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Review

A systematic review of the neurophysiology of mindfulness on EEG oscillations

Tim Lomas[a,*], Itai Ivtzan[a], Cynthia H.Y. Fu[a,b]

[a] *School of Psychology, University of East London, London, UK*
[b] *Centre for Affective Disorders, Institute of Psychiatry, Psychology and Neuroscience, King's College London, London, UK*

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ABSTRACT

Mindfulness meditation has been purported to be a beneficial practice for wellbeing. It would therefore be expected that the neurophysiology of mindfulness would reflect this impact on wellbeing. However, investigations of the effects of mindfulness have generated mixed reports of increases, decreases, as well as no differences in EEG oscillations in comparison with a resting state and a variety of tasks. We have performed a systematic review of EEG studies of mindfulness meditation in order to determine any common effects and to identify factors which may impact on the effects. Databases were reviewed from 1966 to August 2015. Eligibility criteria included empirical quantitative analyses of mindfulness meditation practice and EEG measurements acquired in relation to practice. A total of 56 papers met the eligibility criteria and were included in the systematic review, consisting of a total 1715 subjects: 1358 healthy individuals and 357 individuals with psychiatric diagnoses. Studies were principally examined for power outcomes in each bandwidth, in particular the power differentials between mindfulness and a control state, as well as outcomes relating to hemispheric asymmetry and event-related potentials. The systematic review revealed that mindfulness was most commonly associated with enhanced alpha and theta power as compared to an eyes closed resting state, although such outcomes were not uniformly reported. No consistent patterns were observed with respect to beta, delta and gamma bandwidths. In summary, mindfulness is associated with increased alpha and theta power in both healthy individuals and in patient groups. This co-presence of elevated alpha and theta may signify a state of relaxed alertness which is conducive to mental health.

Contents

1. Introduction

Meditation refers to a diverse range of mental activities which share a common focus on the regulation of attention and awareness (Cahn and Polich, 2006) in order to improve voluntary control of mental processes, which is purported to foster general wellbeing

* Corresponding author at: School of Psychology, University of East London, Arthur Edwards Building, Water Lane, London E15 4LZ, UK.
E-mail address: t.lomas@uel.ac.uk (T. Lomas).

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(Walsh and Shapiro, 2006). Most world cultures have developed their own forms of meditation; for example, Christianity has a long tradition of contemplative prayer (Egan, 1978). Much of the recent scientific interest in meditation has centred on mindfulness meditation, a practice that is believed to have originated with Buddhism around the fifth century B.C., although its roots may stretch back further to the third millennium B.C. in Hindu culture (Cousins, 1996).

The most common forms of meditation may be conceptualized as involving either focused attention or an open-monitoring process (Lutz et al., 2008). Focused attention practices can be operationalized into their respective attention networks (Posner and Petersen, 1990; Mirsky et al., 1991): sustained attention (e.g. towards a target, such as the breath), executive attention (e.g. preventing one's focus from 'wandering'), attention switching (e.g. disengaging from distractions), selective attention and attention re-orienting (e.g. redirecting focus back to the breath), and working memory (Lutz et al., 2008; Vago and Silbersweig, 2012). Open-monitoring refers to a broader receptive awareness, a capacity to detect events within an unrestricted awareness without a specific focus (Raffone and Srinivasan, 2010), which can include a process of 'meta-awareness' (i.e. awareness of awareness, in which practitioners are able to reflect on the process of consciousness itself).

Mindfulness has been described as the awareness that arises through purposeful, nonjudgmental attentiveness to present moment experience (Kabat-Zinn, 2003). While mindfulness has been commonly viewed as an example of open-monitoring, it has been proposed to involve an admixture of focused attention and open-monitoring (Lutz et al., 2008; Vago and Silbersweig, 2012) as most mindfulness practices begin with a period of focused attention on a target, such as the breath, in order to focus awareness, followed by the more receptive state of open-monitoring (Cahn and Polich, 2006). In Vago and Silbersweig's model (2012), the practice of mindfulness leads to three overarching self-related capacities: meta self-awareness, self-regulation, and self-transcendence. These are subserved by numerous cognitive subcomponents, including motivation (which is crucial in terms of people practicing meditation in the first place), attention regulation (via the development of attention modalities), and de-centring (an ability, defined below, that arises from enhanced attention regulation, and which facilitates self-awareness and transcendence). It is further proposed that these three overarching capacities modulate 'self-specifying and narrative self-networks' through an integrative fronto-parietal control network.

Mindfulness has been applied as a clinical intervention based on the notion that it is a method for training attention and awareness. By developing the ability to observe one's thoughts and feelings, practitioners learn how to perceive them as temporary, objective events in the mind as opposed to reflections of the self that are necessarily true, which has been termed as the ability to "decentre" (Fresco et al., 2007). As a clinical intervention, it involves a process of engaging with negative experiences, such as pain or dysphoric emotions, with more dispassion and less reactivity (Shapiro et al., 2005). Mindfulness was initially applied as an intervention for chronic pain with Kabat-Zinn's (1982) Mindfulness-Based Stress Reduction (MBSR) program. The MBSR program has since been applied in the treatment for number of conditions, including cancer (Ledesma and Kumano, 2009) and migraine (Schmidt et al., 2010), and adapted as a treatment to prevent relapse in depression (Mindfulness-Based Cognitive Therapy; Segal et al., 2002) and for the treatment of substance abuse (Mindfulness-Based Relapse Prevention; Bowen et al., 2014, Mindfulness-Oriented Recovery Enhancement; Garland et al., 2014).

The effectiveness of mindfulness has been assessed by measures such as for depression and quality of life (Hofmann et al., 2010). As mindfulness may be considered to be a method of attention training and emotion regulation, we would expect that the corresponding neurophysiological states should be observable. Electroencephalography (EEG) is a non-invasive technique that analyses spatiotemporal aspects of underlying brain activity, providing a measure of the large-scale synchronization of neural networks (Cacioppo et al., 2007). Patterns of EEG activity for particular meditative states have been investigated. A commonly reported feature of meditation has been theta and alpha event-related synchronization (Fell et al., 2010), which are regarded as markers of internally-directed attention processing (Shaw, 1996). Such synchronization has been observed across different meditation practices, including mindfulness, as well as practices such as transcendental meditation, which involves focused attention upon an internally-voiced mantra. However, different types of meditation practice have been associated with unique frequency patterns, reflecting the form of attention (Dunn et al., 1999). For example, mindfulness has been associated with increased alpha power, while focused attention has been associated with increased gamma activity, and idiosyncratic meditation with decreased alpha and beta (Hinterberger et al., 2014).

Additionally, event-related potentials (ERPs) provide a measure of a large number of time-locked experimental trials, enabling the analysis of sensory, perceptual, and cognitive processing (Light et al., 2010). Such studies involve the precision analysis of populations of neuronal transients directly manifested via a stimulus/event, which is frequently a stimulus connected to an attention-based task (e.g. listening to an auditory signal) (Schoenberg and Speckens, 2014). The high temporal resolution of this approach, involving millisecond precision, allows the investigation of early information processing stages and subsequent transitions to higher-level cognitive operations. ERP studies have been used to corroborate the idea of mindfulness as a system of attention training. For example, van Leeuwen et al. (2012) examined the impact of mindfulness practice on hierarchical stimulus processing and attentional selection, focusing on differences in early components of the evoked visual response (e.g. P1 and N1 components) in meditators versus matched controls. Meditators exhibited faster attentional disengagement from a dominant global presentation in order to focus in on specific stimuli, suggesting that meditation enhances speed of attention allocation and relocation, thus increasing the depth of information processing.

In the present review, we have focused on mindfulness meditation. We have examined factors which appear to impact upon EEG measures, including the experience of the meditator (being a novice or relative expert), as experience has been reported to accentuate amplitude differences between meditation and the resting state (Hinterberger et al., 2014), although the converse has also been observed (Cahn et al., 2010). An additional factor includes the location of the brain activity. For example, increased alpha during mindfulness has been localized to frontal regions (Takahashi et al., 2005) but has also been observed in posterior regions (Lagopoulos et al., 2009; Cahn et al., 2010). Furthermore, EEG analysis of meditation may be affected by whether the control task is a resting state or a cognitive task, as increased theta amplitude during meditation has been observed in comparison to a resting state baseline, but was comparable in amplitude to an executive attention task, with these patterns further modulated by the experience of the meditator (Lomas et al., 2014).

We sought to perform a systematic review of patterns of electrophysiological activity associated with mindfulness in order to examine its impact on neurophysiology, as assessed by EEG bandwidth activation and other measures, including hemispheric asymmetry or event-related potentials, and the functional significance of these activities. If mindfulness is expected to impact on functioning attentional networks as well as open-monitoring, then we would expect to observe distinct neural features associated with its practice. We also expected that the experience of the meditator, type of control task, and location of the EEG oscillation would moderate the impact of mindfulness on neurophysiology.

2. Methods

The literature search was conducted using the MEDLINE and Scopus electronic databases with the criteria: "EEG" (AND) "mindfulness OR meditation", in all fields in MEDLINE, and limited to article title, abstract, and keywords in Scopus, with the dates from 1966 to 1st August 2015. Regarding the participants, interventions, comparisons, outcomes and study design (PICOS) characteristics, the key criteria were, interventions: mindfulness meditation or functional equivalent; participants: adults; and outcomes: EEG analysis. Studies were required to be published, or a manuscript in press, and to be in English. The review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The review protocol was registered with the International Prospective Register of Systematic Reviews (PROSPERO) database on 15th September 2014. Registration number: CRD42014013766 (http://www.crd.york.ac.uk/PROSPERO).

Inclusion criteria were: (1) mindfulness meditation practice or functional equivalent, such as Vipassana or Zen meditation; (2) EEG measurements acquired in relation to mindfulness meditation practice (whether assessment during the practice itself or connected to its practice, e.g. pre- and post-intervention); (3) quantitative analysis supported by appropriate statistical methodology; and (4) adult sample. Exclusion criteria were theoretical articles or commentaries without statistical analyses.

The following variables were extracted from each paper: experimental protocol (control condition, meditation condition, and/or experimental task), experience of participants (novice or expert), sample features (clinical or non-clinical), outcomes for each individual bandwidth (alpha, beta, theta, delta, and gamma), hemispheric asymmetry, and any event-related potential outcomes.

The primary summary measures were differences in levels of power in each of the bandwidths. Neural activity generates electrical potentials which can be analyzed in terms of parameters of amplitude, frequency, coherence and synchrony. Amplitude (or power, which is the square of the amplitude) reflects the magnitude of the electrical signal, representing the level of synchronized activity in the underlying tissue, i.e. neurons discharging simultaneously. Frequency is the number of oscillatory cycles per second and is usually divided into the following bandwidths: Delta (1–4 Hz); Theta (4–8 Hz); Alpha (8–13 Hz); Beta (13–30 Hz); and Gamma (36–44 Hz) (Cacioppo et al., 2007). EEG connectivity is the functional integration of spatially distributed neural populations which can be assessed in terms of synchrony (the degree of leading or lagging in the relationship between signals from electrode pairs) and coherence (the stability of that phase relationship).

The primary summary variable was principally the difference in power between a meditation condition and a resting state condition. Secondary power differentials included longitudinal pre- and post-differences, such as, in meditation and/or resting state and/or task conditions before and after an intervention. If applicable, outcomes relating to coherence, synchrony, asymmetry and event-related potentials were also noted.

Of note, there was considerable diversity in how the experience of the participants was defined. In terms of years meditating, the range for which papers rated participants as being 'experienced' varied from 1 year (Kasamatsu and Hirai, 1966) to 9 years (Lagopoulos et al., 2009). Likewise, in terms of hours meditating, the range for which papers rated participants as being 'experienced' varied from 40 h (Hinterberger et al., 2011) to 1740 h (Berkovich-Ohana et al., 2012). In the present systematic review, we have applied the lowest of these cutoffs, such that an 'experienced' (i.e. non-novice) meditator was considered to have been meditating for longer than 1 year or to have completed more than 40 h of meditation.

The Quality Assessment Tool for Quantitative Studies (QATQS; National Collaborating Centre for Methods and Tools, 2008) was used to assess the quality of the studies. QATQS assesses methodological rigour in six areas: (a) selection bias; (b) design; (c) confounders; (d) blinding; (e) data collection method; and (f) withdrawals and drop-outs. Each area is assessed on a quality score of 1 to 3 (1 = strong; 2 = moderate; 3 = weak). Scores for each area were collated, and a global score was assigned to each study. If there are no weak ratings, the study is given a score of 1 (judged as strong); one weak rating leads to a score of 2 (moderate); and two or more weak ratings generates a score of 3 (weak) (Supplementary Materials). QATQS scoring was conducted (II) and checked independently (TL). Any discrepancies were resolved by discussion with agreement reached in all cases.

The first authors of each paper were contacted for additional information as needed (Amihai and Kozhevnikov, 2014; Arita, 2012; Cahn et al., 2010, 2013; Hinterberger et al., 2011, 2014; Howells et al., 2012; Huang and Lo, 2009; Lagopoulos et al., 2009; Lehmann et al., 2012; Lo et al., 2003; Milz et al., 2014; Murata et al., 2004; Saggar et al., 2012; Stinson and Arthur, 2013; Tang et al., 2009; Xue et al., 2014). Data were extracted (TL) and reviewed (II) with guidance and review (CF).

3. Results

3.1. Search results

Following removal of duplicate citations, 284 potentially relevant papers were identified. From the abstract review, 120 papers were excluded. From the full text reviews of 164 papers, 108 papers were excluded. Thus, a total of 56 papers were included in the systematic analysis. Ten of these papers were identified as reporting on overlapping samples: (Berkovich-Ohana et al., 2012; Berkovich-Ohana et al., 2013); (Cahn et al., 2010; Cahn et al., 2013); (Slagter et al., 2007; Slagter et al., 2009); (Hinterberger et al., 2011; Hinterberger et al., 2014); (Schoenberg and Speckens, 2014; Schoenberg and Speckens, 2015). As such, the 56 papers included in the systematic analysis represented results from 51 independent participant samples ($n = 1715$ subjects; age range = 19–72 years) (Fig. 1). 46 papers focused on healthy participants, representing results from 42 independent samples ($n = 1358$ subjects; age range = 18–72 years) (Table 1), and 10 papers included participants with a psychiatric disorder, representing results from 9 independent samples ($n = 357$ subjects; age range = 22–64 years): 3 studies on depressed patients in remission ($n = 157$), 1 study of patients with suicidal depression ($n = 22$), 1 study involving patients diagnosed with major depressive disorder, reported across 2 papers (Schoenberg and Speckens, 2014, 2015) ($n = 51$), 1 study of patients with bipolar disorder ($n = 21$), 1 study of patients with chronic pain ($n = 27$), 1 study of patients with chronic pain with risk of opioid abuse ($n = 29$), and 1 study of patients with attention-deficit/hyperactivity disorder (ADHD) ($n = 50$) (Table 2).

The findings fall into two main types: (a) studies examining the effects of mindfulness in comparison with a resting state; and (b) studies examining longitudinal changes in EEG patterns relating to practicing mindfulness (Table 3, Supplementary Tables 3–9).

Table 1
Demographics of healthy participants.

First author	Year	Meditators	Meditators (male)	Controls	Mean age meditators	Mean years meditating	Meditation type	Study type
Davidson	2003	25 (from 32)	6	16	36	0	MBCT	Pre-post
Dunn	1999	9 (from 10)	NR	–	NR	0	FA & MM	Pre-post
Kerr	2011	12 (from 16)	1	6	31	0	MBCT	Pre-post
Lomas	2014	30	30	–	42.3	10.1	Various (inc. MM)	Pre-post
Moore	2012	12 (from 19)	NR	16 (from 23)	36.9	0	MM	Pre-post
Saggar	2012	22 (from 30)	12	22 (from 30)	49.5	Experienced (years NR)	MM (retreat)	Pre-post
Slagter	2007	17	17	23	NR	Experienced (years NR)	Vipassana (retreat)	Pre-post
Slagter	2009	17	17	23	NR	Experienced (years NR)	Vipassana (retreat)	Pre-post
Tang	2009	40	NR	40	NR	0	Mind-body training	Pre-post
Xue	2014	45	29	24	22.9	0	Mind-body training	Pre-post
Ahani	2014	34	6	–	61	0 (6 weeks training)	MM	Non pre-post
Amihai	2014	19	16	–	44.4	7.7	Vipassana	Non pre-post
Arita	2012	15	NA	–	NA	NA	Zen	Non pre-post
Becker	1981	30 (Zen = 10)	17 (Zen = 8)	10	32.7 (Zen = 37.8)	6.5 (Zen = 7.5)	Zen, TM & Yoga	Non pre-post
Berkovich-Ohana	2012	36	NR	12	41.7	3673 (hours)	MM	Non pre-post
Berkovich-Ohana	2013	36	NR	12	41.7	3673 (hours)	MM	Non pre-post
Brown	2010	12	6	15	34	NR	Various (inc. MM)	Non pre-post
Cahn	2010	16	11	–	45.5	20	Vipassana	Non pre-post
Cahn	2013	16	11	–	45.5	20	Vipassana	Non pre-post
Chan	2008	19	8	–	19–22 (range)	NR	Triarchic	Non pre-post
Delgado	2013	10	10	0	20–61 (range)	7.5	Vipassana	Non pre-post
Ferrarelli	2013	29	14	29	50.7	15.6	MM	Non pre-post
Hauswald	2015	11	5	–	50	12	Zen	Non pre-post
Hinterberger	2011	49	33	–	45	40–1000 (hours; range)	Various (inc. MM)	Non pre-post
Hinterberger	2014	49	33	–	45	40–1000 (hours; range)	Various (inc. MM)	Non pre-post
Huang	2009	23	16	23	31.5	8.4	Zen	Non pre-post
Jo	2014	20	7	19 (from 20)	40.7	3 (minimum)	Zen	Non pre-post
Kasamatsu	1966	48	48	18	24–72 (range)	1–20 (range)	Zen	Non pre-post
Kubota	2001	25	11	–	23.1	0	Zen	Non pre-post
Lakey	2011	18	7	–	18–33 (range)	0	MM	Non pre-post
Lagopoulos	2009	18	13	–	52	9–14 (range)	Acem	Non pre-post
Lehmann	2012	71 (Zen = 15)	NR	–	41.4 (Zen = 42)	11.3 (Zen = 12.3)	Various (inc. Zen)	Non pre-post
Lo	2003	20	NR	10	NR	NR	Zen	Non pre-post
Lo	2013	10	7	10	28	5.8	Zen	Non pre-post
Milz	2014	23	23	2	23.2	0	MM	Non pre-post
Murata	2004	22	22	–	23.3	0	Su-soku	Non pre-post
Pasquini	2015	17	9	14	44.6	2 (minimum)	Zen	Non pre-post
Ren	2011	32	23	16	23.3	0	Su-soku	Non pre-post
Sobolewski	2011	13	7	13	38.7	5 (minimum)	MM	Non pre-post
Stinson	2013	13	NR	–	NR	0	Neurofeedback	Non pre-post
Takahashi	2005	20	20	–	28.6	0	Zen	Non pre-post
Tanaka	2014	10	4	10	49.2	11.6	MM	Non pre-post
Teper	2013	20	9	18	33	3.19	MM	Non pre-post
Teper	2014	45 (from 47)	27	–	19.26	0	Trait mindfulness	Non pre-post
van Leeuwen	2012	8	5	8	29	5	MM	Non pre-post
Yu	2011	15	14	–	38	0	Zen	Non pre-post

Note: MBCT, mindfulness-based cognitive therapy; MM, mindfulness meditation; NCC, neural correlates of consciousness; NR, not recorded; RCT, randomized controlled trial; TM, transcendental meditation. Number of meditators is presented in column headed by Meditators.

Table 2
Demographics of participants with a clinical history.

First author	Year	*n* meditators	*n* males meditators	*n* controls	Mean age meditators	Meditation type	Psychiatric disorder
Barnhofer	2007	10 (from 16)	5	12 (from 18)	48	MBCT	Suicidal depression
Barnhofer	2010	8	1	8	31.6	MM	Previously depressed
Bostanov	2012	32 (from 45)	9	32 (from 46)	50.9	MBCT	Depressed (remission)
Brown	2013	12	NA	15	NA	MM pain manage	Chronic pain
Garland	2015	11	NA	18	NA	MORE	Chronic pain
Howells	2012	12	2	9	37	MBCT	Bipolar disorder
Keune	2013	40 (from 53)	10	37 (from 50)	48.9	MBCT	Depressed (remission)
Schoenberg et al.	2014	26 (from 32)	NA	24 (from 29)	NA	MBCT	ADHD
Schoenberg (and Speckens)	2014	26	6	25	47.8	MBCT	Depression (current)
Schoenberg (and Speckens)	2015	26	6	25	47.8	MBCT	Depression (current)

Note: MBCT, mindfulness-based cognitive therapy; MM, mindfulness meditation; MORE, mindfulness-oriented recovery enhancement. All studies featured pre-post designs, and all except Howells were RCTs. All subjects participating had no previous experience of meditation.

3.2. *Effects of mindfulness on neurophysiology*

Twenty-one studies examined the alpha bandwidth, reporting greater amplitude during mindfulness in comparison with an eyes-closed resting state ($n = 12$), lower amplitude ($n = 1$), and no significant differences ($n = 3$) (Table 3). Most of the studies involved experienced meditators; novice participants were involved in 4 of the reports of greater amplitude and 1 of the reports of no significant differences. Coherence was examined in 2 papers, with mixed results, and more complex analyses in another 2 papers.

Table 3
Results synthesis of papers according to principle findings and according to bandwidth or asymmetry.

Outcome	MED > RS	MED = RS	MED < RS	Pre < post (linked to MED)	Pre > post (linked to MED)
Alpha power	***Ahani et al. (2014)***; Arita (2012); Cahn et al. (2013); ***Dunn et al. (1999)***; Hinterberger et al. (2014); Huang and Lo (2009); Kasamatsu and Hirai (1966); Lagopoulos et al. (2009); Lo et al. (2003); ***Milz et al. (2014)***; Murata et al. (2004; coherence); ***Takahashi et al. (2005)***; ***Yu et al. (2011)***	Berkovich-Ohana et al. (2013; coherence); Cahn et al. (2010); ***Kubota et al. (2001)***; Lehmann et al. (2012)	Amihai and Kozhevnikov (2014)		Saggar et al. (2012)
Beta power	***Ahani et al. (2014)***; Cahn et al. (2013); ***Dunn et al. (1999)***; Lo et al. (2003; synchrony)	Cahn et al. (2010); Lagopoulos et al. (2009); Lehmann et al. (2012); ***Milz et al. (2014)***; Murata et al. (2004; coherence); ***Yu et al. (2011)***	Amihai and Kozhevnikov (2014)	***Howells et al. (2012)***	Saggar et al. (2012)
Theta power	***Ahani et al. (2014)***; Arita (2012); Cahn et al. (2010); Chan et al. (2008); Kasamatsu and Hirai (1966); ***Kubota et al. (2001)***; Lagopoulos et al. (2009); Lehmann et al. (2012); Lomas et al. (2014); ***Takahashi et al. (2005)***; ***Tanaka et al. (2014)***	Amihai and Kozhevnikov (2014); Berkovich-Ohana et al. (2013; coherence); ***Milz et al. (2014)***; Murata et al. (2004; coherence)	***Dunn et al. (1999)***; Huang and Lo (2009); ***Yu et al. (2011)***	***Howells et al. (2012)***; ***Xue et al. (2014)***	Saggar et al. (2012; in RS); ***Tang et al. (2009)***
Delta power	Cahn et al. (2010; at frontal brain regions)	Amihai and Kozhevnikov (2014); Cahn (2010; at central and parietal brain regions); Lagopoulos et al. (2009); ***Milz et al. (2014)***	***Dunn et al. (1999)***		
Gamma power	Berkovich-Ohana et al. (2012); Cahn et al. (2010); Hauswald et al. (2015); Lehmann et al. (2012)	Amihai and Kozhevnikov (2014); Berkovich-Ohana et al. (2012; coherence); ***Milz et al. (2014)***			
Greater relative left-sided activation	Amihai and Kozhevnikov (2014); Chan et al. (2008)	***Milz et al. (2014)***		***Barnhofer et al. (2007)***; ***Barnhofer et al. (2010)***; ***Davidson et al. (2003)***	***Keune et al. (2011***; CNT also decreased)

Note: >, significantly greater than; <, significantly lower than; =, no significant differences; CNT, control group; MED, meditation; RS, resting state. Studies featuring novice participants are indicated by the author/year being italicized in bold. All findings refer to amplitude, unless stated otherwise (e.g. coherence).

The beta bandwidth was examined in 12 studies which compared mindfulness with a resting state, reporting greater amplitude during mindfulness ($n = 3$; including $n = 1$ with novice meditators), lower amplitude ($n = 1$), and no significant differences ($n = 5$, $n = 2$ with novices). Coherence ($n = 1$, with no difference found), synchrony ($n = 1$, finding higher synchrony with meditation) and more complex analyses ($n = 1$) were also examined.

The theta bandwidth was examined in 19 studies, reporting greater amplitude during mindfulness ($n = 11$; $n = 3$ with novices), lower amplitude ($n = 3$; $n = 2$ with novices), and no significant differences ($n = 2$; $n = 1$ with novices). Coherence ($n = 2$, with no difference found), and more complex analyses ($n = 1$) were also examined.

The delta bandwidth was examined in 5 studies, reporting greater amplitude during mindfulness ($n = 1$, with novices, limited to frontal regions) as well as no significant differences ($n = 3$; $n = 1$ with novices). More complex analyses ($n = 1$) were also examined.

The gamma bandwidth was examined in 7 studies, reporting greater amplitude during mindfulness ($n = 3$) and no significant differences ($n = 2$; $n = 1$ with novices). Gamma amplitude during mindfulness also correlated with trait mindfulness and years of practice ($n = 1$). Coherence ($n = 1$, with no difference found), and asymmetry ($n = 3$, finding greater left-sided activation ($n = 2$) and no differences ($n = 1$)) was also examined.

Event-related potentials were examined in 15 studies, with mindfulness found to have an impact on attention processing measures including P300 ($n = 5$; $n = 2$ on P3b specifically), Late Positive Potential ($n = 2$), Feedback Related Negativity ($n = 1$), Error Related Negativity ($n = 1$), Readiness Potential ($n = 1$), pain-evoked ERPs ($n = 2$), Late Contingent Negative Variation ($n = 1$), and a Go/NoGo task ($n = 2$).

3.3. Longitudinal neurophysiological changes associated with mindfulness practice

In healthy individuals, learning mindfulness was associated with decreased alpha amplitude ($n = 2$ studies), increased ($n = 1$) as well as decreased ($n = 1$) theta amplitude, and changes in asymmetry with an increase in relative left-sided activation ($n = 1$).

In participants with chronic pain, a course of mindfulness was associated with a decrease in beta amplitude ($n = 1$). In patients with depression and suicidal ideation, a relative increase in left-sided activation following mindfulness training was observed, while the inverse pattern (with a relative decrease in left-sided activation) was reported in patients in remission from depression.

4. Discussion

The main finding to emerge from the systematic review is an increase in alpha power associated with mindfulness relative to a resting state. Additional effects have been reported in the other oscillation bandwidths, including a majority trend towards increased theta power during meditation compared to a resting state. The patterns of increased alpha and theta amplitude

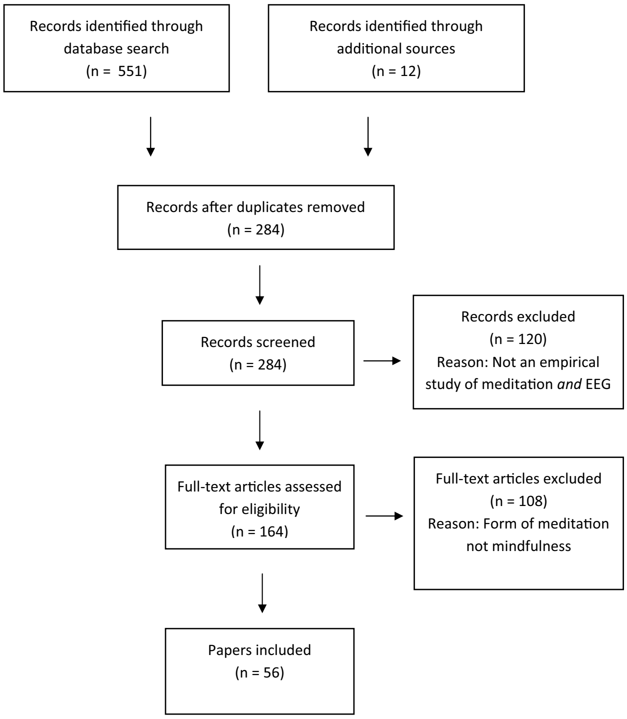

Fig. 1. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram.

associated with meditation were observed in both experienced and novice meditators. Clinical studies of mindfulness-based interventions revealed a shift towards greater relative left-sided activation which may be associated with increased positive affect. However, these findings have been mixed, with reports of increases, decreases as well as no differences, particularly in other bandwidths, but also in alpha and theta bandwidths.

Alpha synchronization has been regarded as one of the 'signatures' of meditation as it has been consistently observed across a range of different meditation practices relatively independent of both technique and degree of practice (Fell et al., 2010). In the present review, increased alpha synchronization during meditation as compared to a resting state was reported in 67% of papers that analyzed this outcome (12 out of 18), all of which involved healthy participants, including both novice (Lo et al., 2003; Milz et al., 2014; Takahashi et al., 2005; Yu et al., 2011) and experienced meditators (Ahani et al., 2014; Arita, 2012; Cahn et al., 2013; Dunn et al., 1999; Hinterberger et al., 2014; Huang and Lo, 2009; Kasamatsu and Hirai, 1966; Lagopoulos et al., 2009). Most of the studies had examined participants during mindfulness in comparison to a resting state with eyes closed with a few exceptions (ex. Takahashi et al., 2005). However, the findings have not been wholly consistent as a few studies found no differences between mindfulness and a resting state in novice (Kubota et al., 2001) or experienced (Cahn et al., 2010; Lehmann et al., 2012) participants, as well as decreased alpha power during mindfulness (Amihai and Kozhevnikov, 2014). It is of note that none of the studies involving clinical populations had analyzed or reported findings on alpha power. Comparisons of mindfulness with performance on attention tasks reported no differences in alpha power with eyes closed while attending to auditory clicks (Becker and Shapiro, 1981), with a time production task (Berkovich-Ohana et al., 2013), and with an eyes-open session watching a video about neurofeedback (Stinson and Arthur, 2013), although Ren et al. (2011) found lower levels of alpha compared to a problem-solving task.

The functional significance of alpha has been much debated. Alpha synchronization has been understood as reflecting the 'de-activation' of cortical areas as a signifier of the brain 'idling' since it occurs during relaxed eyes closed wakefulness (Shaw, 1996; Pfurtscheller et al., 1996). The increase in alpha synchronization with mindfulness as compared to eyes closed rest may indicate even greater levels of synchronization associated with mindfulness. According to the 'brain idling' hypothesis, the effect suggests that meditation generates greater cortical de-activation than during an eyes closed resting state. However, Shaw (1996) proposes that there is a paradoxical response which distinguishes between 'outer-directed' and 'inner-directed' attention. While 'outer-directed' attention is associated with alpha desynchronization, 'inner-directed' attention, which is also referred to as 'intention,' is associated with increases in alpha power. In support, tasks requiring memory (Jensen et al., 2002) and imagination (Cooper et al., 2006) lead to increases in alpha power. Mindfulness improves the training and development of various attention networks (sustained, executive, selective, and re-orienting) in terms of its focused-attention aspects and awareness in terms of its open-monitoring aspects (Lutz et al., 2008; Vago and Silbersweig, 2012). As such, it is possible to infer that increased alpha power associated with mindfulness is evidence that alpha synchronization is indeed a signifier of increased processing in these various attention modalities (e.g. as per Vago and Silbersweig's (2012) model) with respect to internally generated stimuli.

With regards to beta oscillations, of the 12 studies which compared beta activity in meditation with eyes closed rest in healthy individuals, only 3 studies reported that beta amplitude was higher in meditation, involving experienced meditators (Ahani et al., 2014; Cahn et al., 2013) and novices (Dunn et al., 1999). Five studies found no significant differences in experienced practitioners (Cahn et al., 2010; Lagopoulos et al., 2009; Lehmann et al., 2012) and in novices (Milz et al., 2014; Yu et al., 2011), while one study observed lower beta amplitude in meditation in experienced practitioners (Amihai and Kozhevnikov, 2014), and 5 studies found no significant differences (Cahn et al., 2010; Lagopoulos et al., 2009; Lehmann et al., 2012; Milz et al., 2014; Yu et al., 2011). A comparison of mindfulness with task performance, an eyes open session watching a video about neurofeedback, reported lower amplitude in meditation relative to the task (Stinson and Arthur, 2013). Only one paper reported on beta power in clinical populations, observing pre-post longitudinal decreases in beta power during the resting state which was linked to the practice of mindfulness (Howells et al., 2012).

Interpretations of the significance of beta are mixed because it has been proposed to reflect a reduction in cortical activity as it is associated with barbiturates and benzodiazepines use (Herning et al., 1994); beta activity has also been attenuated with increasing cognitive task demands (Ray and Cole, 1985) while around 20% of patients with ADHD exhibit 'excessive' beta activity, which is associated with elevated behavioural problems (Clarke et al., 2001).

Increased theta power has been considered to be another key feature of meditation (Josipovic, 2010; Fell et al., 2010). This pattern was to some extent borne out in the present review and was observed in both novice and experienced meditators, although there did appear to be a slight weighting towards this effect being more prevalent in experienced practitioners. Of the 19 studies that compared theta activity in meditation with eyes closed rest, a majority ($n = 11$) reported that theta power was higher in mindfulness, including 8 with experienced practitioners (Ahani et al., 2014; Arita, 2012; Cahn et al., 2010; Chan et al., 2008; Kasamatsu and Hirai, 1966; Lagopoulos et al., 2009; Lomas et al., 2014), but only 2 with novices (Kubota et al., 2001; Takahashi et al., 2005), plus also Tanaka et al. (2014), who found this effect with both novice and experienced practitioners. Against this, 3 studies reported that theta was lower during mindfulness compared to eyes-closed rest, 2 of which involved novices (Dunn et al., 1999; Yu et al., 2011) and 1 involving experienced practitioners (Huang and Lo, 2009). Moreover, 2 studies found no significant differences in experienced (Amihai and Kozhevnikov, 2014) and novice practitioners (Milz et al., 2014). An additional 2 longitudinal studies also observed pre-post decreases in theta power during the resting state which was linked to the practice of mindfulness (Saggar et al., 2012; Tang et al., 2009). Only one paper reported on theta power in clinical populations, observing pre-post longitudinal increases in theta power (during the resting state) linked to the practice of mindfulness (Howells et al., 2012).

The presence of theta along with alpha synchronization during mindfulness lends support to the hypothesis that increased alpha power during mindfulness signifies internalized attention rather than the brain 'idling' because theta synchronization is widely viewed as a marker of executive functioning. Theta activity has been linked to various types of cognitive activity, including switching and orienting attention (Dietl et al., 1999), processing of new information (Grunwald et al., 1999), and memory in episodic encoding and retrieval (Klimesch et al., 1997), and theta power increases as task demands increase (Klimesch et al., 1997). Taken together, the findings suggest that mindfulness constitutes a state of enhanced internally-directed attention. Theta oscillations during wakefulness generally occur maximally in the frontal-midline regions of the brain, particularly in the prefrontal cortex (Asada et al., 1999) and may be localized to the anterior cingulate cortex (Onton et al., 2005), in contrast to theta activity during REM sleep, which is generated mainly by the hippocampus (Cantero et al., 2003). These regions are centrally involved in the executive control of attention, as well as other higher-level cognitive activities such as volition and planning (Posner and Dehaene, 1994; Miller and Cohen, 2001), and have been proposed as central to the development of attention and awareness in meditation (Newberg and Iversen, 2003).

This interpretation is strengthened by the differences observed between experienced and novice practitioners, in which the former were more reliably found across the studies to exhibit higher levels of theta activation during meditation in comparison to a resting state, suggesting that enhanced theta activation during meditation is to some extent a function of training and practice in meditation (in terms of learning to maintain inner-directed attention). Furthermore, it has been suggested that the co-presence of theta and alpha in mindfulness indicates a state of 'relaxed alertness' (Britton et al., 2014), which is corroborated by qualitative self-reports of practitioners' experiences in mindfulness (Cahn and Polich, 2006).

Fewer studies have reported delta and gamma activity, with mixed findings, and have all been limited to healthy individuals. Slow wave delta band activity is more commonly associated with sleep, particularly deep non-REM stages (Hofle et al., 1997). It has been suggested though that an increase in delta activity during wakefulness reflects attention to internal processing during the performance of cognitive tasks, such as difficult arithmetical calculation tasks (Harmony et al., 1996). The reports of delta activity associated with mindfulness have generally found no differences (Lagopoulos et al., 2009; Amihai and Kozhevnikov, 2014; Milz et al., 2014), although reduced (Dunn et al., 1999) as well as increased amplitudes, which were localized to frontal regions (Cahn et al., 2010), have been described in comparison to an eyes closed resting state, with these various studies featuring both novice (Dunn et al., 1999; Milz et al., 2014) and experienced (Lagopoulos et al., 2009; Cahn et al., 2010; Amihai and Kozhevnikov, 2014) meditators. Stinson and Arthur (2013) also found lower amplitude during meditation compared to a control task of watching a neurofeedback video.

Gamma synchronization is purported to reflect activity in the default mode network (Berkovich-Ohana et al., 2012) which refers to the self-referential and reflective thoughts that occur in the absence of requirements to respond to external stimuli (Buckner et al., 2008). With mindfulness, gamma power has been reported as increased (Berkovich-Ohana et al., 2012; Cahn et al., 2010; Lehmann et al., 2012) as well as showing no differences (Amihai and Kozhevnikov, 2014; Milz et al., 2014) in comparison with an eyes closed resting state. Of interest, increased gamma activity was observed in experienced meditators (Berkovich-Ohana et al., 2012; Cahn et al., 2010; Lehmann et al., 2012), although no differences were also found in both experienced (Amihai and Kozhevnikov, 2014) and novice (Milz et al., 2014) meditators. In comparison with a control task, lower amplitude was reported during mindfulness as compared to a neurofeedback video task (Stinson and Arthur, 2013). In addition, studying experienced Zen meditators, Hauswald et al. (2015) found that gamma power during meditation correlated both with levels of trait mindfulness and years of meditation practice. Ferrarelli et al. (2013) also reported a correlation between meditation experience and gamma power during non-REM sleep, but Berkovich-Ohana et al. (2012) found no difference in coherence between meditation and rest. Gamma oscillations have been implicated in theories of consciousness, in which the fast rhythmic synchronization of neural discharges is theorised as providing the necessary spatial and temporal links to bind processing across different brain areas, thereby integrating disparate experiential qualia into a coherent state of moment-to-moment awareness (Singer, 1993; Tallon-Baudry and Bertrand, 1999). Increased gamma power during mindfulness thus might indicate a more unified and coherent mental state.

In addition to analysis of specific bandwidths, patterns of asymmetric brain activation have been examined in which left prefrontal activity has been associated with positive affect and 'approach-related' behaviour, and right prefrontal activity with negative affect and 'withdrawal-related' behaviour (Davidson, 1992). If mindfulness is associated with enhanced subjective wellbeing, then its practice should be linked to greater left prefrontal activity. Such an asymmetry has been observed during mindfulness in experienced meditators relative to an eyes closed resting state (Amihai and Kozhevnikov, 2014; Chan et al., 2008). Following mindfulness training, similar changes have been reported in novice participants who were healthy volunteers (Davidson et al., 2003) as well as people with a history of suicidal ideation (Barnhofer et al., 2007). In novice participants with a history of depression, there have been reports of no differences (Milz et al., 2014), increased (Barnhofer et al., 2010) and decreased (Keune et al., 2011) left-sided activation.

Using event-related potentials, reduced P3b in response to distractor stimuli (Slagter et al., 2007) and faster attentional disengagement from a dominant global presentation in order to focus in on specific stimuli (van Leeuwen et al., 2012) were observed in experienced meditators. Likewise, Delgado-Pastor et al. (2013) found that experienced Vipassana meditators demonstrated larger P3b amplitudes to a target tone after meditation than before meditation; these findings are interpreted as reflecting increased attentional engagement following meditation, given that P3b is seen as reflecting allocation of attentional resources to incoming stimulation to facilitate information processing, thus corroborating the notion of mindfulness as a system of attention training. Moreover, anticipatory and pain-evoked ERPs to acute pain were reduced in participants who received mindfulness training but not in controls (Brown and Jones, 2013). Sobolewski et al. (2011) explored the impact of meditation practice on late positive potential (LPP), the amplitude of which tends to be greater in ERPs evoked by emotionally arousing images, particularly ones that are negatively valenced. While control participants with no meditation experience showed an increase in LPP amplitude in response to negative stimuli, no such increases were observed in meditators, suggesting that the latter were less affected by negative emotional load than control participants; in contrast, both groups responded equally to positively-valenced stimuli. Teper and Inzlicht (2014) explored participants' neuroaffective reaction to rewarding, aversive and neutral feedback, as gauged by feedback-related negativity (FRN), a brain response that differentiates positive from negative feedback, reporting that trait levels of mindfulness in novice meditators predicted less differentiation of reward from neutral feedback. Lakey et al. (2011) explored the impact of brief mindfulness training on performance of a P300-based brain-compute interface task. Compared to non-meditating control participants, the experimental subjects produced significantly larger P300 amplitudes and were also more accurate at the task, which was understood as suggesting that the experimental participants were better able to harness present-moment attentional resources.

Working with patients with ADHD, Schoenberg et al. (2014) explored the impact of Mindfulness-Based Cognitive Therapy (MBCT) on error processing (ERN, Pe), conflict monitoring (NoGo-N2), and inhibitory control (NoGo-P3) in relation to a continuous performance task (CPT-X). Compared to matched controls, MBCT was linked to increased Pe and NoGo-P3 amplitudes, which coincided with reduced 'hyperactivity/impulsivity' and 'inattention' symptomatology. In a trial involving patients currently diagnosed with major depressive disorder, Schoenberg and Speckens (2014) found that an MBCT intervention had a modulating effect on evoked FM-theta power during a Go/NoGo task: enhanced event-related synchronization (ERS) in the late temporal window was observed pre-to-post for the experimental group, with the reverse pattern found in control participants. It was suggested that these findings were reflective of optimized allocation of attentional resources as a result of the intervention. Moreover, these modulated ERS dynamics were also found to correlate with ameliorated depressive and rumination symptoms in the MBCT group. Studying patients with chronic pain at risk of opioid abuse, Garland et al. (2015) found that a Mindfulness-Oriented Recovery Enhancement intervention was able to enhance natural reward processing. In particular, the intervention was associated with increases in LPP in response to natural reward stimuli relative to neutral stimuli, which also correlated with reduced opioid craving from pre- to post-treatment. Jo et al. (2014) explored the Readiness Potential correlates of the intentional binding effect, and found that early neural activity correlated with the participants' reports of initiating a voluntary action; however, there were no differences between experienced Zen meditators and matched controls in this regard.

A significant limitation of the present systematic review has been the variability of the measures which were acquired and reported, such that a meta-analysis was not feasible for any of the measures because there were no more than 3 studies which used the same measure at the same site. There was also considerable variation in terms of quality, as assessed using the Quality Assessment Tool for Quantitative Studies (National Collaborating Centre for Methods and Tools, 2008). Clinical studies were generally of higher quality as they tended to keep track of withdrawal and attrition rates and used standardized meditation protocols. Furthermore, a key issue was limited reporting on participants' prior level of meditation experience. Some studies reported this in terms of years, some in terms of total number of hours, and a few omitted to specify this. Moreover, there was variation in the criteria for which studies rated participants as 'experienced'; in terms of years, this ranged from 1 year (Kasamatsu and Hirai, 1966) to 9 years (Lagopoulos et al., 2009), while in terms of hours this ranged from 40 h (Hinterberger et al., 2011) to 1740 h (Berkovich-Ohana et al., 2012). We applied the lowest of these cutoffs such that an 'experienced' (i.e. non-novice) meditator was considered to have been meditating for longer than 1 year or to have completed more than 40 h of meditation. Arguably hours would be a better metric than years since it better reflects a person's general amount of practice; however, it is recommended that future studies report both hours and years which would provide some indication of the 'intensity' of participants' practice. Another issue was poor and/or inconsistent reporting on the nature of participants' meditation practice. Although all the studies included in the review featured mindfulness specifically (or a functional equivalent), even this is a somewhat generic label, with nuances and differences among practices that can be classified as being mindfulness, and many studies had not described in detail the form and type of mindfulness practice engaged in by participants.

In conclusion, the burgeoning literature on EEG investigations of mindfulness is beginning to highlight some consistent trends, most notably with respect to increased amplitude in the alpha and theta bandwidths. The co-presence of elevated alpha and theta waves may reflect a state of 'relaxed alertness' as alpha and theta can both be interpreted as signifiers of increased attention, with alpha specifically representing internalized attention, and both have also been identified as indexing states of relaxation. Further work will be needed to explore the nuances of brain states associated with mindfulness, particularly with respect to the other bandwidths and measures such as ERP and asymmetry, to elucidate the differences between mindfulness and other meditation practices, and to further explore the impact of factors such as degree of meditation practice.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.neubiorev.2015.09.018.

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