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Mindfulness Meditation and Network Neuroscience: Review, Synthesis, and Future Directions

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Abstract

Network neuroscience is an interdisciplinary field, which can be used to understand the brain by examining the connections between its constituent elements. In recent years, the application of network neuroscience approaches to study the intricate nature of the structural and functional relationships within the human brain has yielded unique insights into its organization. In this review, we begin by defining network neuroscience and providing an overview of the common metrics that describe the topology of human structural and functional brain networks. We then present a detailed overview of a limited but growing body of literature that leverages network neuroscience metrics to demonstrate the impact of mindfulness meditation on modulating the fundamental structural and functional network properties of segregation, integration, and

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influence. Although preliminary, results across studies suggest that mindfulness meditation results in a shift in connector hubs, such as the anterior cingulate cortex, the thalamus, and the mid-insula. Although there is mixed evidence regarding the impact of mindfulness training on global metrics of connectivity, the default mode network exhibits reduced intra-connectivity following mindfulness training. Our review also underscores essential directions for future research, including a more comprehensive examination of mindfulness training and its potential to influence structural and functional connections at the nodal, network, and whole-brain levels. Furthermore, we emphasize the importance of open science, adoption of rigorous study designs to improve the internal validity of studies, and the inclusion of diverse samples in neuroimaging studies to comprehensively characterize the impact of mindfulness on brain organization.

Introduction

Mindfulness meditation comprises a family of practices originating from Buddhist contemplative traditions, emphasizing the cultivation of focused attention and non-judgmental internal awareness. Scientific investigations on meditation began to proliferate in the 1960's, when psychophysiological tools were used to study acute and long-term effects of diverse meditation techniques in experienced practitioners (1–3). By 1979, Jon Kabat-Zinn had developed Mindfulness-Based Stress Reduction (MBSR; 4) — a seminal eight-week training program for novices that has now become the most well-researched structured mindfulness training program to-date (5,6).

Over the past two decades, there has been significant interest in using structural and functional MRI to examine the effects of mindfulness meditation on the brain. Many early neuroimaging studies characterizing the neural correlates of MBSR relied on univariate methods, including general linear models (GLMs). Typically, these studies involved using GLMs to compare the activity of specific brain metrics—whether derived at the voxel level, within region-of-interest parcellations, or across networks—to identify statistically significant patterns of brain activation following MBSR training. With the advent of functional and structural connectivity approaches, there has also been growing interested in examining large-scale network changes in mindfulness meditation, including the functional reorganization of attentional networks including the frontoparietal network (FPN), the salience network (SN), and the default mode network (DMN) (7,8), along with changes in functional connectivity between sensory networks and attentional networks.

However, the majority of neuroimaging investigations of mindfulness meditation have primarily adopted methodological approaches that have focused on specific sets of brain regions, small constellations of connections, and canonical brain systems in isolation, and have mostly examined pairwise associations between these regions. Meanwhile, the broader human neuroimaging community has adopted techniques from network science—the study of complex systems of interacting elements—to understand the structure and function of the nervous system. Despite these advancements, network science techniques have not yet been widely implemented by the mindfulness meditation community. In this review, we: 1) outline the network neuroscience approach, focusing on its contributions to our understanding of brain organization, 2) review current approaches for studying brain-based correlates of mindfulness, and 3) present a path for future research that has the potential to rigorously and causally demonstrate effects of mindfulness meditation on structural and functional features of the human brain.

Introduction to Network Neuroscience

Network science is a multidisciplinary field where systems of interacting elements are modeled as “graphs” or networks. The application of network science to the study of nervous systems constitutes the broad field of network neuroscience. Nervous systems are multi-scale, complex, dynamical systems (9,10) composed of neural elements, such as neurons, populations, and areas that interact with one another, forming extensive brain-wide connectivity patterns. It is through and along these “connectomes” that neural elements signal one another. Both the physical connections and the outcome of the signaling processes can be modeled and understood through a network science lens (11).

Brain networks are typically differentiated based on the imaging modality from which they were reconstructed and based on the connections they represent. Figure 1 outlines the basic methodology of network neuroscience approaches. These networks can be decomposed into its ‘nodes’ and ‘edges,’ representing the elements of the system and their pairwise interactions, respectively. In human imaging, nodes can be defined at different spatial resolutions, from fine-scale voxels and surface vertices to coarse-scale parcels and regions (11). As shown in Figure 1, edges can represent both structural and functional connections. In structural networks, edges often correspond to white-matter fascicles linking pairs of gray matter parcels (12). Functional connectivity is estimated as a measure of statistical dependence between the activities recorded from two different nodes (13). Although this definition allows for any measure of dependence, most studies define functional connectivity as the bivariate product-moment correlation between the timeseries of two nodes. Generally, regions that are strongly functionally connected are thought to be “communicating” or engaged in similar functions (14). For example, Figure 1 represents the correlation between timeseries of nodes 2 and 3 to measure the functional connection between these two nodes. Both types of connectivity can be modeled as networks and studied using network science.

What have we learned about brain network organization?: Network neuroscience is a relatively young field; nonetheless, it has compiled an impressive set of “canonical” network features that have clear functional significance and are consistent across structural and functional networks, phylogeny, and spatiotemporal scales.

Small-world properties. At their core, connectomes are communication networks. A network is said to exhibit small world properties if its clustering coefficient—a measure of whether nodes’ neighbors are connected to one another—is relatively large, while its characteristic path length—the mean number of hops in the shortest path from a source to a target node—is sufficiently short. In other words, small-world networks exhibit dense, local circuitry for carrying out specialized information processing, and short processing paths so that signals can be delivered rapidly from one location to another. Importantly, small-worldness is ubiquitous across connectomes (15–17); it has been observed in the synaptic wiring of the nematode *C. elegans* (18), interareal connectomes of flies (19), mice, rats, and non-human primates, and the human connectome reconstructed from dMRI data (10).

Hubs and rich-clubs. Another ubiquitous feature of connectomes is their heterogeneity with respect to the connectivity patterns of specific nodes; some nodes occupy positions of influence and importance within a network while others do not (20). For instance, we can identify influential nodes in the network by counting the number of connections they make (their degree) or the total weights of their connections (their strength) (12). Like social media influencers with large numbers of followers, nodes that are more connected exhibit greater capacity for influence within the network and are imbued with the ability to deliver signals to many parts of the brain quickly. Degree, however, is only one method for quantifying node properties; it describes node influences in terms of their structural position. However, even low-degree and weakly connected nodes can be “central” to dynamical processes unfolding over the network. Perhaps the best-known measure of importance is the metric of “betweenness centrality”, which counts the number of shortest paths in the network that involve a given node (21).

Influential nodes can also form higher-order structures, including “rich-clubs” (21). A rich-club refers to a collection of high-degree nodes that are more densely connected to one another than expected under a chance model. This type of structure appears in other complex networks, for example in air travel networks, where “hub” airports often maintain direct flights to other hubs, whereas non-hub “peripheral” airports connect indirectly via hubs. Indeed, rich clubs act as highly integrative structures within the human connectome. For example, Figure 1A and 1B highlight nodes 6, 13, 17, and 23 as forming the rich club due to their central role in connecting nodes of different modules with one another. The majority of shortest paths in connectomes must traverse through these rich club nodes, which are represented in virtually every functional system. Thus, these rich-clubs integrate information and signals across specialized sub-systems.

Modules. Another key architectural feature of brain networks is their propensity to be organized into sub-networks called “modules” or “communities.” As an example, Figure 1 showcases four modules: module 1 (green), module 2 (blue), module 3 (yellow), and module 4 (brown). These modules are typically defined to be internally dense and externally sparse, a feature thought to support specialization of function. In functional networks, detected modules resemble the brain’s functional systems (even at rest), with module boundaries sometimes circumscribing task activations. Modules in structural brain networks tend to exhibit weaker correspondence with functional systems (22). In both cases, modules can be used to further characterize the “hubness” or importance of nodes in the network. As shown in Figure 1, nodes 6, 13, 17, and 23 function as hubs due to their connections with nodes in other modules, as well as their connections with one another. Measures like participation coefficient describe how a node’s connections are concentrated within a single module (low participation) or uniformly distributed across modules (high participation). Participation tends to be much lower in unimodal and sensory systems and greater in higher-order, heteromodal systems (23), which is thought to reflect differences in both the complexity and breadth of computations that those systems support.

Cost-efficient spatial embedding. Small-worldness, hubs and rich-clubs, and modules all have functional significance. They facilitate reduced processing time (24), integration of information across brain systems (24), and performance of specialized information processing (25). The brain must balance the formation of these functionally adaptive features with volumetric, material, and metabolic constraints (26). Connectomes favor cost-efficient short-range (low-cost) connections, as shorter connections require proportionally less material to form and energy to maintain and use for signaling, over longer, more expensive connections, a feature evident across phylogeny (27). This exposes tradeoffs in the brain—given the finite budget for space and energy, the formation of costly mesoscale features means that other costly features cannot be formed (28).

To summarize, network neuroscience approaches can offer insights on the topological properties of brain networks. The canonical features of brain organization, reviewed in this section, are increasingly being investigated as mechanistic and outcome variables in studies investigating the effects of mindfulness meditation on the brain. One of the key advantages of applying network neuroscience approaches to the study of mindfulness is that these measures allow us to go beyond simply describing specific connection changes following mindfulness training to understanding how these connections evolve and their impact on signaling processes for local and global efficiency. As mindfulness meditation is increasingly investigated in the context of ‘emergent’ behaviors, including cognition (29) — known to have emergent properties — the application of network neuroscience enables us to study the dynamics of brain regions and how they work in concert to support the prophylactic effects of mindfulness meditation.

In the following section, we briefly review early research that used univariate approaches to investigate changes in brain activity and connectivity following mindfulness training. We then provide a comprehensive review of the current, albeit limited, literature that builds on these univariate studies, focusing specifically on how changes in connections between brain regions may contribute to more efficient local and global neural circuitry.

Mindfulness Meditation and the Brain

Pioneering neuroimaging studies on mindfulness meditation aimed to achieve two primary objectives. First, researchers sought to identify neural processes associated with mindfulness meditation, examining brain activity differences between expert meditators vs. novices as well as studying changes in activity before, during, and after meditation (30–39). Second, these studies aimed to understand relations among neural activation patterns and psychological processes involved in meditation, including the assessment of behavior, cognition, and emotion (40,41).

These studies revealed discrete regions that are involved in mindfulness meditation, including the posterior cingulate cortex (PCC) (42), the medial prefrontal cortex (MPFC) (43,44), the dorsal anterior cingulate cortex (dACC) (33), the anterior insula (aINS) (45), and the striatum (46–48). To illustrate, the PCC and mPFC, commonly associated with self-related processing (49,50) may support attenuating self-related processing (51) during meditation (42–44). Similarly, the dACC, aINS, often involved in salience detection and attentional control (52,53), may support attentional processes during meditation

(33,45). Finally, the striatum, linked to reward processing (53,54), may contribute to emotion regulation in mindfulness meditation (46,48). However, these methods have largely remained within the univariate-based GLM frameworks, examining brain activation within single or small sets of regions.

Resting-state functional connectivity is an approach used to examine the intrinsic functional organization of the brain by analyzing data acquired when an individual is not engaged in any specific task. The resting state was initially hypothesized to mirror the experience of meditative practices, and launched a new era in mindfulness studies. Many of these studies examined changes in functional connectivity between nodes previously found to be involved in task-based studies, such as the PCC and the dorsolateral prefrontal cortex (dlPFC), with more recent investigations examining changes in total intra- and inter-network connectivity of several canonical brain networks.

This research on mindfulness training and resting-state functional connectivity has revealed insights into the impact of mindfulness practices on large-scale network changes, including the functional reorganization of attentional networks including the frontoparietal network (FPN), the salience network (SN), and the default mode network (DMN) (7,8,40), along with changes in functional connectivity between sensory networks and attentional networks (55). The FPN—sometimes divided into the dorsal and lateral FPN (56)—involves regions such as the middle frontal gyrus, anterior inferior and superior parietal lobules, intraparietal sulcus, midcingulate gyrus, intraparietal sulcus, middle temporal cortex, ventral motor cortex, and right-lateralized dorsolateral prefrontal cortex.(56) Broadly, the FPN is largely responsible for goal-directed thinking, inhibitory control and working memory, and task-switching (56–58). Relatedly, the SN encompasses the bilateral anterior insula, anterior midcingulate cortex, inferior parietal cortex, right temporal-parietal junction, lateral PFC, and subcortical structures (56). The primary role of the SN is to detect behaviorally-relevant stimuli that arise from both external and internal sources (56,59). Lastly, the core regions of the DMN include the medial FPC, posterior cingulate cortex, posterior portions of the inferior parietal lobule, inferior frontal gyrus, middle temporal gyrus, superior temporal sulcus, and the parahippocampal cortex (59). Although functions of the DMN are widespread, its primary role involves detecting the associative relevance of both internal and external information and is commonly implicated in imagination, memory, and self-referential processes such as mind-wandering or spontaneous thought (56,60–62).

A definitive conclusion, however, has yet to be reached due to mixed findings across studies, such as increased and decreased functional connectivity in key brain networks (40). For instance, mindfulness training has been associated with increased connectivity within and between auditory and visual networks (55), as well as decreased connectivity between regions of the posteroventral DMN and nodes of the task positive networks, including the salience (55,63), frontoparietal (55), and auditory networks (55). In contrast, other research has also reported increased connectivity between nodes of the DMN (i.e., PCC) and task positive networks, such as the dlPFC, following mindfulness training (64). Further, inconsistencies in the directionality of functional connectivity changes between the rostral ACC and dorsomedial PFC are also present, with mindfulness training either increasing (65) or decreasing connectivity (66). Many inconsistencies within this literature are likely due to differences in training programs, with duration varying from three-day intensive retreats to eight week training programs; differences in the populations studies, ranging from community participants to those with neurological or psychiatric disorders; and varying analytic pipelines. Nonetheless, these findings underscore the potential of mindfulness on brain networks related to attention, self-awareness, and emotional processing, highlighting key networks that may undergo reorganization following mindfulness practices.

Applying Network Neuroscience to Mindfulness Meditation: The functional connectivity studies summarized above have been instrumental in helping us understand the role of key canonical networks by primarily providing information about the strength of connections at the nodal, network, or whole-brain levels. Building on previous functional connectivity research, network neuroscience studies of mindfulness meditation use graph theoretical methods to provide a more comprehensive understanding of the integration and segregation of nodes and networks. Additionally, these studies examine reconfiguration of both functional and structural architectures across various levels, including the nodal, network, or whole-brain level.

In contrast to the extensive literature focused on univariate functional connectivity analyses, only a few studies have investigated multivariate metrics of segregation and integration following mindfulness training. Figure 2 summarizes the preliminary results of mindfulness meditation on a select metrics from network neuroscience. One of the first studies used graph theory methods to examine the efficiency and connectivity of the anterior cingulate cortex (ACC) after 11 hours of mindfulness training in an undergraduate cohort (67). The ACC showed increased network efficiency and degree connectivity in participants who practiced mindfulness meditation compared to those engaged in relaxation training. Following mindfulness training, the ACC not only demonstrated increased connectivity with various other brain regions but also more efficient information transfer to distributed regions of the brain. Network efficiency, a measure of the mean inverse shortest path length within a local sub-network, is commonly used to measure the small-world properties of a network. This preliminary study suggests that mindfulness training enhances efficient information flow through the ACC. In contrast, the supplementary motor area was characterized by a decrease in degree connectivity and efficiency following mindfulness training, suggesting that reduced connections within this part of the motor network may potentially facilitate the meditative state of “being.”

Cross-sectional studies comparing expert to novice meditators, and those examining individual differences in dispositional mindfulness and nodal properties, have provided further insight into how the various regions of the brain typically activated in mindfulness training studies reconfigure or shift alliance in more mindful individuals. For example, the caudate, a key region of the striatum, is known for its flexible functional coupling with various brain networks to prioritize task-relevant motivational signals (68). Furthermore, univariate mindfulness studies have shown an increase in caudate activity following mindfulness training (36), an elevated BOLD response in this region and others within the striatum among meditators compared to novices (69,70), and an increase in the volume of the caudate post-mindfulness training (71). Building on this literature, Gard et al. (72) and Lardone et al. (73) demonstrated higher betweenness centrality of the caudate in meditators compared to novices, with the increased functional coupling underscoring the hub-like nature of the caudate for information transfer across the entire functional connectome following mindfulness meditation. Similarly, Wang et al. (74) found a negative correlation between a trait measure of mindfulness and network properties of the thalamus, indicating that more mindful individuals exhibit lower global efficiency, lower clustering coefficient, and lower degree connectivity between the thalamus and the other nodes of the DMN. Wang et al.'s findings, which extend beyond the functional connectivity studies, also suggest that the segregation of the thalamus from the other canonical regions of the DMN is a significant correlate of dispositional mindfulness.

Adding to these nodal studies, Jao et al. (75) examined state-dependent shifts in the reconfiguration of hubs during meditation compared to rest. No differences in global topology networks were identified between the meditative and rest states in experienced meditators. However, experienced meditators showed expertise-dependent reorganization of the hubs, particularly in regions of the sensory-motor cortex, the primary visual cortex, and the auditory cortex. Nodes of these regions showed the highest degree connectivity during rest, but during meditation, their connectivity was significantly reduced. In contrast, key regions of the DMN and the FPN, including the precuneus, the medial PFC, the intra-parietal lobule, and the dlPFC, showed increased degree connectivity in the meditative state. Together, these node-based examinations of network properties corroborate prior literature while providing additional insights into their specific connectivity patterns within the functional brain connectome.

One of the fundamental principles in the organization of connectomes, as discussed above, is the tendency to minimize communication cost while simultaneously enhancing global communication and information transfer. This balance is often quantified using metrics of segregation like the clustering coefficient. This measure quantifies the density of connections among spatially adjacent nodes. Alternatively, integration measures, such as global efficiency, quantify efficient neural communication between spatially and functionally distant brain regions. Mindfulness training has been shown to reduce functional segregation between the DMN, the DAN, the salience network, and the FPN in individuals with cancer (76). Similarly, a brief mindfulness training program in older adults resulted in reduced intra-connectivity among the nodes of the DMN, the salience, and the somato-motor networks (77). A study examining adherence to meditative practices (focused attention and open monitoring) found system segregation and clustering were predictive of participation and the number of classes attended (78).

System-wide integration metrics, such as path length and global efficiency, have been increasingly examined in studies comparing experienced to novice meditators (79). In a study of aging meditators compared to novices, Gard et al. reported shorter path lengths in meditators, with scores on the Five Factor Mindfulness Questionnaire (80) correlating positively with global efficiency and negatively with path length. In related research, Van Lutterveld et al. (81) employed EEG to examine differences in functional network topology in the theta, alpha, and lower beta frequency bands between experienced and novice meditators. They found increased network integration (higher betweenness centrality, decreased diameter, and decreased eccentricity) in meditators compared to novices, particularly in the alpha band. Relatedly, greater overall alpha connectivity has also been observed before and after cessation events— momentary lapses of consciousness that occur with mastery of mindfulness meditation and are followed by reports of incredible clarity and calm (82).

To summarize, network science provides a formal structure for investigating brain connectivity. While its application in mindfulness meditation is in its early stages, the handful of investigations conducted so far are providing further insight on how the organization and operation of different nodal structures and networks restructure following engagement in mindfulness meditation. However, there are key limitations to these studies, which we discuss in the next section and offer avenues for future research.

Limitations and Future Directions

Most current research has focused on exploring functional connectivity differences among various brain regions resulting from engagement in meditative practices. However, there have been relatively few studies examining whole-brain, network, or nodal reconfiguration through metrics of segregation, integration, or influence. Since these metrics can be computed on existing resting-state and task-based fMRI data, we encourage future research to utilize readily available toolkits, such as the Brain Connectivity Toolbox (83), to examine changes in network segregation and integration measures.

Another key limitation of much of this research is the predominant focus on resting-state functional connectivity. Increasing evidence suggests that participants experience various mental states during resting-state paradigms, including mind-wandering, introspection, and consolidation of episodic memory (84,85). Thus, there may be significant mental state variability among participants during resting-state data collection which may influence global and local properties of brain networks. In an attempt to address this issue, a recent study by Dixon et al. examined global and local metrics of segregation and integration during a mindful acceptance condition and compared these to nodal and network reconfigurations during an elaborative narrative form of processing (86). Notably, there was an increase in overall global network connectivity, within-network connectivity, and between-network connectivity in the acceptance versus the narrative-elaborative condition. These conditions also differed with respect to connector and provincial hubs. During the acceptance condition, areas of the FPN, including the dlPFC, the inferior frontal sulcus, and the intraparietal sulcus, served as connector hubs exerting cognitive control and meta-awareness. In contrast, the left PCC, the left inferior frontal gyrus (near Broca's area), and the mid-cingulate cortex, were identified as the hubs during the narrative-evaluation condition. These regions are canonical nodes of the DMN and have been implicated in self-referential processing. Thus, it is crucial for future research to integrate the phenomenology of self-reported experiences with graph theoretic metrics of brain organization, as this triangulation is necessary to develop a comprehensive understanding of how mindfulness influences the landscape of brain connectivity.

Several developments in the field of network neuroscience will facilitate future research. For example, future studies may move beyond "static" measures of functional connectivity to include time-varying or "dynamic" functional connectivity (87). This approach builds on the intuition that the connectivity estimated over a 5–30 minute scan window only offers a “static” view of brain organization and that, over shorter intervals, brain network architecture is variable. Implicitly, approaches for estimating time-varying connectivity ascribe observed fluctuations in network structure to ongoing thought, physiological responses, and changes in brain state with promising support for mindfulness training to increase the frequency of brain states associated with focused attention (88) Dynamic functional connectivity studies, employing network neuroscience, can additionally track variation in network attributes across time with the aim of developing a better understanding of the principle by which networks reconfigure. Recent studies of time-varying modularity have been especially influential, yielding the measure “flexibility”, which can describe how frequently a node can change its community assignment across time (89–91). Flexibility appears to be a powerful biomarker and can be examined in future mindfulness training studies to examine how network properties can reconfigure following training.

Relatedly, brain-based fingerprinting and precision mapping have recently been employed in neuroimaging to identify individualized network features. In a study applying these techniques to mindfulness meditation, Kajimura et al. (92) acquired over 50 hours of fMRI data from a single participant engaged in meditation practice. Despite being a single-case experiment, the study demonstrated changes in the community size of the frontoparietal and default mode networks over time, with nodes in the frontoparietal network showing enhanced flexibility as practice increased. Although the generalizability of these results is limited due to the focus on a single participant, combining precision neuroscience with network neuroscience approaches in the future, particularly in novice meditators, could offer valuable insights into individual differences in the reconfiguration of nodes and networks.

Finally, it is important to note that, similar to the broader mindfulness literature, significant methodological concerns compromise the internal and external validity of network neuroscience studies on mindfulness meditation. As critiqued in Prakash et al. (93), many mindfulness meditation studies have small sample sizes (e.g., N=10), provide limited information on the content of training—making comparisons challenging across studies—and do not adequately quantify expectancy effects that could potentially influence study results. Studies involving expert meditators, in addition to having small sample sizes, often group various meditation practices into a single broad category, thus missing nuanced distinctions between different meditation traditions that may influence brain network properties. Additionally, the majority of mindfulness studies continue to oversample non-Hispanic white individuals, with limited recruitment of participants from minoritized groups (94). It is critical for future research to consider and address these threats to internal and external validity to ensure rigorous scientific study of mindfulness meditation.

Conclusions

In the approximately two decades since the advent of network neuroscience, the field has matured, and developed its own set of tools and sub-disciplines. This brief review highlights a select set of these approaches as applied to the study of mindfulness meditation. Preliminary evidence suggests that mindfulness meditation has the potential to alter both the global and local properties of brain organization, with several notable trends. Specifically, increased engagement with mindfulness meditation, whether in novices undergoing brief training or in those with extended experience, appears to shift connector hubs that facilitate efficient flow of information. These nodes include the ACC, the PCC, and the mid-insula. Additionally, the DMN shows reduced segregation among its canonical nodes following mindfulness training. There is mixed evidence on whether mindfulness training can impact the global landscape of interconnectivity, and future studies would benefit from further exploration of the effects of mindfulness meditation on global metrics of integration, segregation, and influence.

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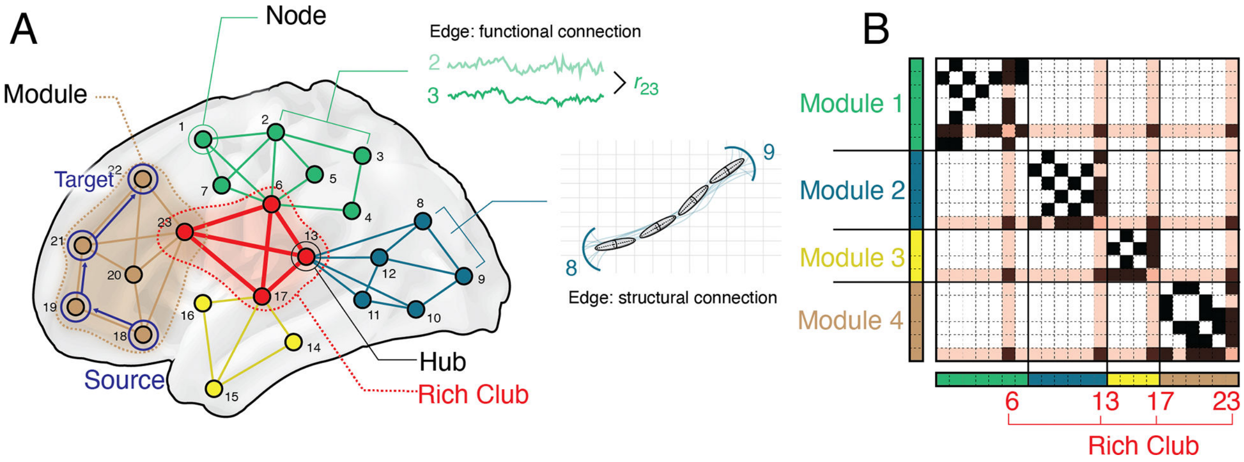

Figure 1. Network Neuroscience Methods:

The application of network science to study the functional or structural organization of the brain typically involves parcellating brain regions into nodes (points where paths intersect) and examining their edges (the functional or structural connections between nodes). Panel A. includes several constructs described in the main text, including nodes, edges, modules, hubs, and rich clubs. Edges can be defined either functionally (e.g., correlation between BOLD fMRI time-courses) or structurally (e.g., criteria related to tractography as computed from diffusion-weighted imaging). Panel B. depicts a connectivity matrix generated through computing relations (e.g., cross-correlations) between all pairs of regions of the brain.

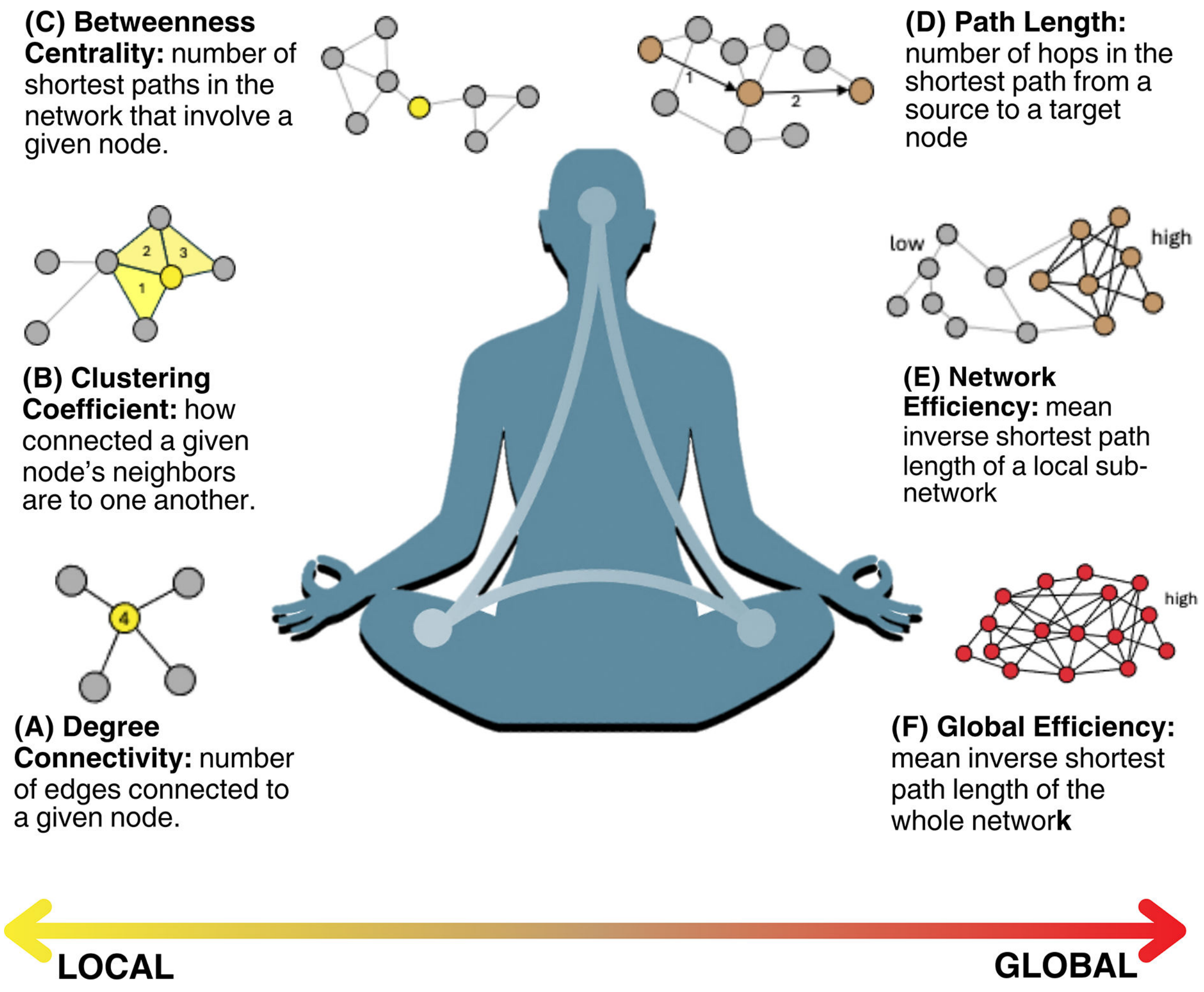

Figure 2. Network properties investigated in relation to mindfulness meditation.

From metrics assessing local to global connectivity: A) degree connectivity is increased in the anterior cingulate cortex and decreased in the supplementary motor area after mindfulness training (67). Trait mindfulness is linked to lower degree connectivity between the thalamus and other nodes of the DMN (74), and nodes within several canonical networks (DMN, FPN) demonstrate increased degree connectivity during meditative states. B) Clustering coefficient is lower between the thalamus and other nodes of the DMN (74), and predicted meditation practice participation and class attendance (78). C) Betweenness centrality of the caudate is higher in meditators compared to novices (72,73). D) Path length is shorter on average in meditators compared to novices and an association between path length and the Five Factor Mindfulness Questionnaire demonstrated that average path length decreases as trait mindfulness increases (95). E) Network (local) efficiency of the ACC is shown to increase in participants receiving mindfulness training, whereas network efficiency of the supplementary motor area decreased (67). F) Global efficiency has been shown to be higher in individuals with higher trait mindfulness (95).