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ENIGMA-Meditation: Worldwide consortium for neuroscientific investigations of meditation practices

Saampras Ganesan^{#,1,2,3}, Aki Tsuchiyagaito^{4,5,6}, Greg J Siegle⁷, Philippe Goldin⁸, Lisa T. Eyler^{9,10}, Isaac N Treves¹¹, Antoine LUTZ^{12,13}, Giuseppe Pagnoni¹⁴, Paulina Clara Dagnino¹⁵, Anira Escrichs¹⁵, Luigi F. Saccaro^{16,17}, Matthew D. Sacchet¹⁸, Vaibhav Tripathi¹⁹, Ishaan Batta²⁰, Ruchika S. Prakash^{21,22}, Kirk Warren Brown²³, Nicco Reggente²⁴, Sahib S. Khalsa^{4,5}, Timothy J. McDermott²⁵, Sofie Valk^{26,27,28}, Yi-Yuan Tang²⁹, Negar Fani²⁵, Gustavo Deco¹⁵, Eric L. Garland³⁰, Vince D. Calhoun²⁰, Svend Davanger³¹, Camille Piguet¹⁶, Clemens C.C. Bauer^{11,32}, Fernando A. Barrios³³, Gaël Chetelat³⁴, Namik Kirlic⁴, David M. Fresco³⁵, Hadley Rahrig³⁶, Alyssa Torske³⁷, Yoona Kang³⁸, Joshua A. Cain²⁴, Norman A.S. Farb^{55,56}, Rahul Garg^{39,40}, Matthew D. Turner⁴¹, Suruchi Fialoke⁴⁰, Danella M. Hafeman⁷, Janine M. Dutcher²³, Judson A. Brewer^{52,53}, J. David Creswell²³, Lei Cao⁴¹, Todd S. Braver⁴², Fadel Zeidan^{43,44}, David R. Vago⁴⁵, Sara W. Lazar⁵⁴, Richard J. Davidson^{36,46,47}, Christopher R. K. Ching⁴⁸, Neda Jahanshad⁴⁹, Sophia I Thomopoulos⁴⁹, Paul M. Thompson⁴⁹, Andrew Zalesky^{1,3}, Jessica A. Turner⁴¹, Anthony P King^{*,41,51}

¹Department of Biomedical Engineering, The University of Melbourne, Carlton, Victoria 3053, Australia

²Contemplative Studies Centre, Melbourne School of Psychological Sciences, The University of Melbourne, Melbourne, Victoria 3010, Australia

³Systems lab of neuroscience, neuropsychiatry and neuroengineering, The University of Melbourne, Parkville Victoria, 3010, Australia

⁴Laureate Institute for Brain Research, Tulsa, Oklahoma, USA

⁵Oxley College of Health & Natural Sciences, The University of Tulsa, Tulsa, Oklahoma, USA

⁶Research Center for Child Mental Development, Chiba University, Chiba, Japan

⁷Department of Psychiatry, University of Pittsburgh, Pittsburgh, PA, USA

⁸University of California Davis, Sacramento CA, USA

⁹Department of Psychiatry, University of California, San Diego, La Jolla, CA, USA

¹⁰Desert-Pacific Mental Illness Research Education and Clinical Center, VA San Diego Healthcare System, San Diego, CA, USA

¹¹Brain and Cognitive Science, McGovern Institute for Brain Research, Massachusetts Institute of Technology, Cambridge, USA

¹²Eduwell team, Lyon Neuroscience Research Centre, INSERM U1028, CNRS UMR5292, Lyon 1 University, Lyon, France

¹³Lyon Neuroscience Research Centre, INSERM U1028, France

¹⁴Department of Biomedical, Metabolic, and Neural Sciences, University of Modena & Reggio Emilia, Modena, Italy

¹⁵Computational Neuroscience Group, Center for Brain and Cognition, Department of Information and Communication Technologies, Universitat Pompeu Fabra, Barcelona, Catalonia, Spain

- ¹⁶Psychiatry Department, Faculty of Medicine, University of Geneva, Geneva, Switzerland
- ¹⁷Psychiatry Department, Geneva University Hospital, Geneva, Switzerland
- ¹⁸Meditation Research Program, Department of Psychiatry, Massachusetts General Hospital, Harvard Medical School, Boston, Massachusetts, USA
- ¹⁹Center for Brain Science & Department of Psychology, Harvard University, Cambridge, MA, USA
- ²⁰Center for Translational Research in Neuroimaging and Data Science (TReNDS): Georgia State University, Georgia Institute of Technology, and Emory University, Atlanta, USA
- ²¹Department of Psychology, The Ohio State University, Columbus, OH, 43210, USA
- ²²Center for Cognitive and Behavioral Brain Imaging, Department of Psychology, The Ohio State University, Columbus, OH, 43210, USA
- ²³Department of Psychology, Carnegie Mellon University, Pittsburgh, PA, USA
- ²⁴Institute for Advanced Consciousness Studies, Santa Monica, CA, USA
- ²⁵Department of Psychiatry and Behavioral Sciences, Emory University, Atlanta, Georgia, USA
- ²⁶Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany,
- ²⁷Institute of Systems Neuroscience, Heinrich Heine University Düsseldorf, Düsseldorf, Germany
- ²⁸Institute of Neuroscience and Medicine (INM-7: Brain & Behaviour) Research Centre Jülich, Jülich, Germany
- ²⁹College of Health Solutions, Arizona State University, Phoenix, AZ, USA
- ³⁰Center on Mindfulness and Integrative Health Intervention Development, University of Utah Salt Lake City, UT, USA
- ³¹Division of Anatomy, Institute of Basic Medical Sciences, University of Oslo, Oslo, Norway
- ³²Department of Psychology, Northeastern University, USA
- ³³Universidad Nacional Autónoma de México, Instituto de Neurobiología, Querétaro, México
- ³⁴Normandie Univ, UNICAEN, INSERM, U1237, Neuropresage Team, Cyceron, 14000 Caen, France
- ³⁵Department of Psychiatry and Institute for Social Research, University of Michigan, Ann Arbor, MI, USA
- ³⁶Psychology Department, University of Wisconsin-Madison, Madison, Wisconsin, USA
- ³⁷Department of Diagnostic and Interventional Neuroradiology, School of Medicine and Health, Technical University of Munich, Munich, Germany
- ³⁸Department of Psychology, Rutgers University - Camden, Camden, NJ, USA
- ³⁹Department of Computer Science and Engineering, Indian Institute of Technology, New Delhi, India
- ⁴⁰National Resource Center for Value Education in Engineering (NRCVVE), Indian Institute of Technology, New Delhi, India
- ⁴¹Department of Psychiatry and Behavioral Health, Ohio State University Medical Center, Columbus, OH, USA
- ⁴²Department of Psychological and Brain Sciences, Washington University, St. Louis, MO, USA
- ⁴³Anesthesiology, University of California, San Diego, La Jolla, CA, USA
- ⁴⁴T. Denny Sanford Institute for Empathy and Compassion, San Diego, La Jolla, CA, USA
- ⁴⁵Psychiatry, Brigham & Women's Hospital, Boston, MA, USA
- ⁴⁶Center for Healthy Minds, University of Wisconsin-Madison, Madison, Wisconsin, USA ⁴⁷Department of Psychiatry, University of Wisconsin-Madison, Madison, Wisconsin, USA
- ⁴⁸Imaging Genetics Center, Mark and Mary Stevens Neuroimaging and Informatics Institute, Keck School of Medicine, University of Southern California, Los Angeles, CA, USA
- ⁴⁹Imaging Genetics Center, Mark and Mary Stevens Neuroimaging and Informatics Institute, Keck School of Medicine of USC, University of Southern California, Marina del Rey, CA, USA 90292
- ⁵¹Institute for Behavioral Medicine Research, Ohio State University Medical Center, Columbus, OH, USA
- ⁵²Department of Behavioral and Social Sciences, Brown University, School of Public Health Providence, RI, USA
- ⁵³Department of Psychiatry, Warren Alpert Medical School, Brown University, RI, USA

⁵⁴Department of Psychiatry, Massachusetts General Hospital, Harvard Medical School, Boston, Massachusetts, USA

⁵⁵Department of Psychology, University of Toronto, Mississauga, Ontario, Canada

⁵⁶Department of Psychological Clinical Science, University of Toronto, Scarborough, Canada

#First author

`Last author

Corresponding authors:

Saampras Ganesan

Email: saamprasg@student.unimelb.edu.au

Anthony P. King

Email: Anthony.King@osumc.edu

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abstract

Meditation is a family of ancient and contemporary contemplative mind-body practices that can modulate psychological processes, awareness, and mental states. Over the last 40 years, clinical science has manualised meditation practices and designed various meditation interventions (MIs), that have shown therapeutic efficacy for disorders including depression, pain, addiction, and anxiety. Over the past decade, neuroimaging has examined the neuroscientific basis of meditation practices, effects, states, and outcomes for clinical and non-clinical populations. However, the generalizability and replicability of current neuroscientific models of meditation are yet to be established, as they are largely based on small datasets entrenched with heterogeneity along several domains of meditation (e.g., practice types, meditation experience, clinical disorder targeted), experimental design, and neuroimaging methods (e.g., preprocessing, analysis, task-based, resting-state, structural MRI). These limitations have precluded a nuanced and rigorous neuroscientific phenotyping of meditation practices and their potential benefits. Here, we present ENIGMA-Meditation, the first worldwide collaborative consortium for neuroscientific investigations of meditation practices. ENIGMA-Meditation will enable systematic meta- and mega-analyses of globally distributed neuroimaging datasets of meditation using shared, standardized neuroimaging methods and tools to improve statistical power and generalizability. Through this powerful collaborative framework, existing neuroscientific accounts of meditation practices can be extended to generate novel and rigorous neuroscientific insights, accounting for multi-domain heterogeneity. ENIGMA-Meditation will inform neuroscientific mechanisms underlying therapeutic action of meditation practices on psychological and cognitive attributes, advancing the field of meditation and contemplative neuroscience.

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Meditation encompasses contemplative mind-body practices characterized by diverse techniques, philosophies, and religious traditions (1–5). Broadly, meditation involves purposeful attention, voluntary regulation of psychological and embodied processing, and modulation of conscious awareness (6–9). Meditation practice can enable salutary psychological, psychosomatic and/or spiritual states of consciousness with acute and enduring positive impacts on mood, cognition, and general well-being (10–12). Scientific investigations of meditation have predominantly involved techniques including mindfulness, focused attention, open-monitoring, loving-kindness, compassion, mantra, non-dual awareness, and their variations (2,9,13,14). Some of these meditation forms have been incorporated directly into Western medical contexts in psychotherapies such as Mindfulness-based Stress Reduction (MBSR) (15), Mindfulness-based Cognitive Therapy (MBCT) (16), Mindfulness-Oriented Recovery Enhancement (MORE) (17), compassion meditation training (18), transcendental meditation training (19), etc. (20), and indirectly in interventions influenced by meditation traditions such as Acceptance and Commitment Therapy (ACT) (21) and Dialectical Behavior Therapy (DBT) (22) among others (20). Such psychotherapeutic meditation interventions (MIs) have transdiagnostic value (23), and can impart neuroprotective effects (24), improve stress management in medical conditions like cancer, chronic pain, and fibromyalgia, and combat psychiatric conditions including anxiety, depression, posttraumatic stress disorder (PTSD), and alcohol and substance use disorders (25–28). However, similar to other clinical interventions (29), MIs can also sometimes produce adverse events (30).

The past several decades have witnessed burgeoning neuroscientific examinations of meditation practices using magnetic resonance imaging (MRI) and electroencephalography (EEG). Meta-analyses of MRI and EEG literature suggest that meditative practices are associated with acute and enduring changes in brain structure (31,32) and function (13,33–39), including alterations in functional networks, morphology, and neural oscillations (40,41) associated with relevant cognitive and psychological processes (such as self-related processing, awareness, attentional and emotional regulation). However, the replicability and generalizability of neuroscientific findings from the meditation literature are challenged by modest sample sizes and substantial heterogeneity in experimental design, data processing techniques, and meditation practices, impeding deep neuroscientific phenotyping of meditation. Developing a more nuanced and rigorous understanding of the neural basis of meditation can potentially improve estimates of moderators and mediators of the effects of different meditation practices, and identify predictors of individual differences in brain mechanisms underlying clinical action of MIs. Such advantages can in turn enable effective patient stratification for clinical trials involving MIs, improve prognostic assessments of clinical outcomes of MIs, and inform augmentation approaches such as neuromodulation, biofeedback, and personalization.

Here we introduce Enhancing Neuroimaging Genetics through Meta Analysis (ENIGMA)-Meditation - a newly established innovative global consortium for collaborative neuroimaging of meditation that will address existing challenges and deepen the neuroscientific understanding of

meditation. ENIGMA-Meditation brings together neuroimaging data from meditation researchers worldwide to facilitate large-scale meta- and mega-analysis projects using shared, strategically-planned, standardized processing, and statistical analyses. The primary goal of ENIGMA-Meditation is to systematically and reliably characterize the neuroscience of different meditation practices, evaluate commonalities and distinctions between diverse practice forms and stages, and investigate how their neuroscientific substrates relate to impact on pertinent psychological, physiological, clinical, and cognitive attributes.

Neuroimaging literature of meditation in healthy individuals

Meta-analyses of the functional MRI (fMRI) literature on cross-sectional investigations of meditation in healthy populations indicate widespread involvement and interplay between distributed brain regions spanning the default-mode network (DMN), salience network (SN), and central executive network (CEN) (13,33,35,36). These brain networks are typically thought to underpin putative neurocognitive mechanisms of meditation practice, such as self-referential processing and stimulus-independent thought (DMN), arousal and interoceptive awareness (SN), and executive function and attentional regulation (CEN) (6,8,33). Emerging evidence also highlights inter-individual variations in self-report measures of dispositional mindfulness (33,39,42–44) and differences in meditation experience between adept practitioners and novices (33,34,39,45–48) influencing functional connectivity (FC) and activation changes within and between some of these brain networks. The insula, associated with emotional processing, awareness, and interoception (49,50) and the anterior cingulate cortex (ACC) implicated in attentional regulation and conflict monitoring (51,52) are two key SN regions commonly engaged in diverse meditation techniques (13). Similarly, while structural MRI differences between adept meditators and novices may be widespread throughout the brain (53), meta-analytic evidence from cross-sectional literature suggests these differences may be more pronounced in the insula and ACC (SN) (31,32).

Neural correlates of MI-related improvements among healthy individuals in memory (54) and executive functioning (55), emotion regulation and reactivity (56,57), and pain perception (58) are widely associated with dissociable activation and FC changes within the DMN, SN, and/or CEN, as well as the amygdala (59), thalamus, and orbitofrontal cortex (OFC) (58). Recent meta-analysis (38), review (39) and trials (60–65) examining longitudinal resting-state FC changes associated with mindfulness-focused MIs have identified modifications in these networks, implicating dorsolateral prefrontal cortex (DLPFC) (CEN), PCC (DMN) and insula (SN). Evidence on longitudinal brain structure alterations associated with MIs however remains mixed. Some studies have found distributed training-related morphometric effects within DMN and SN (66–70) but others have not replicated earlier findings (71,72).

Taken together, in healthy individuals, meditation and its outcomes demonstrate functional and structural changes in brain regions within intrinsic brain connectivity networks associated with self-referential processing, interoception and awareness, and executive functioning (i.e., DMN,

SN and/or CEN), in addition to other networks. While some reviews and studies implicate DMN, SN and CEN, or a subset of these networks, others found no effects at all (e.g., with structural MRI), thus highlighting the discordance in the current literature. Notably, meditation-related changes in the insula have been most consistently reported, but there remains substantial variability across the literature.

Neuroimaging literature of meditation in individuals with clinical conditions

The neural substrates that appear to underlie impacts of MIs in transdiagnostic clinical samples also show overlap with DMN, SN and/or CEN among other brain networks and regions, as evidenced by reviews and seminal randomized control trials (RCTs).

A review of FC effects of MIs found that in individuals with chronic stress and disorders including MDD and PTSD, MIs commonly modulate resting-state FC between PCC (DMN) and DLPFC (CEN) (39) which may relate to attentional control over mind wandering. Recent meta-analytic evidence of structural alterations associated with MIs in both healthy and clinical samples implicate the insula (SN) and precentral gyrus (73). A review of MIs for pain suggested that the analgesic effect of MIs involves functional changes in ACC and insula (SN), thalamus and reward/evaluation-related OFC (74). A systematic review of MIs for substance-use disorders observed therapeutic action consistently accompanied by changes in ACC (SN) and striatum (75). A recent RCT reported that emotion regulation strategies adopted by social anxiety patients after MBSR training involve differential engagement of ACC (SN), medial PFC (DMN) and DLPFC (CEN) (76). Several RCTs involving MIs for major depressive disorder (MDD) have reported that FC, activation, and structural (77) changes in DLPFC (CEN) (77–79) and amygdala (77,79) accompany clinical outcomes. An RCT involving MI for attention deficit and hyperactivity disorder (ADHD) observed dominant activation changes in the insula (SN), precuneus (DMN) and inferior parietal lobe (CEN) following the intervention, with hyperactivity symptoms linked to medial PFC and PCC (DMN) activity changes (80). Improvements associated with a 3-month MI targeting age-related mild cognitive impairment (MCI) were tracked by changes in FC dynamics primarily involving ACC (SN), PCC and superior temporal gyrus (DMN), and insula (SN) (81). Another RCT investigating white matter changes observed effects in the ACC (SN) following an MI for panic disorder (82).

Taken together, MIs targeting diverse clinical conditions also appear to commonly modulate function and structure of distinct hubs within DMN, SN and/or CEN. Additionally, studies of MIs in clinical samples have also shown evidence of involvement of other cortical and subcortical neural circuits associated with social-emotional, threat, and reward processes, including the amygdala, OFC, and striatum. Variability in the implicated neural circuits across the literature may reflect factors related to clinical studies, such as type of disorder and underlying brain network dysregulation, and specific features of the intervention and/or comparison treatment group.

Limitations in the current state of meditation neuroscience

The existing cross-sectional and longitudinal neuroimaging studies of meditation have enabled mapping of functional and structural brain changes underlying distinct meditation practices and states in clinical and non-clinical cohorts that include novices and experienced meditation practitioners. The current state of meditation neuroscience, while providing valuable insights, confronts significant variability and methodological challenges.

Although existing meta-analyses in the field find convergent activation / FC / structural changes in DMN, SN and/or CEN, the concordance between meta-analytic findings at the level of specific brain regions remains low, with changes in insula being the most consistent finding (13,31–36,38,73). Such low generalizability, specificity and discordance likely stem from inadequate statistical power driven by small study samples (< 20 studies) of meta-analyses (83) and considerable variability in sample characteristics, control conditions, task, inclusion criteria, and statistical processes. Similar challenges also hinder the generalizability of findings from reviews, many of which collapse inferences from studies involving varying meditation techniques, levels of meditation experience, and manualized MIs (32,39,75,84,85), with limited consideration of this heterogeneity across studies. Another concern is lack of adequate control for confounds (physiological responses, head motion, multiple comparisons) that can substantially contaminate fMRI signals and inferences (86). For example, less than 20% of the reviewed cross-sectional fMRI literature on focused attention meditation accounted for these confounds in their analyses (33).

Several cortical (e.g., somatomotor and attention network regions, occipital regions, OFC), subcortical (e.g., amygdala, hippocampus, thalamus, striatum) and cerebellar areas have also been implicated in the clinical and non-clinical literature, albeit variably across studies and clinical conditions. For instance, MIs can impact MDD symptoms by modulating the amygdala which is involved in affective processing (77,79), pain by modulating OFC and thalamus which are implicated in sensory evaluation and processing (58), and addiction by modulating striatal regions involved in reward-processing (75). Gaps still remain in characterizing the key brain mechanisms unique to and common across different clinical conditions and their mechanisms of action. Brain networks widely associated with meditation like the DMN, CEN and SN have also been otherwise implicated in general cognitive task demands (87,88), dysfunction across diverse psychiatric disorders (triple network model of psychopathology (89)), and other psychological processes like hypnosis (90). Greater clarity is required on the functional specificity of such brain networks pertaining to meditation practices. Meditation may also involve whole-brain distributed or multivariate effects on brain function (91–94) and structure (53,94), beyond their impact on localized regions, circuits, or networks. Robust decoding of such neural effects requires greater statistical power.

To address gaps in the literature and reliably decode the roles of diverse brain areas and complex whole-brain states unique to meditation and MIs, unified analytical methods that can

increase statistical power and sensitivity, and account for confounds, are warranted. To that end, we have adopted the ENIGMA framework.

The ENIGMA framework

The ENIGMA consortium was founded in 2009 to improve the replication and generalizability of neuroimaging and genetics analyses. Early ENIGMA projects focused on genome-wide associations to detect genetic markers influencing brain morphometry, by leveraging existing worldwide brain MRI and genetic datasets and applying standardized processing, quality control, and analysis techniques (95). The ENIGMA approach differs from the classic literature-based meta-analysis (combining effects from published studies that used variable processing and analysis techniques) as it uses standardized processing, quality control and analyses shared across all the participating datasets to boost statistical power. The ENIGMA consortium now includes over fifty Working Groups (WGs) developing scalable, open-source methods to study neurological conditions such as Parkinson's disease, epilepsy and stroke, adult and adolescent onset psychiatric disorders, from schizophrenia and MDD to anxiety and Tourette syndrome, as well as normative brain variation (96–98). Today, in addition to meta-analysis, many ENIGMA Working Groups perform both federated analyses as well as pooled mega-analysis where participant-level raw or derived brain measures are centralized to facilitate more complex analyses (e.g., machine / deep learning, etc.) (99–103). Through numerous large-scale collaborative projects, ENIGMA WGs have mapped the structural and functional brain correlates of various disorders in large demographically and ancestrally diverse samples. The scale of these studies allows for the modeling of complex clinical and comorbid features (e.g., symptom severity, duration of illness, and medication) both within and across brain conditions (104).

By using pre-existing, independently collected data, the ENIGMA approach boosts sample sizes and statistical power in a cost-effective manner. The standardized application of open-source neuroimaging pipelines and analytical models used within ENIGMA improves the reliability and transparency of study findings. By pooling diverse samples from around the world, ENIGMA studies improve replication power and generalizability of results. For instance, an all-Japan cohort investigating schizophrenia independently replicated the regional gray matter volume effect sizes observed by ENIGMA-Schizophrenia (105).

An ENIGMA meta-analysis typically involves two stages: 1) estimation of site-level summary statistics (such as effect sizes, standard errors / confidence intervals) from participant-level data using standard quality checks and statistical protocols performed at participating sites, and 2) centrally performed meta-analysis of the derived summary statistics for inference across sites. Additionally, the ENIGMA framework also confers a unique capacity for world-wide “mega-analysis” involving samples much larger than individual study samples. Mega-analysis is a single-stage analysis that uses shared standard methods and computing environments to

directly analyze participant-level raw data and/or derived data (e.g., brain structure volumes, or FC values) furnished by the participating sites to the central facility (106).

ENIGMA-Meditation

ENIGMA-Meditation is a recently launched WG that aims to conduct large-scale meta- and mega-analyses of globally distributed datasets using unified analytical processes to elucidate and clarify the neuroscience of meditation.

The primary goal of ENIGMA-Meditation is to advance the field of meditation neuroimaging by addressing limitations described earlier. The current literature primarily comprises small datasets with heterogeneity along several domains, including (i) meditation techniques (e.g., focused attention, open monitoring, loving-kindness, compassion), (ii) MIs (e.g., MBSR, MBCT, MORE), (iii) characteristics and meditation experience of samples (e.g., novice vs. experienced, tradition of practice, religio-cultural context, demographics) (iii) experimental design (e.g., longitudinal, RCT, cross-sectional), (iv) control conditions and comparison groups (e.g., rest or active task, exercise or relaxation for comparison intervention), (v) neuroimaging parameters (e.g., MRI scanner magnetic field strength, imaging protocols, sampling rates), (vi) analysis methods (e.g., FC, activation, multivariate), and (vii) preprocessing steps (e.g., head motion and physiological denoising, smoothing, filtering). Consequently, the generalizability and specificity of inferences drawn from existing neuroimaging reviews and meta-analyses in the field are limited.

Meta- and mega-analyses using participant-level data from diverse sites enabled by ENIGMA-Meditation will boost statistical power and account for some of the heterogeneity within a tightly controlled analytical framework ([Figure 1](#)). Pooled datasets can be harmonized using shared, standardized analysis and preprocessing protocols, and the effect of different covariates (e.g., meditation experience, meditation technique, physiological confounds, key sample characteristics, clinical disorders) can be controlled for / modeled at the site-level (meta-analysis) or even participant-level (mega-analysis) as mediators or moderators. As data accumulates with ENIGMA-Meditation, subsets of the aggregated data with comparable study designs and protocols (cross-sectional or longitudinal paradigms of functional or structural MRI), and / or homogenous samples (novices or experts, patients with specific disorders or healthy populations) can also be pooled and harmonized separately to enable targeted participant-level meta- or mega-analyses that address narrower hypotheses (e.g., neuroscientific mechanisms of MBSR to improve psychological distress or MBCT for MDD, functional activation changes during open-monitoring meditation, resting-state FC changes pre-to-post meditation retreats in healthy adults, etc.). Furthermore, neurobehavioural associations underlying meditation states, self-report measures and clinical scales may potentially be examined by harmonizing distinct but related assessment scores across sites and datasets (107,108). Taken together, such collaborative well-powered approaches may help to distinguish consistent, generalizable

findings from false positives and discordant outcomes that are prevalent among smaller individual studies (106,109).

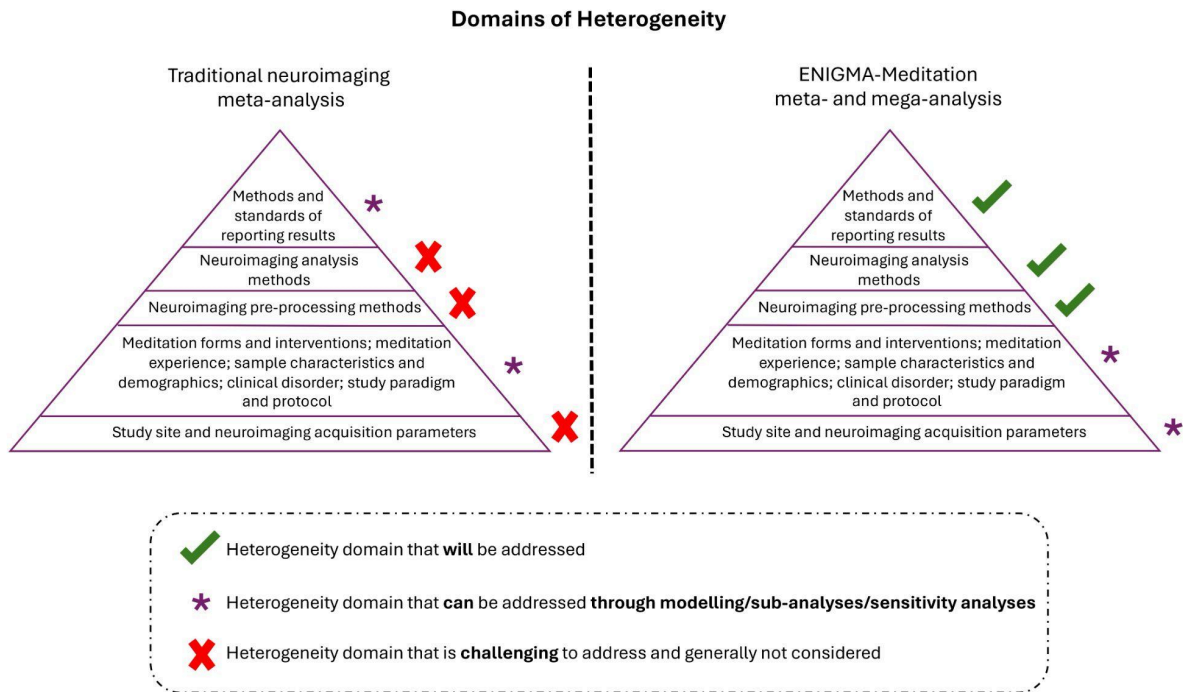


Figure 1: Comparison of the traditional meta-analytic approaches with ENIGMA-driven approaches, which can offer greater power to control for, or model, heterogeneity across multiple domains.

The main purpose of ENIGMA-Meditation is to tackle pressing neuroscientific questions surrounding meditation practices, and generate novel hypotheses. ENIGMA-Meditation will illuminate the role of complex whole-brain states and diverse cortical, subcortical and cerebellar regions in meditation practices and related states and traits. With large samples, it will examine consistent trends that may not attain statistical significance in individual underpowered studies (110). Importantly, participant-level mega-analyses can help disentangle physiological responses (e.g., changes in breathing, heart rate) and other nonspecific artifacts (e.g., head motion) from fMRI signals and inferences that are typically attributed to meditative states and effects (e.g., fMRI signals of DMN (86)). ENIGMA-Meditation will also evaluate transdiagnostic as well as disorder-specific neural mechanisms of action underlying various documented clinical effects of MIs. The statistical power of ENIGMA-Meditation analyses can generate insights into generalizable and replicable alterations of brain function and structure that are both unique to and common across meditation techniques and interventions, and levels of meditation experience among healthy and clinical populations. Recent cross-diagnostic analyses across ENIGMA WGs have successfully compared brain structural aberrations across diverse psychiatric disorders including schizophrenia, bipolar disorder, MDD, ADHD, PTSD and others (111,112). In ENIGMA-Meditation, such kinds of analyses will enable systematic comparisons

between the effect sizes and brain maps associated with distinct meditation techniques and interventions, levels of meditation experience or clinical disorders targeted by MIs.

Future directions

Extensive neuroscientific mapping of meditation with ENIGMA-Meditation can potentially provide a scientific basis to understand and elucidate traditional (and often ancient) practices and contribute to their validation in modern and secular therapeutic contexts (6,8). Some of the key future directions and scope possible with ENIGMA-Meditation include:

- Different traditions and frameworks describe states and practices of meditation using varied terms and concepts (2,5,9,113,114). Reliable neural maps enabled by ENIGMA-Meditation may help to identify and harmonize common constructs across varied meditation practices and states by exploring their subjective, cultural, semantic and conceptual pluralities (9,115,116). For example, compassion, empathy, meta-awareness, equanimity, bliss, non-duality, and decentering among others are often considered essential outcomes, phenomenological dimensions and states across different meditation practices (9,14,114,117–121). Statistically empowered participant-level mega-analyses from ENIGMA-Meditation can potentially illuminate some of the relationships between these phenomenological and neuroscientific dimensions.
- In meditation research, outcomes, quality, expertise, and experience associated with meditation practices and states are often based on self-report measures, which are prone to retrospective and demand biases (122–124) especially among novices and developing practitioners (123,125). Complementing and comparing first-person self-reports with robust neuroscientific (“third-person”) accounts derived from ENIGMA-Meditation findings can improve rigor by accounting for some of these biases (116,126,127), and also leverage a dimensional and multi-level approach to meditation research. Specifically, ENIGMA-Meditation will enable integration of aggregated neuroscientific datasets with their associated phenomenological and pathological measurements, which can provoke unprecedented multi-dimensional characterization of meditation practices and their effects on health and illness (similar to the Research Domain Criteria (RDoC) framework (128)).
- Several ENIGMA WGs use data-driven methods, such as non-linear, multivariate, machine and deep learning approaches to predict / determine brain-aging related abnormalities in MDD (99) and schizophrenia (129), predict alcohol dependence (100), or classify anxiety disorder cases vs. controls (101) and OCD cases vs. controls (102) based on brain structure. Similarly, ENIGMA-Meditation can develop powerful computational models that use neuroscientific data to distinguish levels of meditation experience or predict individual-level/patient-level responses to specific meditation

practices and MIs (130), complementing efforts that predict meditation outcomes using self-report data (131–133). Such efforts may also help demystify the neuroscientific mechanisms and predispositions underlying various documented contraindications to meditation practice (30,134).

- Existing data-driven approaches to decode meditation states and outcomes developed using smaller datasets (91–93,135–137) can be tested and improved using the large datasets and unified analytical framework available with ENIGMA-Meditation. Well-validated data-driven neuroscientific models may then inform neural decoding algorithms in emerging non-invasive neuromodulation (138) and neurofeedback (139) technologies aimed at augmenting meditation practice.
- Neuroimaging studies of meditation have typically involved young-to-middle aged adults. However, the emergence of individual studies exploring meditation-related effects on children (140), adolescents (141) and older individuals (55) will enable large-scale aggregate analyses with ENIGMA-Meditation that dissect age-related differences and potential developmental effects of meditation on brain function and structure.

Although the current scope of ENIGMA-Meditation involves multi-modal MRI research of meditation practices, ENIGMA WGs typically expand over time and birth various subgroups (98). Therefore, the inclusion of EEG (40,41) and other contemplative practices and arts (e.g., Yoga (142), Tai-chi (143)) in ENIGMA-Meditation is imminent, as these fields are also burdened by similar challenges as in the meditation neuroscience literature.

Current state

As of April 2024, several research groups have expressed interest to contribute data to ENIGMA-Meditation from published studies as well as prospective trials, which span over 65 investigators across North America, Oceania, Asia and Europe. [Figure 2](#) shows a map illustrating the current geographic diversity of ENIGMA-Meditation.



Figure 2: Geographical distribution of the current ENIGMA-Meditation membership (as of April 2024).

The currently available datasets include multimodal MRI neuroimaging data already or imminently acquired pre-to-post interventions (resting-state fMRI, structural MRI) and during meditation-related tasks (task-fMRI) associated with a variety of samples (healthy individuals, individuals with clinical conditions, novice meditator and expert meditator), contemplative practices (mindfulness, focused attention, compassion / loving-kindness, Vipassana, Yoga, Zen) and MIs (e.g., MBSR, MBCT, MORE, retreats). A number of resting-state and task-based EEG datasets have also been identified for future inclusion. Most of the datasets also include standardized self-report measurements such as Five Facet Mindfulness Questionnaire (FFMQ), Mindful Attention Awareness Scale (MAAS), State Mindfulness Scale (SMS), Cognitive Affective Mindfulness Scale (CAMS), etc. Supplementary Table 1 lists neuroimaging datasets currently available to ENIGMA-Meditation. Overall, ENIGMA-Meditation currently has access to MRI data from >200 expert meditators, >1300 healthy beginner-level individuals, and >600 patients with different psychiatric disorders, including MDD, PTSD, dissociation, social anxiety and early-life adversity.

There is an ongoing call for additional groups / investigators to join ENIGMA-Meditation. Information on how to participate is available on the ENIGMA-Meditation website (<https://enigma.ini.usc.edu/ongoing/enigma-meditation/>). ENIGMA-Meditation aspires to expand its membership which will increase the size and diversity of its datasets, samples, investigators, and studies.

Some of the initial projects being planned by ENIGMA-Meditation broadly include meta- and / or mega-analyses of enduring structural MRI and resting-state FC changes associated with MIs in healthy and clinical populations, fMRI activation / FC correlates of MRI meditation tasks, and associations between brain function / structure and self-reported meditation expertise.

Challenges with ENIGMA-Meditation

Although ENIGMA-Meditation and the broader ENIGMA framework offer scope and opportunities for advancement as a field, some challenges remain.

ENIGMA's projects are limited by the type and quality of data originally acquired by participating sites. While legacy datasets acquired years ago may have poor data quality due to technological and methodological limitations at the time of data acquisition, higher quality datasets acquired using newer neuroimaging techniques (e.g., multi-band, 7T, etc.) or other modalities (e.g., functional near infrared spectroscopy (fNIRS), MEG, etc.) are currently fewer. It can hence be challenging to fully account for heterogeneity in data quality, neuroimaging site, and depth of phenotyping (98). However, the global ENIGMA framework has been consistently developing methods and tools to address some of these limitations (144–147), such as harmonization of distinct symptom / neuropsychological scales, self-report measures, and site and protocol effects (107). This aspect is vital for ENIGMA-Meditation, since assessments of subjective experience and compliance with meditation instructions are often lacking, biased, or inconsistent across meditation neuroimaging studies (113). Data aggregated by ENIGMA-Meditation will not be sufficiently large or powered for reliable population-level inferences that are possible with prospectively-sampled large-scale neuroimaging databases like UK biobank (N>500,000) (148). However, findings from ENIGMA-Meditation can motivate large-scale prospective data collection efforts specific to meditation in the future.

Meditation and contemplative practices are culturally and geographically sensitive. Due to the expense of MRI scanning, representation from low- and middle-income countries with limited scientific resources will be impeded (149,150). Consequently, ENIGMA-Meditation might not fully capture the wide spectrum of meditation practices globally. Future inclusion of less expensive and more accessible neuroimaging data such as EEG can guide ENIGMA-Meditation to foster a more globally inclusive approach to meditation research, embracing a diverse range of practices, voices and perspectives from across the world.

Conclusions

We present a global collaborative consortium - ENIGMA-Meditation - which currently comprises >65 neuroimaging research groups across four continents. This consortium aims to perform rigorous neuroscientific examinations of meditation and other contemplative practices while

accounting for key issues of multi-domain heterogeneity and modest sample sizes prevalent in the current literature. By enabling large-scale integration of meditation neuroimaging datasets across continents and cultures, this initiative will set out to test and elaborate on the prevailing neuroscientific models of meditation practices with high analytical power. ENIGMA-Meditation will rigorously examine nuanced and novel neurocognitive and neuroplastic mechanisms that subserve the assortment of meditation practices, states, and their documented effects on psychopathology, health, and wellness. The standardized processing and statistical protocols along with advancements in big data analytics developed and tested over a decade by the ENIGMA framework and neuroimaging community will empower ENIGMA-Meditation to systematically elucidate and demystify the links between neuroscientific processes and meditation practices, experience, expertise, states, and outcomes. Consequently, the global consortium would help to illuminate the modern and secular therapeutic value of ancient contemplative practices through rigorous neuroscience research. By ensuring transparency, cultural sensitivity, humility, and inclusivity in its research practices, ENIGMA-Meditation is well-positioned to advance the field of meditation and contemplative neuroscience in a respectful, culturally informed, and scientifically rigorous manner.

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