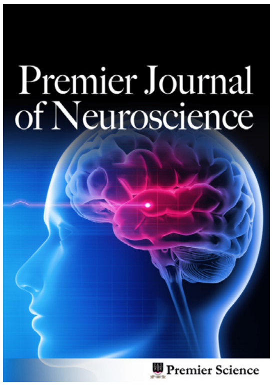

Real-Time Brain Feedback Reveals the DMN's Role in Creativity and Idea Formation

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ABSTRACT

The default mode network (DMN) is a critical neural system supporting self-referential thinking, autobiographical memory, and creative ideation. Its dysregulation has been implicated in conditions such as major depressive disorder and anxiety, where hyperconnectivity, particularly in the subgenual anterior cingulate cortex (sgACC), sustains ruminative thought patterns and emotional distress.

Mindfulness-based neurofeedback (mbNF), a non-invasive intervention, has shown measurable benefits in regulating DMN activity. Studies demonstrate that mbNF reduces DMN overactivity by 30–40%, decreases sgACC-medial prefrontal cortex connectivity by up to 35%, and improves mindfulness levels by 25%, promoting emotional stability and cognitive clarity. Beyond reducing hyperconnectivity, mbNF enhances functional integration between large-scale brain networks. Improved connectivity between the DMN, central executive network, and salience network optimizes transitions between introspection and task-oriented cognition, fostering creativity and problem-solving. Functional connectivity analysis reveals significant network-level changes, with 14 out of 19 key regions showing improved interactions post-mbNF training. These adaptations also facilitate emotional regulation and sustained reductions in repetitive negative thinking, with effects persisting for several weeks. The practical applications of mbNF extend beyond mental health care to education and workplace settings, where it can improve focus, stress management, and cognitive flexibility. Portable electroencephalography-based neurofeedback devices are making mbNF increasingly accessible, providing scalable tools for enhancing mental well-being and productivity. By addressing the complex dynamics of brain network interactions, mbNF represents a scientifically supported and practical approach to improving creativity, emotional regulation, and adaptive thinking.

Keywords: Default mode network, Mindfulness-based neurofeedback, Emotional regulation, Creative thinking, Brain connectivity

Introduction

The Discovery of the Default Mode Network (DMN)

The discovery of the DMN has fundamentally transformed our understanding of human brain function.[1,2] The DMN comprises a collection of distributed and interconnected brain regions, including the medial prefrontal cortex (mPFC), posterior cingulate cortex (PCC), angular gyrus (AG), and medial temporal lobe (Figure 1).[3] These regions synchronously coactivate during periods of wakeful rest or introspection and are suppressed during attention to external stimuli. This network supports internally focused cognitive processes such as self-reflection, daydreaming, mind wandering, recall of personal experiences, and envisioning the future.[4]

Unlike networks involved in sensory or motor functions, the DMN's activity is characterized by its deactivation during externally demanding cognitive tasks and its engagement during "rest" or quiet wakefulness. This pattern of activity was first identified through reductions in blood flow to DMN regions during active tasks, highlighting its role in introspective mental processes.[5] The DMN facilitates reflection on experiences, social interactions, and emotional states, contributing to self-referential thought and understanding.

Cognitive Roles and Functions

Over the past two decades, the DMN has emerged as a central focus in neuroscience. Research has shown its critical role in a wide array of cognitive domains, including episodic memory, future-oriented thought, social cognition, and language comprehension. Episodic memory operations, for instance, rely on interactions between the hippocampus and cortical nodes of the DMN, such as the PCC and mPFC, to encode, retrieve, and elaborate autobiographical memories.[3] These cortical nodes contribute to specific aspects of memory processing: the PCC is associated with autobiographical recall, the RSC with spatial navigation, the mPFC with regulation of memory encoding and recall, and the AG with elaboration of memory contents.[3] These findings underscore the DMN's integrative role in memory construction and the subjective experience of remembering.

The DMN's clinical relevance has also become increasingly apparent. Dysregulation of DMN connectivity has been implicated in various mental health disorders, including major depressive disorder (MDD), schizophrenia, and autism.[6–9] In MDD, for example, hyperconnectivity within the DMN, particularly in the subgenual anterior cingulate cortex (sgACC), is associated with rumination and self-referential distress.[10,11] These disruptions contribute to the maintenance and recurrence of depressive symptoms. Emerging therapeutic strategies, such as transcranial magnetic stimulation (TMS) and neurofeedback using functional magnetic resonance imaging (fMRI) or electroencephalography (EEG), aim to normalize DMN activity and alleviate symptoms.[8,12,13] Notably, EEG-based neurofeedback presents a scalable and cost-effective alternative, enabling real-time interventions to address DMN dysregulation.[14]

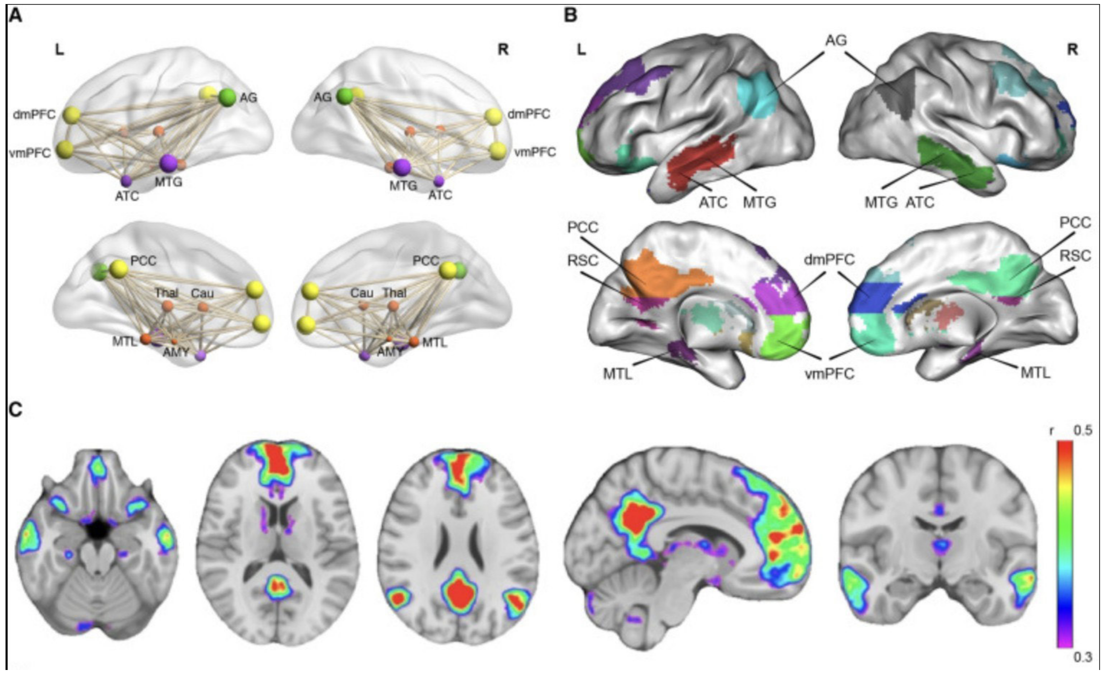

Fig 1 | (A) Representation of DMN nodes as a functionally and anatomically integrated system. (B, C) Cortical no des of the DMN: PCC and retrosplenial cortex (RSC) in the posterior medial parietal cortex; mPFC with dorsomedial (dmPFC) and ventromedial (vmPFC) subdivisions; anterior temporal cortex; middle temporal gyrus (MTG) in the lateral temporal cortex; MTL; and AG in lateral parietal cortex

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Interaction with Brain Networks

Interactions between the DMN and other large-scale brain networks further illuminate its role in cognition. The central executive network (CEN) and salience network (SN) are key counterparts to the DMN, with the SN, particularly its right fronto-insular cortex (rFIC), mediating transitions between internally focused and externally oriented cognitive states (Figure 2).[3] This dynamic interaction forms the basis of the triple network model, which posits that disruptions in the balance between the DMN, CEN, and SN underlie various psychiatric disorders. For instance, in schizophrenia, reduced anticorrelation between the DMN and CEN impairs cognitive flexibility, while hyperconnectivity within self-referential nodes of the DMN exacerbates symptoms such as hallucinations.[15]

The origins of the DMN's discovery lie in observations of consistent deactivation patterns during externally focused tasks. Meta-analyses of over 8000 task-based fMRI studies have reinforced the DMN's direct role in multiple cognitive functions, including self-reference, social cognition, episodic memory, and mind wandering.[16] These studies emphasize the dynamic and overlapping contributions of individual DMN nodes to cognitive operations. For example, the mPFC supports self-referential processing and social cognition, while the PCC and AG facilitate memory retrieval and narrative construction.[3] Furthermore, intrinsic functional connectivity within the DMN, as revealed by advanced neuroimaging, demonstrates how its nodes integrate information across domains to sustain complex cognitive functions.

DMN dysfunction is not limited to psychiatric conditions. Research has highlighted its involvement in neurodegenerative diseases such as Alzheimer's disease, where deficits in coactivation of the hippocampus and other DMN nodes are linked to episodic memory impairments.[17] These findings underscore the need for innovative approaches to quantify and understand DMN connectivity, including advanced neuroimaging and non-invasive neurofeedback techniques.

Idea Formation Theories

The DMN plays a foundational role in the formation of ideas, integrating past experiences, semantic knowledge, and self-referential processes to generate novel insights. Idea formation involves a dynamic interplay between internal reflection and external stimuli, mediated by the DMN's core nodes. By synthesizing disparate elements of cognitive and affective information, the DMN facilitates the generation of meaningful and creative ideas.

Mind wandering, a hallmark of DMN activity, is particularly relevant to creativity. This process allows for spontaneous, stimulus-independent thought, enabling the brain to form unconventional associations between seemingly unrelated concepts.[3] Neuroimaging studies have consistently shown activation of the mPFC, PCC, and AG during mind wandering, linking these regions to self-referential thinking, episodic memory retrieval, and semantic processing.[18,19] These findings highlight the DMN's capacity to construct

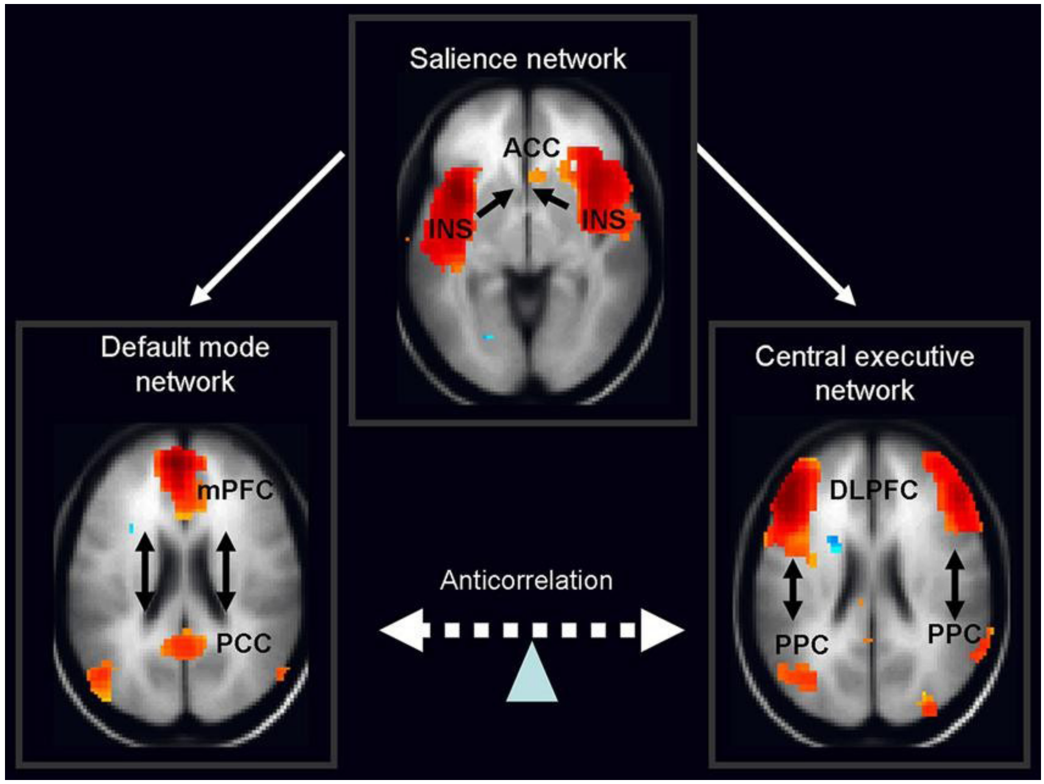

Fig 2 | The salience network is thought to facilitate switching between the DMN and the CEN
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internal narratives and simulate alternative scenarios, both of which are essential for creative ideation.

Creativity Through Network Integration

The interplay between the DMN and other brain networks refines the idea formation process. The CEN and SN regulate transitions between introspection and task-focused cognition, ensuring that creative thought remains contextually relevant and goal-directed. For example, the SL detects significant stimuli and facilitates the shift between the DMN and CEN, enabling adaptive cognitive responses.[3] This dynamic balance between internally and externally oriented networks underpins the flexibility and depth of creative thought.

Advances in neuroimaging have expanded our understanding of the DMN's role in creativity. Real-time functional magnetic resonance imaging (rtfMRI) allows individuals to observe and modulate DMN connectivity, enhancing cognitive flexibility and creative performance. Studies have shown that rtfMRI-based neurofeedback can improve the regulation of DMN activity, fostering innovative thinking. Similarly, mindfulness practices, which reduce DMN overactivity, have been associated with increased focus and reduced distractions during creative tasks.[20]

DMN contributions to idea formation extend to language and semantic memory. The AG and temporal-parietal junction, for instance, support the integration of diverse perspectives and the simulation of social scenarios, enriching the contextual and narrative aspects of ideation. Furthermore, the DMN's role in episodic future thinking enables individuals to imagine and evaluate potential outcomes, a critical component of planning and problem-solving.[3]

Research on DMN activity during creative tasks has also highlighted its connections to other cognitive processes, such as working memory and emotional regulation. By integrating inputs from multiple domains, the DMN constructs cohesive frameworks for understanding and innovation.[3] These insights underscore the DMN's position as a neural hub for creativity, linking introspection and external engagement to generate novel ideas.

In summary, the DMN serves as a critical framework for understanding idea formation, linking introspective processes to creative insights. Its interactions with other large-scale networks and its modulation through targeted interventions offer promising pathways for enhancing creativity and cognitive performance. By leveraging advancements in neuroimaging and neurofeedback, researchers can further explore the mechanisms underlying DMN activity and its contributions to human cognition (Figure 3).

DMN and Creativity

Neurofeedback combined with mindfulness meditation has grown in popularity since the early 2010s, and it is now often known as mindfulness-based neurofeedback (mbNF), which is a non-invasive technique that allows people to track and modulate brain function. mbNF has shown clear effects on modulating

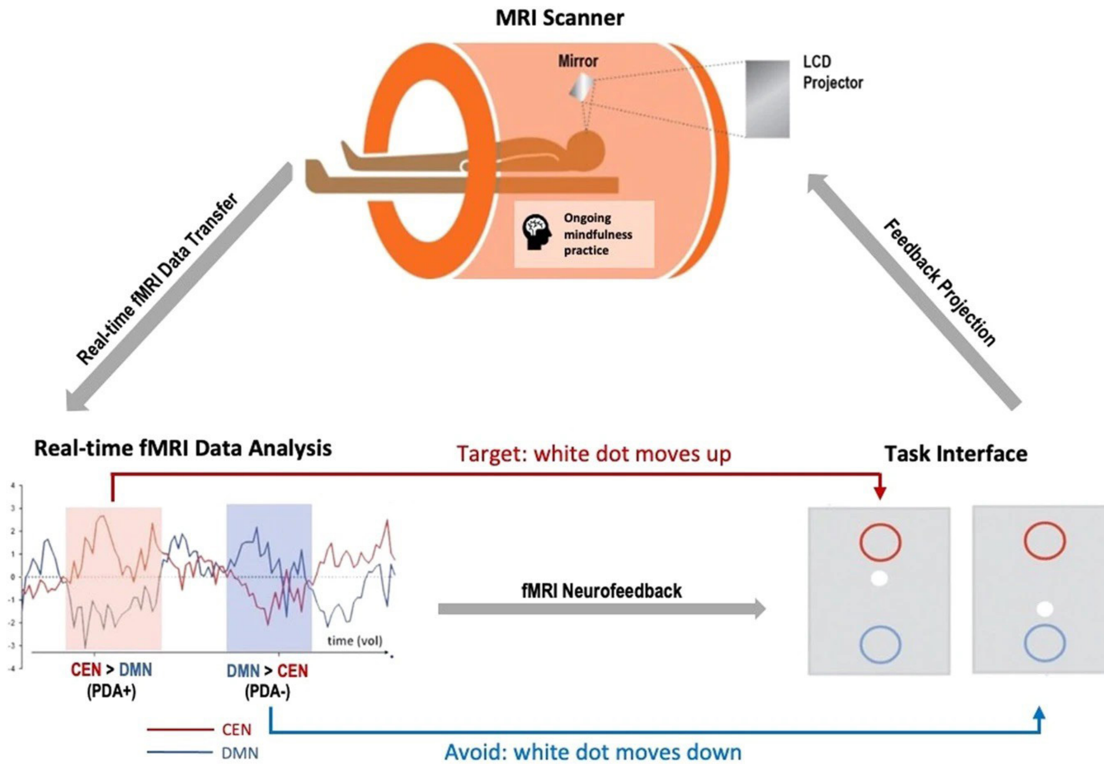

Fig 3 | During mbNF, participants were told to use mindfulness to move the white dot on the screen up into the red circle. The mobility of the white dot was determined by real-time analysis of fMRI data that calculated the difference in individualized DMN and CEN activations. When DMN activation is less than CEN activation, the white dot goes upward; when DMN activation is more than CEN activation, the white dot moves downward

Credits: https://doi.org/10.1038/s41380-023-02032-z

the DMN. Studies indicate that participants engaging in mbNF reduced DMN activation relative to the CEN during training sessions.[20] This change was linked to decreases in the sgACC connectivity with the mPFC. Improved neurofeedback performance correlated directly with increased mindfulness. The sgACC emerged as a critical area, especially in managing ruminative thought patterns, which are common in MDD.[20–22]

Detailed analyses provided insights into the DMN's structure. The anterior DMN, involving regions like the ventral mPFC, PCC, bilateral MTG, and AG, supports self-referential thinking and episodic memory. The posterior DMN integrates sensory and contextual data.[23] Alongside, the CEN includes the bilateral dorsolateral prefrontal cortex and posterior parietal cortex, which are critical for goal-oriented tasks and working memory.[20] The SN, covering the anterior cingulate cortex and bilateral insula, detects and prioritizes important stimuli. These networks work together to manage attention and cognitive transitions.[20]

Neurofeedback strengthened connections between the superior temporal gyrus (STG) and the insula, which are critical for integrating sensory and emotional information. This led to improved emotional regulation and creativity, as demonstrated by participant performance in problem-solving tasks. Among 19 key region-of-interest (ROI) pairs, 14 showed increased connectivity in participants undergoing neurofeedback, compared to only 4 in controls.[24] Connectivity improvements between the left STG and left insula/inferior frontal gyrus (IFG) were strongly linked to better psychological outcomes.[24]

Participants trained to regulate activity in DMN regions like the PCC and sgACC sustained reductions in DMN connectivity over time. For example, a study involving adolescents found that neurofeedback decreased DMN connectivity and improved mindfulness immediately after training, with effects lasting a week.[25,26] Neurofeedback enabled participants to adjust their neural activity toward specific goals, supporting both emotional regulation and creative thinking. By guiding this alignment, mbNF fosters reduced repetitive thinking and enhances problem-solving.

Rather than focusing on isolated brain regions, network-based neurofeedback addresses the complex interactions between the DMN, CEN, and SN. This approach significantly outperformed traditional methods like TMS. Personalized neurofeedback targeting specific network areas provided superior outcomes.[20] Experimental participants improved connectivity in 14 ROI pairs, underscoring the effectiveness of tailored interventions. For instance, enhanced communication between the DMN and SN—particularly through the rFIC—allowed smooth transitions between introspection and action, a vital process for creativity.[24,27]

All 9 participants in one study, including those with MDD and anxiety, reduced DMN connectivity and improved mindfulness.[20] Reductions in sgACC-MPFC connectivity explained behavioral changes, highlighting the physiological impact of network adjustments. Enhanced connections, such as those between the STG and IFG, strengthened the DMN's role in generating ideas and refining them into actionable thoughts (Figure 4).

The DMN contributes to creativity by enabling spontaneous thoughts. However, its collaboration with the CEN and SN ensures that these ideas are evaluated and shaped. For example, the SN's involvement in monitoring salience ensures relevant ideas are prioritized, while the CEN refines and organizes thoughts into actionable outcomes.[20,28] Neurofeedback targeting these interactions enhances the DMN's ability to balance creativity and structured thinking.

Studies further confirmed that participants achieved long-term neural changes through neurofeedback. Aligning brain activity with targeted patterns during training sessions allowed participants to effectively regulate DMN activity. For individuals with conditions like MDD and anxiety, these changes supported emotional regulation and adaptive thinking. Participants consistently reduced DMN hyperactivity, improving both mental clarity and cognitive flexibility.[20]

Research integrating neurofeedback results with behavior demonstrated that network-based approaches directly enhanced creative thinking and emotional well-being. Key ROI pairs, such as the connections between the STG and insula/IFG, showed robust associations with psychological improvements.[29,30] These findings emphasize the need to address interactions across brain networks rather than focusing on single areas.

The practical scalability of mbNF makes it an appealing intervention. While rtfMRI remains effective for monitoring DMN activity, emerging technologies like EEG-based neurofeedback offer more accessible options. These approaches make network-targeted interventions practical for broader populations, extending their reach in mental health care and cognitive enhancement.

By reducing DMN hyperconnectivity and improving its balance with other networks, mbNF provides a pathway for enhancing creativity, emotional regulation, and flexible thinking. Ongoing research will refine these techniques, making them more effective and accessible, ultimately transforming their application in mental health and creativity.

Limitations

Limitations in the current research on mbNF primarily revolve around sample size, study design, and technology accessibility. Many studies, including those demonstrating significant changes in DMN connectivity, were conducted with small participant groups, often fewer than 10 individuals, limiting the generalizability of findings. The lack of control groups in some research makes it difficult to isolate the specific effects of neurofeedback from other factors, such as mindfulness practice alone or placebo effects.

Additionally, fMRI-based neurofeedback, while effective, is resource-intensive and costly, making it impractical for widespread use. Although EEG-based alternatives are emerging, they require further validation to ensure comparable efficacy. Variability in participants' strategies during neurofeedback tasks adds another layer of complexity, as different cognitive approaches may affect outcomes. Addressing these limitations requires larger, controlled trials, more accessible technologies, and standardized protocols to ensure consistent and replicable results.

Potential Application

mbNF can be applied in many practical ways. In mental health, it helps with conditions like depression, anxiety, and post-traumatic stress disorder by reducing overactivity in the DMN and balancing brain networks. This leads to fewer intrusive thoughts, less rumination, and better emotional control. People with depression, for

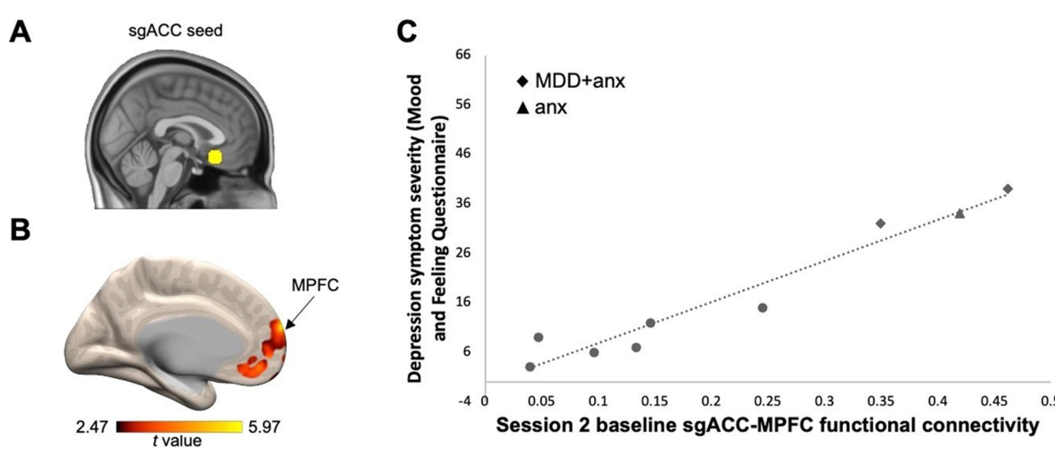

Fig 4 | Higher DMN functional connectivity was linked to more severe depression symptoms at baseline. (A) 8 mm spherical seed in the sgACC, (B) functional connectivity between the sgACC seed and the MPFC positively correlated with symptom severity, (C) illustrates the correlation between baseline MFQ and baseline sgACC-MPFC functional connectivity

Credits: https://doi.org/10.1038/s41380-023-02032-z example, often show improved connectivity between key brain regions and report better mental clarity.

In education, mbNF can help students focus better, manage stress, and improve creative thinking. It could also support those with attention deficits by training their brains to stay on task and solve problems more effectively. Portable neurofeedback tools could even be used during study sessions to optimize learning.

In professional settings, mbNF can be useful for people in high-pressure jobs. For example, air traffic controllers or surgeons could use real-time feedback from wearable devices to stay focused and make better decisions under stress. Creative professionals could use mbNF to get past mental blocks and generate new ideas more easily.

In rehabilitation, mbNF can support stroke recovery by retraining the brain to improve motor control and cognitive function. It could also help people recovering from brain injuries or managing neurodegenerative conditions by restoring balance between brain networks.

At home, mbNF could be used for stress relief, better focus, and improved mental well-being. Athletes might use it to stay calm before competitions, improve reaction times, or recover more effectively. Artists and musicians could benefit from better access to their creativity by training their brains to enter a flow state.

As mbNF becomes more portable and affordable, it could be part of daily life—helping people manage stress, improve focus, and stay creative in their work and personal lives. Its ability to target specific brain activity makes it a versatile and practical tool for mental health, education, work, and recovery.

Conclusion

mbNF has proven to be a valuable method for improving brain function by targeting the DMN. It reduces DMN hyperactivity and improves interactions with other networks, such as the CEN and SN. These changes lead to better emotional regulation, cognitive flexibility, and creativity. Research consistently shows that mbNF reduces symptoms of conditions like MDD and anxiety while enhancing mindfulness and adaptive thinking.

The personalized nature of mbNF makes it highly effective in addressing individual brain activity patterns. Advances in portable technologies, including EEG-based neurofeedback, make it more accessible and practical for widespread use. This opens up new possibilities for its application in mental health treatment, education, and professional development. As the field progresses, mbNF is set to become a key tool for enhancing well-being and unlocking human potential.

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