Cogn Process (2015) 16:87–96
DOI 10.1007/s10339-014-0637-x

RESEARCH REPORT

Zazen meditation and no-task resting EEG compared with LORETA intracortical source localization

Pascal L. Faber · Dietrich Lehmann · Lorena R. R. Gianotti · Patricia Milz · Roberto D. Pascual-Marqui · Marlene Held · Kieko Kochi

Received: 16 April 2014 / Accepted: 26 September 2014 / Published online: 5 October 2014

Abstract Meditation is a self-induced and willfully initiated practice that alters the state of consciousness. The meditation practice of Zazen, like many other meditation practices, aims at disregarding intrusive thoughts while controlling body posture. It is an open monitoring meditation characterized by detached moment-to-moment awareness and reduced conceptual thinking and self-reference. Which brain areas differ in electric activity during Zazen compared to task-free resting? Since scalp electroencephalography (EEG) waveforms are reference-dependent, conclusions about the localization of active brain areas are ambiguous. Computing intracerebral source models from the scalp EEG data solves this problem. In the present study, we applied source modeling using low resolution brain electromagnetic tomography (LORETA) to 58-channel scalp EEG data recorded from 15 experienced Zen meditators during Zazen and no-task resting. Zazen compared to no-task resting showed increased alpha-1 and alpha-2 frequency activity in an exclusively right-lateralized cluster extending from prefrontal areas including the insula to parts of the somatosensory and motor cortices and temporal areas. Zazen also showed decreased alpha and beta-2 activity in the left angular gyrus and decreased beta-1 and beta-2 activity in a large bilateral posterior cluster comprising the visual cortex, the posterior cingulate cortex and the parietal cortex. The results include parts of the default mode network and suggest enhanced automatic memory and emotion processing, reduced conceptual thinking and self-reference on a less judgmental, i.e., more detached moment-to-moment basis during Zazen compared to no-task resting.

Keywords Zen meditation · Zazen · EEG · LORETA · No-task resting · Source modeling

Dietrich Lehmann: Deceased.

P. L. Faber (✉) · D. Lehmann · L. R. R. Gianotti · P. Milz · R. D. Pascual-Marqui · M. Held · K. Kochi
The KEY Institute for Brain-Mind Research, Department of Psychiatry, Psychotherapy and Psychosomatics, University Hospital for Psychiatry, 8032 Zurich, Switzerland
e-mail: pfaber@key.uzh.ch

Present Address:
L. R. R. Gianotti
Social Psychology and Social Neuroscience, Department of Psychology, University of Bern, 3012 Bern, Switzerland

Present Address:
M. Held
Institute for Psychology, Clinical Psychology and Psychotherapy, University of Bern, 3012 Bern, Switzerland

Introduction

Meditation is a volitionally self-induced practice that alters the state of consciousness. Many different practices exist. They usually involve the regulation of attention, awareness and emotion (Raffone and Srinivasan 2010; Shapiro and Walsh 2003). Attempts have been made to classify the many different meditation practices into useful categories. Based on their focus of attention, meditation practices have been classified as either *focused attention* or *open monitoring* practices (Dunn et al. 1999; Lutz et al. 2008; Raffone and Srinivasan 2010). The former put the focus of attention on one chosen object, whereas the latter train an effortless, open and nonjudgmental awareness in the present moment.

Where does the Zen-Buddhism practice of Zazen fit in? In many meditation practices, specific instructions are given such as attending to or counting one's breath, or continually repeating a visual or auditory mantra, or doing repetitive limb or body movements, or assuming certain body positions. The classical instruction for the practice of Zazen is "sitting fixedly, think of not thinking. How do you think of not thinking? Nonthinking. This is the art of Zazen" (Zazen gi: Dogen 1243/2001). Zazen, like other meditation practices, aims at disregarding any intrusive thoughts (Cahn and Polich 2006) arising from memory or outside sources. It favors the detached mindful perception of the ongoing moment-to-moment experience (Austin 2013), which leads to a calm awareness that in turn allows for the emergence of undisturbed introspective memory processes (Austin 2011). Zazen belongs to those meditation practices that have been described as means to recognize the nature of emotional and cognitive patterns (Lutz et al. 2008; Raffone and Srinivasan 2010). It is also characterized by reduced conceptual processing and self-reference (Pagnoni et al. 2008). Based on these descriptions and the obvious emphasis on aspects of open monitoring, Zazen can be considered a typical open monitoring practice.

Zazen is subjectively different from simple non-meditative no-task resting. While the task-free resting state is characterized by mind wandering, Zazen is characterized by reduced conceptual thinking and self-reference, momentary awareness and the active upholding (executive control) of detachment from spontaneous mentation and perceptions. Also, Zazen requires continual control of the sitting posture. The question arises: Given that higher brain functions are incorporated by networks of activated local brain areas (Britz et al. 2010; Laufs et al. 2003; Mesulam 1990), what is the localization of the brain areas whose activity differs between the state of consciousness reached during Zazen and the state of consciousness during non-meditative no-task resting? Open monitoring in general can be expected to engage brain areas implicated in monitoring, vigilance and the disengagement of attention from distracting perceptions, and brain areas implicated in interoception as well as in the regulation of emotional processes (Lutz et al. 2008). A side issue is whether meditation experience affects the activity of these brain areas during Zazen and resting.

The "default mode of brain function" (Raichle et al. 2001) describes a resting state network more active during waking rest than during specific goal-directed behaviors. This default mode network (DMN) consists of regions in the medial prefrontal cortex, the posterior cingulate cortex (PCC) and precuneus, the angular gyrus and the left superior and middle frontal gyri, hippocampus and parahippocampus (Buckner et al. 2008, Gusnard et al. 2001, Raichle et al. 2001). The brain areas constituting the DMN are of special interest for the study of meditation as their activity has been linked to mind wandering (Mason et al. 2007), episodic memories (Buckner et al. 2008; Greicius et al. 2004) and conceptual processing (Binder et al. 1999), all important for maintaining the sense of self (Gusnard et al. 2001; Lou et al. 2004). As all these processes are affected by meditation, the DMN brain regions are key areas where brain electric differences between Zazen and no-task resting would be expected.

When assessing brain activity, electroencephalography (EEG) recommends itself over other techniques (e.g., fMRI, PET and NIRS), because the very high time resolution of EEG makes it possible to distinguish inhibiting from facilitating brain activity. With increasing wave frequency, the functional significance of EEG waveshapes changes from inhibition to routine functioning to facilitation (Makeig and Jung 1995; Niedermeyer and Lopes da Silva 2005; O'Gorman et al. 2013).

Several studies reported EEG findings concerning Zazen meditation compared to resting (Becker and Shapiro 1981; Kasamatsu and Hirai 1966; Murata et al. 1994) and concerning other Zen meditations practicing attention to breathing (Huang and Lo 2009; Kubota et al. 2001; Takahashi et al. 2005; Yu et al. 2011). Most of these studies found an increase of alpha and theta EEG frequency activity during meditation. All of these studies analyzed scalp recorded EEG waveshapes and therefore conclusions about activations of brain areas derived from these analyses are problematic.

Localization of brain activity based on scalp EEG waveshape analysis has been criticized because the recorded EEG waveshapes depend on the chosen recording reference (there is no zero reference, Geselowitz 1998). As a solution, the computation of intracerebral source models from scalp EEG data has been proposed (Ruchkin 2005).

EEG-based source modeling has been applied to meditation data in several studies. During concentration meditation, compared to resting increased beta frequency activity and decreased gamma activity was reported (Lavallee et al. 2011). During transcendental meditation, increased alpha frequency activity and decreased beta activity was observed (Travis et al. 2010; Yamamoto et al. 2006).

To our knowledge, the present study is the first to use source modeling to analyze multichannel EEG data to localize the active brain areas during Zazen and no-task resting. We use a well-validated method that implements source model computation of scalp EEG data: low resolution brain electromagnetic tomography (LORETA; Pascual-Marqui et al. 1994, 1999).

We hypothesized that Zazen and resting will activate different brain areas. Based on the above reviewed modulation of processes concerning memory, emotion, conceptual thinking, self-reference and detached momentary awareness during Zazen, we specifically hypothesized that source localization differences between the Zazen meditation state and the no-task resting state comprise brain areas that are part of the DMN: the PCC, precuneus, angular gyrus, hippocampus and parahippocampus. We expected these areas to show decreased facilitatory activity during Zazen. We also expected brain areas involved in monitoring body posture (sensory and motor areas) to show increased facilitatory activity during Zazen.

Materials and methods

Participants

Experienced meditators were recruited at a local Soto Zen meditation center in Zurich (Zen Dojo Zürich, www.zen.ch). Multichannel EEG was recorded from 15 meditators (9 males). Their mean age was 42 years (SD 7.9; range 29–56). Their mean experience in Zen meditation was 12.3 years (SD 5.6; range 5–21). Each participant received CHF 40 as financial compensation. All participants were right-handers. All reported no previous or current psychiatric diagnosis, head trauma or drug usage, and none used any centrally active medication. After complete information about the study design, all participants gave their written consent. The study was approved by the local Ethics Committee and thus conforms to the ethical standards of the 1964 Declaration of Helsinki.

Recording conditions

The EEG was recorded during the following conditions:

(1) Initial resting: The participants were sitting comfortably in a chair with arm- and backrest. Duration: 4 min (20 s eyes open, 40 s eyes closed, repeated four times). This design was used to avoid that participants became sleepy during this resting condition. Only the eyes closed data were used for analysis.
(2) Zazen: The participants were sitting on a meditation cushion (zafu) in a full or part Lotus position with their hands held together in front of the navel. They sat about 1 m from the unstructured, gray wall of the dimly lit recording chamber with their eyes two-thirds closed. Duration: 60 min.
(3) Final resting: same as condition (1) initial resting.

EEG recording and questionnaires

The EEGs were recorded at the University Hospital of Psychiatry, Zurich, in a sound and electrically shielded EEG chamber. A total of 58 electrodes were placed on the scalp with an "Easy Cap" (Easycap, Herrsching-Breitbrunn, Germany) using the following locations according to the International 10–10 system (Nuwer et al. 1998): Fp1/2, AF7/8, AF3/4, AFz, F7/8, F5/6, F3/4, F1/2, Fz, FT7/8, FC5/6, FC3/4, FCz, T7/8, C5/6, C3/4, C1/2, Cz (reference), TP7/8, CP5/6, CP3/4, CP1/2, CPz, P7/8, P5/6, P3/4, P1/2, Pz, PO7/8, PO3/4, POz, O1/2, Oz. Horizontal and vertical eye movements were recorded with electrodes at the left and right outer canthi and left infraorbital. Impedances were kept below 5 kΩ. The signals were amplified, band passed from 0.5 to 100 Hz and digitized at 250 samples/s using a 64-channel EEG/ERP system (M&I Ltd., Prague, Czech Republic).

During the application of the electrodes, the participants filled out three questionnaires. One questionnaire asked about past head traumata, psychiatric illnesses, drug abuse and medication and asked for gender, age, education and Zen meditation experience. A questionnaire (Chapman and Chapman 1987) determined the handedness; all participants were right-handed (mean score = 13.6, SD = 1.02).

Data conditioning

Off-line, the EEG data were carefully reviewed using the BrainVision Analyzer software (Brain Products, Munich, Germany). Eye-movement artifacts were corrected using independent component analysis. EEG data containing muscle, movement and/or technical artifacts were marked; noisy channels were linearly interpolated. All artifact-free data were parsed into 2 s epochs for analysis. On average, 119 s (SD = 18.1) of EEG data were available per participant for the initial resting condition, 114 s (SD = 32.8) for final resting condition and 1632 s = 27.2 min (SD = 692 s = 11.5 min) for the Zazen condition.

Data analysis

Intracortical functional source localization

The 58-channel EEG data were analyzed using the sLORETA software version (standardized low resolution brain electromagnetic tomography, Pascual-Marqui 2002; free academic software available at http://www.uzh.ch/keyinst/loreta.htm) of the LORETA functional tomography analysis approach (Pascual-Marqui et al. 1994, 1999). sLORETA is a properly standardized discrete, linear, minimum norm, inverse solution that yields images of standardized current density with exact localization (Pascual-Marqui 2009), albeit with low resolution. sLORETA images consist of standardized current density at each of 6,239 cortical voxels (spatial resolution 5 mm) in Montreal Neurological Institute (MNI) space (Evans and Collins 1993).

sLORETA functional images were computed for each subject and condition separately in each of the seven classical independent frequency bands (Kubicki et al. 1979; Niedermeyer and Lopes da Silva 2005, p. 1234): delta

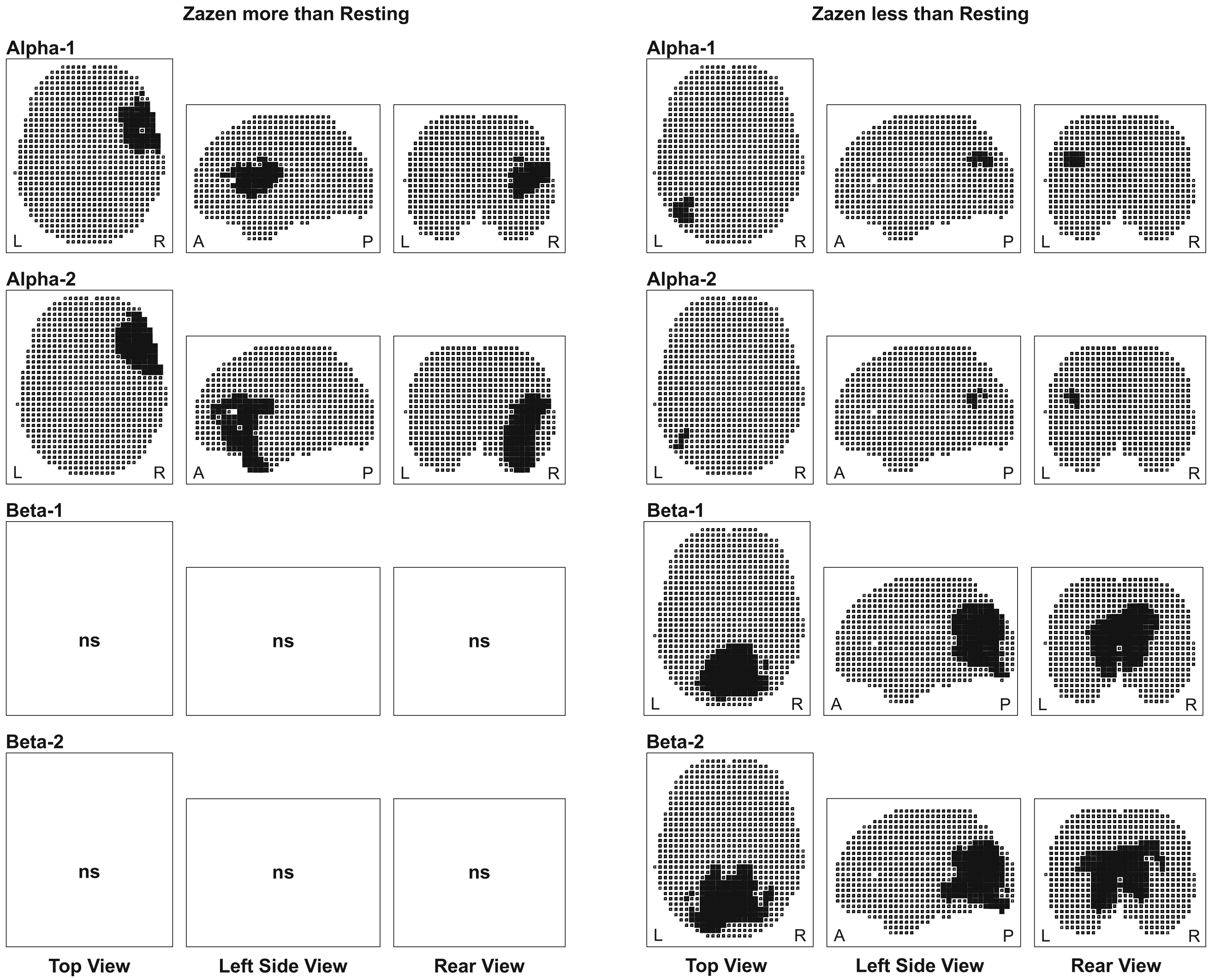

Fig. 1 Comparison of brain activity during Zazen and resting. Glass brain views, from *left* to *right*: axial, sagittal and coronal views. *Left column*: Zazen had stronger activity than resting in the alpha-1 and alpha-2 EEG frequency bands. *Right column*: resting had stronger activity than Zazen in the alpha-1, alpha-2, beta-1 and beta-2 EEG frequency bands. *Dark voxels*: Differences between Zazen and resting at $p < 0.05$ after correction for multiple testing. *Light voxels*: sLORETA voxel space (MNI; left to right: −70 to +70 mm; posterior to anterior: −100 to +65 mm; inferior to superior: −45 to +70 mm)

(1.5–6 Hz), theta (6.5–8 Hz), alpha-1 (8.5–10 Hz), alpha-2 (10.5–12 Hz), beta-1 (12.5–18 Hz), beta-2 (18.5–21 Hz) and beta-3 (21.5–30 Hz) and in an additional eighth gamma frequency band (35–44 Hz), since this band reportedly is of interest in meditation research (Lehmann et al. 2001, 2012; Lutz et al. 2004).

All testing was done on the frequency band-wise normalized and log-transformed sLORETA images. Initial resting and final resting were compared using classical voxel-wise *t* tests. Correction for multiple testing was applied using nonparametric randomization (Nichols and Holmes 2002) implemented in the sLORETA software package. The two resting conditions did not differ significantly in any of the eight frequency bands. Therefore, for further comparisons, the sLORETA functional images for initial resting and final resting were averaged per subject and frequency band into a combined “resting” condition.

Zazen was then compared to resting using the same *t* test procedure with correction for multiple testing as above. Significant voxels were attributed to the corresponding Brodmann areas (“BAs”). BAs are reported using the MNI space with correction to Talairach space (Brett et al. 2002).

Correlations with meditation experience and age

Correlations (Pearson’s *r*) were computed between participants’ years of meditation experience and age and the sLORETA source localization results for Zazen and resting. Correction for multiple testing (Nichols and Holmes 2002) was applied.

Table 1 sLORETA frequency band results of the comparison of Zazen versus resting

BA	Region	Zazen more than resting							Zazen less than resting						
		LH		M		RH		Total	LH		M		RH		Total
		A1	A2	A1	A2	A1	A2		A1	A2	A1	A2	A1	A2	
Alpha-1 and alpha-2 frequency bands															
3	Primary somatosens. cortex	–	–	–	–	1	4	5	–	–	–	–	–	–	–
4	Primary motor cortex	–	–	–	–	5	–	5	–	–	–	–	–	–	–
6	Supplementary motor area	–	–	–	–	17	11	28	–	–	–	–	–	–	–
9	Dorsolateral prefrontal cortex	–	–	–	–	5	1	6	–	–	–	–	–	–	–
10	Anterior prefrontal cortex	–	–	–	–	–	10	10	–	–	–	–	–	–	–
11	Orbitofrontal area	–	–	–	–	–	15	15	–	–	–	–	–	–	–
13	Insular cortex	–	–	–	–	55	26	81	–	–	–	–	–	–	–
19	Associative visual cortex	–	–	–	–	–	–	–	1	–	–	–	–	–	1
20	Inferior temporal gyrus	–	–	–	–	–	1	1	–	–	–	–	–	–	–
21	Middle temporal gyrus	–	–	–	–	–	11	11	–	–	–	–	–	–	–
22	Superior temporal gyrus	–	–	–	–	5	3	8	–	–	–	–	–	–	–
38	Temporopolar area	–	–	–	–	–	54	54	–	–	–	–	–	–	–
39	Angular gyrus	–	–	–	–	–	–	–	24	10	–	–	–	–	34
42	primary auditory cortex	–	–	–	–	1	–	1	–	–	–	–	–	–	–
43	Primary gustatory cortex	–	–	–	–	11	–	11	–	–	–	–	–	–	–
44	pars opercularis of Broca	–	–	–	–	28	26	54	–	–	–	–	–	–	–
45	pars triangularis of Broca	–	–	–	–	25	27	52	–	–	–	–	–	–	–
46	Dorsolateral prefrontal cortex	–	–	–	–	8	23	31	–	–	–	–	–	–	–
47	Inferior prefontal gyrus	–	–	–	–	10	80	90	–	–	–	–	–	–	–
		B1	B2	B1	B2	B1	B2	Total	B1	B2	B1	B2	B1	B2	Total
Beta-1 and beta-2 frequency bands															
7	Somatosensory assoc. cortex	–	–	–	–	–	–	–	14	11	8	6	55	25	119
17	Primary visual cortex	–	–	–	–	–	–	–	16	23	–	–	12	4	55
18	Secondary visual cortex	–	–	–	–	–	–	–	72	88	16	13	65	39	293
19	Associative visual cortex	–	–	–	–	–	–	–	19	61	1	–	54	37	172
22	Superior temporal gyrus	–	–	–	–	–	–	–	–	–	–	–	–	2	2
23	Ventral posterior cingulate	–	–	–	–	–	–	–	4	4	7	7	11	10	43
27	Parahippocampal gyrus	–	–	–	–	–	–	–	–	2	–	–	–	5	7
29	Retrosplenial cingulate	–	–	–	–	–	–	–	4	5	–	–	4	4	17
30	Part of cingulate cortex	–	–	–	–	–	–	–	28	36	3	3	32	39	141
31	Dorsal posterior cingulate	–	–	–	–	–	–	–	35	32	10	8	51	42	178
35	Perirhinal cortex	–	–	–	–	–	–	–	–	–	–	–	–	1	1
36	Parahippocampal cortex	–	–	–	–	–	–	–	–	–	–	–	–	2	2
39	Angular gyrus	–	–	–	–	–	–	–	–	3	–	–	5	9	17

Listed are the numbers of significant voxels by Brodmann area (BA), anatomical region and frequency bands (A1 = alpha-1, A2 = alpha-2, B1 = beta-1, B2 = beta-2)

LH left hemisphere, *M* midline, *RH* right hemisphere

Results

Intracortical functional source localization

The sLORETA analysis revealed significant differences between Zazen and resting at $p < 0.05$ after correction for multiple testing. The t threshold required for significance was $t = 5.86$. The following results met this threshold.

Current density in the alpha-1 and alpha-2 frequency bands increased during Zazen compared to resting in a large anterior right-hemispheric cluster as illustrated in Fig. 1. Table 1 specifies the number of significant voxels, the BAs and brains regions which extended from prefrontal areas including the insula to parts of the somatosensory and motor cortices. In the alpha-2 band, the cluster additionally included anterior temporal areas. There also was a small cluster in the left angular gyrus where alpha-1 and alpha-2 activity decreased.

Current density in the beta-1 and beta-2 frequency bands decreased in a large bilateral posterior cluster during Zazen compared to resting (Fig. 1). Table 1 shows that about 60 % of all voxels in this cluster were located in the visual cortices and in the somatosensory association cortex that includes the precuneus. The other nearly 40 % were located in the posterior cingulate cortex (PCC).

Correlations with meditation experience and age

Neither meditation experience nor participants' age correlated significantly with the current density values of the sLORETA tomographies in Zazen or resting in any of the eight frequency bands.

Discussion

As hypothesized, Zazen compared to resting showed significant differences in activated brain areas. Differences concerned primarily increased right-hemispheric activity in the EEG alpha frequency bands and decreased bilateral posterior activity in the EEG beta frequency bands. Contrary to various earlier reports on EEG changes in meditation (Cahn and Polich 2006; Lutz et al. 2004), no effects in theta and gamma frequency bands were observed.

The functional significance of the EEG alpha frequency band activity is discussed controversially (Bazanova and Vernon 2013). Power in the alpha bands increases with internally directed attention (Cooper et al. 2003) and in a relaxed state of alert wakefulness (Işoğlu-Alkaç and Strüber 2006; Klimesch 1999; Müller et al. 1999). Alpha activity also increases with active memory processes (Palva and Palva 2007) and during sensory processing (Schürmann et al. 1997). The alpha rhythm was also reported to reflect the anticipatory processing of events (Karakas 1997; Klimesch 1999). These functions are in line with the meditator's stance of open monitoring during Zazen, that is of an alert wakefulness, expecting events such as thoughts (arising from memory) or sensory perceptions (e.g., body posture or external noises) to spontaneously occur with the intention of only witnessing them without further processing, i.e., without "getting attached" to them (see Austin 2013). We note that task-related posterior alpha reportedly implements an inhibitory function (e.g., Klimesch et al. 2007). But during Zazen compared to resting, we observed increased anterior and temporal alpha activity.

The observed increased alpha activity during Zazen exclusively concerned the right hemisphere. The right hemisphere has been linked to emotion processing (e.g., Keil et al. 2001; Laurian et al. 1991; Zhang and Zhou 2014). The right insula (BA 13), the right superior temporal gyrus (BA 22) and the right middle and superior frontal sulci (BAs 9 and 10) showed increased alpha activity during Zazen; these areas are part of the emotion circuitry of the brain (Gray et al. 2002; Lutz et al. 2008). BAs 9, 10 and 13 were also found to be thicker in experienced meditators (Lazar et al. 2005).

Increased alpha activity in the prefrontal cortex (BAs 44, 45, 46 and 47), the insula (BA 13) and the somatosensory cortex (BA 3) as observed in our analysis presumably is related to self-reference based on momentary experience (Farb et al. 2007). This is in line with Austin's (2013) description of the Zazen practice as favoring the momentary experience. According to Austin, this leads to a calming of the awareness which allows introspective memory processes to emerge. Right prefrontal and insular areas were reported to be engaged in response inhibition (Dambacher et al. 2014; Eckert et al. 2009). Thus, in addition to the focus on momentary experience, the increased right prefrontal and insular alpha activity also agrees with an increased executive control needed for upholding the detached non-discursive mental state during Zazen.

The increased alpha activity in sensory and motor-related areas (BAs 3, 4, 6) in our results might reflect the increased moment-to-moment proprioception, including automatic information processing on body posture while sitting erect on a meditation cushion during Zazen.

In sum, the increased right-hemispheric alpha activity during Zazen thus on the one hand confirms our hypothesis of increased memory and emotion processing during meditation, and on the other hand reflects the present-centeredness of experience and the maintenance of a detached non-discursive stance during meditation.

About 60 % of the voxels with decreased beta frequency band activity during Zazen were in the visual cortices (BAs 17, 18, 19) and in BA7 that includes the precuneus, encompassing the dorsal visual stream (Ungerleider and Mishkin 1982). The reduction in activity in BAs 17, 18 and 19 during Zazen suggests reduced visual imagery (Kosslyn et al. 1993, 1999). This is especially noteworthy since our practitioners had their eyes only two-thirds closed during Zazen compared to having them completely closed during resting. The precuneus has been reported to be involved in self-related mental imagery (Cavanna and Trimble 2006). The reduced activation of this dorsal visual stream during meditation might reflect the decreased need of vision-for-action (Goodale 2011; Goodale and Milner 1992).

The other nearly 40 % of the voxels showing decreased beta activity during Zazen were located in the posterior cingulate cortex (PCC; BAs 23, 29, 30 and 31). The deactivation of this important hub of the DMN has been related to effortless awareness (Garrison et al. 2013a) and was also found deactivated in an fMRI study during focused attention meditation (Garrison et al. 2013b). PCC deactivation reportedly reflects increased present-centered awareness, whereas PCC activation is related to being caught up in mental content and is associated with decreased attention (Brewer et al. 2013). Our results thus suggest that during meditation the practitioners are less engaged in their thoughts and more centered in the present moment. Unfortunately, in the present study, no subjective reports were gathered about mentation during Zazen and resting, which makes this interpretation tentative. On the other hand, an attentive, yet detached present-centeredness and a reduced amount of spontaneous thoughts correspond to reported descriptions of the subjective experience during Zazen meditation (Austin 2013). It has been suggested that the PCC implements evaluation or judgment of experience (Legrand and Ruby 2009; Qin and Northoff 2011). Thus, the PCC deactivation during Zazen also fits the description of greater detachment from perceptions claimed to be present during meditation.

The angular gyrus (BA39) showed decreased activity in the alpha (left hemispheric) and beta (bilateral) frequency bands during Zazen. The angular gyrus is an important hub of the posterior part of the DMN which has been shown to be active during memory-based decision making (Sestieri et al. 2011) and semantic processing (Seghier et al. 2010). In a lexical decision task (discriminating words from nonwords) including the instruction to refocus on breathing after each decision, Zen meditators showed a shortened post-stimulus tail and decreased post-stimulus left angular gyrus BOLD activity compared to controls (Pagnoni et al. 2008). This was interpreted as indicating a faster refocusing of attention on the breath in meditators and a reduction in conceptual processing. A reduction in conceptual processing might be an indicator for non-dual awareness during Zazen, thus adding an aspect to Zazen outside the classification as an open monitoring practice (Josipovic 2010; Travis and Shear 2010a, b). Future research needs to take into account subjective reports in order to get information on the dual versus non-dual aspect of experience during the practice of Zazen.

In sum, the posterior alpha and beta decreases suggest an increased present-centeredness that is detached, non-judgmental and non-discursive with reduced semantic processing and self-reference during Zazen compared to resting.

How do our results compare to those based on similar analysis methods and concerning other meditation practices? There are only three studies that tested practicing meditation versus no-task resting and that used intracerebral EEG source analysis (Lavallee et al. 2011; Travis et al. 2010; Yamamoto et al. 2006). The practice in the study on concentration meditation (Lavallee et al. 2011) obviously would be classified as focused attention meditation, whereas our Zazen practice is an open monitoring meditation (Lutz et al. 2008). The practice used in the studies on transcendental meditation (Travis et al. 2010; Yamamoto et al. 2006) would be classified as *automatic self-transcending* meditation in another classification scheme (Travis and Shear 2010a). Our present results were different from both concentration on breathing and from transcendental meditation.

We note that age and meditation experience of the participants did not correlate significantly with our sLORETA current density images during Zazen or resting in any frequency band. Other studies have reported correlations between meditation experience and brain electric measures in some but not all frequency bands (e.g., Cahn et al. 2010; Lutz et al. 2004; Murata et al. 1994; Travis and Arenander 2006). Berkovich-Ohana et al. (2012) did not find a correlation with experience in their EEG gamma band study, while Brefczynski-Lewis et al. (2007) reported an inverted *U*-shaped dependence of results on experience, with very experienced meditators having again minimal effects on results. One possible explanation for our lack of correlations with experience could be due to our sample of participants consisting of experienced meditators only: There were no beginners, and the least experienced participant had already 5 years of meditation experience. A wider range of meditation experience might have been informative.

A potential limitation of the present study concerns the resting state of our meditators. It is known that long-term meditation alters the resting state EEG (e.g., Aftanas and Golosheykin 2005; Lutz et al. 2004; Tebecis 1975; Tei et al. 2009). Therefore, it is possible that the resting state of our experienced meditators is different from the resting state of non-meditators. Our reported differences between Zazen and resting might be affected by the possibly altered resting state of our meditators. Brewer et al. (2011) also brought up this problem and ventured to suggest an altered default mode during resting in meditators. A longitudinal approach could shed light on this issue or the direct comparison of the resting state of Zen meditators with the resting state of a matched control group consisting of non-meditators.

To elucidate the idiosyncrasies of the different types of meditation practices, future studies should directly compare Zazen as an open monitoring practice with focused attention meditation practices (e.g., breath counting) or automatic self-transcending (transcendental meditation).

Conclusion

In conclusion, the results confirmed our hypotheses of different activated brain areas during Zazen compared to no-task resting and specifically of the involvement of parts of the DMN. The findings reflect enhanced present-centeredness with automated and effortless memory and emotion processing, reduced conceptual thinking and self-reference, greater detachment from perceptions and body posture-related processing during Zazen compared to resting.

Acknowledgments Supported in part by Grant Nr. 44/06 from the Bial Foundation, S. Mamede do Coronado, Portugal.

References

Aftanas L, Golosheykin S (2005) Impact of regular meditation practice on EEG activity at rest and during evoked negative emotions. Int J Neurosci 115(6):893–909

Austin JH (2011) Meditating selflessly: practical neural zen. MIT Press, Cambridge

Austin JH (2013) Zen and the brain: mutually illuminating topics. Front Psychol 4:784. doi:10.3389/fpsyg.2013.00784

Bazanova OM, Vernon D (2013) Interpreting EEG alpha activity. Neurosci Biobehav Rev. doi:10.1016/j.neubiorev.2013.05.007

Becker DE, Shapiro D (1981) Physiological responses to clicks during Zen, Yoga, and TM meditation. Psychophysiology 18(6):694–699

Berkovich-Ohana A, Glicksohn J, Goldstein A (2012) Mindfulness-induced changes in gamma band activity—implications for the default mode network, self-reference and attention. Clin Neurophysiol 123(4):700–710. doi:10.1016/j.clinph.2011.07.048

Binder JR, Frost JA, Hammeke TA, Bellgowan PS, Rao SM, Cox RW (1999) Conceptual processing during the conscious resting state. A functional MRI study. J Cogn Neurosci 11(1):80–95

Brefczynski-Lewis JA, Lutz A, Schaefer HS, Levinson DB, Davidson RJ (2007) Neural correlates of attentional expertise in long-term meditation practitioners. Proc Natl Acad Sci USA 104(27): 11483–11488

Brett M, Johnsrude IS, Owen AM (2002) The problem of functional localization in the human brain. Nat Rev Neurosci 3(3):243–249

Brewer JA, Worhunsky PD, Gray JR, Tang YY, Weber J, Kober H (2011) Meditation experience is associated with differences in default mode network activity and connectivity. Proc Natl Acad Sci USA 108(50):20254–20259. doi:10.1073/pnas.1112029108

Brewer JA, Garrison KA, Whitfield-Gabrieli S (2013) What about the "self" is processed in the posterior cingulate cortex? Front Hum Neurosci 7:647

Britz J, Van De Ville D, Michel CM (2010) BOLD correlates of EEG topography reveal rapid resting-state network dynamics. Neuroimage 52(4):1162–1170. doi:10.1016/j.neuroimage.2010.02.052

Buckner RL, Andrews-Hanna JR, Schacter DL (2008) The brain's default network: anatomy, function, and relevance to disease. Ann N Y Acad Sci 1124:1–38. doi:10.1196/annals.1440.011

Cahn BR, Polich J (2006) Meditation states and traits: EEG, ERP, and neuroimaging studies. Psychol Bull 132(2):180–211

Cahn BR, Delorme A, Polich J (2010) Occipital gamma activation during Vipassana meditation. Cogn Process 11(1):39–56. doi:10.1007/s10339-009-0352-1

Cavanna A, Trimble M (2006) The precuneus: a review of its functional anatomy and behavioural correlates. Brain 129(Pt 3):564–583. doi:10.1093/brain/awl004

Chapman LJ, Chapman JP (1987) The measurement of handedness. Brain Cogn 6(2):175–183

Cooper NR, Croft RJ, Dominey SJ, Burgess AP, Gruzelier JH (2003) Paradox lost? Exploring the role of alpha oscillations during externally vs. internally directed attention and the implications for idling and inhibition hypotheses. Int J Psychophysiol 47(1):65–74

Dambacher F, Sack AT, Lobbestael J, Arntz A, Brugmann S, Schuhmann T (2014) The role of right prefrontal and medial cortex in response inhibition: interfering with action restraint and action cancellation using transcranial magnetic brain stimulation. J Cogn Neurosci 26(8):1775–1784. doi:10.1162/jocn_a_00595

Dogen (1243/2001) Treasury of the eye of the true dharma, Book 11. Principles of Zazen (Zazen gi). http://scbs.stanford.edu/sztp3/translations/shobogenzo/translations/zazengi/zazengi.translation.html. Accessed 31 March 2014

Dunn BR, Hartigan JA, Mikulas WL (1999) Concentration and mindfulness meditations: unique forms of consciousness? Appl Psychophysiol Biofeedback 24(3):147–165

Eckert MA, Menon V, Walczak A, Ahlstrom J, Denslow S, Horwitz A, Dubno JR (2009) At the heart of the ventral attention system: the right anterior insula. Hum Brain Mapp 30(8):2530–2541. doi:10.1002/hbm.20688

Evans AC, Collins DL (1993) A 305-member MRI-based stereotactic atlas for CBF activation studies. Proceedings of the 40th Annual Meeting of the Society for Nuclear Medicine

Farb NA, Segal ZV, Mayberg H, Bean J, McKeon D, Fatima Z, Anderson AK (2007) Attending to the present: mindfulness meditation reveals distinct neural modes of self-reference. Soc Cogn Affect Neurosci 2(4):313–322. doi:10.1093/scan/nsm030

Garrison KA, Santoyo JF, Davis JH, Thornhill TA 4th, Kerr CE, Brewer JA (2013a) Effortless awareness: using real time neurofeedback to investigate correlates of posterior cingulate cortex activity in meditators' self-report. Front Hum Neurosci 7:440. doi:10.3389/fnhum.2013.00440

Garrison KA, Scheinost D, Worhunsky PD, Elwafi HM, Thornhill TA 4th, Thompson E, Saron C, Desbordes G, Kober H, Hampson M, Gray JR, Constable RT, Papademetris X, Brewer JA (2013b) Real-time fMRI links subjective experience with brain activity during focused attention. Neuroimage 81:110–118

Geselowitz DB (1998) The zero of potential. IEEE Eng Med Biol Mag 17(1):128–132

Goodale MA (2011) Transforming vision into action. Vision Res 51(14):1567–1587. doi:10.1016/j.visres.2010.07.027

Goodale MA, Milner AD (1992) Separate pathways for perception and action. Trends Neurosci 15(1):20–25. doi:10.1016/0166-2236(92)90344-8

Gray JR, Braver TS, Raichle ME (2002) Integration of emotion and cognition in the lateral prefrontal cortex. Proc Natl Acad Sci USA 99:4115–4120

Greicius MD, Srivastava G, Reiss AL, Menon V (2004) Default-mode network activity distinguishes Alzheimer's disease from healthy aging: evidence from functional MRI. Proc Natl Acad Sci USA 101(13):4637–4642

Gusnard DA, Akbudak E, Shulman GL, Raichle ME (2001) Medial prefrontal cortex and self-referential mental activity: relation to a default mode of brain function. Proc Natl Acad Sci USA 98(7):4259–4264

Huang HY, Lo PC (2009) EEG dynamics of experienced Zen meditation practitioners probed by complexity index and spectral measure. J Med Eng Technol 33(4):314–321. doi:10.1080/03091900802602677

Işoğlu-Alkaç U, Strüber D (2006) Necker cube reversals during long-term EEG recordings: sub-bands of alpha activity. Int J Psychophysiol 59(2):179–189

Josipovic Z (2010) Duality and nonduality in meditation research. Conscious Cogn 19(4):1119–1121. doi:10.1016/j.concog.2010.03.016

Karakas S (1997) A descriptive framework for information processing: an integrative approach. Int J Psychophysiol 26(1–3):353–368

Kasamatsu A, Hirai T (1966) An electroencephalographic study on the zen meditation (Zazen). Folia Psychiatr Neurol Jpn 20(4):315–336

Keil A, Müller MM, Gruber T, Wienbruch C, Stolarova M, Elbert T (2001) Effects of emotional arousal in the cerebral hemispheres: a study of oscillatory brain activity and event-related potentials. Clin Neurophysiol 112:2057–2068

Klimesch W (1999) EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Res Brain Res Rev 29(2–3):169–195

Klimesch W, Sauseng P, Hanslmayr S (2007) EEG alpha oscillations: the inhibition–timing hypothesis. Brain Res Rev 53:63–88

Kosslyn SM, Alpert NM, Thompson WL, Maljkovic V, Weise SB, Chabris CF, Hamilton SE, Rauch SL, Buonanno FS (1993) Visual mental imagery activates topographically organized visual cortex: PET investigations. J Cogn Neurosci 5(3): 263–287. doi:10.1162/jocn.1993.5.3.263

Kosslyn SM, Pascual-Leone A, Felician O, Camposano S, Keenan JP, Thompson WL, Ganis G, Sukel KE, Alpert NM (1999) The role of area 17 in visual imagery: convergent evidence from PET and rTMS. Science 284(5411):167–170

Kubicki S, Herrmann WM, Fichte K, Freund G (1979) Reflections on the topics: EEG frequency bands and regulation of vigilance. Pharmakopsychiatr Neuropsychopharmakol 12:237–245

Kubota Y, Sato W, Toichi M, Murai T, Okada T, Hayashi A, Sengoku A (2001) Frontal midline theta rhythm is correlated with cardiac autonomic activities during the performance of an attention demanding meditation procedure. Brain Res Cogn Brain Res 11(2):281–287

Laufs H, Krakow K, Sterzer P, Eger E, Beyerle A, Salek-Haddadi A, Kleinschmidt A (2003) Electroencephalographic signatures of attentional and cognitive default modes in spontaneous brain activity fluctuations at rest. Proc Natl Acad Sci USA 100: 11053–11058

Laurian S, Bader M, Lanares J, Oros L (1991) Topography of event-related potentials elicited by visual emotional stimuli. Int J Psychophysiol 10(3):231–238

Lavallee CF, Hunter MD, Persinger MA (2011) Intracerebral source generators characterizing concentrative meditation. Cogn Process 12(2):141–150. doi:10.1007/s10339-011-0394-z

Lazar SW, Kerr CE, Wasserman RH, Gray JR, Greve DN, Treadway MT, McGarvey M, Quinn BT, Dusek JA, Benson H, Rauch SL, Moore CI, Fischl B (2005) Meditation experience is associated with increased cortical thickness. NeuroReport 16(17): 1893–1897

Legrand D, Ruby P (2009) What is self-specific? Theoretical investigation and critical review of neuroimaging results. Psychol Rev 116(1):252–282. doi:10.1037/a0014172

Lehmann D, Faber PL, Achermann P, Jeanmonod D, Gianotti LR, Pizzagalli D (2001) Brain sources of EEG gamma frequency during volitionally meditation-induced, altered states of consciousness, and experience of the self. Psychiatry Res 108(2): 111–121

Lehmann D, Faber PL, Tei S, Pascual-Marqui RD, Milz P, Kochi K (2012) Reduced functional connectivity between cortical sources in five meditation traditions detected with lagged coherence using EEG tomography. Neuroimage 60(2):1574–1586. doi:10.1016/j.neuroimage.2012.01.042

Lou HC, Luber B, Crupain M, Keenan JP, Nowak M, Kjaer TW, Sackeim HA, Lisanby SH (2004) Parietal cortex and representation of the mental Self. Proc Natl Acad Sci USA 101(17):6827–6832

Lutz A, Greischar LL, Rawlings NB, Ricard M, Davidson RJ (2004) Long-term meditators self-induce high-amplitude gamma synchrony during mental practice. Proc Natl Acad Sci USA 101(46):16369–16373

Lutz A, Brefczynski-Lewis J, Johnstone T, Davidson RJ (2008) Regulation of the neural circuitry of emotion by compassion meditation: effects of meditative expertise. PLoS One 3(3): e1897. doi:10.1371/journal.pone.0001897

Makeig S, Jung TP (1995) Changes in alertness are a principal component of variance in the EEG spectrum. NeuroReport 7(1):213–216

Mason MF, Norton MI, Van Horn JD, Wegner DM, Grafton ST, Macrae CN (2007) Wandering minds: the default network and stimulus-independent thought. Science 315(5810):393–395

Mesulam MM (1990) Large-scale neurocognitive networks and distributed processing for attention, language, and memory. Ann Neurol 28:597–613

Müller TJ, Federspiel A, Fallgatter AJ, Strik WK (1999) EEG signs of vigilance fluctuations preceding perceptual flips in multistable illusionary motion. NeuroReport 10(16):3423–3427

Murata T, Koshino Y, Omori M, Murata I, Nishio M, Sakamoto K, Horie T, Isaki K (1994) Quantitative EEG study on zen meditation (Zazen). Jpn J Psychiatr Neurol 48(4):881–890

Nichols TE, Holmes AP (2002) Nonparametric permutation tests for functional neuroimaging: a primer with examples. Hum Brain Mapp 15:1–25

Niedermeyer E, Lopes da Silva F (2005) Electroencephalography: basic principles, clinical applications, and related fields, 5th edn. Lippincott Williams Wilkins, Philadelphia

Nuwer MR, Comi G, Emerson R, Fuglsang-Frederiksen A, Guérit JM, Hinrichs H, Ikeda A, Luccas FJ, Rappelsburger P (1998) IFCN standards for digital recording of clinical EEG. International Federation of Clinical Neurophysiology. Electroencephalogr Clin Neurophysiol 106:259–261

O'Gorman RL, Poil SS, Brandeis D, Klaver P, Bollmann S, Ghisleni C, Luchinger R, Martin E, Shankaranarayanan A, Alsop DC, Michels L (2013) Coupling between resting cerebral perfusion and EEG. Brain Topogr 26(3):442–457

Pagnoni G, Cekic M, Guo Y (2008) "Thinking about not-thinking": neural correlates of conceptual processing during Zen meditation. PLoS One 3(9):e3083. doi:10.1371/journal.pone.0003083

Palva S, Palva JM (2007) New vistas for alpha-frequency band oscillations. Trends Neurosci 30(4):150–158

Pascual-Marqui RD (2002) Standardized low resolution brain electromagnetic tomography (sLORETA): technical details. Methods Find Exp Clin Pharmacol 24(Suppl D):5–12

Pascual-Marqui RD (2009) Theory of the EEG inverse problem. In: Tong S, Thakor NV (eds) Quantitative EEG analysis: methods and clinical applications. Artech House, Boston, pp 121–140

Pascual-Marqui RD, Michel CM, Lehmann D (1994) Low resolution electromagnetic tomography: a new method for localizing electrical activity in the brain. Int J Psychophysiol 18(1):49–65

Pascual-Marqui RD, Lehmann D, Koenig T, Kochi K, Merlo MC, Hell D, Koukkou M (1999) Low resolution brain electromagnetic tomography (LORETA) functional imaging in acute, neuroleptic-naive, first-episode, productive schizophrenia. Psychiatry Res 90(3):169–179

Qin P, Northoff G (2011) How is our self related to midline regions and the default-mode network? Neuroimage 57(3):1221–1233. doi:10.1016/j.neuroimage.2011.05.028

Raffone A, Srinivasan N (2010) The exploration of meditation in the neuroscience of attention and consciousness. Cogn Process 11(1):1–7. doi:10.1007/s10339-009-0354-z

Raichle ME, MacLeod AM, Snyder AZ, Powers WJ, Gusnard DA, Shulman GL (2001) A default mode of brain function. Proc Natl Acad Sci USA 98(2):676–682

Ruchkin D (2005) EEG coherence. Int J Psychophysiol 57(2):83–85

Schürmann M, Başar-Eroglu C, Başar E (1997) A possible role of evoked alpha in primary sensory processing: common properties of cat intracranial recordings and human EEG and MEG. Int J Psychophysiol 26(1–3):149–170

Seghier ML, Fagan E, Price CJ (2010) Functional subdivisions in the left angular gyrus where the semantic system meets and diverges from the default network. J Neurosci 30(50):16809–16817. doi:10.1523/JNEUROSCI.3377-10.2010

Sestieri C, Corbetta M, Romani GL, Shulman GL (2011) Episodic memory retrieval, parietal cortex, and the default mode network: functional and topographic analyses. J Neurosci 31(12):4407–4420. doi:10.1523/JNEUROSCI.3335-10.2011

Shapiro SL, Walsh R (2003) An analysis of recent meditation research and suggestions for future directions. Humanistic Psychologist 31(2–3):86–114. doi:10.1080/08873267.2003.9986927

Takahashi T, Murata T, Hamada T, Omori M, Kosaka H, Kikuchi M, Yoshida H, Wada Y (2005) Changes in EEG and autonomic nervous activity during meditation and their association with personality traits. Int J Psychophysiol 55(2):199–207

Tebēcis AK (1975) A controlled study of the EEG during transcendental meditation: comparison with hypnosis. Folia Psychiatr Neurol Jpn 29(4):305–313

Tei S, Faber PL, Lehmann D, Tsujiuchi T, Kumano H, Pascual-Marqui RD, Gianotti LRR, Kochi K (2009) Meditators and non-meditators: EEG source imaging during resting. Brain Topogr 22:158–165. doi:10.1007/s10548-009-0107-4

Travis F, Arenander A (2006) Cross-sectional and longitudinal study of effects of transcendental meditation practice on interhemispheric frontal asymmetry and frontal coherence. Int J Neurosci 116(12):1519–1538

Travis F, Shear J (2010a) Focused attention, open monitoring and automatic self-transcending: Categories to organize meditations from Vedic, Buddhist and Chinese traditions. Conscious Cogn 19(4):1110–1118. doi:10.1016/j.concog.2010.01.007

Travis F, Shear J (2010b) Reply to Josipovic: duality and non-duality in meditation research. Conscious Cogn 19(4):1122–1123. doi:10.1016/j.concog.2010.04.003

Travis F, Haaga DA, Hagelin J, Tanner M, Arenander A, Nidich S, Gaylord-King C, Grosswald S, Rainforth M, Schneider RH (2010) A self-referential default brain state: patterns of coherence, power, and eLORETA sources during eyes-closed rest and Transcendental Meditation practice. Cogn Process 11(1):21–30. doi:10.1007/s10339-009-0343-2

Ungerleider LG, Mishkin M (1982) Two cortical visual systems. In: Ingle DJ, Goodale MA, Mansfield RJW (eds) Analysis of visual behavior. MIT Press, Boston, pp 549–586

Yamamoto S, Kitamura Y, Yamada N, Nakashima Y, Kuroda S (2006) Medial profrontal cortex and anterior cingulate cortex in the generation of alpha activity induced by transcendental meditation: a magnetoencephalographic study. Acta Med Okayama 60(1):51–58

Yu X, Fumoto M, Nakatani Y, Sekiyama T, Kikuchi H, Seki Y, Sato-Suzuki I, Arita H (2011) Activation of the anterior prefrontal cortex and serotonergic system is associated with improvements in mood and EEG changes induced by Zen meditation practice in novices. Int J Psychophysiol 80(2):103–111. doi:10.1016/j.ijpsycho.2011.02.004

Zhang J, Zhou R (2014) Individual differences in automatic emotion regulation affect the asymmetry of the LPP component. PLoS One 9(2):e88261. doi:10.1371/journal.pone.0088261