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Reduced functional connectivity between cortical sources in five meditation traditions detected with lagged coherence using EEG tomography

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ABSTRACT

Brain functional states are established by functional connectivities between brain regions. In experienced meditators (13 Tibetan Buddhists, 15 QiGong, 14 Sahaja Yoga, 14 Ananda Marga Yoga, 15 Zen), 19-channel EEG was recorded before, during and after that meditation exercise which their respective tradition regards as route to the most desirable meditative state. The head surface EEG data were recomputed (sLORETA) into 19 cortical regional source model time series. All 171 functional connectivities between regions were computed as 'lagged coherence' for the eight EEG frequency bands (delta through gamma). This analysis removes ambiguities of localization, volume conduction-induced inflation of coherence, and reference-dependence. All significant differences (corrected for multiple testing) between meditation compared to no-task rest before and after meditation showed lower coherence during meditation, in all five traditions and eight (inhibitory as well as excitatory) frequency bands. Conventional coherence between the original head surface EEG time series very predominantly also showed reduced coherence during meditation. The topography of the functional connectivities was examined via PCA-based computation of principal connectivities. When going into and out of meditation, significantly different connectivities revealed clearly different topographies in the delta frequency band and minor differences in the beta-2 band. The globally reduced functional interdependence between brain regions in meditation suggests that interaction between the self process functions is minimized, and that constraints on the self process by other processes are minimized, thereby leading to the subjective experience of non-involvement, detachment and letting go, as well as of all-oneness and dissolution of ego borders during meditation.
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1. Introduction

Meditation is currently an important topic in affective and cognitive neuroscience. Many physiological and psychological aspects of meditation practice have been reported applying very different measurement and analysis approaches (e.g. Luders et al., 2009; Lutz et al., 2009; van den Hurk et al., 2010; for an earlier review of the extended literature see Cahn and Polich, 2006).

Brain states of higher cognitive functions such as meditation are implemented as spatially distributed dynamical neuronal networks (Mesulam, 1990; Tononi et al., 1998) that constitute webs of functional connections between brain regions. The brain mechanisms of a functional state are appropriately described by the functional connections between the active brain regions (Singer, 2009). Such descriptions can document characteristic changes between various mental states (e.g. Burgess and Ali, 2002; Mizuhara et al., 2005; Stam, 2000; Walter et al., 1967; White et al., 2009).

The EEG measure of functional connectivity implemented as coherence between head surface recorded EEG time series has been used to assess brain states during meditation. These studies have shown increased EEG coherence during Transcendental Meditation (e.g. Gaylord et al., 1989; Levine, 1976; Travis and Orme-Johnson, 1989; Travis et al., 2002, 2010); experienced practitioners of Transcendental Meditation as well as novices showed increased alpha coherence compared to resting (Dillbeck and Bronson, 1981; Travis, 2001; Travis and Wallace, 1999). Zen meditation reportedly increased alpha coherence in meditation novices (Murata et al., 2004). Sahaja Yoga in long-term meditators produced theta coherence increases between some brain areas but decreases between other areas; in short term meditators, theta coherence only decreased (Aftanas and Golocheikine, 2001). Also, increase of phase locking in gamma frequency during Buddhist meditation has been reported (Lutz et al., 2004) but the authors stressed that phase locking differs from coherence (although both are measures of 'similarity'

Abbreviations: TB, Tibetan Buddhists; QG, QiGong; SY, Sahaja Yoga; AY, Ananda Marga Yoga; ZA, Zen; sLORETA, Standardized Low Resolution Electromagnetic Tomography; PCA, Principal Component Analysis; ROI, Region of Interest; Initial rest, no-task resting before meditation; Final rest, no-task resting after meditation.

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between pairs of signals measured at two locations, and are thus interpreted as measures of connectivity between the locations).

However, it has been questioned to what extent conventional computation of head surface EEG coherence reveals true functional connectivity between the brain regions under the locations of the recording electrodes because neuronal electric sources do not necessarily project radially to the scalp; computing EEG coherence between intracerebral generator model sources avoids this problem (see also Ruchkin, 2005). Also, the confounding effect of volume conduction in the conventional computation of EEG coherence has been criticized, and omission of zero phase angle coherence values was proposed as remedy (Nolte et al., 2004). Moreover, since the waveform of an EEG time series from a head surface electrode depends on the chosen reference, conventional head surface coherence is reference-dependent (examples in Lehmann et al., 2006).

The present study examines the intracortical functional connectivity of brain electric activity during meditation and during task-free resting preceding and following meditation. The analysis applies 'lagged' coherence that partials out the effect of zero phase angle coherence (Pascual-Marqui, 2007; Pascual-Marqui et al., 2011), thereby removing the volume conduction artifact. Further, it applies the method to cortical time series of electric neuronal generator activity estimated via LORETA-based source modeling of the head surface-recorded EEG data (sLORETA, Pascual-Marqui, 2002) which removes the ambiguity of source localization. Analyzing the source model-generated time series also solves the problem of reference dependence present in the head surface EEG signals. Conventionally computed coherence between the originally recorded head surface EEG time series is reported for comparison.

There are obvious differences between meditation traditions and meditation techniques. Considering these differences, taxonomies of meditation techniques have been proposed (e.g. Fischer, 1971; Lutz et al., 2008; Mikulas, 1990; Travis and Shear, 2010; distinctions were emphasized by Kabat-Zinn, 1982). Data available to us for the present study were from experienced practitioners of five different meditation traditions: Tibetan Buddhism, QiGong, Sahaja Yoga, Ananda Marga Yoga, and Zen. The meditators were recorded while performing that meditation exercise which their respective tradition regards as the route to the most desirable meditative state; recordings during no-task resting before and after meditation were also done. Because of the obvious differences between meditation traditions, the data from each of the five groups were analyzed separately.

On the other hand, apparently there are common goals resulting in common subjective experiences of the meditation practices across schools and traditions (Brewer et al., 2011; Cahn and Polich, 2006; Fischer, 1971; Goleman, 1996; Hinterberger et al., 2011; Kabat-Zinn, 1990; Walsh, 1982): The handling of the contents of consciousness (avoiding intruding unintended thoughts as described in terms such as e.g. letting go, benevolent disregard, detachment), and the quality of the conscious self-awareness (attaining a pleasant, peaceful state of mind as described in terms such as all-oneness, bliss, oceanic feeling, transcending, expanded consciousness).

The present study separately analyzed each of the five groups in order to examine how brain electric functional connectivities differ between resting and meditation, and whether changes into and out of meditation are compensatory. Analyzing the brain activity of meditators from different traditions resulted in the surprising finding that the optimal meditation state in all the five traditions is characterized by reduced intracortical functional connectivity compared to no-task resting.

2. Methods

2.1. Participants

We analyzed EEG data from five groups of experienced meditators that were available to us. The meditators belonged to different meditation traditions: 13 Tibetan Buddhists (TB), 15 QiGong practitioners (QG), 14 Sahaja Yoga practitioners (SY), 14 Ananda Marga Yoga practitioners (AY) and 15 Zen practitioners (ZA). The study was approved by the Ethics Committee of the Tokyo University Medical School (#1364) for the TB, QG, SY and AY, and by the Ethics Committee of the University Hospital Zurich for the ZA. The participants were fully informed about the goal and methods of the study, and gave their written consent.

Gender, and mean years of age, and mean years of meditation experience (we asked for the year when the meditator had started practicing meditation everyday) with standard errors and ranges of the meditators of the five traditions are listed in Table 1. All participants used their right hands for writing. The participants had no history of head trauma or mental diseases, did not take centrally active medication and were not drug users.

The TB were Lamas from Tibet and India, from the Nyingmapa and Kagyupa traditions, who temporarily stayed in Taipei for missionary work; they meditate daily for at least 60 minutes. The QG were Taiwanese lay people who studied under Qigong Master Feng-San Lee at Taipei; they meditate daily for at least 45 minutes. The SY were Taiwanese lay people who meditate daily for at least 30 minutes; the AY were westerner and Hindu monks and nuns who live in Taipei; they meditate daily at least for 2 hours; the ZA were Swiss lay people who regularly participate in meditation exercises at the Zen Dojo Zurich, a Soto Zen institution; they meditate daily for at least 60 minutes. The meditators of all five groups have the habit to participate occasionally in retreats.

TB were paid 1000 NT$/person; QG, SY and AY were unpaid volunteers; ZA were paid 40 CHF/person.

2.2. Recording

The EEG recordings of TB, QG, SY and AY were done at the EEG Laboratory of the Department of Neurology, General Veterans Hospital in Taipei, during September-December 2006. The EEG was recorded versus combined ears (the 19 standard EEG channels of the international 10/20 system were analyzed), together with eye movement, muscle and ECG channels, using silver/silver-chloride electrodes with the Hospital's 32-channel Nicolet Voyager Digital EEG system; EEG was band passed from 1 to 70 Hz and digitized at 256 samples/s.

The EEG recordings of ZA were done at the KEY Laboratory at the University Hospital of Psychiatry in Zurich, using a 64-channel M&I system (Prague, Czech Republic), 58 electrodes were attached (Easycap System Munich, Germany) at locations of the international 10–10 system (Nuwer et al., 1998) with 2 additional channels for eye movement recordings. EEG was band-passed from 0.5 to 125 Hz and digitized at 250 samples/s, off-line up-sampled to 256 samples/s.

2.3. Protocol

The protocol comprised 6 sequential recording conditions, but only conditions 1, 3 and 4 were done in all five groups:

1- Initial resting: 20 s eyes opened, 40 s eyes closed; 4 cycles. TB, SY, and AY: lotus position, QG: sitting on stool, ZA: sitting on chair

Table 1
Demographics of the meditators of the five traditions (groups).

	Number		Years of age				Years of meditation experience			
	total	men	mean	SEM	max	min	mean	SEM	max	min
Tibetan Buddhists	13	13	38.9	2.3	58	27	12.2	1.9	25	1
QiGong	15	15	37.2	2.0	49	25	6.6	0.9	13	2
Sahaja Yoga	14	4	43.9	2.7	63	26	8.5	1.6	20	1
Ananda Marga Yoga	14	9	45.2	2.1	56	31	16.9	2.4	33	5
Zen	15	9	42.0	2.0	56	29	12.3	1.4	21	5

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