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Consciousness and Cognition xxx (2008) xxx–xxx
Consciousness and Cognition
www.elsevier.com/locate/concog

EEG paroxysmal gamma waves during Bhramari Pranayama: A yoga breathing technique

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Received 11 May 2007

Abstract

Here we report that a specific form of yoga can generate controlled high-frequency gamma waves. For the first time, paroxysmal gamma waves (PGW) were observed in eight subjects practicing a yoga technique of breathing control called Bhramari Pranayama (BhPr). To obtain new insights into the nature of the EEG during BhPr, we analyzed EEG signals using time-frequency representations (TFR), independent component analysis (ICA), and EEG tomography (LORETA). We found that the PGW consists of high-frequency biphasic ripples. This unusual activity is discussed in relation to previous reports on yoga and meditation. It is concluded this EEG activity is most probably non-epileptic, and that applying the same methodology to other meditation recordings might yield an improved understanding of the neurocorrelates of meditation.

Keywords: Electroencephalography; Meditation; Yoga; Epilepsy; Temporal lobe; Brain mapping; Signal processing; Gamma

1. Introduction

Meditation is a psychologically induced, altered state of consciousness (Vaitl et al., 2005), and its study provides insights into cognitive and emotional brain correlates of consciousness (e.g. Lou, Nowak, & Kjaer, 2005). Analysis of such correlates is crucial for contemporary investigations of consciousness (Zeman, 2005). However, despite almost 50 years of study, a comprehensive empirical and theoretical foundation for meditation is still only now just emerging, and studies of its clinical impact are required (Cahn & Polich, 2006). Meditation techniques such as transcendental meditation (e.g. Yamamoto, Kitamura, Yamada, Nakashima, & Kuroda, 2006); Zen or other Buddhist meditations (Lutz, Greischar, Rawlings, Ricard, & Davidson,

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doi:10.1016/j.concog.2008.01.004

2004); yoga type meditation practices such as pranayama,[1] dhyāna[2] or samadhi[3] (e.g. Yoga Nidra in Lou et al, 1999; or Lou et al., 2005); and shamanic trances (Oohashi et al., 2002), etc. These can be divided into those practices involving movements, like walking, dancing, and singing, and the "silent" meditation methods, which are usually practiced in a characteristic sitting position (Vaitl et al., 2005). This considerable diversity complicates the description of a uniform theory of meditation. Usually, most studies concerning meditation focus on transcendental meditation, because the technique is comparatively simple and hence easily reproducible.

BhPr is a pranayama technique, therefore a technique of breathing control. However, because of its hypnotic and repetitive aspect it is also very close to and to some degree overlapping with mantra repetition techniques. Finally, BhPr changes the breathing rhythm, with very long exhalations and short inhalations, which may have a physiological effect. BhPr practiced for 5 to 10 consecutive minutes induces subjective feelings of mind refreshment and blissfulness, and even sometimes a state close to dhyāna. Therefore, BhPr is a pranayama technique, but also a meditation technique.[4] Very few scientific studies on the effects of this technique have been done. It has been claimed that BhPr may reduce hormonal imbalance manifestation such as hypertension, anxiety, and abnormal blood pressure (Singh, 1995). It has also been said to have a calming effect, which was used in a program for substance dependence recovery (Nespor, 2000).

A dramatic increase of activity in the gamma band in association with meditation—visible in the raw EEG—was reported in a study using trained practitioners of meditation (Lutz et al., 2004). This activity has been hypothesized to be representative of epilepsy (Nicholson, 2006), but this interpretation has been rejected by other studies (St. Louis & Lansky, 2006).

Using high-density array EEG (Biosemi system, 128 electrodes) and video control, we investigated the EEG in eight subjects performing Bhramari Pranayama (BhPr) yoga meditation (one trained for a 4 month period, six trained for 1 month, and one beginner). All displayed a similar, high-frequency pattern during BhPr.

2. Methods

2.1. Bhramari Pranayama

Subjects used the BhPr yoga technique, which involves producing a vibrating sound while exhaling strictly through the nasal airways. The oral cavity was closed at the lips, the ear canals were closed by depressing the tragus with fingers, and the eyelids were closed. The generated sound may be described as emulating the buzzing of bumblebees, having a constant pitch. The index finger was placed onto the forehead along the eyebrows, middle fingers were placed at the base of the nose near the corners of the eyes, and the little fingers were placed along the nose such that they lay next to the nostrils. Elbows were raised horizontally. As subjects sat on a thin cushion on the floor of the experimental room, their legs were crossed at the knees with their ankles placed on top of their thighs. While performing BhPr, subjects concentrated on an imaginary point located between their eyebrows. This yoga technique is demanding: (a) the humming sound must come from the nose and should remain constant; (b) the leg posture requires flexibility in the hips; and (c) the shoulders tire quickly in this posture.

For this study, we recruited eight volunteer subjects (all male and right-handed) complying with the constraints of BhPr yoga (able to maintain the yoga posture and produce the humming sound):

1. Subject B_1 (beginner): never practiced BhPr before the recording session;

[1] Breath control technique.

[2] Dhyāna in Sanskrit or jhāna in Pāli refers to a type or aspect of meditation, when the mind attains the ability to sustain its attention without getting distracted.

[3] Samadhi is a Hindu and Buddhist term that describes a non-dualistic state of consciousness in which the consciousness of the experiencing subject becomes one with the experienced object, and in which the mind becomes still though the person remains conscious.

[4] We insist however on the fact the BhPr is a specific technique that should not be confused with other meditation techniques, such as, for instance, Zen meditation or transcendental meditation.

2. Subject I_1–I_6 (intermediate): practiced BhPr (two sessions per day) for 31–34 days before the recording session;
3. Subject E_1 (expert): practiced BhPr (two sessions per day) every day for 4 months before the recording session.

The Ethical Committee of Riken Brain Science Institute (BSI) in Wako-Shi, Japan, approved the project, and written informed consent was obtained from the subjects. The subjects had no history of neurological, psychiatric, (or) epileptic (diseases) or other severe diseases. All experiments were performed with the informed and explicit consent of each participant, in line with the code of Ethics of the World Medical Association (Declaration of Helsinki) and the standards established by the Riken BSI's Institutional Review Board.

2.2. EEG recording

Recordings were performed in an electrically shielded room. EEG was recorded with 128 active electrodes (Biosemi system) at a sampling frequency of 2048 Hz. Signals were analog bandpass filtered between 1 and 300 Hz, and notch filters were applied at 50 Hz and at every harmonic of 25 Hz to substantially remove any external noise related to line power frequencies.

Postural electromyographic (EMG) noise was monitored and controlled by recording EEG during false BhPr. In false BhPr, the subjects assumed the BhPr position, but did not produce the humming noise. Instead, they attempted to mimic the BhPr respiratory rhythm to reveal the potential effects of hypoventilation.[5] Respiratory patterns were controlled by recording respiration with a respiratory belt. In three intermediate subjects (I_2, I_4, and I_6),[6] we also recorded three EMG channels from the temporalis (forefront), masseter (cheek), and sternocleidomastoideus (SCM, neck) muscles.

BhPr was recorded in one or two consecutive sessions in which each subject performed approximately 20 breathing episodes. EEG was also recorded before and after BhPr in the resting/eyes-closed condition. Subjects were video monitored with a security camera. Trials consisted of an inhalation period and exhalation period (humming period).

2.3. Software programs

Signal analysis was performed using MATLAB®, EEGLAB (Delorme & Makeig, 2004), SigmaStat®, LORETA (Pascual-Marqui, 1999; Pascual-Marqui, Michel, & Lehmann, 1994), and ICALAB (Cichocki et al., online toolbox; Cichocki & Amari, 2003). MATLAB® was used for the wavelet transforms and preprocessing of signals. EEGLAB was used for topographic mapping, ICALAB for independent component analysis, and SigmaStat® for statistical tests. LORETA was used to compute EEG low-resolution tomography sources.

2.4. Signal processing

2.4.1. Independent component analysis

Let us consider the case of multiple EEG channel sampling of brain activity over time. If the signals from each channel form the rows of the data matrix D, then each column of D is a time point. The problem is to find the original brain sources, which were mixed in the EEG channels. This is a typical problem of blind source separation (BSS). Independent components analysis (ICA) is a valid solution to BSS in the context of EEG recordings (Makeig, Bell, Jung, & Sejnowski, 1996; Tang, Sutherland, & McKinney, 2005; Cichocki et al., 2005), and finds the unmixing square matrix W ($n = m =$ the number of channels) such that $W.D = C$ (Brown, Yamada, & Sejnowski, 2001). The rows of C are called "independent components" because they are forced to be as independent as possible and are the sources being searched. It was shown

[5] Imitating the posture of BhPr is not enough, because this technique alters the breathing rhythm (which may generate both EMG and hypoventilation).

[6] Because EMG reduces subject's concentration, only three subjects used it.

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in Delorme, Sejnowski, and Makeig (2007) that preprocessing EEG data using ICA allows effective artifact separation. The SOBI algorithm, in particular, is especially well suited for analysis of high-density EEG (Tang et al., 2005).

2.4.2. Spectral analysis

A digital FFT-based power spectrum analysis (Welch technique, Hanning windowing function, no phase shift) computed the power density of EEG rhythms with windows of 500 m sec. The resulting values were afterwards normalized into a relative power. We used fixed but narrow bands for the theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–80 Hz) ranges. The use of fixed frequency bands allowed a better comparison with previous literature, a more direct comprehension of results, and an enhancement of even slight differences.

2.4.3. Wavelets

There is a wide variety of wavelets. In the present study, complex Morlet wavelets (Kronland-Martinet, Morlet, & Grossmann, 1987) were used:

$$\Psi(k) = A.\exp\left(\frac{-k^2}{2\sigma_t^2}\right).\exp(2i\pi f_0 k),$$

where $\sigma_t{}^2$ and f_0 jointly determine the number of oscillations in the wavelet. In the present investigation, the wavelet family defined by $2\pi\ \sigma_t f = 7$ was chosen, as described in (Tallon-Baudry, Bertrand, Delpuech, & Pernier, 1996). Complex Morlet wavelets are appropriate for time–frequency analysis of electroencephalographic signals (Caplan, Madsen, Raghavachari, & Kahana, 2001; Düzel et al., 2003; Martin, Gervais, Hugues, Messaoudi, & Ravel, 2004; Ohara, Crone, Weiss, & Lenz, 2004; Tallon-Baudry & Bertrand, 1999; Tallon-Baudry et al., 1996). They produce a precise time–frequency representation for the analysis of EEG signals, because of their symmetric shape in both time and frequency. The (continuous) wavelet transform **W** of a time series **x** is obtained by:

$$\mathbf{W}(k,s) \triangleq \sum_l \mathbf{x}(\mathbf{l})\Psi^*\left(\frac{\mathbf{l}-\mathbf{k}}{\mathbf{s}}\right),$$

where $\psi(k)$ is the (complex) "mother"' wavelet and s is a scaling factor.

2.4.4. LORETA

We employed LORETA (Pascual-Marqui et al., 1994; Pascual-Marqui, 1999) to compute 3-D linear solutions (LORETA solutions) for the EEG inverse problem within a three-shell spherical head model including scalp, skull, and brain compartments. LORETA is presently used by independent laboratories worldwide for EEG source analysis. We used a two-step approach, combining LORETA and ICA (Marco-Pallarés, Grau, & Ruffini, 2005), which brings further information for identified specific EEG patterns. The brain compartment was restricted to the cortical gray matter/hippocampus and was coregistered into the Talairach probability brain atlas, digitized at the Brain Imaging Center of the Montreal Neurologic Institute (Talairach & Tournoux, 1988). This compartment included 2394 voxels (7-mm resolution), each voxel containing an equivalent current dipole. LORETA solutions consisted of voxel current density values able to model EEG spectral power density at scalp electrodes.

3. Results

3.1. Basic traits

We compared relative Fourier power before and after BhPr (Fig. 1). Low-frequency power was diminished, significantly for the theta range (4–8 Hz, $p < .05$) and non-significantly for the alpha range. We also analyzed the evolution of this effect as compared to the subject's training. No significant effect could be observed in relation to the training (Pearson R correlation test, $p >> .10$).

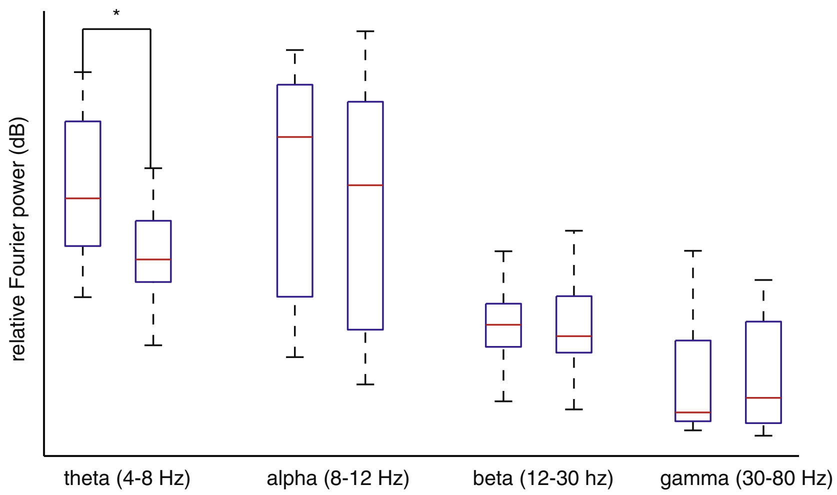

Fig. 1. Basic traits. Fourier relative power before and after BhPr (all subjects). Only theta range activity exhibited a significant effect.

3.2. Paroxysmal gamma wave

During the humming period, all subjects exhibited paroxysmal gamma waves (PGW). This activity was revealed by distinct high-frequency hyperphasic patterns, biphasic, and with a very spiky shape (close to a Dirac pulse, Fig. 2). The large amplitude voltage transients (peaks at +/- 10–30 μV) occurred at a sustained fast rhythm of approximately 10–30 spikes/sec.

For subject B_1, the high-frequency pattern was present only during BhPr (not during false BhPr). For other subjects, however, similar-looking patterns were observed outside of the BhPr condition as well, except that these patterns were usually less “spiky” (ripple shaped) and rhythmic than the patterns recorded during actual BhPr (Fig. 3). The rhythm generally increased by approximately twofold during BhPr: while the frequency of the post-BhPr rhythm was 11.8 ± 1 spikes/sec, the actual BhPr rhythm frequency was 21.5 ± 0.6 spikes/sec. For subjects B_1, I_2, I_4, and I_5 the onset latency of this activity was longer, 1.2 ± 0.1 sec after the start of exhalation, but tended to shorten with each trial (0.26 ± 0.16 sec after the start of exhalation for the last trials). For the other subjects, evaluating the onset was less reliable, since the activity was present during the inhalation as well as during exhalation periods.

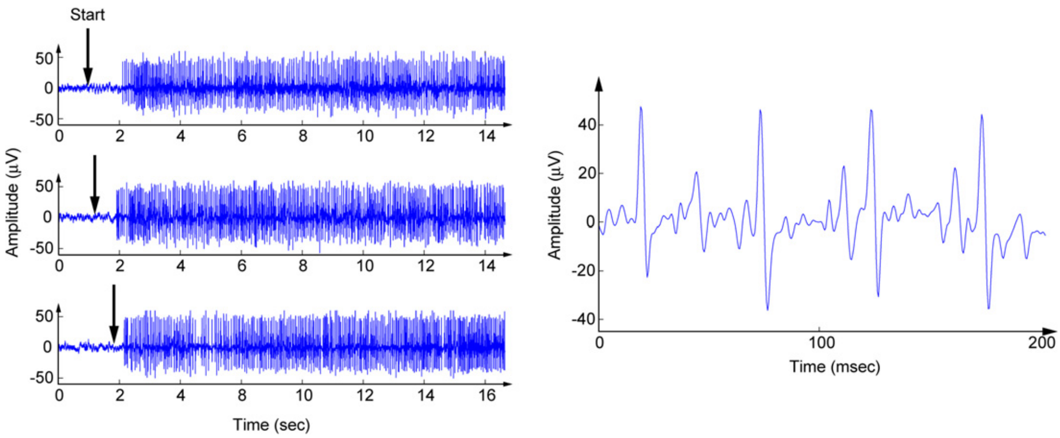

Fig. 2. Paroxysmal gamma wave. Left, raw EEG from three trials. Right, close-up of the hyperphasic activity. The fast voltage reversal is easily identified.

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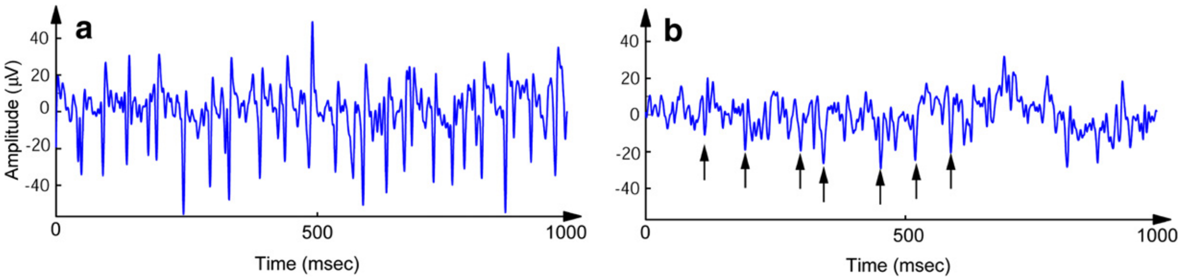

Fig. 3. Subject E_1. (a) Raw EEG *during* BhPr. (b) Raw EEG *after* BhPr. When ICA Is applied to these raw signals, it extracts a similar PGW shape, having a similar location (see Fig. 5), but with a less spiky and rhythmic pattern.

Using complex Morlet wavelets and Fourier spectrum procedures, we analyzed the spectral properties of the epileptiform period (Fig. 4). The Fourier spectrum was also computed, during inhalation and again separately during exhalation periods. In all subjects, after the start of exhalation, a dramatic increase in high frequencies was observed in the EEG. This increase was not observed during false BhPr. Only activity in the beta (15–35 Hz) and gamma (>35 Hz) ranges exhibited this paroxysmal increase.

Additionally, we applied ICA, which allowed us to identify statistically near-independent sources in the EEG (Cichocki et al., 2005, see Section 2.4.1). Using SOBI, we successfully identified one epileptiform source component during the BhPr trials for each subject (Fig. 5) that differed from EMG sources. For subject E1, and intermediate subjects, we also identified an epileptiform source component after BhPr (note that for subject I_6, EEG data was strongly corrupted by ECG noise, both during and after BhPr, so that the source extraction was less reliable). We could not reliably extract this component for subject B_1 after BhPr. For subjects I_5 and I_6, we found a bilateral distribution of the activity in both brain hemispheres, whereas for all other subjects the activity was located in only the left hemisphere.

Combined ICA-LORETA EEG tomography (Marco-Pallarés et al., 2005; Pascual-Marqui, 1999; Pascual-Marqui et al., 1994), with activity restricted to cortical gray matter, located the source of the PGW in the middle temporal gyrus, with overall temporal evolution constrained to the left temporal area (Fig. 6).

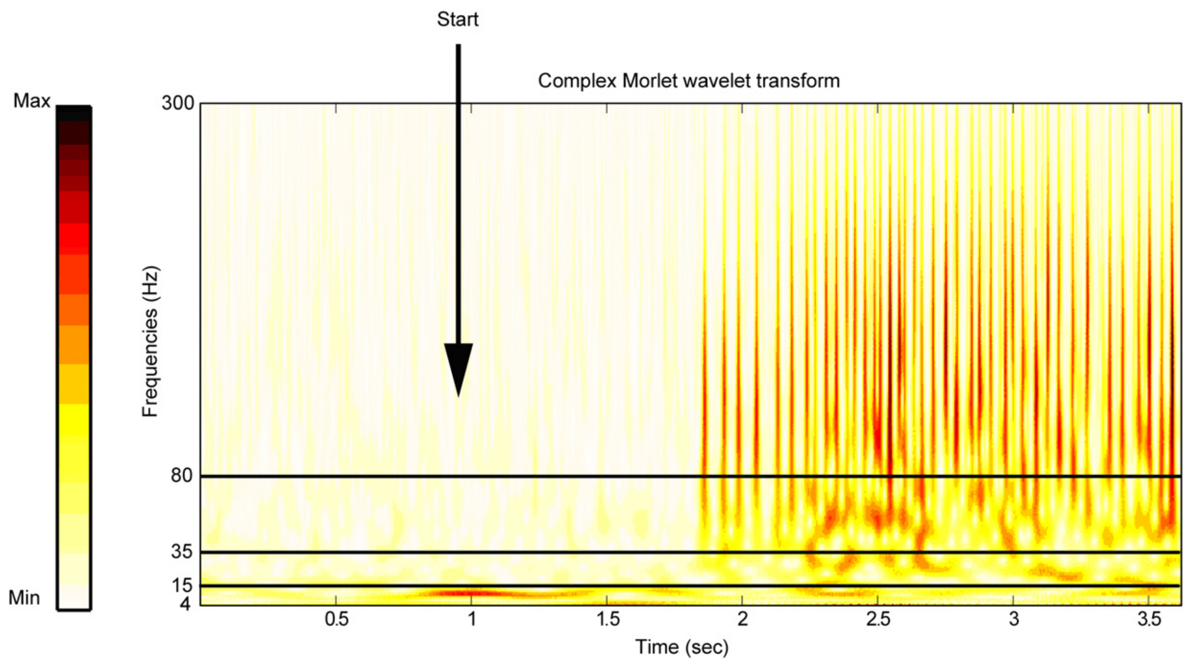

Fig. 4. Time–frequency representation of PGW activity (Morlet wavelet).

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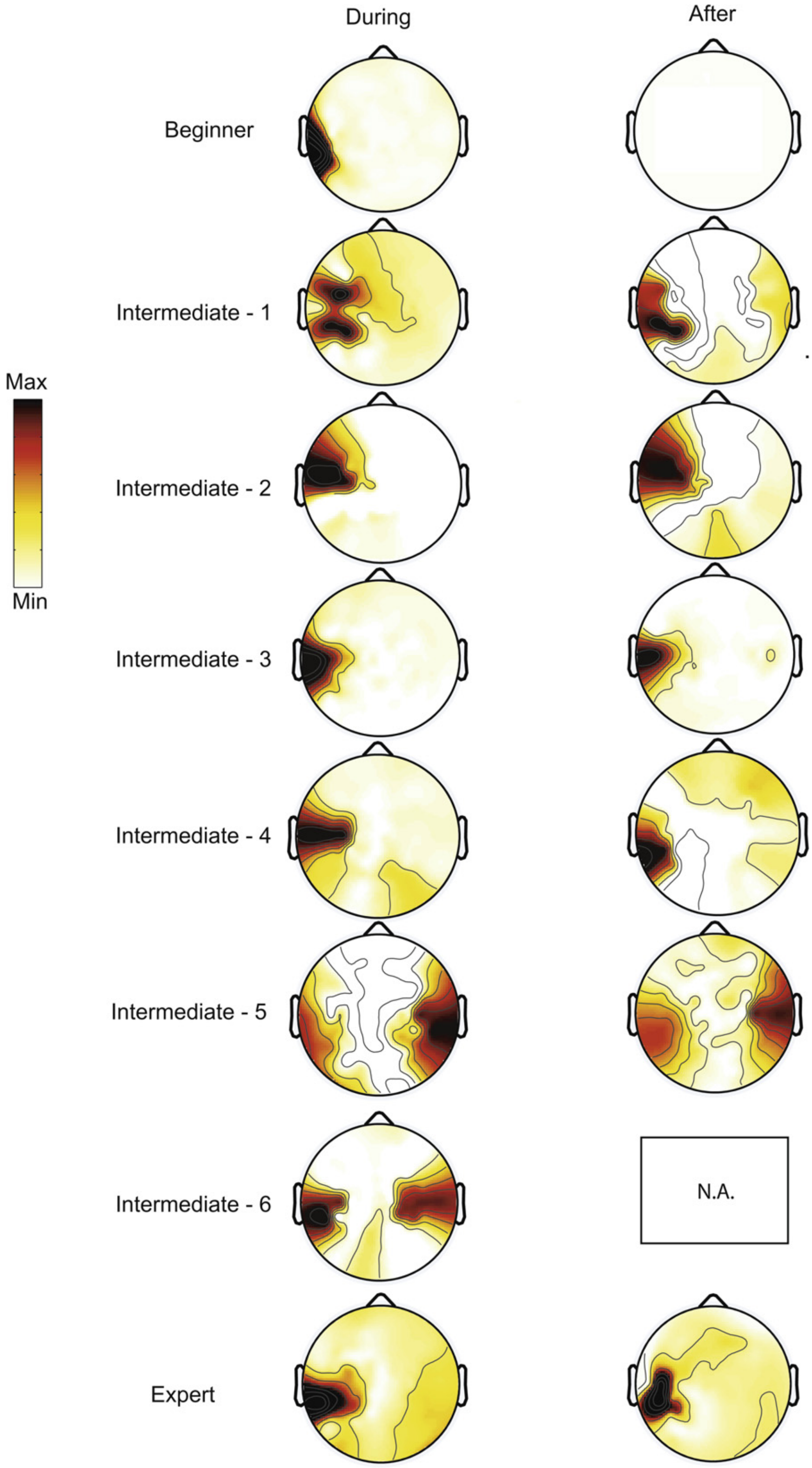

Fig. 5. ICA analysis of the epileptiform wave back-projected onto a scalp diagram. The component is located in the left temporo-parietal zone. For trained subjects (I_1–I_5 and E_1; I_6 was rejected due to highly noisy signals), the component remains after BhPr.

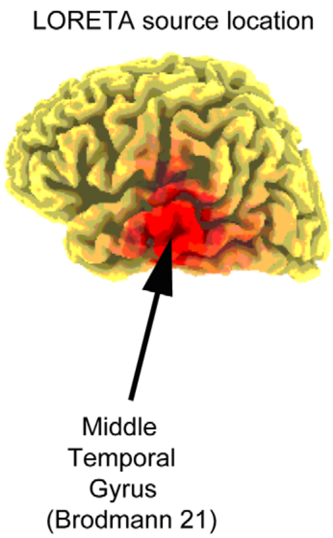

Fig. 6. LORETA tomography of the ICA source. The peak of this activity is located in the left middle temporal lobe (here, for E_1 after BhPr).

3.3. EMG rejection

We excluded the possibility that PGW came exclusively from EMG noise or artifacts, since we carefully analyzed and compared EMG and EEG data for different conditions (during, and after BhPr, and during false BhPr) and obtained consistent results. Moreover, the frequency of the large EEG oscillations did not overlap with that of the humming sound acoustic vibrations. BhPr is performed with a humming sound, which produces vibrations. These vibrations are not the cause of PGW, because these waves persist at least 2 min after humming (in the rest period).

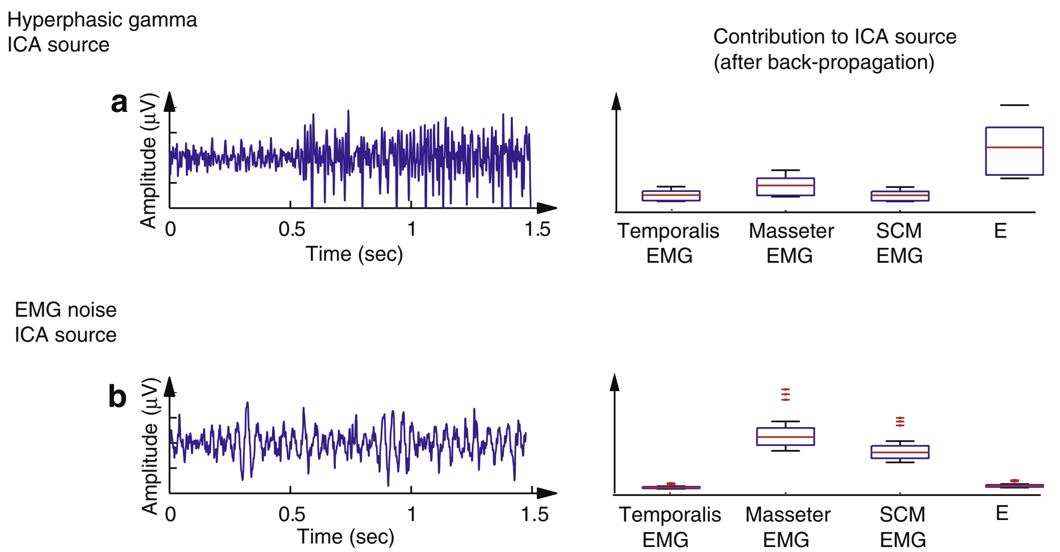

Fig. 7. Example of EMG rejection analysis. Source contributions to left-temporal EEG and EMG sensors are analyzed with a sliding window of 500 msec: top, a PGW source, with its contributions to EEG and EMG; bottom, EMG noise, with its contributions to EEG and EMG. It is quite simple to determine that the PGW origin cannot be attributed to EMG.

For the three subjects with EMG recordings (I2, I4, and I6), we applied additional control of the signals after BhPr and removed artifact periods prior to further analysis. Only the data from subject I6 could not be cleared of artifacts due to strong and continuous ECG noise corruption of the signal during and after BhPr.

During BhPr, the presence of EMG noise is to be expected due to the nature of the experimental task requiring muscle activity and to glossokinetic artifacts elicited by the humming sound. Our challenge under these conditions was to identify if the PGW originated from the brain. We computed the ICA sources using the SOBI algorithm, while including also the available EMG channels into the data matrix. After identification of the PGW source, the relative contribution of EEG and EMG to the source was computed. After this preprocessing, EMG noise originating from the muscles should have a higher EMG amplitude as compared to the EEG. For all three subjects, PGW were attributed to the EEG (Fig. 7).

4. Discussion

The basic trait we observed for BhPr is an increase theta range activity, which is similar to results obtained with other meditation techniques (Hebert & Lehmann, 1977; Aftanas & Golocheikine, 2001; Aftanas, Varlamov, Pavlov, Makhnev, & Reva, 2001; Vaitl et al., 2005). In these previous reports, the theta activity correlated with subjective reports of ‘‘blissful mental quiescence’’, described as a state in which thoughts are absent but consciousness remains. We cannot find comparisons of our results with previous reports specific to BhPr, as to the best of our knowledge no previous scientific investigation of this technique using EEG has been published.

We also reported a biphasic hypersynchronous activity, in the high gamma range. The three main possible interpretations of this PGW phenomenon are as follows:

1. *Epileptic activity*. We consider this interpretation to be very unlikely. Finding an EEG waveform with certain characteristics in common with epileptic EEG patterns does not necessarily link these patterns to epilepsy, any more than, for instance, finding symptoms of fever in a patient indicates a link to tuberculosis, even though fever accompanies tuberculosis. Since our subjects had no history whatsoever of neurological, psychiatric, or epileptic diseases, a link with epilepsy on such evidence is excessively speculative. Recently, a putative role for meditation practice in the generation of epileptic seizures has been hypothesized (see for instance Nicholson, 2006; Persinger, 1993; St. Louis & Lansky, 2006), which has since become a subject of controversy and scientific debate (e.g. Orme-Johnson, 2006). High-frequency epileptiform EEG has received experimental attention only recently (Fisher, Webber, Lesser, Arroyo, & Uematsu, 1992; Jirsch et al., 2006), most likely due to the poor representation and limited possibilities for reliable signal analysis in conventional scalp EEG for frequencies above the beta range. The BhPr activity we observed thus might represent epileptic activity. This interpretation would be consistent with the spike shape of the recorded signals (Figs. 2 and 3) and the temporal lobe location of the BhPr-associated activity (Figs. 5 and 6), both of which are similar in high-frequency epilepsy (Fisher et al., 1992; Jirsch et al., 2006), and musicogenic epilepsy (Brien & Murray, 1984). However, the isolated scalp location of the BhPr-associated activity did not propagate to other brain areas during or after BhPr, which is not consistent with epilepsy (as has been reported by St. Louis & Lansky, 2006, for other types of meditation). Furthermore, simultaneous video recording did not identify any epileptic behavior in either subject. Moreover, the subjects subjectively reported only a feeling of peacefulness. Finally, the EEG waveform remained temporally stable, without showing epileptiform activity in low-frequency ranges (<15 Hz). Therefore, while this activity resembles epileptic fast ripples, it is more likely to be a normal variant[7] and should not be interpreted as conventional epilepsy.
2. *Anti-epileptic activity*. Similar investigations (meditation on self-generated sound patterns) have shown a significant activation in the same left temporal lobe location (Lazar et al., 2000; Lehmann et al., 2001), but did not report any epileptic-like behavior. In population studies, meditation and yoga appeared not to induce but rather reduce epilepsy (Orme-Johnson, 2006; Yardi, 2001; Sathyaprabha et al., 2007), even

[7] Normal variant: epileptiform EEG not related to epilepsy (e.g., phantom spike waves, SREDA, wicket spikes).

in individuals with drug-resistant chronic epilepsy (Rajesh, Jayachandran, Mohandas, & Radhakrishnan, 2006). The ‘‘anti-epileptic’’ effect of yoga on epileptic seizures could be attributed to high-frequency hypersynchrony: it is well known that regular high-frequency stimulation in the limbic area reduces epilepsy (e.g. Lee et al., 2005). This activity may also ultimately produce high-frequency stimulation of the temporo-limbic system. Conceivably, we can infer that this type of high-frequency stimulation could then induce a Hebbian[8] process, which in turn would protect the temporo-limbic zone from low-frequency epileptogenic activity (e.g., typical absence seizures at 3 Hz). Nevertheless, however attractive this interpretation may be, it remains speculative, as no direct observation of such a process was made: only one recent study (Lazar et al., 2005) reported increase of cortical thickness in long-term meditationers, but unfortunately, on another type of meditation, and with a location inconsistent with the one in this study. Moreover, BhPr requires a nasal sound during exhalation, which is not common even among meditative breathing techniques, much less among most yoga or classical meditation techniques. Therefore, we remind the reader that despite the possibility that future work may indicate these results to be more generally applicable, the present investigation reports only results specific to the BhPr technique. These results may or may not be relevant to the question of whether other specific meditation techniques (which do not use any breathing technique, nor humming) may be protective against epilepsy.

3. *Hyperphasic-meditation wave.* It was already reported in a previous study that trained practitioners of Buddhist meditation (Lutz et al., 2004) display high-frequency gamma waves of unusually strong amplitude. We studied here a yoga meditation type and found a similar trait. It is logical then to infer that these activities might be of similar nature. There could be a link between these two different kinds of meditation, and therefore it could represent an interesting candidate for unifying traits of the different types of meditation. However, it is to be noted that the PGW signature identification method was developed here for the first time; and that before advancing such a theory, replication of this method on other type of meditation recordings should first be performed. Out of the three interpretive hypotheses provided here, this third one is the easiest to test, by applying similar methods of signal processing to other datasets in order to investigate PGW activity.

In summary, we consider the epileptiform-like waves measured during BhPr to be representative of non-epileptic hypersynchrony. One month of training appeared sufficient to allow this activity to remain stable several minutes after BhPr. The interpretation of how such an activity could influence the brain, and thereby induce a subjective feeling such as ‘‘bliss’’, is highly speculative.[9] In the absence of further information, we will therefore leave this as an open question.

Acknowledgments

We thank our collaborators from LABSP for helping in the experimental design and for constructive critical discussions. Pacific Edit reviewed the manuscript prior to the final submission.

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[8] The temporo-limbic system would become accustomed to self-produced gamma waves.

[9] For instance, a previous reductionist hypothesis (Persinger, 1983) tried to assimilate all religious and mystical experiences to temporal electrical microseizures in temporal areas, but this would be an extrapolation going too far from our observed facts.

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