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Spectral power and functional connectivity changes during mindfulness meditation with eyes open: A magnetoencephalography (MEG) study in long-term meditators

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ABSTRACT

Whilst a number of previous studies have been conducted in order to investigate functional brain changes associated with eyes-closed meditation techniques, there is a relative scarcity in the literature with regards to changes occurring during eyes-open meditation. The current project used magnetoencephalography (MEG) to investigate differences in spectral power and functional connectivity between 11 long-term mindfulness meditators (LTMMs) with >5 years of experience and 12 meditation-naïve control participants both during baseline eyes-open rest and eyes-open open-monitoring (OM) mindfulness meditation. During resting with eyes-open, prior to meditating, greater mean alpha power was observed for LTMMs in comparison to controls. However, during the course of OM meditation, a significantly greater increase in theta power was observed over a broad fronto–centro-parietal region for control participants in comparison to LTMMs. In contrast, whole-head mean connectivity was found to be significantly greater for long-term meditators in comparison to controls in the theta band both during rest as well as during meditation. Additionally, mean connectivity was significantly lower for long-term meditators in the low gamma band during rest and significantly lower in both low and high gamma bands during meditation; and the variance of low-gamma connectivity scores for long-term meditators was significantly decreased compared to the control group. The current study provides important new information as to the trait functional changes in brain activity associated with long-term mindfulness meditation, as well as the state changes specifically associated with eyes-open open monitoring meditation techniques.

1. Introduction

Meditation, an ancient technique of mind training, has long been practised across various eastern cultures including India, China, Japan and Thailand. The roots of meditation practice may be traced back to the Buddhist traditions which began over 2500 years ago (Kabat-Zinn, 2003). A central component of meditation practice is mindfulness, which is defined as an open and non-judgemental awareness or observation of the ongoing cognitive processing of thoughts in the present moment whilst constantly sustaining attention (Cahn and Polich, 2006). Since the early 1970s meditation practice has become increasingly popular in the West, and this growing interest has been paralleled by the scientific study of these practices. More recently, modern neuroimaging techniques have been applied in order to better understand the neurobiological underpinnings of mindfulness, as well as to investigate more fundamental questions of basic science regarding human consciousness and mind–brain–body interactions.

Meditation practice can be broadly categorised into two common styles of meditation (i) Focused attention; FA and (ii) Open monitoring; OM (Lutz, 2008). FA, or concentrative meditations, include practices such as qigong yoga, yoga nidra and Shamatha meditations (Ivanovski and Malhi, 2007). FA practices primarily involve voluntarily focusing and sustaining attention on a chosen object of meditation such as one's own breath/body sensations (e.g. breath counting) or a mantra/visualisation. By contrast, OM or mindfulness-based meditations such as the Vipassana (insight) practice from Theravada Buddhism and the 'shikantaza' practice from the Soto school of Zen Buddhism involve the non-reactive cognisance of the stream and content of ongoing experience with no explicit attentional focus on any specific object of meditation and the non-judgemental awareness of subjective cognitive and emotional appraisal in the present moment. Whilst there may be some variation of these

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styles in various Buddhist meditation traditions and secular/clinical programmes (e.g. Transcendental meditation), the underlying characteristics of the respective meditation styles is still generally subsumed within this operational framework (Lutz, 2008; Travis and Shear, 2010).

Modern functional neuroimaging technologies such as electroencephalography (EEG), functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) are increasingly being used in order to investigate state and trait changes in the brain associated with meditation practice (see Cahn and Polich (2006) for review). An implicit assumption associated with the use of these techniques is that they may help to bridge the gap between the phenomenological experience of meditation and the underlying brain function associated with changes in consciousness (Lutz and Thompson, 2003). These techniques provide the ability to be able to objectively measure distinct brain activity and neural connectivity in precise brain regions corresponding to specific cognitive processes. In this way, they offer explanations of behavioural changes at a more mechanistic level and enable insight into the neurophysiological effects of meditation on human brain dynamics.

The default mode network (DMN) has provided a theoretical framework for understanding changes in the brain that may occur as a function of meditation practice. The DMN includes the medial prefrontal cortex (mPFC), the inferior parietal lobule (IPL), the precuneus (PC), the posterior cingulate cortex (PCC), as well as the infero-lateral temporal cortex (ITC), and is understood to be activated whenever the brain is not actively engaged in specific goal-directed task processing (Brewer et al., 2011; Raichle et al., 2001; Taylor et al., 2013). There have been a number of neuroimaging studies which have investigated changes in activity amongst the various nodes of the DMN as a result of meditation. In particular the PCC, which is a central hub of the DMN, has been heavily implicated (Brewer and Garrison, 2014; Brewer et al., 2011, 2013; Garrison et al., 2013; Taylor et al., 2013). For example, Garrison et al. (2013) reported that PCC activation was aligned with self-reported subjective experiences of "distracted awareness" and "controlling" during mind-wandering and self-referential processing; whilst PCC deactivation was found to be aligned with self-reports of "undistracted awareness" and "effortless doing" during meditation. However, other fMRI mindfulness studies to investigate the DMN (Holzel et al., 2007; Ives-Deliperi et al., 2011; Jang et al., 2011) have provided more equivocal results. In relation to EEG studies which have investigated activity within the DMN during a resting state, preliminary evidence suggests that activity within this network is most reliably related to increases in global alpha and beta EEG power (Chen et al., 2008), as well as *decreases* in frontal and midline theta power (Knyazev, 2013; Meltzer et al., 2007; Mizuhara et al., 2004; Scheeringa et al., 2008). In relation to activity within the prefrontal node of the DMN, increased EEG gamma power has been found to be most closely related (Chen et al., 2008; Jerbi et al., 2010; Mantini et al., 2007). However, whilst changes in the activity and connectivity of various nodes of the DMN have been demonstrated across a number of meditation studies, there is currently no consensus as to whether increases or decreases in the activation of this network are to be expected.

Whilst a large number of electrophysiological studies have investigated acute changes in brain activity associated with mindfulness meditation practice and/or changes associated with short term training programmes such as mindfulness-based stress reduction (MBSR; Kabat-Zinn, 2003), comparatively few studies have investigated longer term changes in brain activity associated with mindfulness practice. In consideration of the fact that meditation is a difficult skill, which often requires years of regular practice and retreat participation in order to become proficient at, then it could be argued that reliable brain activity trait effects will only become apparent when studying long-term experienced practitioners. Within the various OM techniques there is another important distinction which has often been overlooked in previous research; whether the eyes are kept open or closed. In consideration of the well-documented differences in resting state oscillatory activity that exist between eyes-open and eyes-closed states, this is a distinction which cannot be overlooked.

However, a more fundamental rationale for investigating eyes-open meditation in contrast to eyes-closed practice is that it cannot be assumed that the neural correlates are the same. Instructions for eyes-open meditation typically emphasise the need to maintain visual awareness of the surrounding environment, without explicit focus on any particular object. With an emphasis on remaining visually aware of surroundings it could be argued that there exists less of an introspective focus in comparison to a practitioner who sits with their eyes closed. It could also be argued that maintaining visual awareness throughout the meditation session could foster a deeper experience of present-centred awareness. Meditating with the eyes open lends itself very well to open monitoring, and it is perhaps for this reason that a substantial number of the OM techniques, such as shikantaza, have instruction requiring that the eyes be kept open. From a neurophenomological perspective it is apparent that a different experience of meditation may also be reflected by a different pattern of activation within the default mode network. Table 1 provides a summary of previous EEG and MEG studies investigating long-term changes in brain function associated with long-term OM mindfulness meditation, listing each according to whether they utilised an eyes-closed or an eyes-open technique.

In studies which have investigated eyes-closed OM meditation practice in long-term practitioners, increases in theta power (4–8 Hz) during meditation have frequently been observed in frontal regions for long-term meditators (Aftanas and Golocheikine, 2001, 2002, 2003; Cahn et al., 2010; Cahn and Polich, 2006; Lagopoulos et al., 2009), although only a small number of these studies have evidenced greater theta increases in long-term meditators in comparison to a control group (Aftanas and Golocheikine, 2001, 2002, 2003). In an attempt to align the different meditation techniques with specific frequency band power changes, Travis and Shear (2010) have suggested that OM meditation is in fact characterised specifically by theta activity, in contrast to focused attention techniques which are characterised by beta/gamma activity. One interpretation of increases in frontal EEG theta activity associated with long-term meditation practice is that it reflects suppression of DMN activity in the frontal areas (Knyazev, 2013). Alternatively, frontal theta activity is also typically observed during the completion of working memory tasks (Brookes et al., 2011; Klimesch, 1999), and so this activity could be interpreted as being indicative of improved anterior cingulate (ACC) function and sustained attention (Baijal and Srinivasan, 2010). Although, this latter account would appear to fit more closely with the meditation technique of focussed attention (FA) rather than OM meditation. Finally, theta activity also has a well-documented association with states of deep relaxation (Vaitl et al., 2005) and has been proposed to play an important role in the integration of activity in widely distributed neural circuits (Von Stein and Sarnthein, 2000).

In addition to the well-documented theta changes associated with meditation, increased alpha power during meditation has also been observed across a number of studies involving long-term meditation practitioners (Aftanas and Golocheikine, 2001, 2003; Huang and Lo, 2009), and higher frequency changes in gamma band power have also begun to be reported more recently. For example, in a recent study Berkovich-Ohana et al. (2012) reported that long-term meditators displayed trait decreases in gamma power over frontal and midline regions together with increased right parieto-occipital gamma power during an eyes-closed resting state, when compared to short-term meditators. State increases in gamma power in largely right-lateralised temporal and parieto-occipital regions were also observed in the same study for long-term practitioners during eyes-closed meditation (Berkovich-Ohana et al., 2012). The authors interpreted these frontal decreases in gamma power as evidencing decreased DMN activity in frontal areas related to self-referential processing, whilst the increases in right parieto-occipital gamma were interpreted as reflecting greater activity in viscerosomatic areas, the secondary somatosensory cortex and inferior parietal lobule, areas which could foreseeably facilitate heightened sensory awareness (Berkovich-Ohana et al., 2012). These findings corroborate