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# Current trends and challenges in EEG research on meditation and mindfulness

**Paul Barrows**[1] · **William Van Gordon**[1] · **Paul Gilbert**[2,3]

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**Abstract**
During the last four decades there has been a significant growth of interest in mindfulness-based practices and their potential to foster improvements in health, wellbeing and human functioning in a variety of clinical and nonclinical populations. With this growth has come a renewed interest in understanding the psychological processes involved as well as the neuropsychological mechanisms by which such practices operate and effect transformative personal experiences and positive change. The current perspective paper (i) presents a basic taxonomy of meditation types and the structure and function of the processes believed to be involved, (ii) describes these components in terms of key neuroanatomical regions of interest, and (iii) critically appraises current findings regarding EEG measures as they relate to different aspects of meditation, functional activity and connectivity across regions of interest. The correlates between mindfulness and EEG are well described in terms of attentional and interoceptive processes and neuroanatomical regions of interest. To a lesser extent, there is also a growing understanding of such correlates for meditation techniques centred on compassion and loving-kindness meditation. However, the same does not apply to wisdom-based and null-state meditation practices where consistent associations between neuropsychological processes and EEG characteristics have proven elusive. These latter practices are viewed by many as key to fostering the deeper transformative experiences underlying psychological and spiritual development, and although studies of null-state meditation have yielded promising theoretical developments, more research is required. Future research could also benefit from better standardisation of EEG measures and analytic techniques to allow more robust metanalyses, and greater consistency of terminology regarding the fundamental components of meditation practice.

**Keywords** EEG · Neuropsychology · Meditation · Mindfulness · Compassion · Non-dual · Buddhism

## 1 Introduction

Meditation is a broad concept encompassing a diverse range of practices, with different modalities existing across almost all cultures and religions [1]. Although lacking a clear operational definition, meditation basically means observing with focused attention. It can be broadly conceived of as having at least three basic functions; (i) the deliberate exploration of the nature and contents of one's mind, called mind awareness and familiarisation. This form of meditation involves simply observing what arises as it arises without analytical thought or chasing thoughts or thinking about them [2]; (ii) the cultivation of focused attention on an object or process such as the breath or a sound to create specific mental

✉ Paul Barrows, p.barrows@derby.ac.uk; William Van Gordon, w.vangordon@derby.ac.uk; Paul Gilbert, p.gilbert@derby.ac.uk | [1]School of Psychology, University of Derby, Kedleston Road, Derby, Derbyshire DE22 1GB, UK. [2]Centre for Compassion Research and Training, College of Health, Psychology and Social Care, University of Derby, Derby, UK. [3]The Compassionate Mind Foundation, Derby, UK.

states. Again the key intention being to not engage analytical thought in order to still and settle the mind. This and clearing the clutter for conscious awareness enables new insights to arise into the nature of mind [3]; (iii) the cultivation of discernment enabling awareness of what is helpful (e.g., compassion, courage) and what is unhelpful (e.g., hatred, jealousy) [4]. These in turn can support the development of spiritual insight [5], the promotion of wellbeing [6], and enhanced concentration, attentional control and emotional regulation [1, 7, 8].

However, while there has been a significant increase of empirical interest in the applications of meditation to foster growth and wellbeing across physical, psychological and spiritual domains, many questions remain about the psychological processes involved, the underlying neuropsychology, and the mechanisms by which these practices effect positive change. The current perspective paper explores key areas where such ambiguity exists. Specifically, this paper seeks to (i) present a basic taxonomy of meditation types and the structure and function of the processes believed to be involved, (ii) describe these components in terms of key neuroanatomical regions of interest, and (iii) critically appraise current findings regarding EEG measures as they relate to different aspects of meditation, functional activity and connectivity across regions of interest.

## 2 Meditation types and taxonomies

As alluded to above, meditation has been proposed to involve two main components: focused attention (FA) and open monitoring (OM) [7]. The first of these aspects involves directing and sustaining attention towards a particular object or activity, such as the breath and sensations associated with respiration. This type of awareness has been termed 'bare' attention or 'lucid' awareness—the raw, immediate awareness of sensations, thoughts, and feelings as they impinge upon the mind, but unbiased by conceptual thought or judgement [9]. The second aspect entails the non-reactive monitoring of the flow of moment-to-moment experience through a form of 'watchful awareness'; this awareness, however, should entail an attitude of acceptance and openness even to experiences that may be difficult or distressing [10, 11].

Thus, FA comprises practices aimed at sustaining attentional focus on a particular object or activity, improving concentration, and the ability to notice mind wandering and enabling the mind to 'settle' from the autonomous flow of thoughts and states, thus quieting the default mode network [3]. The default mode network (DMN) consists of broadly distributed regions across the frontal, parietal, and temporal cortex which appear most active when we are not engaged in a task. These cortical regions are furthest away from sensorimotor areas involved in perception and action and less constrained by external input, and it is believed that their location reflects the endpoint of processing streams, whereby increasingly abstract features are encoded [12]. As such the DMN is understood to be key to our sense of self, relating to a variety of self-referential processes such as reflection and self-awareness, planning, decision-making, and imagining the future [13].

However, this mobilisation of attention comes with inevitable distractors which disrupt the desired level and object of focus [7]. Consequently, there follows a constant series of adjustments, as attention is consciously disengaged from the distracting thoughts or sensations and returned to its intended object. At the same time, these distractors are contained and minimised by positive cognitive reappraisals that reinforce the recognition of distractions as a natural part of the process by which attentional focus is strengthened and refined. By accompanying the return of attention to the desired object with an acceptance of the fact that attention was temporarily lost, the meditator avoids triggering a potential cascade of further distractors relating to negative self-appraisal and consequent shame or self-admonishment. OM, on the other hand has no specific focus and is predominated by meta-cognitive monitoring, where one attends to and non-reactively observes the sensations, thoughts and feelings as they arise in the mind [7]. Often, however, these elements are combined, with FA being used to first enable the practitioner to maintain and focus their attention, and OM being subsequently applied to examine and reflect upon mental phenomena in more depth [7, 14, 15].

The practice of FA and OM meditation generally serves to develop and discipline the mind in preparation for more advanced practice. Initially the focus may be on cultivating mental calmness and quiescence, subduing mental noise, settling the default mode and enhancing the clarity of consciousness. Once a steady and stable state of mind has been achieved, attentional focus can then be developed, enhancing the ability to ride over distractions, and allowing the scope of attention to be broadened, focused or directed at will [5]. FA and OM practices are generally regarded as central to the cultivation of 'skilful mindfulness' and are frequently used in this context as a way of enhancing concentration, mental wellbeing, and mind awareness. However, this focus on mental training which is typical of first-generation mindfulness-based interventions (FG-MBIs) has been criticised as presenting a narrow view of meditation that has been stripped of its roots in traditional Buddhist teachings, in which ethics and wisdom components play a major part in the development of deeper and more transformative experiences [16]. Increasingly, an arguably more encompassing conceptualisation of mindfulness—known as second-generation mindfulness-based interventions (SG-MBIs)—has been posited as an important step in repositioning secular mindfulness approaches as part of an integrated group of supporting contemplative principles [10].

Indeed, beyond the basic FA/OM subdivision, other types of meditation are frequently adopted, particularly as part of more advanced and inclusive practices. There exist a multitude of meditative practices across a wide range of contemplative traditions, and it is hard for any taxonomy to do justice to their sheer diversity [17]. However, there are some important key features which appear to have persistently predominated. In Buddhism, such features are organised within a tripartite, 'three trainings' (Pāli: *tisikkhā*) principle, comprising techniques concerned with (i) meditation, (ii) ethics and (iii) wisdom [14, 18]. In this context, meditation includes OM and FA that are typical aspects of mindfulness and related concentrative techniques, while the ethics component, incorporates (for example) compassion and loving-kindness (CLK) meditation practices that are concerned with cultivating a sense of deeper connectedness to others and the world around us [19]. In essence FA and OM can be regarded as psychological competencies and skills that people can practice and train in. However, competencies such as mindfulness or empathy require a motive in order for them to be used in particular ways. By themselves, they are neutral unless they facilitate some new insight such as self-transcendence which stimulates compassion, or compassion is chosen as the reason for cultivating mind awareness. Indeed, one of the criticisms of secular mindfulness is that it teaches a competency without a motivational and ethical context or focus [20].

The key intention of such ethics-based practices is to cultivate an unconditional compassionate and loving attitude towards oneself and others, although the specific operations of such techniques vary across different meditation traditions [21, 22]. Such ethics-based practices serve to further an important goal of Buddhism, that is, ego-transcendence, although the focus here is on the emotional dimension of this pursuit via the deepening of socio-empathic awareness that can help erode the boundaries between self and other [23].

For the wisdom component, the focus is upon the deeper inquiry into the nature of phenomena as they emerge in the mind. In psychological terms, this type of meditation aims to bring about a more profound understanding of reality, with a focus on truths such as of the impermanence of all things (Pāli: *anicca*), the fact that everything, including human beings, are devoid of an inherently independent existent self (Pāli: *anattā*) and that phenomena are thereby based in 'emptiness' (Pāli: *suññatā*) [24]. For example, brains are made up of elaborate, interconnected networks of nerve cells, which are in turn ultimately made up of atoms and molecules. However, it is from the energy patterns emerging from the totality of neurological activity that mental states and ideas of a separate self emerge in consciousness. With ageing and decaying into conditions such as dementia, that sense of self begins to disappear and ultimately, at death, as the body decomposes, the building blocks of a body, mind and sense of self revert back to simply what they are. The atoms in one's brain today may turn up in a tree in 100 years' time. Forms, then, are emergent patterns of energy rather than having any inherent existence beyond the organisation of energy. This is not to suggest that selfhood and reality have no existence, but that phenomena exist only in a relative sense, as an inseparable part of an interconnected and interdependent whole [18]. This is a view which is consistent with the picture of the universe that has emerged from the forefront of modern physics [25].

This wisdom component of Buddhist meditation is central to practices such as *zen*, *vipassanā* or *suññatā* meditation. Such practices focus on confronting the mind with the direct experience of reality at the inception of consciousness, as a boundless quintessence, an ontic ground from which all phenomena emerge. This 'emptiness' or *suññatā* is also essentially the stuff of Buddhist's *nirvana*, or non-duality, a mode of awareness in which the distinction between self, other, and all phenomena is transcended [24, 26]. The types of meditation which seek such non-dual states are sometimes referred to as 'null-directed' methods, as they aim to reveal the ground of consciousness in its pure undifferentiated state. Since this state is devoid of phenomenological content, it has been argued that it is neither affective nor cognitive in nature, therefore opinion is divided as to whether such practices should be considered insight/wisdom-based, or whether they defy such categorisation [27]. However, it might be argued that both CLK and insight meditation both have the deeper objective of duality transcendence, as it is only through transcending the Cartesian divide of subject and object that unconditional compassion and insight can be fully experienced and expressed. Therefore, both CLK and wisdom meditation could be viewed as inseparable from non-dual states which are ultimately required to cultivate and deepen both empathic awareness and metaphysical insight.

This triad of CLK, insight, and non-dual meditation methods is reflected very similarly in the taxonomy proposed by Nash et al. [28]. Here, CLK methods come under the 'Affective Domain' and are classified as affective-directed methods (ADM). Non-dual methods, such as *suññatā* meditation, Zen *satori* and transcendental meditation (TM) are viewed as part of the 'Null Domain' and are characterised as the aforementioned null-directed methods (NDM). Techniques which purport to develop enhanced cognitive states, such as *samatha* and *vipassanā* meditation, meanwhile, are included under the 'Cognitive Domain', classified as cognitive-directed methods (CDM). Elsewhere, Dahl et al. [29] have proposed a variant tripartite typology not unlike the Buddhist 'three trainings' principle. Here, an 'attentional family' encompasses a variety of practices focussed broadly on the FA and OM domains of the 'meditation' sub-division. A second 'constructive family' is focussed on practices employing the CLK methods and values orientation of the 'ethics' branch, while a third, 'deconstructive family' includes the insight or 'wisdom' practices seeking to cultivate deeper understanding and realisation. Non-dual methods are also included in this latter category.

There is, however, much crossover between many of these concepts and corresponding types of meditation because they are so deeply interconnected, with these different facets comprising different phases of the process through which the meditator first develops attention and stabilises awareness [1], and then progresses towards the realisation of deeper, mystical or revelatory states, such as those involving non-dual perceiving. Indeed, all of these aspects are themselves *anattā*—interdependent and complementary approaches which may be explored and balanced using a variety of techniques, and employing practices that engage various sensory, affective and cognitive modalities. Furthermore, these different elements of meditation practice are often combined in different ways under different Buddhist traditions, and even within a given tradition they are not always applied uniformly or consistently. Consequently, it is often challenging to isolate and study these different elements and their associations with outcomes or particular neuropsychological processes and their observable markers.

## 3 EEG: a brief overview

In examining the relationship between psychological function and brain activity, imaging techniques such as functional MRI (fMRI) have increasingly been used to understand the patterns of neurological activity associated with particular mental activity. Though fMRI has the advantage of high spatial resolution, and the capacity to discern highly localised activity, there are also a number of disadvantages that make it unsuitable or impractical for use in many research settings. Its high spatial resolution comes at the cost of relatively poor temporal resolution, with images being produced only once per second at best. Another disadvantage is the high cost and relatively low availability of this equipment and its unsuitability for use in ordinary settings. Its method of determining brain activity is also indirect, and reliant on blood-oxygen-level-dependent (BOLD) signals reflecting the uptake of oxygen across the brain. These indirect markers do not always offer the most accurate pictures of actual neurological activity, as the relationship between BOLD signals and brain activity is complex.

Electroencephalography (EEG), on the other hand, gives a direct measure of electrical activity within a region of the brain via the placement of electrodes across the surface of the scalp. Though the spatial resolution of EEG is relatively poor, it has high temporal resolution, with changes being observable in real-time with milliseconds precision [30]. This means that important details of electrical activity can be recorded and analysed that are inaccessible to fMRI methods. EEG equipment is also relatively inexpensive, lightweight and portable, and suitable for use in most real-world environments.

EEG comprises a combination of electrical waves mainly in the 0–30 Hz range, and these are divided into bands which are used to organise and make sense of frequency characteristics as they relate to phenomena under investigation. This information includes the frequency of activity, as well as the amplitude and power of activity in these wavebands. Furthermore, synchronisation of these waveforms across different neuroanatomical locations can yield valuable information about functional connectivity underlying different types of mental activity.

EEG is divided in five bands: Delta, Theta, Alpha, Beta, and Gamma. These bands cover ranges in ascending order of frequency, with higher frequencies broadly reflecting higher levels of psychological activity or arousal. Opinion, however, is somewhat divided over the exact frequencies that mark the upper and lower boundaries of these ranges, with evidence that these bands vary somewhat between individuals [31].

### 3.1 Delta

Delta waves are the slowest and highest amplitude brainwaves, with frequencies of < 4 Hz [32], and are believed to originate predominantly from the thalamus and cortex [33]. They are usually most prominent frontally in adults and posteriorly in children, with slow-wave delta rhythms being commonly associated with sleep [34], especially deep sleep beyond Stage 3, or *N3 slow-wave sleep* [35, 36].

### 3.2 Theta

Theta waves are rhythms occurring in the 4–8 Hz range, and are found in cortical and subcortical structures, with particularly marked activity in the hippocampus [37]. Increased cortical and subcortical theta activity has been linked with a variety of learning and recall tasks in humans [38, 39], as well as tasks involving working memory [40] and spatial navigation [37, 41], and there is evidence to suggest that increased theta activity prior to a memory task is associated with successful episodic memory retrieval [42]. Theta activity has proven to be prevalent once a task has been repeated to the point that it becomes autonomous, relying on little conscious attention to be completed [43]. Theta rhythms have also demonstrated synchronisation across multiple neuroanatomical regions during complex cognitive tasks [44].

### 3.3 Alpha

Alpha waves are rhythms that occur in the 8–12 Hz range. They occur strongly and most predominantly in the occipital cortex during wakeful relaxation, when a person is at rest with their eyes closed, but not tired or asleep. The amplitude of alpha rhythms are suppressed by eye-opening and attending to visual stimuli but are enhanced during cognitive tasks such as mental arithmetic or engagement of working memory, and have therefore been thought to reflect cortical 'idling' while in a relaxed but alert state, or the inhibition of task-irrelevant cortical activity [45]. There is growing evidence that alpha waves play a significant role in spatial attention, as well as an active role in network communication and coordination in perception and memory [45–47].

An alpha-like variant called a mu wave can also be found around the sensorimotor cortex. Though these waves are in the same frequency range as alpha, they are not eliminated by eye-opening like the posterior-dominant alpha waves in the occipital cortex; however, they are suppressed by intended or executed movement, or when a person is observing the movements of others [48].

### 3.4 Beta

Beta rhythms occur in the 12–30 Hz range, and can be broadly divided into two types, focussed on different neuroanatomical regions [49]. The first type, Rolandic beta rhythm, appears to be dominant in the sensory-motor strip and is typically modulated during motor and cognitive tasks. Beta rhythms are present in this area, for example, during muscle contractions and slow movements [50, 51] and are believed to reflect increased sensorimotor transmission and communication [52]. Beta waves can occur both with or without mu rhythms and appear to originate from areas that are anatomically distinct from those producing mu waves. A second type of beta rhythm is located more anteriorly and seems to be prevalent in cognitive tasks related to the assessment and responses to particular stimuli. Unlike Rolandic beta, these frontal waves appear to be associated with the completion of a task, and are often preceded by beta desynchronisation [49].

Beta activity is associated with a heightened state of awareness, with increases in beta activity being associated with increases in academic performance [53] and better arithmetic calculation ability [54].

### 3.5 Gamma

Gamma waves are rhythms that occur in the 30–100 Hz range. These brain waves were first detected in the visual cortex of primates and are thought to play a key role in conscious attention. In particular, gamma rhythms are believed to be involved with the widescale integration of sensory information through synchronisation of activity throughout many brain regions [55], and the coordination of motor responses [56]. The role of gamma in the binding and organisation of high-level features of vision has been extensively examined in humans and primates [57, 58] and similar findings have been observed across other sensory modalities [55, 56].

Gamma waves feature prominently in theories of perception, attention and consciousness, and are hypothesised to be part of a 40 Hz thalamocortical loop wherein lower order sensory features are organised into higher order percepts through temporal binding [59]. This binding of local activity into superordinate abstractions of more widely distributed neural activity in the gamma range is viewed by some prominent theorists as the means by which the unity of cognitive experience—and consciousness generally—emerges from activity across such diverse neuroanatomical regions [36, 59].

## 4 Meditation and the brain: networks and regions of interest

Despite a great deal of research, little is still known about the neuropsychology of processes involved in meditational practices and their long-term effects. Many of the early studies lacked a clear definition of meditation [27], and the overly generic conceptualisation of meditation as a mere relaxation technique often failed to capture the variety and complexity of the various practices which comprise it [7]. This, combined with heterogeneity of samples, lack of control populations, and difficulty in controlling for degree of expertise meant that many studies lacked methodological rigor and have been limited in their statistical power, generalisability and replicability [1, 7]. There have also been concerns over the limits of introspection, the reliability of self-report measures and the impossibility of true double-blinding in such studies [60]. However, this shortcoming has been improved somewhat by more nuanced and detailed examinations of the types of practices encompassed by meditation and how such practices confer benefits in terms of the key psychological and physiological processes involved [27].

### 4.1 Mindfulness meditation (OM/FM)

Lutz et al. [7] provided a basic subdivision of meditation into the aforementioned FA and OM practices, including a description of their key constituent processes and likely correlates in neuropsychological activity. Tang et al. [1] have similarly characterised FA and OM practices in terms of three core psychological components: *attention control*, *emotion regulation* and *self-awareness*. Focussing their examination on theories of how these practices effect positive psychological change, they have likewise focussed on what is known about the neuropsychology of these processes, the underlying neuroanatomical regions that are implicated, and neuroanatomical changes due to meditation.

Theories of the way FA practices operate have become closely aligned with neuropsychological conceptualisations of attention, which is unsurprising given that attentional processes and their role in goal-directed behaviour reflect one of the most extensively studied areas in Western psychology [61, 62]. Evidence from fMRI studies have suggested a broad division of the attention system into two subsystems. A dorsal frontoparietal system has been proposed as the seat of a cognitive control network comprising the dorsolateral prefrontal cortex (DLPFC), dorsal anterior cingulate cortex (dACC) and dorsal parietal cortex (DPC), which mediates top-down guided deployment of attention to salient environmental features, whereas a ventral frontoparietal system is believed to be involved in monitoring unattended or unexpected stimuli and triggering shifts of attention [63, 64]. Another network, the 'salience network' is centred on the anterior insula (AI) and the anterior cingulate cortex (ACC). This network plays an important role in detecting and responding to stimuli that are behaviourally relevant or emotionally salient and determines the orientation of attention towards these [65]. For selective spatial attention, the ventrolateral prefrontal cortex (VLPFC), temporo-parietal junction (TPJ), inferior parietal lobule (IPL), intraparietal sulcus (IPs) and frontal eye fields (FEF) typically show elevated patterns of activation [62] with right-side lateralisation of activity in these areas [61, 66], while conflict monitoring is thought to involve engagement of the DLPFC and dACC [67].

Sustained attention has been characterised in terms of a 'vigilant attention network' spanning many of these areas involved in selective attention, including right TPJ, IPL, IPs, and midlateral PFC, bilateral AI, bilateral thalamus, bilateral pre-supplementary motor area (pre-SMA), anterior medial prefrontal cortex (mPFC) and ventral premotor cortex (vPMC) [68]. The lateral posterior-pulvinar complex of the thalamus has also been implicated in maintaining and directing cortical activity in attention-demanding tasks. [69]. It's been noted that these regions overlap with the dorsal and ventral attention systems, as well as executive control attention networks [65, 70]. Findings from a review of the neurobiology of meditation shows support for the involvement of these attention networks in FA meditation [71]. OM practices, on the other hand, involve no specific attentional focus but the cultivation of a heightened awareness of the flow of moment-to-moment subjective experiences. This suggests that these practices will (i) predominately involve interoceptive processes which represent the perception and monitoring of internal bodily sensations, and (ii) involve reduced engagement of brain regions typically implicated in directing and sustaining attention on a particular object.

On the first point, interoceptive processing is now understood to centre upon the primary interoceptive cortex, an area spanning the dorsal posterior insula which receives impulses relating to the body's internal state [72]. This forms part of a wider network spanning the somatosensory cortex, anterior cingulate cortex (ACC) and anterior insula (AI) [73, 74], and some evidence supports more elevated activity in this network in OM meditators [71, 75]. On the second point, findings from studies of OM meditators have provided some support for this [76, 77]. For example, in one study OM meditators performed better on a sustained attention task than FA meditators when the stimulus was unexpected, but about equally when the stimulus was expected, suggesting stronger engagement of the ventral attention network and more distributed attentional focus in OM meditators [78].

### 4.2 Compassion and loving-kindness meditation (CLK/ADM)

Although compassion and loving-kindness have been an important feature of meditation across a wide range of traditional spiritual practices [79], it is only relatively recently that such techniques have been widely incorporated into secular, therapeutic interventions to address mental health problems and promote physical health and wellbeing [21, 80]. A substantial body of research has now accumulated attesting to the benefits of compassion-based interventions both as forms of psychotherapy and in their more traditional role as meditative practices in both novice and expert meditators [19, 81, 82]. With these developments, progress has also been made in understanding the neuropsychological basis of compassion and processes likely at play in effecting the positive changes of such interventions [83].

Due to their focus on cultivating a deep sense of compassion, such ADM practices involve the engagement of many of the areas related to OM meditation, with the experience of emotion deeply involved with the interoceptive processes. Lindquist et al. [84] suggest a neural reference space in which many structures communicate to form our experience of affective states. In addition to the ACC, AI and the other aforementioned regions implicated in interoceptive processes generally, the amygdala, insula, medial and inferior orbitofrontal cortex (MOFC/IOFC), thalamus, hypothalamus and periaqueductal grey matter are thought to form a network involved in *core affect*, while the ventromedial prefrontal cortex (vmPFC), dorsomedial prefrontal cortex (dmPFC), and medial temporal lobe (mTL) comprise an interconnected network involving the psychological construction of complex emotions and associated cognitions [84, 85]. This is consistent with a meta-analysis of 16 fMRI studies of expert ADM meditators, in which the involvement of some of these key areas (particularly ACC, AI, and periaqueductal grey) was reported [86].

Research into compassion specifically has shed further light on the processes and networks involved in this type of meditation. Compassion has been defined as a sensitivity to the suffering of others along with a desire to alleviate that suffering. Compassion differs from empathy in that while empathy involves indirectly sharing the experience of another's emotional state, compassion relates specifically to another's suffering, and a number of studies have explored the neural underpinnings of this. Compassion can be divided into three basic components: (1) an affective aspect relating to another's suffering, (2) a cognitive faculty in which one can take the perspective of another while differentiating one's own pain from that of another, and (3) a component of intentionality which is prosocial and directed at the alleviation of suffering [87]. One prominent metanalysis revealed support for a 'compassion network' focussing on the AI, ACC and amygdala. Even receiving a signal that indicated a loved one was experiencing a painful stimulus which they themselves had recently experiences caused activity in these areas [88]. These areas were coactivated depending on the nature of the elicitation of empathy, with abstract visual information about another's affective states activating structures involved with representing mental states of oneself and others, such as the vmPFC, superior temporal cortex, precuneus, superior temporal cortex and temporo-parietal junction. With empathic experience of another's pain the AI and rostral ACC were activated, though not the somatosensory components of the 'pain matrix', such as the posterior insular, primary and secondary somatosensory cortex [89]. Furthermore, the amygdala has been strongly implicated in the direct experience of negative affect generally [90].

In one notable FMRI study [7], 15 experienced Buddhist loving-kindness/compassion meditators compared to 15 novice volunteers were used to examine identified ROIs while participants listened to positive, negative, and neutral sounds during meditation and rest blocks. Results showed enhanced activity in the anterior insula (AI) and secondary somatosensory cortex (SII) in experts compared to novices, particularly during meditation and in response to emotional vocalizations. Furthermore, stronger activation during compassion meditation was observed in the AI and ACC, as well as in the temporal lobes, posterior superior temporal sulcus (pSTS), TPJ, medial prefrontal cortex (mPFC), and PCC/Precuneus, the latter cluster associated with perspective taking, mentation, and Theory of Mind.

### 4.3 Insight meditation (CDM)

Insight meditation such as *vipassanā*, has proven somewhat more difficult to identify with specific neuroanatomical regions of interest, as the processes involved have much in common with FA methods, and are thought to be similarly involved with the aforementioned neuropsychological conceptualisations of attention [7, 62]. The key distinction appears to be the focus of the former practice on contemplation of the true nature of the mind and reality, in particular the 'three marks of existence' that comprise the core of Buddhist ontology: *anicca* (impermanence), *dukkha* (dissatisfaction or suffering) and *anattā* (non-self), insights into which are deemed to be prerequisites to the attainment of wisdom and awakening. With such a significant overlap between these practices and the processes which comprise them, one might expect the involvement of similar brain regions, however what limited evidence exists for *vipassanā* seems to suggest involvement of the ACC and DMPFC, however there is insufficient detail to suggest the underlying processes that might be involved and how they might compare to either FA or OM meditation [71, 91].

The difficulty of reliably associating types of meditation with activity of particular cortical and subcortical networks, however, does underline the aforementioned limitation in general taxonomies regarding the nature of meditation. Though the subdivisions detailed have proven useful in understanding the neuropsychological processes involved, meditation is never practiced purely as any single 'component' and its phenomenology rarely exists as discrete states that can be clearly delineated. Care must be taken in clearly characterising meaningful distinctions between the content and purpose of meditation practices to form clear theories regarding the underlying processes involved.

Studies of insight meditation in relation to underlying neuropsychological processes appear all but absent from the literature, however given the preoccupation of insight meditation with the philosophical introspection and reflection, clues might be gleaned from evidence relating to the neuroscience of internally directed cognition and cultivation of wisdom. However, such abstract and complex processes are difficult to characterise so reductively. Nonetheless 'wisdom' has been characterised as concerning prosociality, social decision-making, emotional regulation and self-other reflection and as "facilitated by the coordinated effort of higher-order processing systems in the prefrontal and temporal cortices, the anterior cingulate cortex, and the ability of these regions to regulate otherwise automatic processing in deeper brain regions, such as the amygdala and ventral striatum, that are associated with fear, reward, and punishment" [92].

Also, given the role of such practices in the cultivation of revelatory 'enlightenment' experiences such as in *satori*, clues might also be found in the literature relating to the cognition of insight, in particular the "Aha!" moment that marks the sudden awareness or understanding of a solution to a problem. There is a convergence of evidence in this area implicating the role of a region of the right anterior superior temporal gyrus (rSTG), with a specific signature marking moments of insight [93, 94].

### 4.4 Non-dual states (NDM)

Finally, and perhaps of most interest in terms of the deeper, mystical or revelatory experiences emerging from meditation is the non-dual state itself. An interesting theory is that our inherent sense of subject-object duality may be down to the separation of two key cortical networks, and that the dualistic divide that we sense is broadly reflected in the functional and connective separation of the brain into intrinsic and extrinsic networks [13]. Each of these networks comprise sub-networks relating to our sensory modalities, motor function, attention, memory, motor control and executive function. The extrinsic network is involved with the processing of external stimuli, and encompasses the dorsal attention network, prefrontal cognitive control network and sensorimotor regions, as well as large regions of the posterior cortex. The intrinsic (or *default mode*) network, on the other hand, is most active when we are not engaged in a task, and is associated the aforementioned self-referential processes, including reflection, self-awareness, decision-making, and envisaging the future [13].

The DMN is complex, as it is concerned with functional networks spanning many neuroanatomical areas, rather than distinct regions of interest per se. The key defining feature of these areas appears to be that they lie furthest away from sensorimotor areas involving perception and action, are less constrained by external input and represent the apex of processing streams where increasingly abstract features are encoded [12]. They are regions whose activities appear most correlated to one another over time and can broadly be divided into midline core areas including the medial prefrontal cortex (MPFC), anterior cingulate cortex (ACC), inferior frontal gyrus (IFG), posterior cingulate cortex (PCC) and posterior medial cortex (PMC), and lateral regions including the mid-temporal cortex (MTC), angular gyrus (AG), inferior parietal cortex (IPC), and hippocampal area [12, 95, 96].

The two apparently distinct—intrinsic and extrinsic—functional networks (Fig. 1) are widely believed to underly our experience of the cartesian divide between our inner and outer worlds, where the intrinsic network (DMN) is the seat of our sense of selfhood and the extrinsic network represents our engagement with external stimuli. When we are engaged in tasks relating to external stimuli, DMN activity appears suppressed while activity in sensorimotor areas increases. Conversely, when we withdraw from activities and retreat into a quiescent state, DMN activity increases while sensorimotor activity subsides.

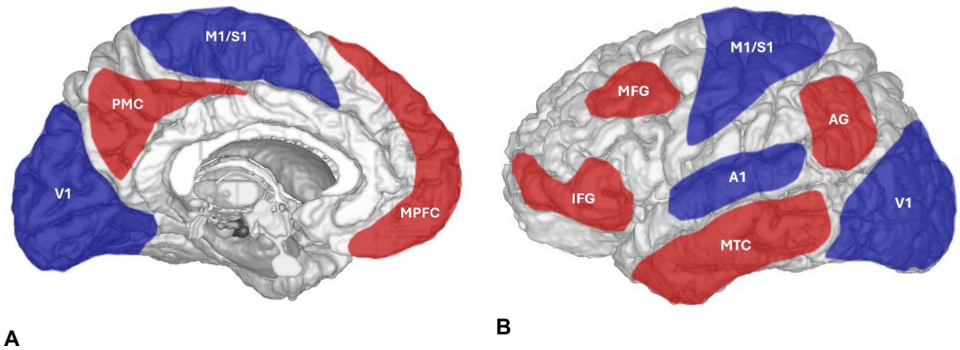


**Fig. 1** Sagittal view showing focus of DMN areas in red and sensory and motor areas in blue. **A** Medial view showing medial prefrontal cortex (MPFC), posterior medial cortex (PMC), and primary sensorimotor (M1/S1) and visual cortex (V1) areas. **B** Lateral view showing regions of mid-temporal cortex (MTC), inferior frontal gyrus (IFG), mid-frontal gyrus (MFG), and primary sensorimotor (M1/S1), auditory (A1), and visual (V1) cortex areas. Adapted from Smallwood et al. [12]

One study of the DMN's role in self-construction, for example, identified two distinct subsystems that differentially responded to types of self-referential thought. The first, *dorsal medial prefrontal cortex (dMPFC) subsystem* includes the dMPFC, temporoparietal junction (TPJ), temporal pole (TP) and lateral temporal cortex (LTC). The second, *medial temporal lobe (MTL) subsystem* includes the ventral MPFC (vMPFC), posterior inferior parietal lobule (pIPL), parahippocampal cortext (PHC) and hippocampal formation (HF). The dMPFC subsystem was preferentially activated when people made self-referential judgements about their present mental state or situation, while MTL subsystem activity predominated when people made episodic decisions concerning their future. Furthermore, envisaging scenarios related to self- versus non-self- conditions revealed increased midline core activity, notably within the anterior MPFC and PCC regions [95].

It is possible that non-dual states may come about through a radical change in the relationship between these two systems in which intrinsic network chatter is suppressed in favour of greatly enhanced attendance to sensory stimuli, or else the emergence of a unique, albeit transient synchronisation between these usually uncorrelated networks [97]. Such synchronisation may result in a temporary breakdown of the functional separation of these systems, with a consequent collapse of the usual division of conscious experience into 'self' and 'other'. The sense of ego dissolution and non-dual awareness that accompanies deeper mystical or transcendent experiences achieved through meditation (or indeed through direct psychopharmaceutical intervention) may reflect radical changes in the relationship between these two systems, and this is an approach that has garnered significant interest in some quarters [13].

## 5 EEG and meditation: key findings

In respect of meditation, a large body of EEG studies have focussed on spectral characteristics, which have generally proved to be of most interest in understanding the relationship between brain activity and particular phenomena. It must be stressed, however, that there are numerous ways in which EEG data can be analysed and organised. In addition to spectral characteristics, there are other key properties such as evoked/event-related potentials, that involve the response of EEG patterns to stimuli over time. A further example is synchrony, which deals with ways oscillatory activity can be subject to cross-region synchronisation through key properties including *frequency*, *amplitude* and *phase*. Advanced techniques such as source analysis, non-linear techniques and network analysis [27] further add to the diversity and heterogeneity in methods used in studies of meditation. However, for the purposes of this paper, the focus will remain on the EEG methods most commonly employed in studies of meditation, that is, spectral characteristics and cross-regional synchronisation.

### 5.1 Mindfulness meditation (FA/OM)

Studies of meditators employing both FA and OM techniques have increasingly focussed on the attention control and regulatory mechanisms discussed earlier, from both state and trait perspectives. One major finding is that alpha and theta power appear related to proficiency of practice. While state alpha power appears to predominate in the early stages for less experienced meditators, there appears to be a reduction of this in more experienced practitioners, suggesting that these alpha power increases may be related to learning [98]. This is consistent with early studies of alpha-blocking in meditators. Alpha-blocking refers to the suppression of alpha that typically accompanies the presentation of stimuli and is thought to be related to active processing of such stimuli [99]. Experienced practitioners of concentrative meditation failed to display alpha blocking in response to stimuli such as auditory noises or placement of hands in cold water, while other studies of Zen and mantra meditators found that alpha power was less disrupted in meditation than control conditions when subjected to loud aversive stimuli [33]. It is believed that during meditative states, practitioners can better regulate attentional processes, a view that is consistent with alpha desynchronisation reflecting attentional engagement [1].

Increases in theta band activity also seems to be evident across a range of different types of meditation practices [98, 100]. Theta waves occur in the frontal midline regions such as the PFC and ACC, and, consistent with the involvement of these areas in concentrative attentional engagement [101] and the association of theta waves with learning processes, increases in theta power have been found to be positively correlated with training and experience in meditation practice. This may account for improvements in memory and attention often found in studies of meditators. Frontal midline theta (Fm theta) has also been associated with internally directed attention, and so as might be expected, evidence exists for increases in Fm theta for both FA and OM practices [102].

There is some evidence to suggest that delta activity is reduced during OM practices. In one long-term study, Cahn et al. [98] report that bilateral frontal—but not midline—delta power was decreased in meditators who reported no drowsiness during meditation. A subsequent study also found a reduction in delta power, however when a distractor item was presented which the meditator was asked to then focus upon, there was an increase in frontal delta power, also suggesting a role of delta waves in attentional engagement [33, 103].

Furthermore, there is growing evidence to suggest increased gamma band activity in advanced meditators. A study compared practitioners from three different traditions of meditation with a control group during an FA exercise and found that the meditation group participants manifested higher, trait parieto-occipital gamma band amplitude than the control group, an effect which was correlated positively with the quality of participant meditation experience [104]. Another study found significantly larger occipital gamma power in meditators with more than 10 years of daily practice, along with corresponding increases in gamma power during meditation [98]. Together, these findings suggest that long-term *vipassanā* meditation involving FA/OM promotes increased parieto-occipital gamma power related to enhanced sensory awareness developed as a result of long-term meditation practice, supporting the view that many meditation practices involve improvements in attentional capacity [33, 98, 105].

### 5.2 Compassion and loving-kindness (CLK/ADM)

Though some studies have examined ADM in expert meditators using fMRI [71], there has been relatively little empirical focus on ADM in the context of characteristics of EEG. However, there has been one notable study involving practitioners of a meditative tradition called Metta Meditation [106]. This a CLK practice where practitioners progressively extend feelings of kindness towards loved ones, acquaintances, strangers, enemies, and humanity, the ultimate goal being to cultivate a pure, non-referential state of loving-kindness. In an initial study comparing eight long-term Metta meditators with ten student volunteers, Lutz et al. [105] examined high-density EEG characteristics at high temporal resolution to study activity and phase synchrony across frontal, temporal and parietal ROIs. The results revealed enhanced gamma-band activity and synchronization in experienced practitioners compared to novices, particularly in frontal and temporoparietal regions associated with affective processing and Theory of Mind.

Although a review by Deolindo et al. [27] drew essentially the same conclusions regarding EEG activity in FA and OA practices, the fact that many studies employed ADM in combination with FA, OA, and CDM made it difficult to isolate reliable findings specific to ADM practices. Other noteworthy findings in meditation that involved ADM practices suggest alpha asymmetry, in terms of greater alpha-band power on the right than on the left, in both frontal and parietal regions [107], with similar findings for the theta band [108]. Since high-powered alpha/theta reflect more quiescent brain-states, then this indicates greater left-hemisphere activity, consistent with theories of affect implicating a left-hemisphere bias in the processing of positive emotions [109].

### 5.3 Insight meditation (CDM)

Insight meditation is often characterised in subtle but importantly different ways. At one extreme, it may consist of simply examining the passage of thoughts that pass through the mind as one experiences their immediate environment, or holding or meditating on a particular thought, as with typical FA or OM practices [7]. At the other extreme it may be of a more intensive and focussed form, as an attempt to reach some deeper understanding of a philosophical or metaphysical nature [29]. In the context of meditation, particularly in Buddhist traditions, it is this latter, deep enquiry into the nature of phenomena that is the focus. Insight may be conceptualised broadly as a contemplation or pursuit of an understanding of the deeper organising principles behind the universe [5]. It may involve contemplation of deeper questions, such as the nature of selfhood and consciousness, as well as the ontological roots of phenomena as they present themselves to us. It is this latter characterisation that is proposed to be an important component of SG-MBIs [10], yet in the context of meditation research, it has often been characterised in the former sense—as a particular 'flavour' of meditation, but one whose practice is essentially viewed as an extension of FA and OM practices.

*Vipassanā* is a Buddhist practice which aims to address these deeper aspects of insight meditation, yet research citing this and other CDM approaches appears to invariably examine it in combination with, or in the context of, FA, OM, and even ADM [27, 33, 98, 103]. As with ADM, there appears to be a dearth of research that specifically address the deeper levels of philosophical enquiry with which such insight methods are concerned.

However, the aforementioned research into insight (or "Aha!") moments in the context of problem-solving do offer clues as to the possible spectral markers that might accompany profound insights, or even enlightenment experiences such as *satori*. According to the three-steps model [94] insight arises from a strong but diffuse activation of general consolidated information in the right hemisphere in the form of multiple potential interpretations for a weaker pattern representing new information. Insight is believed to occur where widely distributed associations across the cortex reach a cognitive apotheosis marking the synthesis of a new pattern emerging from reorganisation of this information [93]. Insight moments have been associated with alpha activity in the parieto-occipital region, followed by a burst of gamma activity on the right temporal pole of the rSTG 300 ms before a button-press indicating a participant's report of a solution to a puzzle (Fig. 2). These findings have been supported by a study of transcranial Alternating Current Stimulation (tACS) in which artificial amplification of these frequencies over the respective regions increased the occurrence of such "Eureka!" moments [110]. One might tentatively hypothesise that insight meditation such as *vipassanā* might involve similar processes and spectral signatures.

### 5.4 Non-dual states (NDM)

Studies of cross-cortical EEG coherence during transcendent/mystical experiences have revealed increased coherence in theta, alpha and beta bands [111]. However, similar findings have been observed in reviews of other forms of meditation [112]. Other studies have examined EEG power and amplitude for particular bands. A small number of these have revealed

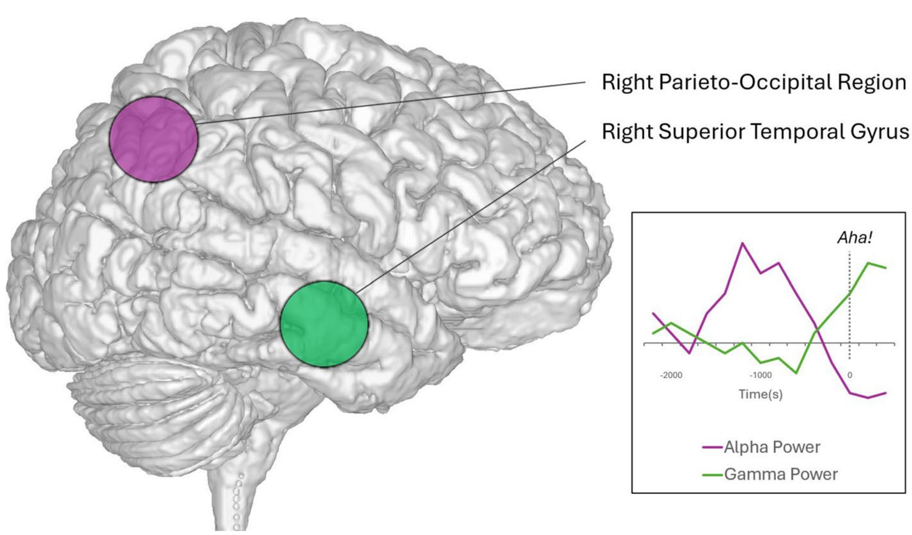


**Fig. 2** Regions of right hemisphere showing the "insight effect", where t = 0 represents the point where a button is pressed indicating an insight solution for a task. Insight solutions are associated with a burst of elevated alpha power from the right parieto-occipital electrode PO8 (magenta circle) from approximately 1400 ms to 400 ms prior to the response, followed by a burst of gamma in the right temporal electrode T8 (green circle) at approximately 300 ms prior to the button press [94]

changes in EEG during transcendent experiences, particularly increases in alpha and theta bands, but this too seems to echo findings in reviews of meditation generally [113].

Of particular interest are studies in which nondual states were compared to other meditative states. Travis and Wallace [114] reported decreases in theta and increases in alpha during transcendent states, while Badawi et al. [115] noted decreases in theta but no change in other frequency bands. Interestingly, both of these studies found an association between respiratory suspension and transcendent states, although changes in EEG did not occur during a breath-holding control condition. Berman and Stevens [116], however, observed increases in delta, theta and alpha during a transcendent state, but increases in beta and gamma throughout the remaining meditation session.

In two other studies, greater theta and gamma power were evidenced when participants reported an experience of union with God, but not with experiencing union with another person [111, 117]. However, increased gamma activity in meditation in general has also been found in other meditation studies, and there appears to be a general lack of agreement in findings regarding the characteristics of EEG associated with nondual states [112].

Research elsewhere has examined cross-cortical EEG synchronisation. For example, in a study of 'fruition' stages of consciousness in Theravada Buddhist practitioners in which transcendent (or 'enlightenment') states were attained, global, long range gamma synchronisation was found. The authors suggest that this gamma synchronisation may reflect an underlying mechanism through which habitual mental patterns are reformed and then reintegrated in the light of deeper revelatory experiences [118]. A similar pattern of oscillatory synchronisation in the gamma band was also noted in the aforementioned study of 'objectless' compassion meditation, in which it was concluded that the size and scale of these oscillations indicated that widely distributed cortical regions were synchronised with high temporal precision in this state, suggesting a possible important marker of nondual states [105].

These latter findings appear consistent with the notion that such states may represent a radical change in the relationship between the intrinsic (DMN) and extrinsic networks [13, 97], which, as discussed earlier, may underpin our fundamental division of the world in 'self' and 'other'. Josipovic [13], furthermore, notes that the precuneus appears to serve as a critical hub in the DMN in that its nodes span both the extrinsic and intrinsic networks. This is consistent with other findings implicating the precuneus and posterior cingulate areas as central to DMN activity [97, 119] and EEG microstate evidence suggesting that this region is consistently active within transient DMN substates between which it appears to alternate [96]. In an fMRI study of experienced meditators comparing FA, OM and NDA conditions, Josipovic [13] noted increased correlations between the central precuneus and both DLPFC and ACC activity, though with decreased correlations between precuneus and the right Angular Gyrus (rAng). With the DLPFC being part of the task positive network involved with working memory, it was speculated that the former relationship reflected the sense of unitary awareness experienced by NDA participants, while the latter relationship, with the decreased connectivity between the precuneus and rAng was thought to be possibly related to the experience of spatial extendedness in NDA, as these areas are involved in spatial self-awareness [120].

This notion of non-dual experience being related in some way cross-cortical synchronisation between usually uncorrelated core networks is, as Josipovic concedes, speculative, however it is consistent with this evidence and a promising avenue of enquiry for future research. The use of EEG methods may prove particularly appropriate to examine such synchronisation, as it can capture the temporal dynamics of cortical activity with much higher precision. The lack of agreement of some of the findings regarding synchronisation [13] also warrants caution, though such findings are unsurprising given the complexity of the possible relationships between these systems and their components. The many ways that activity and synchronisation may occur within and between these networks may indeed underpin a vast range of such experiences and account for both their distinctive strangeness and the diversity with which such experiences manifest.

For example, intrinsic and extrinsic activity may reach something an equilibrium state, with similar levels of activity. This equilibrium, furthermore, may occur at a range of levels of activation, from the depths of trance-like states such as those in hypnosis [121], to high-activated states where intense sensory activity accompanies an equally intense, frenetic cascade of thoughts and feelings, as with Shamanic dance or other similar ritualistic practices marked by intense physical exertion [122]. States with lower levels of activation might include the *Soto* tradition of *Zazen*, where practitioners are not actively engaged in either inner contemplation or outer sensations but are simply absorbed in a peaceful presence, or *Shikantaza* ('just sitting') where sitting is exclusively performed without purpose, requiring only 'completely relaxed awareness' [123].

Higher activation practices might include walking meditation in nature, such as in the tradition of *Thich Nhat Hanh* [124]. The practice involves mindful walking, where the practitioner remains fully aware of their inner sensations and thoughts while also being deeply connected to their natural environment. Through such practice, the boundary between the inner self and the outer environment may dissolve, leading to a harmonious, non-dual experience.

On the other hand, synchronisation of these networks may occur regardless of their relative levels of activation, with non-dual states occurring with asymmetrical levels of extrinsic versus intrinsic activity. Thus, such states may occur during absorption and deep engagement with activities in the external world, but also in quiescent introverted reflection in which one is inwardly focussed and deeply engaged but physically inactive. An example of the former can be found in the forementioned Shamanic ritual dance and contemporary equivalents, such as practices in modern rave culture [125]; through intense rhythmic drumming or loud hypnotic music, self-transcendence may emerge through absorption into intense dance and sensory stimulation. Other examples are *Kinhin* and *Samu* [126]. *Kinhin* is another form of walking meditation in which practitioners walk slowly and mindfully, coordinating their steps with breathing; by paying close attention to the sensations of each step and their surroundings, presence and heightened awareness is cultivated through movement and sensory engagement. The Zen practice of *Samu*, or mindful work involves performing everyday activities such as cooking, cleaning or gardening with full attention and presence cultivating deep absorption through engaged, purposeful action. In all these examples, the focus is on enhancing presence and awareness through purposeful activity and sensory engagement; through focussed absorption with activities and external stimuli, a sense of union may be reached in which the distinction between the self and the external world dissolves.

Conversely, introspection and inner reflection may also give rise to such states. Through introspection and philosophical contemplation, such as in *vipassanā*, flashes of intense insight or realisation may arise through or be accompanied by non-dual awareness. Similarly, compassion and LK meditation such as *tonglen* (meaning *sending and receiving*) may allow such states to be reached through inner cultivation of altruistic and compassionate awareness [19]. *Zazen*, too, with its focus on nonjudgemental observation of thoughts and feelings as they arise, may also be practised in a more inwardly focussed way; through quieting the mind and cultivating deep awareness, the practitioner may reach a state where the boundary between self and experience ceases to be (Fig. 3).

Across this range of scenarios, levels of activation between intrinsic and extrinsic networks, may vary due to differences in spectral power (i.e., dissimilar amplitude) between EEG activity in these areas, however their frequency and phase may remain locked. Alternatively, such asymmetries in non-dual experience might suggest large scale cortical synchronisation that goes beyond normal frequency synchronisation to more complex types, such as sub-harmonic (cross-frequency) coupling between different EEG frequencies [127]. This concept of non-duality as a more fundamental attribute of conscious states is supported by Josipovic's [128] later development of his theory in which he proposes that the traditional '2D' map of awareness—as characterised by global states of activation on the one hand, and phenomenal contents on the other—should include an additional *implicit-explicit* dimension which represents the degree to which nondual awareness—free from any dualistic fragmentation—manifests in a given mental state.

Research into the phenomenology and EEG characteristics of states of deep-trance hypnosis is also informative in this respect, though it does also reveal inconsistencies. People who have undergone deep states of hypnosis often report

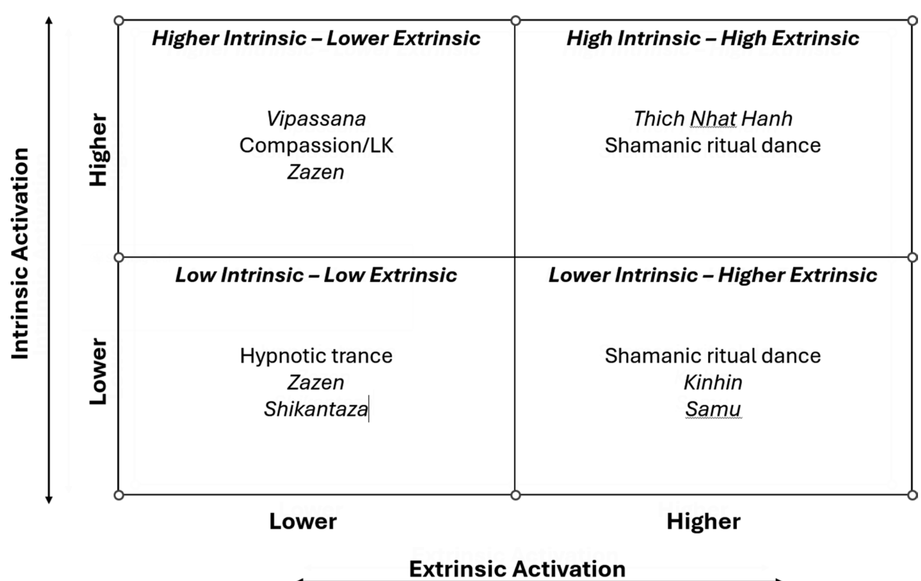


**Fig. 3** Examples of practices illustrating how non-dual states may hypothetically emerge from practices involving symmetrical or asymmetrical but synchronised levels of intrinsic and extrinsic network activity

transcendent experiences similar to those encountered in meditation or through pharmaceutical intervention [121]. The depth of these states appears related to the power in the beta and gamma ranges, bringing to mind the similar elevation of gamma power seen in advanced meditators. However, researchers also noted cortical desynchronisation, likening it to the kind of desynchronisation observed through the administration of psilocybin [129], but given the qualitative difference in hypnotically or pharmaceutically induced altered states of consciousness and the fact that these studies did not involve deliberate attempts to induce NDA states, such variations are not surprising. However, such findings do raise questions about the role of synchronisation in non-dual states and suggest that the use of hypnosis or drugs to induce such states may provide alternative means by which such network synchronisation and EEG characteristics may be examined.

Another possible role of the synchronisation that occurs in non-dual states may be analogous to insight processes proposed by Jung-Beeman [94]. Austin [130] describes how the effects of meditation results from gradual, long-term enhancements in brain function which foster improved attention, emotional regulation, and self-awareness. However, he also believes that sudden 'awakenings', such as in *satori*, involves a radical reorganisation of brain activity that allows an entirely new perspective on reality. Non-dual experiences can be extremely profound and involve just such a reorganisation.

As with the right-parietal alpha observed Jung-Beeman's three-stage process, the right-side bias in alpha power observed [107] might also relate to the state of insight-readiness by which the right hemisphere 'opens up' to new interpretations. It seems very plausible that the gamma synchronisation observed in studies such as the aforementioned study of 'fruition' states [118] may reflect a malleable and receptive brain reorganising to accommodate new realisations and their implications. This might also account for why alpha is less predominant in expert meditators, who have progressed further in their insights and may have fewer metaphysical questions to ponder.

Austin [130] also notes the spontaneous occurrence of periods of breath suspension in meditators reporting moments of 'pure consciousness' and 'thought-free clarity', implicating metabolic processes in states of heightened awareness. These periods are accompanied by peripheral autonomic changes and high alpha-theta EEG coherence over a wide area, ending in bursts of faster beta. He believes that these arise through shifts in functions deep and centrally located in the brain, involving inhibition of respiratory drive in meditation and autonomic changes in which inhibitory impulses in the brain stem may result in the release of endogenous opioids, serotonin and acetylcholine. This does underline the need to explore beyond brain-activity alone and consider the impact of the respiratory and cardiac cycles.

## 6 Discussion and conclusions

EEG findings (summarised in Table 1) appear to show some consistency in the study of FA and OM meditation types, and broadly support existing knowledge regarding attentional and interoceptive processes [1, 7, 27, 65, 71]. However, the study of EEG and meditation generally has been hampered by the substantial disparity in methods regarding the analysis of such data. For example, in addition to spectral analysis, EEG analysis methods include event-related potential, synchrony (which may include synchrony between regions based on phase, frequency or amplitude), source analysis, network analysis, non-linear analysis and multimodal analyses [27, 131]. Though the versatility and variety of EEG analysis techniques is in some ways advantageous, the heterogeneity of studies, lack of standardisation of signal processing methods and the sheer number of parameters that have been studied makes it extremely hard to conduct meta-analyses that permit meaningful comparisons between studies. Furthermore, associations based purely on EEG markers can be difficult to pin down to particular processes because of the limitation in spatial resolution and difficulty in discriminating the many possible causes of such markers. Studies where FMRI data is also included does help, however caution should be taken in drawing firm conclusions. There are also fundamental disagreements as to how different types of meditation should be classified, organised and characterised, making it a challenge to be sure that successive studies are examining meditation practices conducted in the same way.

These latter difficulties are in no small part due to the complex, varied and nuanced phenomenology of meditative states. Varela and Shear [132] have argued that in this respect, the expertise of long-term meditators can be usefully employed to improve our understanding, leading to a finer phenomenology and description of the inner world and, in combination with third-person data, to new insights into the relationship between mind and brain/body. Indeed, given that training in introspective skills is a core feature of many meditative practices across contemplative traditions, EEG data can arguably only be meaningfully interpreted in conjunction with first-person data, whether obtained through self-report, interview or otherwise. Such improved understanding of the phenomenology of meditative states may help

**Table 1** Summary of key EEG findings relating to meditation types

| Meditation type | Spectral band | Findings |
|---|---|---|
| FA/OM | Alpha (α) | (i) α-power related to meditation experience. Greater α in novice practitioners, and reduction of α in more experienced practitioners. Suggests learning effect<br>(ii) Experienced practitioners display less α-blocking in response to aversive stimuli, suggesting improved attention regulation |
| | Theta (θ) | Increased θ-band activity in PFC and ACC in experienced practitioners, consistent with improved attention regulation |
| | Delta (δ) | Bilateral frontal δ decrease in non-drowsy meditators and increased frontal δ power when concentrating on distractor item. Suggests role of δ in attention |
| | Gamma (γ) | (i) Higher trait parieto-occipital γ in meditators compared to control group<br>(ii) Higher occipital trait-γ power in meditators with over 10 years practise, with increased γ power during meditation. Suggests enhanced sensory awareness and attentional capacity |
| CLK/ADM | Alpha (α) | α-power asymmetry, with more α on right-side, and therefore more left-side activation overall. Possibly due to left-hemisphere bias in processing positive emotion |
| | Theta (θ) | θ-power asymmetry. As with α, with more θ on right-side, and therefore more overall left-side activation |
| | Gamma (γ) | Increased γ activity and synchronisation in experienced practitioners compared to novices, especially across frontal and temporoparietal regions associated with affect and theory-of-mind |
| Insight/CDM | Alpha (α), Gamma (γ) | No studies identified which specifically address EEG in insight meditation. However, EEG studies of problem-solving suggest that insight moments are marked by α activity in the parieto-occipital region, followed by a burst of γ activity on the right temporal pole of the STG. This may shed light on associated meditational insight moments |
| NDM | Alpha (α) | Increased α coherence and power during transcendent states |
| | Beta (β) | Increased β coherence and power during transcendent states |
| | Theta (θ) | Increased θ coherence during transcendent states. Most found increased power, one study found decreased power |
| | Delta (δ) | Increased δ coherence and power during transcendent states |
| | Gamma (γ) | Long-range γ synchronisation. Increased γ correlation and possible synchronisation between intrinsic and extrinsic networks |

*FA/OM* Focussed Attention/Open Monitoring, *CLK* Compassion/Loving-Kindness, *NDM* Null-Directed Methods, *CDM* Cognitive-Directed Methods, *ADM* Affect-Directed Methods, *PFC* Prefrontal cortex, *ACC* Anterior cingulate cortex, *STG* Superior temporal gyrus us to better organise them and facilitate closer examination in such studies. In line with this, a neurophenomenological approach has gained traction as a way to examine non-ordinary states of consciousness (NSC) such as those in meditation, hypnosis, or through use of psychedelic drugs. This approach focusses on employing rigorous first-person methodologies with participants trained to describe their experience in detail, for example, thorough structured interviews to elicit reporting of subtle changes of consciousness, such as sense of self, agency, or perception of time. This, combined with neurophysiological data, can allow consistent patterns of experience to be identified along with key associations with neurophysiological mechanisms [133].

The focus of research on generally narrow domains of meditation is reflected in the body of research relating to EEG characteristics. While first-generation FA/OM practices have been widely studied over the years, second-generation techniques such as ADM and particularly CDM [10, 27], which are regarded in Buddhist philosophy as key to spiritual development and the evolution of deeper transformative experiences, have not been investigated in nearly as much depth, and where such techniques have been studied, they have usually been examined in the context of FA/OM practices.

What seems to be emerging from closer examination of these second-generation methods and their phenomenology, however, is the role of non-dual awareness in these deeper forms of meditation. Such non-dual states are understood to be a precursor to the attainment of 'enlightenment' in the form of the direct experience of *nirvana* or *suññatā* (with its revelatory insight into *anatta*) [112] and increasingly appear to be a key feature that distinguishes Westernised, first-generation mindfulness from its second-generation counterparts that are arguably more authentically rooted in their original traditions. Compassion/loving-kindness meditation such as *metta* Meditation, for example, has the ultimate objective of creating a pure, nonreferential field of compassion which is boundless and transpersonal [106], while insight meditation such as *vipassanā* focusses on cultivating a deep understanding of the basic truths of the world, such as the *three marks of existence*, with the aforementioned non-dual states viewed by many as key to transformative 'enlightenment' experiences [134]. Likewise Zen, with its focus on transcendent insight through the direct experience of reality at its deepest ontological level, has at its core the objective of unlocking a deeper, non-dualistic form of knowing [135]. These respective affective and cognitive-directed methods might be viewed as opposing yet complementary paths to transformative experiences which may necessarily involve non-dual states of some kind.

In this respect, Josipovic's [128] conceptualisation of non-duality as a key dimension of consciousness seems plausible, and—though speculative—his theory characterising the neuropsychology of nondual experiences in terms of synchrony between intrinsic and extrinsic networks [13] appears to be a promising area of theoretical development and research, which is supported to at least some degree by convergence with research regarding global gamma synchronisation [105]. The idea of such experiences being mediated by synchrony between these networks, or radical changes in the balance between self-referential (default-mode network) activity and extrinsic network activity may prove to be a fruitful avenue for future research [112]. Furthermore, the question raised herein as to whether such synchronisation may occur with asymmetric levels of intrinsic and extrinsic activity—which might account for the variety of phenomenology in no-dual states—does offer a testable framework for further exploration of EEG and meditation in relation to such states and suggests a focus on large-scale synchronisation and coupling between regions. Austin's [130] observations on breath suspension and the role of the brain stem also include the suggestion that future research might involve examining meditation in people who have deep electrodes in place for an unrelated medical reason.

Most importantly, though, the present paper highlights a dearth of EEG studies which address these second-generation mindfulness techniques, and underlines the fact that contemplative research does not adequately reflect the diversity of techniques employed across many contemplative traditions [136]. Although there have been some promising theoretical developments here, EEG research into both ADMs (such as compassion-focused meditation) and CDM or 'insight-based' practice is sparse, particularly in the case of the latter. This is probably because of the focus on mindfulness as a purely secular practice, coupled with resistance to approaches that embody a more spiritual dimension. In this respect, a much clearer picture of the role of oscillatory neurological activity in second-generation mindfulness may help to foster a better understanding of the functional and neuroanatomical processes at play in these practices and the underlying impairments that they address [18, 137], particularly in the area of CDMs. This would facilitate a deeper and more clinically comprehensible understanding of the various means by which meditation practices affect positive psychological change.

With respect to CDMs, however, the findings from neuroscience implicating the role of right parietal alpha and rSTG gamma in moments of insight [93, 94] might prove to be a fertile line of future research in this area, and may well be key to understanding the cognitive reorganisations at play in deeper transformative enlightenment or satori-like experiences. Though, given the relative rarity and elusiveness of these latter experiences, it may be some time before sufficient data is available draw any conclusions in this respect. However, as technology evolves and the use of permanent implants capable of collecting continuous EEG data becomes more widespread (such as in the emerging field of brain-machine interfaces) routine logging of such data may allow even the rarest of experiences to be examined. Of particular interest also is the possibility that electrophysiologically based stimulation treatments such as tACS may enable such experiences to be facilitated or enhanced artificially [110].

Granting the limitations of conceptualising mindfulness as being reducible to distinct 'components', future research could also benefit from greater standardisation of terminology regarding the facets of meditation practice and clearer elucidation of which schools or types of practice focus on which specific processes. In this respect, the taxonomy adopted herein reflects an emerging convergence amongst researchers [10, 27, 28] and may be helpful for guiding clearer descriptions of the techniques involved in meditation research samples.

## 7 Questions for future research

1. How can current meditation taxonomy be refined to better describe and represent the varieties of meditation types and phenomenology that occur in both research and practice settings, and can corresponding EEG signatures be identified?
2. What are the most important elements of meditation necessary to promote physical, mental and spiritual wellbeing, and which elements are most for suitable for particular participant groups?
3. What are the key markers of transformative meditational states in terms of EEG activity and synchronisation between neuroanatomical regions, and how do they relate to phenomenology as well as learning and insight processes?
4. Are non-dual/transcendent states necessary to effect positive transformation, or are they just catalysts?
5. How do non-dual/transcendent states attained in meditation differ between those attained through hypnosis or ones that are pharmacologically induced, and how is this reflected in their EEG markers, particularly cross-cortical synchrony?
6. Can the therapeutic elements of meditation, including non-dual states, be induced through transcranial stimulation or pharmacological intervention?

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## Declarations

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## References

1. Tang Y-Y, Hölzel BK, Posner MI. The neuroscience of mindfulness meditation. Nat Rev Neurosci. 2015;16(4):213–25. https://doi.org/10.1038/nrn3916.
2. Austin JH. How does meditation train attention? Insight Journal. 2009;32:16–22.
3. Doll A, Hölzel BK, Mulej Bratec S, Boucard CC, Xie X, Wohlschläger AM, et al. Mindful attention to breath regulates emotions via increased amygdala–prefrontal cortex connectivity. Neuroimage. 2016;134:305–13. https://doi.org/10.1016/j.tics.2015.07.001.
4. Lama D. Essential teachings. London: Souvenir Press; 1995.

5. Van Gordon W, Sapthiang S, Barrows P, Shonin E. Understanding and practicing emptiness. Mindfulness. 2021;12:1845–8. https://doi.org/10.1007/s12671-020-01586-1.
6. Eberth J, Sedlmeier P. The effects of mindfulness meditation: a meta-analysis. Mindfulness. 2012;3(3):174–89. https://doi.org/10.1007/s12671-012-0101-x.
7. Lutz A, Slagter HA, Dunne JD, Davidson RJ. Attention regulation and monitoring in meditation. Trends Cogn Sci. 2008;12(4):163–9. https://doi.org/10.1016/j.tics.2008.01.005.
8. Garland EL, Howard MO. Mindfulness-based treatment of addiction: current state of the field and envisioning the next wave of research. Addict Sci Clin Pract. 2018;13(1):14. https://doi.org/10.1186/s13722-018-0115-3.
9. Brown KW, Ryan RM, Creswell JD. Mindfulness: theoretical foundations and evidence for its salutary effects. Psychol Inq. 2007;18(4):211–37. https://doi.org/10.1080/10478400701598298.
10. Van Gordon W, Shonin E, Griffiths MD. Towards a second generation of mindfulness-based interventions. Aust N Z J Psychiatry. 2015;49(7):591–2. https://doi.org/10.1177/0004867415577437.
11. Barrows P, Van Gordon W. Ontological addiction theory and mindfulness-based approaches in the context of addiction theory and treatment. Religions. 2021;12(8):586.
12. Smallwood J, Bernhardt BC, Leech R, Bzdok D, Jefferies E, Margulies DS. The default mode network in cognition: a topographical perspective. Nat Rev Neurosci. 2021;22(8):503–13. https://doi.org/10.1038/s41583-021-00474-4.
13. Josipovic Z. Neural correlates of nondual awareness in meditation. Ann N Y Acad Sci. 2014;1307:9–18. https://doi.org/10.1111/nyas.12261.
14. Shonin E, Van Gordon W, Griffiths MD. The emerging role of Buddhism in clinical psychology: toward effective integration. Psychol Relig Spiritual. 2014;6(2):123–37. https://doi.org/10.1037/a0035859.
15. Van Gordon W, Shonin E, Griffiths MD, Singh NN. There is only one mindfulness: why science and Buddhism need to work together. Mindfulness. 2015;6(1):49–56. https://doi.org/10.1007/s12671-014-0379-y.
16. Purser R. McMindfulness: how mindfulness became the new capitalist spirituality. London: Repeater Books; 2019.
17. Sparby T, Sacchet MD. Defining meditation: foundations for an activity-based phenomenological classification system. Front Psychol. 2022. https://doi.org/10.3389/fpsyg.2021.795077.
18. Van Gordon W, Shonin E, Diouri S, Garcia-Campayo J, Kotera Y, Griffiths MD. Ontological addiction theory: attachment to me, mine, and I. J Behav Addict. 2018;7(4):892–6. https://doi.org/10.1556/2006.7.2018.45.
19. Shonin E, Van Gordon W, Compare A, Zangeneh M, Griffiths MD. Buddhist-derived loving-kindness and compassion meditation for the treatment of psychopathology: a systematic review. Mindfulness. 2015;6(5):1161–80. https://doi.org/10.1007/s12671-014-0368-1.
20. Gilbert P, Van Gordon W. Compassion as a skill: a comparison of contemplative and evolution-based approaches. Mindfulness. 2023;14(10):2395–416. https://doi.org/10.1007/s12671-023-02173-w.
21. Gilbert P, Choden. Mindful compassion: Robinson; 2013. https://books.google.co.uk/books?id=vk2MMgEACAAJ
22. Zeng X, Chiu CPK, Wang R, Oei TPS, Leung FYK. The effect of loving-kindness meditation on positive emotions: a meta-analytic review. Front Psychol. 2015. https://doi.org/10.3389/fpsyg.2015.01693.
23. Barrows P, Shonin E, Sapthiang S, Griffiths MD, Ducasse D, Van Gordon W. The development and validation of the ontological addiction scale. Int J Ment Heal Addict. 2022;21(6):4043–70. https://doi.org/10.1007/s11469-022-00840-y.
24. Van Gordon W, Sapthiang S, Barrows P, Shonin E. Understanding and practising emptiness. Mindfulness. 2021;12:1845–8. https://doi.org/10.1007/s12671-020-01586-1.
25. Dalibard J, Gigan S. A nobel prize for Alain aspect, John Clauser and Anton Zeilinger. Photoniques. 2022;116:23–5. https://doi.org/10.1051/photon/202211623.
26. Van Gordon W, Shonin E, Griffiths MD. Buddhist emptiness theory: implications for psychology. Psychol Relig Spiritual. 2017;9(4):309–18. https://doi.org/10.1037/rel0000079.
27. Deolindo CS, Ribeiro MW, Aratanha MA, Afonso RF, Irrmischer M, Kozasa EH. A critical analysis on characterizing the meditation experience through the electroencephalogram. Front Syst Neurosci. 2020. https://doi.org/10.3389/fnsys.2020.00053.
28. Nash JD, Newberg A, Awasthi B. Toward a unifying taxonomy and definition for meditation. Front Psychol. 2013. https://doi.org/10.3389/fpsyg.2013.00806.
29. Dahl CJ, Lutz A, Davidson RJ. Reconstructing and deconstructing the self: cognitive mechanisms in meditation practice. Trends Cogn Sci. 2015;19(9):515–23. https://doi.org/10.1016/j.tics.2015.07.001.
30. Glover GH. Overview of functional magnetic resonance imaging. Neurosurg Clin N Am. 2011;22(2):133. https://doi.org/10.1016/j.nec.2010.11.001.
31. Lopez KL, Monachino AD, Vincent KM, Peck FC, Gabard-Durnam LJ. Stability, change, and reliable individual differences in electroencephalography measures: a lifespan perspective on progress and opportunities. Neuroimage. 2023;275:120116. https://doi.org/10.1016/j.neuroimage.2023.120116.
32. Schomer DL, Da Silva FL. Niedermeyer's electroencephalography: basic principles, clinical applications, and related fields. Philadelphia: Lippincott Williams & Wilkins; 2012.
33. Cahn BR, Delorme A, Polich J. Event-related delta, theta, alpha and gamma correlates to auditory oddball processing during Vipassana meditation. Soc Cogn Affect Neurosci. 2013;8(1):100–11. https://doi.org/10.1093/scan/nss060.
34. Hofle N, Paus T, Reutens D, Fiset P, Gotman J, Evans AC, et al. Regional cerebral blood flow changes as a function of delta and spindle activity during slow wave sleep in humans. J Neurosci. 1997;17(12):4800–8. https://doi.org/10.1523/jneurosci.17-12-04800.1997.
35. Iber C, Ancoli-Israel S, Chesson AL, Quan SF. The AASM manual for the scoring of sleep and associated events: rules, terminology and technical specifications. Westchester: American Academy of Sleep Medicine; 2007.
36. Llinás R, Ribary U. Coherent 40-Hz oscillation characterizes dream state in humans. Proc Natl Acad Sci. 1993;90(5):2078–81. https://doi.org/10.1073/pnas.90.5.2078.
37. Ekstrom AD, Caplan JB, Ho E, Shattuck K, Fried I, Kahana MJ. Human hippocampal theta activity during virtual navigation. Hippocampus. 2005;15(7):881–9. https://doi.org/10.1002/hipo.20109.

38. Hsieh L-T, Ekstrom AD, Ranganath C. Neural oscillations associated with item and temporal order maintenance in working memory. J Neurosci. 2011;31(30):10803–10. https://doi.org/10.1523/jneurosci.0828-11.2011.
39. Karakaş S. A review of theta oscillation and its functional correlates. Int J Psychophysiol. 2020;157:82–99. https://doi.org/10.1016/j.ijpsycho.2020.04.008.
40. Raghavachari S, Lisman JE, Tully M, Madsen JR, Bromfield EB, Kahana MJ. Theta oscillations in human cortex during a working-memory task: evidence for local generators. J Neurophysiol. 2006;95(3):1630–8. https://doi.org/10.1152/jn.00409.2005.
41. Raghavachari S, Kahana MJ, Rizzuto DS, Caplan JB, Kirschen MP, Bourgeois B, et al. Gating of human theta oscillations by a working memory task. J Neurosci. 2001;21(9):3175–83. https://doi.org/10.1523/jneurosci.21-09-03175.2001.
42. Addante RJ, Watrous AJ, Yonelinas AP, Ekstrom AD, Ranganath C. Prestimulus theta activity predicts correct source memory retrieval. Proc Natl Acad Sci. 2011;108(26):10702–7. https://doi.org/10.1073/pnas.1014528108.
43. Buzsáki G. Theta rhythm of navigation: link between path integration and landmark navigation, episodic and semantic memory. Hippocampus. 2005;15(7):827–40. https://doi.org/10.1002/hipo.20113.
44. Mizuhara H, Wang LQ, Kobayashi K, Yamaguchi Y. A long-range cortical network emerging with theta oscillation in a mental task. NeuroReport. 2004;15(8):1233–8. https://doi.org/10.1097/01.wnr.0000126755.09715.b3.
45. Palva S, Palva JM. New vistas for α-frequency band oscillations. Trends Neurosci. 2007;30(4):150–8. https://doi.org/10.1016/j.tins.2007.02.001.
46. Doesburg SM, Green JJ, McDonald JJ, Ward LM. From local inhibition to long-range integration: a functional dissociation of alpha-band synchronization across cortical scales in visuospatial attention. Brain Res. 2009;1303:97–110. https://doi.org/10.1016/j.brainres.2009.09.069.
47. Foster JJ, Sutterer DW, Serences JT, Vogel EK, Awh E. Alpha-band oscillations enable spatially and temporally resolved tracking of covert spatial attention. Psychol Sci. 2017;28(7):929–41. https://doi.org/10.1177/0956797617699167.
48. Anderson KL, Ding M. Attentional modulation of the somatosensory mu rhythm. Neuroscience. 2011;180:165–80. https://doi.org/10.1016/j.neuroscience.2011.02.004.
49. Kropotov JD. Chapter 3—beta Rhythms. In: Kropotov JD, editor. Quantitative EEG, event-related potentials and neurotherapy. San Diego: Academic Press; 2009. p. 59–76.
50. Brovelli A, Ding M, Ledberg A, Chen Y, Nakamura R, Bressler SL. Beta oscillations in a large-scale sensorimotor cortical network: directional influences revealed by Granger causality. Proc Natl Acad Sci. 2004;101(26):9849. https://doi.org/10.1073/pnas.0308538101.
51. Salenius S, Hari R. Synchronous cortical oscillatory activity during motor action. Curr Opin Neurobiol. 2003;13(6):678–84. https://doi.org/10.1016/j.conb.2003.10.008.
52. Kilavik BE, Zaepffel M, Brovelli A, MacKay WA, Riehle A. The ups and downs of β oscillations in sensorimotor cortex. Exp Neurol. 2013;245:15–26. https://doi.org/10.1016/j.expneurol.2012.09.014.
53. Kora P, Meenakshi K, Swaraja K, Rajani A, Raju MS. EEG based interpretation of human brain activity during yoga and meditation using machine learning: a systematic review. Complement Ther Clin Pract. 2021;43:101329. https://doi.org/10.1016/j.ctcp.2021.101329.
54. Fernández T, Harmony T, Rodríguez M, Bernal J, Silva J, Reyes A, et al. EEG activation patterns during the performance of tasks involving different components of mental calculation. Electroencephalogr Clin Neurophysiol. 1995;94(3):175–82. https://doi.org/10.1016/0013-4694(94)00262-J.
55. Pritchett DL, Siegle JH, Deister CA, Moore CI. For things needing your attention: the role of neocortical gamma in sensory perception. Curr Opin Neurobiol. 2015;31:254–63. https://doi.org/10.1016/j.conb.2015.02.004.
56. Kort NS, Cuesta P, Houde JF, Nagarajan SS. Bihemispheric network dynamics coordinating vocal feedback control. Hum Brain Mapp. 2016;37(4):1474–85. https://doi.org/10.1002/hbm.23114.
57. Hadjipapas A, Adjamian P, Swettenham JB, Holliday IE, Barnes GR. Stimuli of varying spatial scale induce gamma activity with distinct temporal characteristics in human visual cortex. Neuroimage. 2007;35(2):518–30. https://doi.org/10.1016/j.neuroimage.2007.01.002.
58. Gail A, Brinksmeyer HJ, Eckhorn R. Contour decouples gamma activity across texture representation in monkey striate cortex. Cereb Cortex. 2000;10(9):840–50. https://doi.org/10.1093/cercor/10.9.840.
59. Llinás RR, Paré D. Of dreaming and wakefulness. Neuroscience. 1991;44(3):521–35. https://doi.org/10.1016/0306-4522(91)90075-Y.
60. Davidson RJ, Kaszniak AW. Conceptual and methodological issues in research on mindfulness and meditation. Am Psychol. 2015;70(7):581–92. https://doi.org/10.1037/a0039512.
61. Posner MI, Rothbart MK. Research on attention networks as a model for the integration of psychological science. Annu Rev Psychol. 2007;58:1–23. https://doi.org/10.1146/annurev.psych.58.110405.085516.
62. Corbetta M, Shulman GL. Control of goal-directed and stimulus-driven attention in the brain. Nat Rev Neurosci. 2002;3(3):201–15. https://doi.org/10.1038/nrn755.
63. Breukelaar IA, Antees C, Grieve SM, Foster SL, Gomes L, Williams LM, et al. Cognitive control network anatomy correlates with neurocognitive behavior: a longitudinal study. Hum Brain Mapp. 2017;38(2):631–43. https://doi.org/10.1002/hbm.23401.
64. Vossel S, Geng JJ, Fink GR. Dorsal and ventral attention systems: distinct neural circuits but collaborative roles. Neuroscientist. 2014;20(2):150–9. https://doi.org/10.1177/1073858413494269.
65. Petersen SE, Posner MI. The attention system of the human brain: 20 years after. Annu Rev Neurosci. 2012;35:73–89. https://doi.org/10.1146/annurev-neuro-062111-150525.
66. Coull JT. Neural correlates of attention and arousal: insights from electrophysiology, functional neuroimaging and psychopharmacology. Prog Neurobiol. 1998;55(4):343–61. https://doi.org/10.1016/s0301-0082(98)00011-2.
67. Weissman DH, Roberts KC, Visscher KM, Woldorff MG. The neural bases of momentary lapses in attention. Nat Neurosci. 2006;9(7):971–8. https://doi.org/10.1038/nn1727.
68. Langner R, Eickhoff SB. Sustaining attention to simple tasks: a meta-analytic review of the neural mechanisms of vigilant attention. Psychol Bull. 2013;139(4):870–900. https://doi.org/10.1037/a0030694.
69. Yu C, Li Y, Stitt IM, Zhou ZC, Sellers KK, Frohlich F. Theta oscillations organize spiking activity in higher-order visual thalamus during sustained attention. eNeuro. 2018. https://doi.org/10.1523/eneuro.0384-17.2018.

70. Fortenbaugh FC, DeGutis J, Esterman M. Recent theoretical, neural, and clinical advances in sustained attention research. Ann N Y Acad Sci. 2017;1396(1):70–91. https://doi.org/10.1111/nyas.13318.
71. Travis F. On the neurobiology of meditation: comparison of three organizing strategies to investigate brain patterns during meditation practice. Medicina. 2020. https://doi.org/10.3390/medicina56120712.
72. Wilson-Mendenhall CD, Henriques A, Barsalou LW, Barrett LF. Primary interoceptive cortex activity during simulated experiences of the body. J Cogn Neurosci. 2019;31(2):221–35. https://doi.org/10.1162/jocn_a_01346.
73. Garfinkel SN, Critchley HD. Interoception, emotion and brain: new insights link internal physiology to social behaviour. Commentary on: "Anterior insular cortex mediates bodily sensibility and social anxiety" by Terasawa et al. (2012). Soc Cogn Affect Neurosci. 2013;8(3):231–4. https://doi.org/10.1093/scan/nss140.
74. Simmons WK, Avery JA, Barcalow JC, Bodurka J, Drevets WC, Bellgowan P. Keeping the body in mind: insula functional organization and functional connectivity integrate interoceptive, exteroceptive, and emotional awareness. Hum Brain Mapp. 2013;34(11):2944–58. https://doi.org/10.1002/hbm.22113.
75. Farb NA, Segal ZV, Mayberg H, Bean J, McKeon D, Fatima Z, et al. Attending to the present: mindfulness meditation reveals distinct neural modes of self-reference. Soc Cogn Affect Neurosci. 2007;2(4):313–22. https://doi.org/10.1093/scan/nsm030.
76. Tang Y-Y, Ma Y, Wang J, Fan Y, Feng S, Lu Q, et al. Short-term meditation training improves attention and self-regulation. Proc Natl Acad Sci. 2007;104(43):17152–6. https://doi.org/10.1073/pnas.0707678104.
77. Jha AP, Krompinger J, Baime MJ. Mindfulness training modifies subsystems of attention. Cogn Affect Behav Neurosci. 2007;7(2):109–19. https://doi.org/10.3758/cabn.7.2.109.
78. Valentine ER, Sweet PLG. Meditation and attention: a comparison of the effects of concentrative and mindfulness meditation on sustained attention. Ment Health Relig Cult. 1999;2(1):59–70. https://doi.org/10.1080/13674679908406332.
79. Kristeller J. Spirituality and meditation. In: Aten JD, McMinn MR, Worthington EL, editors. Spiritually oriented interventions for counseling and psychotherapy. Washington, DC: American Psychological Association; 2011. p. 197–227.
80. Gilbert P. Compassion: from its evolution to a psychotherapy. Front Psychol. 2020. https://doi.org/10.3389/fpsyg.2020.586161.
81. Kirby JN, Tellegen CL, Steindl SR. A meta-analysis of compassion-based interventions: current state of knowledge and future directions. Behav Ther. 2017;48(6):778–92. https://doi.org/10.1016/j.beth.2017.06.003.
82. Millard LA, Wan MW, Smith DM, Wittkowski A. The effectiveness of compassion focused therapy with clinical populations: a systematic review and meta-analysis. J Affect Disord. 2023;326:168–92. https://doi.org/10.1016/j.jad.2023.01.010.
83. Engen HG, Bernhardt BC, Skottnik L, Ricard M, Singer T. Structural changes in socio-affective networks: multi-modal MRI findings in long-term meditation practitioners. Neuropsychologia. 2018;116(Pt A):26–33. https://doi.org/10.1016/j.neuropsychologia.2017.08.024.
84. Lindquist KA, Wager TD, Kober H, Bliss-Moreau E, Barrett LF. The brain basis of emotion: a meta-analytic review. Behav Brain Sci. 2012;35(3):121–43. https://doi.org/10.1017/s0140525x11000446.
85. Russell JA. Emotion, core affect, and psychological construction. Cogn Emot. 2009;23(7):1259–83. https://doi.org/10.1080/02699930902809375.
86. Kim JJ, Cunnington R, Kirby JN. The neurophysiological basis of compassion: an fMRI meta-analysis of compassion and its related neural processes. Neurosci Biobehav Rev. 2020;108:112–23. https://doi.org/10.1016/j.neubiorev.2019.10.023.
87. Stevens L, Benjamin J. Chapter 3—the brain that longs to care for others: the current neuroscience of compassion. In: Stevens L, Woodruff CC, editors. The neuroscience of empathy, compassion, and self-compassion. San Diego: Academic Press; 2018. p. 53–89.
88. Lamm C, Decety J, Singer T. Meta-analytic evidence for common and distinct neural networks associated with directly experienced pain and empathy for pain. Neuroimage. 2011;54(3):2492–502. https://doi.org/10.1016/j.neuroimage.2010.10.014.
89. Singer T, Seymour B, O'Doherty J, Kaube H, Dolan RJ, Frith CD. Empathy for pain involves the affective but not sensory components of pain. Science. 2004;303(5661):1157–62. https://doi.org/10.1126/science.1093535.
90. Ochsner KN, Ray RR, Hughes B, McRae K, Cooper JC, Weber J, et al. Bottom-up and top-down processes in emotion generation: common and distinct neural mechanisms. Psychol Sci. 2009;20(11):1322–31. https://doi.org/10.1111/j.1467-9280.2009.02459.x.
91. Tomasino B, Fabbro F. Editorial: neuroimaging and neuropsychology of meditation states. Front Psychol. 2015. https://doi.org/10.3389/fpsyg.2015.01757.
92. Williams PB, Nusbaum HC. Chapter 21—toward a neuroscience of wisdom. In: Absher JR, Cloutier J, editors. Neuroimaging personality, social cognition, and character. San Diego: Academic Press; 2016. p. 383–95.
93. Kounios J, Fleck JI, Green DL, Payne L, Stevenson JL, Bowden EM, et al. The origins of insight in resting-state brain activity. Neuropsychologia. 2008;46(1):281–91. https://doi.org/10.1016/j.neuropsychologia.2007.07.013.
94. Jung-Beeman M, Bowden EM, Haberman J, Frymiare JL, Arambel-Liu S, Greenblatt R, et al. Neural activity when people solve verbal problems with insight. PLoS Biol. 2004;2(4):E97. https://doi.org/10.1371/journal.pbio.0020097.
95. Andrews-Hanna JR, Reidler JS, Sepulcre J, Poulin R, Buckner RL. Functional-anatomic fractionation of the brain's default network. Neuron. 2010;65(4):550–62. https://doi.org/10.1016/j.neuron.2010.02.005.
96. Pascual-Marqui RD, Lehmann D, Faber PL, Milz P, Kochi K, Yoshimura M, et al. The resting microstate networks (RMN): cortical distributions, dynamics, and frequency specific information flow. arXiv Neurons Cogn. 2014. https://doi.org/10.48550/arXiv.1411.1949.
97. Golland Y, Bentin S, Gelbard H, Benjamini Y, Heller R, Nir Y, et al. Extrinsic and intrinsic systems in the posterior cortex of the human brain revealed during natural sensory stimulation. Cereb Cortex. 2006;17(4):766–77. https://doi.org/10.1093/cercor/bhk030.
98. Cahn BR, Delorme A, Polich J. Occipital gamma activation during Vipassana meditation. Cogn Process. 2010;11(1):39–56. https://doi.org/10.1007/s10339-009-0352-1.
99. Niedermeyer E. Alpha rhythms as physiological and abnormal phenomena. Int J Psychophysiol. 1997;26(1–3):31–49. https://doi.org/10.1016/s0167-8760(97)00754-x.
100. Pasquini HA, Tanaka GK, Basile LF, Velasques B, Lozano MD, Ribeiro P. Electrophysiological correlates of long-term Soto Zen meditation. Biomed Res Int. 2015;2015:598496. https://doi.org/10.1155/2015/598496.

101. Mitchell DJ, McNaughton N, Flanagan D, Kirk IJ. Frontal-midline theta from the perspective of hippocampal "theta." Prog Neurobiol. 2008;86(3):156–85. https://doi.org/10.1016/j.pneurobio.2008.09.005.
102. Takahashi T, Murata T, Hamada T, Omori M, Kosaka H, Kikuchi M, et al. Changes in EEG and autonomic nervous activity during meditation and their association with personality traits. Int J Psychophysiol. 2005;55(2):199–207. https://doi.org/10.1016/j.ijpsycho.2004.07.004.
103. Lee DJ, Kulubya E, Goldin P, Goodarzi A, Girgis F. Review of the neural oscillations underlying meditation. Front Neurosci. 2018. https://doi.org/10.3389/fnins.2018.00178.
104. Braboszcz C, Cahn BR, Levy J, Fernandez M, Delorme A. Increased gamma brainwave amplitude compared to control in three different deditation traditions. PLoS ONE. 2017;12(1):e0170647. https://doi.org/10.1371/journal.pone.0170647.
105. Lutz A, Greischar LL, Rawlings NB, Ricard M, Davidson RJ. Long-term meditators self-induce high-amplitude gamma synchrony during mental practice. Proc Natl Acad Sci. 2004;101(46):16369–73. https://doi.org/10.1073/pnas.0407401101.
106. Analayo B. Compassion and emptiness in early Buddhist meditation. Cambridge: Windhorse Publications; 2015.
107. Sharma K, Chandra S, Dubey AK. Exploration of lower frequency EEG dynamics and cortical alpha asymmetry in long-term Rajyoga meditators. Int J Yoga. 2018;11(1):30–6. https://doi.org/10.4103/ijoy.IJOY_11_17.
108. Chan AS, Han YM, Cheung MC. Electroencephalographic (EEG) measurements of mindfulness-based Triarchic body-pathway relaxation technique: a pilot study. Appl Psychophysiol Biofeedback. 2008;33(1):39–47. https://doi.org/10.1007/s10484-008-9050-5.
109. Davidson RJ. Anterior cerebral asymmetry and the nature of emotion. Brain Cogn. 1992;20(1):125–51. https://doi.org/10.1016/0278-2626(92)90065-t.
110. Santarnecchi E, Sprugnoli G, Bricolo E, Costantini G, Liew S-L, Musaeus CS, et al. Gamma tACS over the temporal lobe increases the occurrence of Eureka! moments. Sci Rep. 2019;9(1):5778. https://doi.org/10.1038/s41598-019-42192-z.
111. Beauregard M, Paquette V. EEG activity in Carmelite nuns during a mystical experience. Neurosci Lett. 2008;444(1):1–4. https://doi.org/10.1016/j.neulet.2008.08.028.
112. Wahbeh H, Sagher A, Back W, Pundhir P, Travis F. A systematic review of transcendent states across meditation and contemplative traditions. Explore. 2018;14(1):19–35. https://doi.org/10.1016/j.explore.2017.07.007.
113. Cahn BR, Polich J. Meditation states and traits: EEG, ERP, and neuroimaging studies. Psychol Bull. 2006;132(2):180–211. https://doi.org/10.1037/0033-2909.132.2.180.
114. Travis F, Wallace RK. Autonomic patterns during respiratory suspensions: possible markers of transcendental consciousness. Psychophysiology. 1997;34(1):39–46. https://doi.org/10.1111/j.1469-8986.1997.tb02414.x.
115. Badawi K, Wallace RK, Orme-Johnson D, Rouzere AM. Electrophysiologic characteristics of respiratory suspension periods occurring during the practice of the transcendental meditation program. Psychosom Med. 1984;46(3):267–76. https://doi.org/10.1097/00006842-198405000-00008.
116. Berman AE, Stevens L. EEG manifestations of nondual experiences in meditators. Conscious Cogn. 2015;31:1–11. https://doi.org/10.1016/j.concog.2014.10.002.
117. Beauregard M, Paquette V. Neural correlates of a mystical experience in Carmelite nuns. Neurosci Lett. 2006;405(3):186–90. https://doi.org/10.1016/j.neulet.2006.06.060.
118. Berkovich-Ohana A. A case study of a meditation-induced altered state: increased overall gamma synchronization. Phenomenol Cogn Sci. 2017;16(1):91–106. https://doi.org/10.1007/s11097-015-9435-x.
119. Fransson P, Marrelec G. The precuneus/posterior cingulate cortex plays a pivotal role in the default mode network: evidence from a partial correlation network analysis. Neuroimage. 2008;42(3):1178–84. https://doi.org/10.1016/j.neuroimage.2008.05.059.
120. Zaehle T, Jordan K, Wüstenberg T, Baudewig J, Dechent P, Mast FW. The neural basis of the egocentric and allocentric spatial frame of reference. Brain Res. 2007;1137:92–103. https://doi.org/10.1016/j.brainres.2006.12.044.
121. Cardeña E. Towards a comprehensive neurophenomenological research in hypnosis and meditation. In: Raz A, Lifshitz M, editors. Hypnosis and meditation: Towards an integrative science of conscious planes. Oxford: Oxford University Press; 2016. p. 281–301.
122. Winkelman M. Shamanism as neurotheology and evolutionary psychology. Am Behav Sci. 2002;45(12):1875–87. https://doi.org/10.1177/0002764202045012010.
123. Martínková I, Wang Q. Shikantaza—the practice of 'just sitting': ultimate slowing down and its effect on experiencing. Sport Ethics Philos. 2022;16(2):221–36. https://doi.org/10.1080/17511321.2022.2045345.
124. Hanh TN. How to walk. New York: Random House; 2016.
125. Winkelman MJ. Biogenetic structural perspectives on shamanism and raves: the origins of collective ritual dance. In: Simão E, da Silva AM, de Magalhães ST, editors. Exploring psychedelic trance and electronic dance music in modern culture. IGI Global: Hershey; 2015. p. 1–37.
126. Sharma DK. Yoga and meditation: integral correlation is a bit of mystery. J Appl Conscious Stud. 2017. https://doi.org/10.4103/ijny.ijoyppp_2_17.
127. Tort AB, Komorowski RW, Manns JR, Kopell NJ, Eichenbaum H. Theta-gamma coupling increases during the learning of item-context associations. Proc Natl Acad Sci. 2009;106(49):20942–7. https://doi.org/10.1073/pnas.0911331106.
128. Josipovic Z. Implicit–explicit gradient of nondual awareness or consciousness as such. Neurosci Conscious. 2021;2021(2):niab031. https://doi.org/10.1093/nc/niab031.
129. Carhart-Harris RL, Erritzoe D, Williams T, Stone JM, Reed LJ, Colasanti A, et al. Neural correlates of the psychedelic state as determined by fMRI studies with psilocybin. Proc Natl Acad Sci. 2012;109(6):2138–43. https://doi.org/10.1073/pnas.1119598109.
130. Austin JH. Zen and the brain: toward an understanding of meditation and consciousness. Cambridge: The MIT Press; 1998.
131. Lomas T, Ivtzan I, Fu CHY. A systematic review of the neurophysiology of mindfulness on EEG oscillations. Neurosci Biobehav Rev. 2015;57:401–10. https://doi.org/10.1016/j.neubiorev.2015.09.018.
132. Varela F, Shear J. First-person methodologies: what, why, how? J Conscious Stud. 1999;6(2–3):1–14.
133. Timmermann C, Bauer PR, Gosseries O, Vanhaudenhuyse A, Vollenweider F, Laureys S, et al. A neurophenomenological approach to non-ordinary states of consciousness: hypnosis, meditation, and psychedelics. Trends Cogn Sci. 2023;27(2):139–59. https://doi.org/10.1016/j.tics.2022.11.006.

134. Van Gordon W, Shonin E, Dunn TJ, Sapthiang S, Kotera Y, Garcia-Campayo J, et al. Exploring emptiness and its effects on non-attachment, mystical experiences, and psycho-spiritual wellbeing: a quantitative and qualitative study of advanced meditators. Explore (NY). 2019;15(4):261–72. https://doi.org/10.1016/j.explore.2018.12.003.
135. Humphreys C, Hodge S. Zen: a way of life. London: Hodder and Stoughton; 2003.
136. Katyal S, Lumma A-L, Goldin PR, Roy S. Editorial: the varieties of contemplative experiences and practices. Front Psychol. 2023. https://doi.org/10.3389/fpsyg.2023.1232999.
137. Shonin E, Van Gordon W, Griffiths MD. Ontological addiction: classification, etiology, and treatment. Mindfulness. 2016;7(3):660–71. https://doi.org/10.1007/s12671-016-0501-4.