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Transformative Effects of Mindfulness Meditation Training on the Dynamic Reconfiguration of Executive and Default Mode Networks in Internet Gaming Disorder

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ABSTRACT

BACKGROUND: Internet gaming disorder (IGD) is a pervasive global mental health issue, and finding effective treatments for the disorder has been challenging. Mindfulness meditation (MM), recognized for its holistic approach that involves integrating mental and physical facets, holds promise for addressing the multifaceted nature of addiction. Nevertheless, the effect of MM on IGD and its associated neural networks, particularly in terms of their dynamic characteristics, remains elusive.

METHODS: A total of 61 eligible participants with IGD (30 in the MM group, 31 in the progressive muscle relaxation [PMR] group) completed the experimental protocol, which involved pretest, an 8-session MM/PMR training regimen, and posttests. The 142 brain regions of interest were categorized into 5 brain networks using dynamic network reconfiguration analysis based on Shen's functional template. A comparative analysis of network dynamic features, including recruitment and integration coefficients, was performed across different groups and tests using resting-state functional magnetic resonance imaging data.

RESULTS: While clinically nonspecific effects were observed in the PMR group, the MM group exhibited a significant reduction in addiction severity and cravings. In the dynamic brain network, MM training increased the recruitment coefficient within the frontoparietal network (FPN) and basal ganglia network (BGN) but decreased it within the default mode network (DMN). Furthermore, MM training increased the integration coefficient in the FPN-DMN and DMN–limbic network (LN).

CONCLUSIONS: MM has demonstrated pronounced efficacy in treating IGD. MM may enhance top-down control functions, cognitive and emotional functions, and reward-system processing, potentially through the reconfiguration of the FPN-DMN pathway, DMN-LN pathway, and BGN.

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Internet gaming disorder (IGD) is categorized as a class of disorders that stem from addictive behaviors associated with abnormal interactions within extensive cerebral network systems (1–4). It is officially recognized in DSM-5 (5). Individuals with IGD are characterized by persistent engagement in gaming activities (6) and exhibit symptoms such as diminished executive function (7), reward deficiency (8), compromised impulse control mechanisms (9), and enhanced craving (10,11).

The pervasiveness of IGD is considerable, eliciting a myriad of deleterious effects. For example, IGD has been linked to impairment in psychological functioning, which manifests in adverse outcomes such as depression, anxiety, and aggressive behaviors (12–15). Moreover, the repercussions of IGD extend into the social domain and encompass diminished academic performance, heightened stress levels, and inadequate sleep (16–18). Consequently, there exists an imperative to develop sophisticated and effective strategies for the prevention and intervention of IGD.

In recent years, there has been a discernible acceleration in the pace of research dedicated to the treatment of IGD (19). Researchers have explored a diverse array of therapeutic modalities, ranging from cognitive behavioral therapy (CBT), pharmacotherapeutic interventions, and family-based therapeutic modalities to motivational interviewing techniques and specialized solution-focused therapies tailored to meet the unique needs of adolescent populations, among other approaches (20). While these treatment methods advance the progress of research in IGD intervention, they also exhibit certain limitations and often yield outcomes that fall short of optimal efficacy. Specifically, studies of CBT have been limited by constraints such as relatively limited sample sizes (21–24). Testing the effectiveness of pharmacotherapeutic interventions is challenging in the absence of randomized control groups (19,25,26), while other research endeavors have also been marked by inadequate experimental design and the absence of well-defined efficacy metrics (19). IGD intervention research clearly remains at an early developmental stage, necessitating comprehensive exploration and advancement.

Mindfulness meditation (MM) has attracted global attention and has undergone rigorous evaluation over recent decades for its efficacy in treating substance use disorders (27). MM has been integrated into the realm of psychological interventions, representing the third wave of behavior therapy (28). MM offers a multitude of advantages in ameliorating core symptoms of IGD and addressing its concomitant comorbidities. First, IGD is characterized by an intense craving for gaming and an inability to regulate this craving (29,30). MM has a rich history in craving control, with beneficial outcomes being attributed to the interruption of craving-related cognitive elaboration through the methods of present-moment awareness. The classic "urge surfing" technique is effective at reducing cravings by methodically deconstructing the intricate facets of the craving experience, which encompass its cognitive, affective, and sensorial dimensions (31,32). In summary, MM has the capacity to aid individuals with IGD in their efforts to effectively manage and suppress cravings. Nevertheless, there remains a gap in understanding the intricate neural mechanisms that underlie the effects of MM on cravings.

Second, the fundamental core symptoms in individuals with IGD are rooted in extensive alterations within their functional brain networks (1). Our previous studies have suggested that the disruption in the equilibrium among the affective system (including limbic and subcortical areas), cognitive control system (including frontoparietal areas), and reward system (including the basal ganglia network [BGN]) is a pivotal mechanism that underlies both the onset and persistence of IGD (11,18,33–37). IGD is characterized by a deficiency in top-down control mechanisms (30) that makes individuals with the disorder incapable of effectively engaging and sustaining the prefrontal-striatal network to regulate cravings and pursuit behaviors, which results in their excessive engagement in gaming activities (38). MM facilitates the enhancement of top-down regulation in cognitive processes, which has been shown to augment self-control, attention regulation, and working memory (39). Studies have suggested that seasoned meditators exhibit heightened activity in the anterior cingulate cortex and medial prefrontal cortex (PFC), which signifies the presence of top-down regulatory mechanisms (40). The studies mentioned above offer substantiating evidence that MM has the potential to exert regulatory influence over neural networks implicated in IGD.

Individuals with IGD have also exhibited comorbidities with various other psychiatric disorders, including depressive disorder (41). In this context, MM shows remarkable breadth, having the capacity to influence a diverse array of cerebral regions (42). Consequently, MM is progressively gaining recognition as a form of holistic mind-body medicine poised to address the multifaceted dimensions of addiction, which include physical, psychological, and spiritual aspects (43). Synthesizing the 3 points mentioned above, it becomes evident that MM holds substantial promise for the treatment of IGD.

Previous network-based investigations into IGD have predominantly assumed the stability of connections between brain networks over time (30,44). However, a notable gap in these studies is the limited attention devoted to the dynamic aspects of brain networks associated with IGD. It is essential to acknowledge the intricate nature of the human brain—a complex and dynamic system wherein spatial patterns of networks undergo constant flux (45). Furthermore, IGD-related functional connectivity may exhibit reduced flexibility or excessive instability, characteristics that static analyses cannot effectively capture. In contrast, dynamic analyses reveal temporal variations in brain network organization, offering a more comprehensive understanding of the neural mechanisms that underlie IGD. Therefore, exploring these dynamic features is crucial for understanding how MM may contribute to the restoration of compromised brain networks in individuals with IGD (30).

In one study, individuals with IGD exhibited a lower recruitment coefficient within the right executive control network (ECN) than individuals with regular gaming use (30). This finding underscores the dynamic network disruption characteristic of IGD. Furthermore, the application of dynamic network reconfiguration extends beyond IGD and has been examined in relation to other psychiatric conditions, such as attention-deficit/hyperactivity disorder (46) and major depressive disorder (47). These findings not only bolster our understanding of the intricate dynamics that govern brain functional networks but also provide invaluable support for the exploration of dynamic network reconfiguration as an indispensable avenue for elucidating the neural mechanisms that underlie various psychiatric disorders.

Building on previous research findings, we focused on 5 IGD-related brain networks: the medial frontal network (MFN), frontoparietal network (FPN), limbic network (LN), default mode network (DMN), and BGN. The primary aim of this study was to evaluate the effects of MM treatment on IGD and to examine the dynamic changes in brain network characteristics following the treatment. We posited that MM treatment would lead to a reduction in craving intensity and DSM-5 scores, accompanied by an improvement in the dynamic interaction of disrupted brain networks.

METHODS AND MATERIALS

Ethics

The study adhered to the Code of Ethics set forth by the World Medical Association and was executed in accordance with the principles of the Declaration of Helsinki. This research received approval from the Human Investigations Committee of Yunnan Normal University. Written informed consent was obtained from all participants before initiation of the experiment. The trial protocol was duly registered with the Chinese Clinical Trial Registry (ChiCTR2300075869).

Participants

Participants were recruited via advertisements and underwent the Internet Addiction Test (IAT) and DSM-5 assessments. Individuals with IAT scores >50 and DSM-5 scores >5 were selected to participate in the experiment.

Initially, there were 80 participants (MM = 40, progressive muscle relaxation [PMR] = 40), but 19 dropped out during the intervention training (MM = 10, PMR = 9), which resulted in a final cohort of 61 participants (MM = 30, PMR = 31). The exclusion criteria for participants are provided in the Supplement.

Groups

Figure 1 describes the intervention training program. Figure 2A to D illustrates the entire research protocol. All eligible participants were randomly assigned in a 1:1 ratio to either the mindfulness training group (30 individuals) or the control group (31 individuals), where individuals in the latter group were instructed to engage in PMR. None of the participants were aware of the presence of the other group. Detailed demographic information for the eligible participants in each group is presented in Table 1. The training process for the 2 groups is provided in the Supplement.

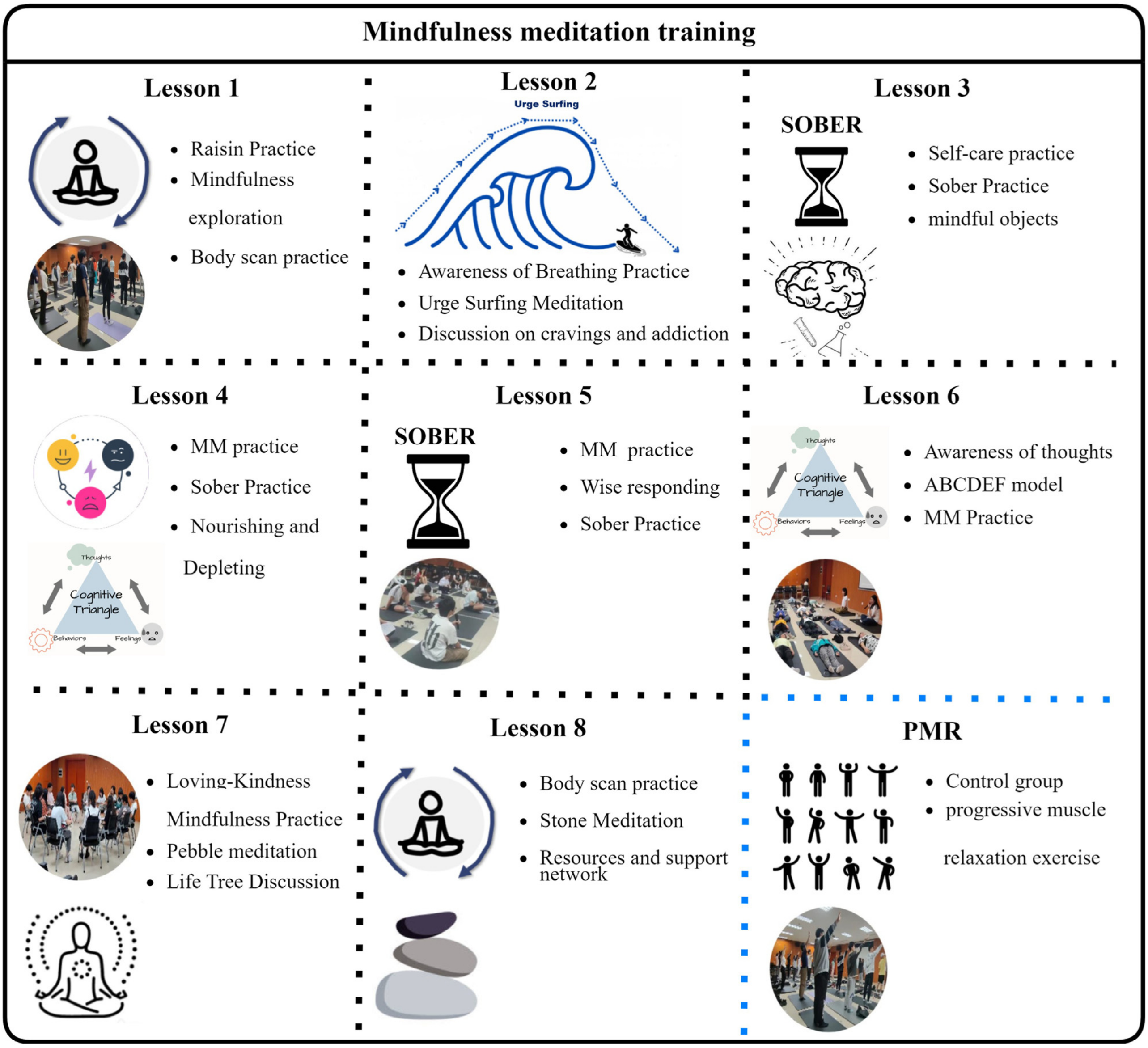

Figure 1. Eight-session mindfulness meditation (MM) training and progressive muscle relaxation (PMR) exercise. Foundational practices (lesson 1): introduction to foundational exercises such as raisin practice, mindfulness exploration, and body scan. Breath and cravings (lesson 2): focus on awareness of breathing, urge surfing meditation, and group discussions on managing cravings and addiction. Mindful engagement (lesson 3): incorporation of practices such as mindful street walking, self-care, sober engagement, and connection with small mindful objects. Challenging situations (lesson 4): MM practices emphasizing nourishing and depleting elements and techniques for maintaining sobriety in challenging situations. Social practices (lesson 5): MM practice, paired sober exercises, and training in wise responding to various situations. Cognitive awareness (lesson 6): exploration of thoughts, application of the ABCDEF model, classroom practice, and group discussions on the relapse cycle. Loving-kindness focus (lesson 7): introduction to loving-kindness mindfulness practice, pebble meditation, and discussions on life trees. Closure and continuation (lesson 8): final lessons include body scan practice, stone meditation, and discussions on resources and support networks for ongoing mindfulness practice. The control group underwent 8 sessions of PMR exercises.

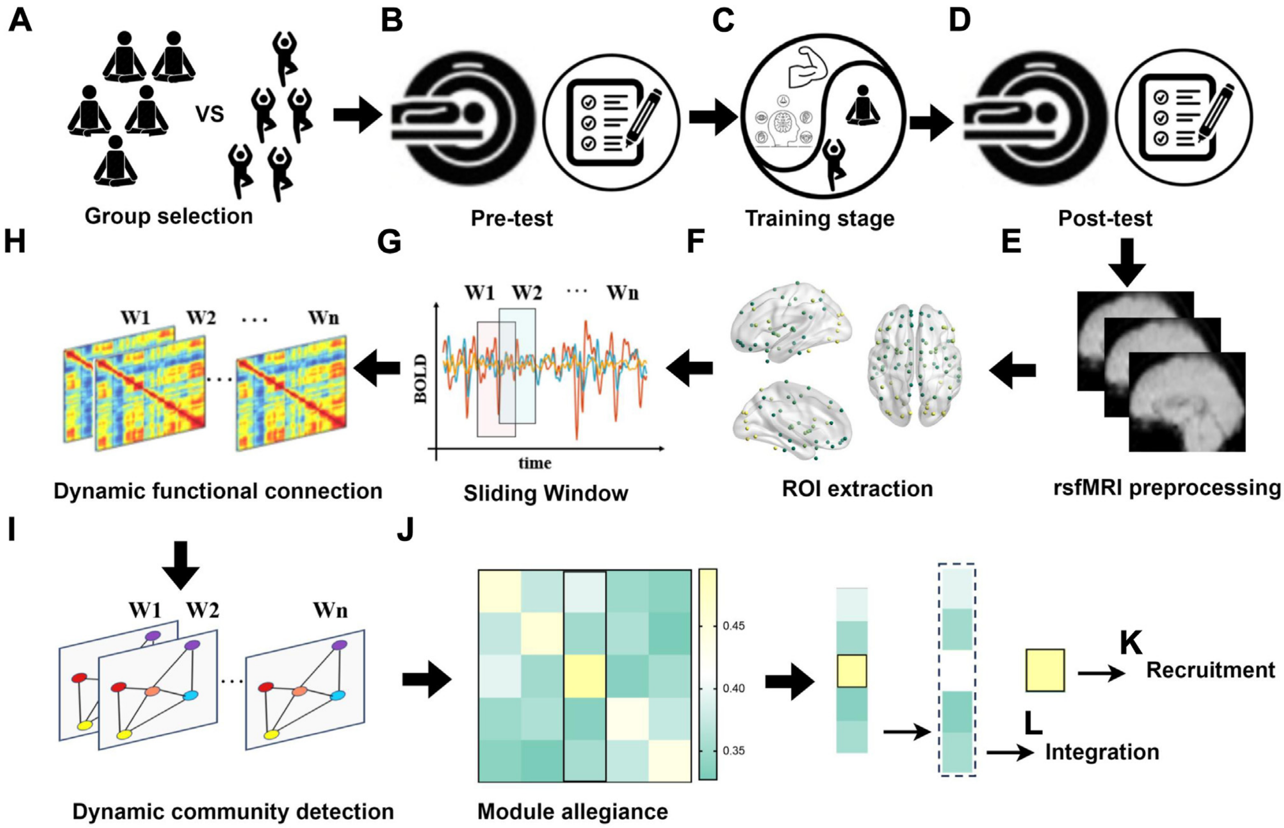

Figure 2. Overview of the experimental process and dynamic network analysis. **(A)** Comparative analysis of resting-state functional magnetic resonance imaging (rsfMRI) datasets in the mindfulness meditation (MM) and progressive muscle relaxation (PMR) groups. **(B)** The pretest phase included an rsfMRI scan and completion of the DSM-5 and gaming craving questionnaire. **(C)** Participants underwent 8 training sessions of either MM or PMR. **(D)** The posttest phase included an rsfMRI scan and the completion of the DSM-5 and gaming craving questionnaire and **(E)** preprocessing of rsfMRI datasets. **(F)** Shen's region of interest (ROI) atlas was used to construct the brain network. **(G)** Time-series data were extracted from 142 ROIs using rsfMRI, using a sliding window strategy (length/step = 15/1 TR, 222 windows in total). **(H)** Estimation of functional connections within each layer was performed using Pearson's correlations. **(I)** Dynamic community structure was identified using the generalized Louvain community detection algorithm. **(J)** Module allegiance matrix. **(K)** Calculation of the recruitment coefficient. **(L)** Calculation of the integration coefficient. BOLD, blood oxygen level–dependent.

Behavioral Measure (Before and After Training)

Before and after the training sessions, the assessment of addiction severity in all participants was conducted based on the criteria outlined in DSM-5. Cravings were evaluated through a revised gaming questionnaire (adapted from the Tiffany Questionnaire for Smoking Urges) at 3 time points: before the initial training, following each training session, and 1 month after the completion of the entire training program. Mindfulness level was measured using the Five Facet Mindfulness Questionnaire.

Table 1. Demographic Characteristics of Participants With Internet Gaming Disorder

	MM, *n* = 30		PMR, *n* = 31	
	Before	After	Before	After
Age, Years	20.33 (1.94)	20.33 (1.94)	20.19 (1.52)	20.19 (1.52)
Sex, Female/Male	16/14	16/14	16/15	16/15
DSM-5 Score	6.97 (0.18)	3.47 (0.23)	7.10 (0.18)	6.36 (0.23)
Craving	59.17 (2.56)	34.37 (2.17)	57.97 (2.52)	51.29 (2.13)

Values are presented as mean (SD) or *n*.

MM, mindfulness meditation; PMR, progressive muscle relaxation.

Resting-State Data Collection and Preprocessing

Resting-state functional data in the form of T2*-weighted images were obtained using a 3T GE Sigma magnetic resonance imaging (MRI) scanner. The parameters for resting-state data collection are provided in the Supplement. Data preprocessing was performed using DPABI V5.3, including (Figure 2E): 1) removal of the first 10 time points, 2) slice timing correction, 3) head motion correction and scrubbing, 4) registration to standard Montreal Neurological Institute space, 5) spatial smoothing using a 3-dimensional isotropic Gaussian kernel with a full width at half maximum of 4 mm, 6) removal of the linear trends, 7) nuisance covariate regression, and 8) filtering with a 0.008–0.1 Hz bandpass filter.

Dynamic Network Reconfiguration Analysis

Multilayer Network Construction. We utilized the Gretna toolbox (https://www.nitrc.org/projects/gretna/) to generate dynamic functional connectivity matrices based on Shen's brain atlas (Figure 2F), which delineates 10 resting-state networks. The MFN, FPN, DMN, LN, and BGN were specifically extracted for the current analysis.

Previous studies have established that a 30-second time window provides a robust and reliable method for quantifying dynamic network reconfiguration (48,49). In this study, we followed this suggested methodological approach and used 30-second windows (15 TR) with a step length of 2 seconds (1 TR) (50), which resulted in a total of 222 windows (236 time points) (Figure 2G). Within each window, functional connectivity was calculated for every pair of regions of interest (ROIs), which yielded a 142 $\times$ 142 adjacency matrix for each participant (Figure 2H).

Multilayer Community Detection. We utilized the GenLouvain multilayer community detection algorithm (https://github.com/GenLouvain/GenLouvain) to identify brain communities characterized by heightened functional connections within themselves (51). The detailed procedure is provided in the Supplement.

Module Allegiance. Module allegiance represents the persistent coherence in the assignment of communities between 2 ROIs over time (52,53). This concept is visualized using a square matrix of dimensions 142 $\times$ 142, where each element indicates the frequency with which 2 particular nodes coexist within the same community throughout the scanning procedure (Figure 2J). It can be described as

$$P_{ij} = \frac{1}{OT} \sum_{0=1}^{0} \sum_{t=1}^{T} a_{i,j}^{k,o} \quad (1)$$

where O represents the repetitions of the multilayer community detection algorithm, T represents the number of layers, and the matrix element $a_{i,j}^{k,o}$ = 1 if nodes i and j share the same community and = 0 otherwise.

Recruitment and Integration. Using the module allegiance matrix, we computed recruitment and integration coefficients to elucidate the dynamic interactions within and between networks, thereby illustrating the transient aspects of intra- and internetwork communication. Recruitment is quantified as the probability of an ROI being assigned to the same community as nodes that originate from the same network (Figure 2K), and it is defined as

$$R_i^N = \frac{1}{m_N} \sum\nolimits_{j \in N} P_{ij} \quad (2)$$

where m_N is the number of regions in module N, and P_{ij} represents the proportional occurrence of nodes i and j being allocated to the same community throughout the temporal domain. A node with heightened recruitment shows a preference for forming connections predominantly with nodes from its own network within the temporal domain.

The integration coefficient gauges the average likelihood of node i being part of the same community as nodes from different networks (Figure 2L). It is calculated using the following equation:

$$I_i^N = \frac{1}{K - m_N} \sum\nolimits_{j \notin N} P_{ij} \quad (3)$$

where K is the total number of nodes.

Statistical Analyses

Firstly, a rigorous examination of the interaction effects involving training time (pretraining or posttraining) and MM group or PMR group was conducted using a repeated-measures analysis of variance. Training time served as a within-subject factor, while group constituted a between-subject factor, encapsulating both behavioral scores and dynamic metrics. Secondly, Spearman correlation analysis was used to scrutinize correlations between brain network dynamics and behavioral features in the MM group. Finally, following the correlation analysis, an exploration of the predictive interrelations between these variables was undertaken using linear regression analysis.

To address the issue of multiple comparisons, false discovery rate (FDR) correction was applied to all findings. The threshold for identifying statistically significant differences was set at $p < .05$.

RESULTS

Behavioral Results

For DSM-5 scores, a significant treatment time $\times$ group interaction was observed ($F_{1,59}$ = 76.508, $p_{\text{Bonferroni}} < .001$, η^2 = 0.565). A simple effect analysis revealed a reduction in DSM-5 scores following training in the MM group (mean = 3.47, SD = 0.23) compared with the pretraining level (mean = 6.97, SD = 0.18) ($p_{\text{Bonferroni}} < .001$) while the PMR group had lower DSM-5 scores on average after training (mean = 6.36, SD = 0.23) than before PMR training (mean = 7.10, SD = 0.18) ($p_{\text{Bonferroni}}$ = .001). The magnitude of change in mean scores (changes [after − before] = −0.74) in the PMR group was smaller than in the MM group (changes [after − before] = −3.5), suggesting the potential influence of clinically nonspecific effects (Figure 3A).

For game craving scores, we found a significant treatment time $\times$ group interaction ($F_{1,59}$ = 23.149, $p_{\text{Bonferroni}} < .001$, η^2 = 0.282). Specifically, game craving scores after training in the MM group (mean = 34.37, SD = 2.17) were lower than before training (mean = 59.17, SD = 2.56) ($p_{\text{Bonferroni}} < .001$). Similarly, in the PMR group, scores after training (mean = 51.29, SD = 2.13) were lower than before training (mean = 57.97, SD = 2.52) ($p_{\text{Bonferroni}}$ = .014), suggesting clinically nonspecific effects (change: −24.8 vs. −6.68) (Figure 3B).

Recruitment and Integration

A 4-week mindfulness meditation training regimen demonstrated a profound impact on the dynamic brain network features (i.e., recruitment and integration coefficients) in individuals with IGD. First, we observed that the MM training altered the dynamic community structure within the FPN. For recruitment, a significant treatment time $\times$ group interaction was observed in

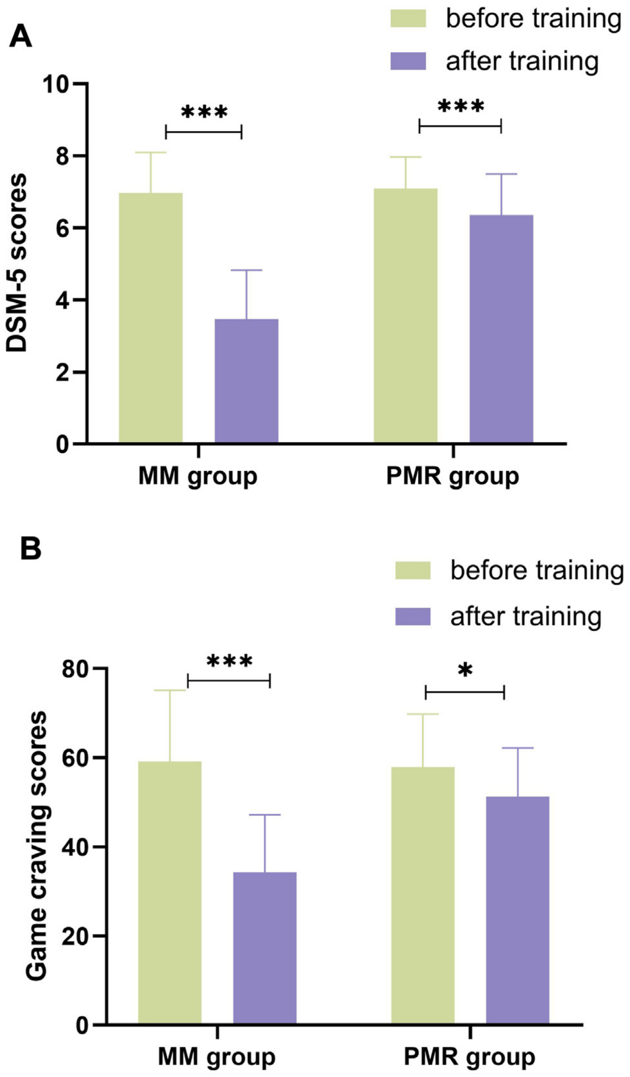

Figure 3. Differences in behavioral results after training between the mindfulness meditation (MM) and progressive muscle relaxation (PMR) groups. **(A)** Changes in DSM-5 questionnaire scores. **(B)** Changes in gaming craving scores. Asterisks indicate significant group differences: *$p < .05$, ***$p < .001$.

the FPN ($F_{1,59}$ = 5.300, $p_{\text{Bonferroni}}$ = .025, p_{FDR} = .0313, η^2 = 0.082). Simple effect analysis showed that in the MM group, the recruitment coefficient increased after MM training compared with pretraining ($p_{\text{Bonferroni}}$ = .024) (Figure 4E). In contrast, there were no statistically significant differences before and after training in the PMR group ($p_{\text{Bonferroni}}$ = .355) (Figure 4F). For integration, when we set the FPN as the network of interest, we observed a marginally significant main effect of treatment time between the FPN and DMN ($F_{1,59}$ = 4.387, $p_{\text{Bonferroni}}$ = .041, p_{FDR} = .071, η^2 = 0.069). To rule out any clinically nonspecific effects of MM training, a paired *t* test was performed for both groups. The findings indicated an increase in the integration coefficient after training in the MM group compared with pretraining (t_{29} = −2.072, p = .047) (Figure 4G). However, no significant difference was observed in the PMR group (t_{30} = −0.972, p = .339) (Figure 4H).

Furthermore, our investigation revealed that MM training induced modifications in the dynamic characteristics exhibited by the DMN region. For recruitment, a significant main effect of treatment time within the DMN emerged ($F_{1,59}$ = 18.758, $p_{\text{Bonferroni}} < .001$, $p_{\text{FDR}} < .001$, η^2 = 0.241). To corroborate the effects of MM training, paired *t* tests were subsequently conducted, which revealed a statistically significant reduction in the recruitment coefficient from pre- to posttraining in both the MM and PMR groups (MM group: t_{29} = 3.086, p = .004; PMR group: t_{30} = 3.088, p = .004) (Figure 4E, F). For integration, when the DMN was designated as the focal network of interest, a main effect of treatment time was identified between the DMN and LN ($F_{1,59}$ = 19.248, $p_{\text{Bonferroni}} < .001$, $p_{\text{FDR}} < .001$, η^2 = 0.246). Furthermore, a parallel paired *t* test analysis revealed that training elicited an increase in the integration coefficient in the MM group (t_{29} = −4.488, $p < .001$) (Figure 4G). Moreover, the integration coefficient displayed an ascending trajectory following training in the PMR group but without reaching a statistically significant level (t_{30} = −1.813, p = .080) (Figure 4H).

Moreover, discernible shifts in dynamic network characteristics were observed within the BGN following MM training. Specifically, a significant main effect of treatment time was identified for recruitment ($F_{1,59}$ = 6.911, p = .011, p_{FDR} = .0217, η^2 = 0.105). Next, a paired *t* test was conducted for a more detailed analysis. The recruitment coefficient increased after training in the MM group compared with pretraining (t_{29} = −2.403, p = .023) (Figure 4E). Conversely, no statistically significant difference was observed in the PMR group (t_{30} = −1.463, p = .154) (Figure 4F). However, no significant difference in the integration coefficient was observed between BGN and other networks.

Regarding MFN and LN, only the main effect of treatment time on the recruitment coefficient reached statistical significance (MFN: $F_{1,59}$ = 6.596, p = .013, p_{FDR} = .0217, η^2 = 0.101; LN: $F_{1,59}$ = 4.332, p = .042, p_{FDR} = .042, η^2 = 0.068). Subsequent in-depth analyses did not yield any other statistically significant findings.

Correlations Between Behavioral Measures and Dynamic Network Features

For a more in-depth examination, we examined correlations between behavioral patterns and the dynamic attributes of network features. We observed that the recruitment coefficient within the FPN before MM training was positively correlated with the change in DSM-5 scores (after − before) (r = 0.520, p_{FDR} = .015).

Unitary Linear Regression Analysis

Based on the correlations mentioned above, we used a unitary linear regression analysis to further explore the quantitative relationship between the 2 variables. The results revealed statistical significance for the regression model established with FPN recruitment before MM training and the change in DSM-5 scores ($F_{1,28}$ = 10.393, p = .003, R^2 = 0.271). The regression equation is represented as follows: Y (change in DSM-5 scores) = −14.502 + 25.003 × X (FPN recruitment coefficient before MM training), where SD = 7.756 and beta = 0.520 (Figure 4I).

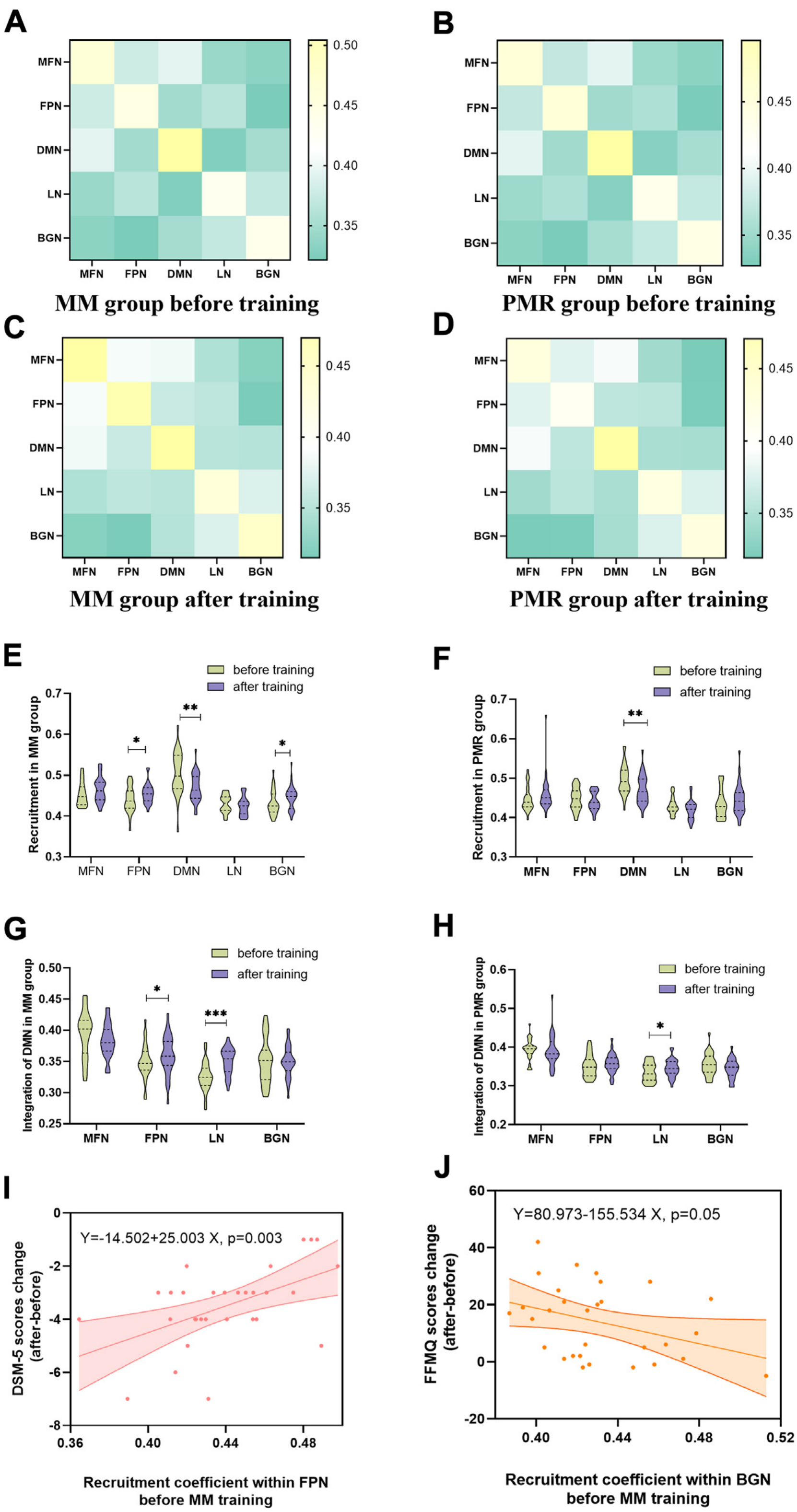

Figure 4. Differences in altered dynamic network features after training between the mindfulness meditation (MM) and progressive muscle relaxation (PMR) groups. **(A)** Module allegiance in the MM group before training. **(B)** Module allegiance in the PMR group before training. **(C)** Module allegiance in the MM group after training. **(D)** Module allegiance in the PMR group after training. **(E)** Recruitment within 5 brain networks in the MM group. **(F)** Recruitment within 5 brain networks in the PMR group. **(G)** Integration between the default mode network (DMN) and other brain networks in the MM group. **(H)** Integration between the DMN and other brain networks in the PMR group. **(I)** Regression equation with DSM-5 questionnaire scores (change) and recruitment within the frontoparietal network (FPN) before MM training. **(J)** Regression equation with Five Facet Mindfulness Questionnaire (FFMQ) scores (change) and recruitment within the basal ganglia network (BGN) before MM training. Asterisks indicate significant group differences: *$p < .05$, **$p < .01$, ***$p < .001$. MFN, medial frontal network; LN, limbic network.

DISCUSSION

MM Training Improved Executive Function in Individuals With IGD by Increasing Communication Stability Within the FPN and FPN-DMN Pathway

Our findings indicate that MM training led to an increase in the recruitment coefficient within the FPN. In this context, recruitment signifies the probability of nodes within the same community between a cerebral region and other nodes within its network (54,55). A heightened recruitment coefficient suggests an increased propensity for intrasubsystem communication among regions within the network, which contributes to the system's robust stability (30). The FPN, encompassing connections between the prefrontal cortex and postparietal cortex, has been associated with multifaceted functionalities, especially cognitive control (56,57). Previous research suggested that individuals with IGD exhibit a diminished recruitment coefficient in the ECN, indicating impaired executive functioning (30). Our findings indicate that MM training contributed to enhancing the stability of executive control networks implicated in IGD. This augmentation results in consistent recruitment of specific brain regions during successive control tasks, thereby elevating the precision and effectiveness of executive control mechanisms.

Simultaneously, MM training increased the integration coefficient of FPN-DMN. Integration denotes the probability that a cerebral region shares the same community as other nodes within the network (54). A larger integration coefficient indicates an increased propensity for communication between brain regions within the designated system and those in other systems (30). Our results show that MM training increased the communication stability between the FPN and DMN. Consistent with our findings, studies have reported increased functional connectivity between the DMN and ventromedial PFC in individuals with a greater depth of meditation experience (58). The principal components of the DMN are the posterior cingulate cortex and the precuneus, which are related to self-referential cognition (59). Studies suggest that as individuals transition from sustained behavioral involvement to profound cognitive immersion, they may encounter a loss of control over their in-game conduct, thereby impeding or disrupting their executive functioning (60,61). Additionally, a study revealed that individuals with IGD demonstrated an inability to inhibit the activity of the DMN during the execution of a decision-making task, which resulted in subpar performance (62).

The collective findings from these studies suggest that IGD may stem from a compromised ability to regulate cognitive behaviors attributed to deficient or unstable communication between the executive control system and the DMN. This identified deficiency in the connectivity pathway between the FPN and DMN has proven to be a crucial factor in understanding IGD, where heightened interactions between these 2 brain networks may be associated with the inhibitory facets of executive control (63). A plausible mechanism through which MM training alleviates impaired executive control in IGD involves the enhancement of the internal stability of the FPN and the reinforcement of coherence in the FPN-DMN pathway. MM training facilitates this improvement by augmenting internal communication within the FPN, thereby enabling top-down regulation of the DMN. Consequently, this process diminishes narrative self-relevance among individuals with IGD. Ultimately, this therapeutic approach is aimed at disentangling individuals from cognitive immersion, fortifying inhibitory functions, and reducing susceptibility to cravings.

MM Training Improved Cognitive and Emotional Functions in Individuals With IGD by Decreasing Communication Stability Within the DMN and Reshaping the DMN-LN Pathway

Our investigation revealed that MM training led to a reduction in the recruitment coefficient of the DMN. A diminished recruitment coefficient suggests that brain regions within the system exhibit a lower preference for intrasystem communication. The DMN comprises interconnected brain regions responsible for intrinsic cognitive processes associated with automated self-referential processing and internal contemplation (64). Heightened activity in the DMN is often observed in individuals with IGD, potentially linked to excessive engagement in online gaming and deficits in self-referential processing (38). Our findings indicate that MM training diminishes the internal neural communication within the DMN, moderating the internal neural dynamics in individuals with IGD. This modulation may be correlated with reduced self-referential processing and spontaneous thought while enhancing cognitive focus and allocation of attention in IGD (65). The capacity of MM to effectively modulate activity within the DMN could play a pivotal role in ameliorating cognitive impairments in IGD.

In addition, MM training exhibited an increase in the integration coefficient between the DMN and LN. The LN, comprising key structures such as the nucleus accumbens, amygdala, and orbital frontal cortex, plays a primary role in orchestrating processes related to reward, emotion, and motivation (66). The increased integration coefficient observed between the DMN and LN suggests that MM contributes to enhancing the stability of communication between these 2 neural networks. Previous research has underscored the significance of both structural and functional alterations within the LN concerning IGD (1).

Research has indicated that individuals with IGD often manifest deficiencies in emotional regulation, potentially attributable to dysfunction within the LN (67). Positioned at the core of the emotional brain network, the LN is dedicated to the intricate processes of emotion processing, regulation, and expression (68). It has been suggested recently that MM may induce neuroplastic modifications within the corticolimbic circuits, playing a pivotal role in managing stress and regulating emotional responses (69). Our findings substantiate this hypothesis, suggesting that MM may ameliorate the emotional facets of IGD by reconfiguring the DMN-LN neural circuitry to modulate LN activity.

MM Training Improved the Reward System in Individuals With IGD by Increasing Communication Stability Within the BGN

We found that MM training led to an increase in the recruitment coefficient of the BGN. The BGN, a pivotal component within the reward system, has been increasingly implicated in addiction, where aberrations in reward-processing systems have been well documented (70). Prior studies have consistently suggested discernible alternations within the reward-processing system in individuals with IGD (71,72). Reports of diminished functional connectivity in cerebral regions linked to reward circuitry in individuals with IGD (73). Our results point toward a positive impact of MM training on the functionality of the reward system in IGD, leading to a reduction in cravings. This improvement in the reward system's functionality, as suggested by the restructuring reward hypothesis, suggests that MM training addresses hedonic dysregulation by enhancing natural reward responsiveness, consequently mitigating cravings and curbing substance use behaviors (31,74).

Limitations

The current study is not without limitations. First, while exploring the impacts of MM interventions on individuals with IGD, we did not differentiate between various MM styles. Consequently, additional research is warranted to comprehensively discern which specific styles of MM are most efficacious for individuals with IGD. Second, due to the relatively short duration of resting-state functional MRI acquisition (approximately 7 minutes), the results of network integration and communication should be interpreted with caution. Future research should consider longer acquisition times to enhance the reliability of network estimations (75). Third, the effect size in this study was relatively small, and the current sample size may limit our ability to detect small to medium effects. Therefore, larger sample sizes are needed in future research to confirm the generalizability and robustness of the findings. Fourth, the current study design lacks a waitlist control group. Including such a group would help distinguish between treatment effects and retest effects, thereby providing clearer results. Future research could benefit from incorporating a waitlist control group. Lastly, due to the use of different brain atlases, despite the fact that the anatomical locations of the regions are similar, it is not possible to directly compare the results of the current study with the results of our previous study (30) in key ROIs. Although the change in the atlas was necessary, it also has disadvantages, particularly regarding the replicability of neuroimaging research, as well as the non-accumulative nature of these findings. In future studies, the investigators should consider using a unified atlas or conducting cross-atlas validation to ensure consistency and comparability of the results.

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SL wrote the first draft of the article. SL, AJ, ZZ, and XM analyzed the data. HN, SL, and HW contributed to task design and fMRI data collection. CL and XS contributed to the MM class design and training. G-HD designed the research and edited the article. All authors contributed to and approved the final version of the article.

The data are stored on our laboratory-based network attachment system: http://QuickConnect.cn/others (ID: guests; PIN dong@123.COM).

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ARTICLE INFORMATION

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