. 4e), lateral occipital lobe (t (95) = 4.177, p = 0.016, Fig. 4b), and precuneus (t (95) = 4.416, p = 0.012, Fig. 4f). All results were corrected for False Discovery Rate (FDR). **Offline**: Face-to-face Mindfulness Meditation; **Online**: Online Mindfulness Meditation; **PMR**: Progressive Muscle Relaxation.

Table 3
Group differences in seed-based structural covariance.

Seed Region	Annot	MNI (X Y Z)			NVts	*t*	*p*
Thickness R Superior Temporal PMR > Off + On	L Lateral Occipital	−45	−74	−5	320	4.140	.016
	L Precuneus	−3	−60	28	662	4.757	.006
	L Middle Temporal	−54	−62	−11	245	4.481	.011
	L Posterior Cingulate	−5	−32	44	429	5.390	.004
	R Inferior Parietal	51	−56	17	288	4.568	.010
	R Lateral Occipital	40	−76	−17	161	4.177	.016
	R Precuneus	2	−61	16	308	4.416	.012

NVts: The number of vertices contained in the cluster; **Annot:** Brain region where ROI are located (defined by the DK atlas); **PMR:** Progressive Muscle Relaxation; **Off:** Face-to-face; **On:** Online Mindfulness Meditation; ***t*:** t-value of the peak; ***p*:** False Discovery Rate (FDR-corrected) p-value. **Note:** All t-values have degrees of freedom 95.

thickness and LGI in the temporal gyrus.

Further, we observed that MM in IGD patients reduced the structural covariance between the right temporal gyrus and the default mode network (including the posterior cingulate gyrus, precuneus, and lateral occipital lobe), as well as between the right temporal gyrus and the auditory-sensory network (regions in the parietal-occipital lobe) (see Fig. 3). This aligns with previous findings, which have shown that MM reduces activity and network connectivity in the default mode network, associated with decreased mind-wandering and enhanced attention (Brewer et al., 2011; Zhang et al., 2023). Consequently, the reduction in covariance between the temporal gyrus and the default and the auditory networks suggests that MM may improve internal awareness and attention, ultimately shifting focus away from external game stimuli and towards the individual's internal experiences (Chen et al., 2021).

4.2.2. *Increased cortical LGI in the right insula*

It is well-known that the insula plays a central role in MM, as it is involved in interoceptive integration, emotional responses, and subjective awareness (Sharp et al., 2018). Studies have also shown that MM leads to increased cortical thickness in the insula (Zeidan and Vago, 2016). On the other hand, the insula, as the core of the interoceptive system, plays a critical role in perceiving bodily signals related to the deprivation of game rewards in IGD and converting these signals into subjective desires (Turel et al., 2021). Research has found abnormal reductions in grey matter density of the insula in IGD individuals (H. Wang et al., 2015). Moreover, studies have also shown that MM can increase the grey matter volume in the insula of opioid-dependent patients (Wolf et al., 2022), which is similar to the findings of our study.

We observed that face-to-face MM increased the cortical LGI in the insula, and this change was more pronounced with a decrease in DSM-5 scores. To summarize, IGD leads to a reduction in structural morphological features in the insula, while MM has the opposite effect. Therefore, this suggests that MM may help alleviate the severity of IGD by enhancing the cortical LGI in the insula of individuals with IGD.

The MM group (Offline + Online) showed differences in cortical area and thickness, while the face-to-face MM group exhibited significant LGI changes. LGI reflects cortical geometric features, including sulcal curvature and complexity (Schaer et al., 2008), and has been linked to addictive disorders (Cerasa et al., 2014; Hu et al., 2022; Sullivan et al., 2020; Trevisan et al., 2023).

For instance, Cao et al. (2025) reported reduced LGI in the postcentral gyrus, temporal gyrus, insula, and parietal lobe in alcohol-dependent patients. As a marker of neuronal connectivity influenced by white matter tension (Herculano-Houzel et al., 2010), LGI is closely tied to cognitive function and activity (Im and Grant, 2019). This suggests that face-to-face MM primarily impacts IGD cortical morphology through geometric structural changes related to connectivity and function.

4.2.3. Increased cortical area in the right postcentral gyrus

In our study, individuals with IGD in the online MM group showed a marginally significant increase in the cortical area in the right postcentral gyrus compared to the PMR group, and this increase was associated with a reduction in IGD severity. A similar pattern was observed in the combined mindfulness group (online + offline) (t (95) = 4.942, p = 0.045, uncorrected across the three-group comparison), with cortical area increases significantly correlated with symptom improvement (IAT: $r = -.206$, $p = 0.038$; DSM-5: $r = -.253$, $p = 0.011$). However, these between-group effects did not survive correction for multiple comparisons and should be interpreted with caution.

The postcentral gyrus, a key region of the sensorimotor cortex, is critically involved in processing somatosensory input and contributes to bodily and self-perception (Salvato et al., 2020). Given that enhancing bodily awareness is a central aim of mindfulness training, structural changes in this region may reflect the neural effects of such interventions. Supporting this, previous studies have reported increased activation and strengthened connectivity in the postcentral gyrus following mindfulness-based practices (Xiao et al., 2019).

In line with these findings, our study showed that individuals with IGD who received mindfulness training—particularly in the online format—exhibited increased cortical area in this region, which was associated with reductions in IGD severity. Although these group differences did not survive correction for multiple comparisons, the observed pattern suggests a potential link between mindfulness-induced bodily awareness and structural plasticity in the postcentral gyrus. These preliminary findings warrant further investigation in studies with larger samples and more stringent statistical thresholds.

4.2.4. Potential effects of mindfulness on comorbid symptoms in IGD

A growing body of research suggests that mindfulness can alleviate symptoms of anxiety and depression (Goldberg et al., 2019; Hofmann and Gómez, 2017), likely by enhancing emotional awareness and promoting non-reactive, accepting attitudes toward internal states (Roemer et al., 2015). At the neural level, this may involve brain regions such as the default mode network (Hölzel et al., 2011), the insula (Siew and Yu, 2023), and the somatosensory areas (Kerr et al., 2013)—regions also implicated in our current findings. However, our study specifically focused on the core symptoms of IGD and excluded participants with a comorbid mood or anxiety disorders. This finding suggests that mindfulness may exert therapeutic effects on IGD independently of emotional comorbidities, possibly by modulating aberrant self-related processing underlying addictive behaviors, particularly craving for gaming. Nevertheless, it is also possible that mindfulness plays a mediating role in treating IGD by improving comorbid emotional symptoms—a possibility that warrants further investigation.

5. Conclusions

This study demonstrates that MM training, both online and face-to-face, effectively reduces the severity of IGD and increased cortical morphological features in the bilateral superior temporal gyrus and the insula. These findings offer empirical support for the neuroanatomical mechanisms through which MM enhances self-awareness, revealing potential neural anatomical targets for improving IGD.

CRediT authorship contribution statement

Haohao Dong: Writing – original draft, Formal analysis. **Huabin Wang:** Data curation. **Xuefeng Xu:** Data curation. **Xuefeng Ma:** Data curation. **Haosen Ni:** Data curation. **Chang Liu:** Methodology, Data curation. **Xiaolan Song:** Methodology, Data curation. **Guangheng Dong:** Writing – review & editing, Methodology, Conceptualization. **Renlai Zhou:** Writing – review & editing.

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Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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