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Brain sources of EEG gamma frequency during volitionally meditation-induced, altered states of consciousness, and experience of the self

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Abstract

Multichannel EEG of an advanced meditator was recorded during four different, repeated meditations. Locations of intracerebral source gravity centers as well as Low Resolution Electromagnetic Tomography (LORETA) functional images of the EEG 'gamma' (35–44 Hz) frequency band activity differed significantly between meditations. Thus, during volitionally self-initiated, altered states of consciousness that were associated with different subjective meditation states, different brain neuronal populations were active. The brain areas predominantly involved during the self-induced meditation states aiming at visualization (right posterior) and verbalization (left central) agreed with known brain functional neuroanatomy. The brain areas involved in the self-induced, meditational dissolution and reconstitution of the experience of the self (right fronto-temporal) are discussed in the context of neural substrates implicated in normal self-representation and reality testing, as well as in depersonalization disorders and detachment from self after brain lesions. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

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1. Introduction

The search for the neural correlates of consciousness is experiencing an unprecedented interest in the scientific community (see Atkinson et al., 2000, for a recent review). This search aims at identifying neural processes that characterize distinct states of consciousness (e.g. dream, hypnosis, wakefulness) or specific contents of consciousness. The content or state of consciousness can be altered by numerous external factors, such as chemical agents (drugs), but also by various forms of external information input, e.g. hypnotic suggestions (Isotani et al., 2001). On the other hand, there are many reports on changes of the state of consciousness as experienced subjectively that were caused by purely internal factors (Pardo et al., 1993; Fink et al., 1999; Kimbrell et al., 1999; Neuper et al., 1999). These changes reportedly can be achieved by self-induction, executing mental routines such as self-hypnosis, autogenic training or meditational exercises. The question arises whether these subjectively experienced differences are associated with measurable differences of brain activity.

A particular component of brain electric activity, the EEG '40-Hz' or 'gamma' frequency band, was described as a prominent characteristic of brain electric activity during meditation (Banquet, 1973). The 40-Hz frequency band has also been hypothesized to play an important role in the brain mechanisms of normal, conscious experience (the 'binding problem') as well as of consciousness in general (Gray et al., 1989; Kulli and Koch, 1991; Singer et al., 1997), after having been reported earlier in various orienting and problem-solving conditions in animal and man (Domino and Ueki, 1960; Bouyer et al., 1980; Spydell and Sheer, 1982). Specifically, gamma band activity has been proposed to act as a mechanism for visual representation of objects and for binding distinct aspects of object perception into a coherent and unitary concept (for review, see Tallon-Baudry and Bertrand, 1999).

We utilized an opportunity to study the brain electric activity of an experienced meditator in order to test whether subjectively different meditations, i.e. different altered states of consciousness, are associated with the activity of different neuronal ensembles that work at the 40-Hz-frequency band. Two independent space-oriented approaches were employed for the analysis of the 27-channel brain electric data: source gravity center localization in the frequency domain (Lehmann and Michel, 1990) and cortical distribution of the generator activity [Low Resolution Electromagnetic Tomography (LORETA), Pascual-Marqui et al., 1994, 1999]. The analyses yielded converging results, describing significantly different brain regions as active during the different meditations.

2. Methods

2.1. Subject, design and data acquisition

Multichannel EEG was recorded from a long-term, advanced meditator (59 years old) during five different meditations. The meditator is a Buddhist Lama, Ole Nydahl, of the Karma Kagyü lineage who teaches Diamond Way Buddhism at various centers. In the evening of July 29, 1999, after a workshop that O.N. held at Herzberg, Aarau, Switzerland, we recorded his EEG during the following five meditations that O.N. described as clearly different subjective experiences: During meditation #1, 'Buddha in front of me', and meditation #2, 'Buddha above', concentration was focused on a visualization of Buddha in front of (above) the meditator. During meditation #3, the verbalization of a 100-Syllables Mantra (Nydahl, 1990, p. 51), the meditator silently recited a sequence of words. During meditation #4, 'self-dissolution', the meditator concentrated on the experience of dissolution of the self into a boundless unity (emptiness). During meditation #5, 'self-reconstitution', the meditator concentrated on experiencing the reconstitution of the self.

Twenty-seven electrodes were placed according to the modified nomenclature of the American Electroencephalographic Society (1994) on the following scalp locations: Fp1/2, Fpz, F7/8, F3/4, Fz, FC1/2, T7/8, C3/4, Cz, CP1/2, P7/8, P3/4, Pz, PO3/4, O1/2, Oz. Additionally, the EOG was recorded in two channels from electrodes at the bilateral outer canthi vs. a site below the left eye, and the EMG in one channel (chin). The data were recorded continuously using a portable Nihon–Kohden Neurofile data acquisition system (dynamic range: 400 mV, 12-bit signal resolution), using a band pass of 0.3–75 Hz at 256 samples/s per channel.

In a large hall, O.N. sat, with his eyes half closed, on a cushion on the floor in 'lotus position' (a cross-legged sitting posture with feet on thighs, traditional for meditation), facing the wall at a distance of about 5 m, with the experimenters and equipment about 2 m behind him. After collecting other recordings not used in the present report, the five meditations as listed above were done in sequence, each meditation lasting for 2 min. After the end of every 2-min period, the experimenter asked O.N. to start the next meditation. A second identical sequence with the same five meditations and identical timing followed the first sequence without intermission.

Off-line, the EEG data were carefully reviewed on a computer display for eye, movement and muscle artifacts in order to identify the first 60 acceptable 1-s epochs of each meditation. The epochs were identified within the first 100 of the 120 s in all meditations except for the visualization meditation #2 and the self-reconstitution meditation: the visualization meditation #2 had no acceptable epochs during the first sequence and therefore was omitted; for self-reconstitution, only 40 (44 in the second sequence) acceptable epochs were found.

The number of epochs eventually available for analysis from the first sequence (in parentheses those from the second sequence) was: visualization meditation #1, $N = 60$ (N = 60); verbalization meditation, $N = 60$ ($N = 60$); self-dissolution meditation, $N = 60$ ($N = 60$); and self-reconstitution meditation, $N = 40$ ($N = 44$). Thus, a total of 444 epochs were entered into analysis.

2.2. Analysis 1, source gravity center locations

The three-dimensional locations of the gravity centers of brain electric activity (model dipole source locations in the frequency domain) of the 35–44 Hz 'gamma' frequency band were computed using FFT dipole approximation (Lehmann and Michel, 1990), consisting of single phase modeling and subsequent conventional, single source (dipole) modeling of the FFT results. The procedure produces for each frequency point (at 1-Hz resolution) and for each of the 444 analysis epochs the intracerebral location coordinates of the gravity center of activity on the anterior–posterior, left–right and inferior–superior brain axes of a standard head model. These location coordinates for each meditation were averaged across frequency points between 35 and 44 Hz.

The differences in gravity center locations between meditations were tested using a one-way fixed effects multivariate analysis of variance (MANOVA) (four meditations as levels of the independent variable) with the gravity center locations on the three head axes as dependent variables, followed by post-hoc Scheffé tests. For every cell, the locations of the gravity center for all available epochs were treated as multiple observations.

As all data epochs were obtained from the same individual, we assessed the degree of interdependence of the utilized measurements. The analysis showed that the assumption of independent measures was satisfactorily met: the mean autocorrelation of the location parameter values across the 12 value series (three brain axes × 4 meditations) was $r = 0.19$ (S.D. = 0.14) which explains less than 5% of the variance.

Results for the two sequences of meditations also were separately computed and compared using t-tests, to study the consistency of the differences.

2.3. Analysis 2, Low Resolution Electromagnetic Tomography (LORETA)

The three-dimensional distribution of the 35–44 Hz 'gamma' band generators was analyzed using Low Resolution Electromagnetic Tomography (LORETA) (Pascual-Marqui et al., 1994) in the version (Pascual-Marqui et al., 1999) that yields current density values of 2394 voxels (spatial resolution: 7 mm) in the cortical areas as defined by the digitized Talairach Human Brain Probability Atlas (Brain Imaging Centre, Montreal Neurologic Institute; MNI305). This LORETA version is available at (http://www.unizh.ch/keyinst/). In order to examine the spatial distributions while avoiding strength as a confounding factor, all 444-LORETA functional images of gamma activity were normalized to unit total power (sum of squared current densities over all voxels be equal to unity). These images were statistically tested for distribution differences during the four meditations, using voxel-by-voxel t-statistics with non-parametric correction for multiple testing (Holmes et al., 1996). LORETA activity for all available epochs was treated as multiple observations. The voxel locations of maximally significant differences were identified in terms of Brodmann areas in the Talairach atlas (Talairach and Tournoux, 1988) using the 'Talairach Daemon' that was developed by Lancaster et al. (1997).

3. Results

3.1. Analysis 1, source gravity center locations

The MANOVA showed a significant difference between meditations ($d.f. = 9{,}1066$; Wilks' Lambda $= 0.69$; Rao's $R = 19.28$; $P < 0.00001$).

The post-hoc tests for the differences between the locations of the source gravity centers during the different meditations showed the significant results illustrated in Fig. 1: the electric gravity center location during the visualizing meditation was more posterior and more inferior than during verbalization, self-dissolution and self-reconstitution; in addition, the localizations during the self-dissolution and self-reconstitution meditations were more inferior than during verbalization. On the other hand, the source gravity center location during the verbalization meditation was more to the left than during visualization, self-dissolution and self-reconstitution. In sum, the locations differed from each other significantly along at least one of the three dimensions in the comparisons between all meditations except for self-dissolution vs. self-reconstitution.

Comparison between the separate results of the first and the second meditation sequence: all 11 significant cases (as reported above) of the possible 18 differences between locations showed the same direction of difference during the two sequences of meditation. Five of the seven non-significant differences were of opposite direction in the two sequences, but none of these five cases that had directions opposing the mean effect reached significance in either sequence.

An independent, basic issue in EEG analysis concerning harmonics of frequency bands was examined with exploratory t-tests. The gamma frequency band, centered around 40 Hz, has about twice the frequency of the beta-2 band (centered around 20 Hz). The question is whether gamma has the same sources as beta-2. Using all 444 available data epochs in all four meditations, we tested the difference between the locations of the center of gravity of the gamma band (here: 35–44 Hz) and the beta-2 band (here: 19–21 Hz). The locations differed significantly on all three brain axes (paired t-tests, all three P-values $P < 0.001$), the gamma source being more anterior, right and inferior than the beta-2 source.

3.2. Analysis 2, Low Resolution Electromagnetic Tomography (LORETA)

All six statistical comparisons of the 35–44 Hz three-dimensional LORETA images between the four meditations reached significance at the single-voxel level when corrected for multiple testing ($P < 0.05$) as reported in Table 1. The results are illustrated in Fig. 2, which displays those brain slices that contained the maximal t-value of each comparison. Table 1 also lists the Brodmann areas and the anatomical structures of these voxels with maximal t-values. For a comprehensive survey of these results, the locations of the maximal t-values of all 12 images were entered into a translucent head and displayed in coronal and transverse views in Fig. 3. Locations concerning each meditation compared to the other three are connected by lines, outlining triangles of maximal difference. It is obvious that the triangles of the four meditations do not overlap, clearly describing a right posterior (inferior) area for the visualizing meditation, a left central (medial) area for the verbalizing meditation, and a right anterior (superior) area for the self-dissolution meditation.

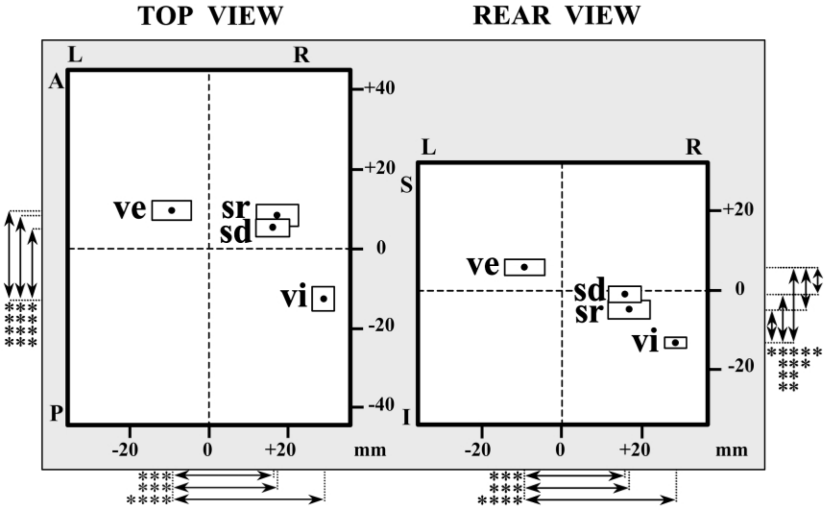

Fig. 1. Locations (dots) of the mean source gravity centers of the EEG gamma (35–44 Hz) frequency band activity during the four meditations (vi visualization, N 120, ve verbalization, N 120, sd self-dissolution, N 120, sr self-reconstitution, N 84) in translucent head views; the rectangles around the locations indicate the magnitudes of standard error. Arrows indicate significant differences in post-hoc Scheffé tests; double-ended P-values are marked: * < 0.05; ** < 0.01; *** < 0.001; **** < 0.0001. Left image: Axial view, head seen from above, nose up, left ear left (left(L)–right(R) vs. anterior(A)–posterior(P) head axes). Right image: Coronal view, head seen from the rear, left ear left (left(L)–right(R) vs. inferior(I)–superior(S) head axes). The values on the axes are distances in millimeters from the origin, i.e. from the midline location (0) at 10% above the zero level of the 'International 10/20 Electrode System'.

The self-reconstitution meditation showed stronger activity than the visualizing meditation near (but much superior) to the left central area of the verbalizing meditation, and stronger activity than the self-dissolution and self-reconstitution meditations near the right posterior and inferior area of the visualizing meditation, conceivably because it involved linguistic as well as visual components.

4. Discussion

Our study found different brain-neuronal populations active in the EEG gamma ('40 Hz') frequency band during the four analyzed meditations that the subject described as clearly different subjective states. Thus, the mediator's verbal definitions of these different meditations are not social conventions in order to label sections of a meditation sequence that are basically similar; they obviously refer to clearly different, physiological brain states. Two of the spatial patterns of activation associated with the phenomenologically distinct, volitionally induced meditative states were consistent with known functional anatomy (visualization, verbalization), and two others (during dissolution and reconstitution of the self) describe novel data. The present results confirm a key role of brain electric activity of the gamma frequency band in the mechanisms implementing states of consciousness (see Introduction), and more specifically, they emphasize that gamma activity may reflect a 'focused arousal' in task-relevant neural circuitries (cf. Spydell and Sheer, 1982). This conclusion is in line with the assumption that rhythmic synchronization of neuronal discharges may act as a link between and within areas involved in a given network (for review, Tallon-Baudry and Bertrand, 1999). Although higher brain functions in general involve extended and distributed neuronal networks, they show clearly organized topographical, spatial patterns (Mesulam, 1990). Our results add to a growing body of evidence suggesting that altered

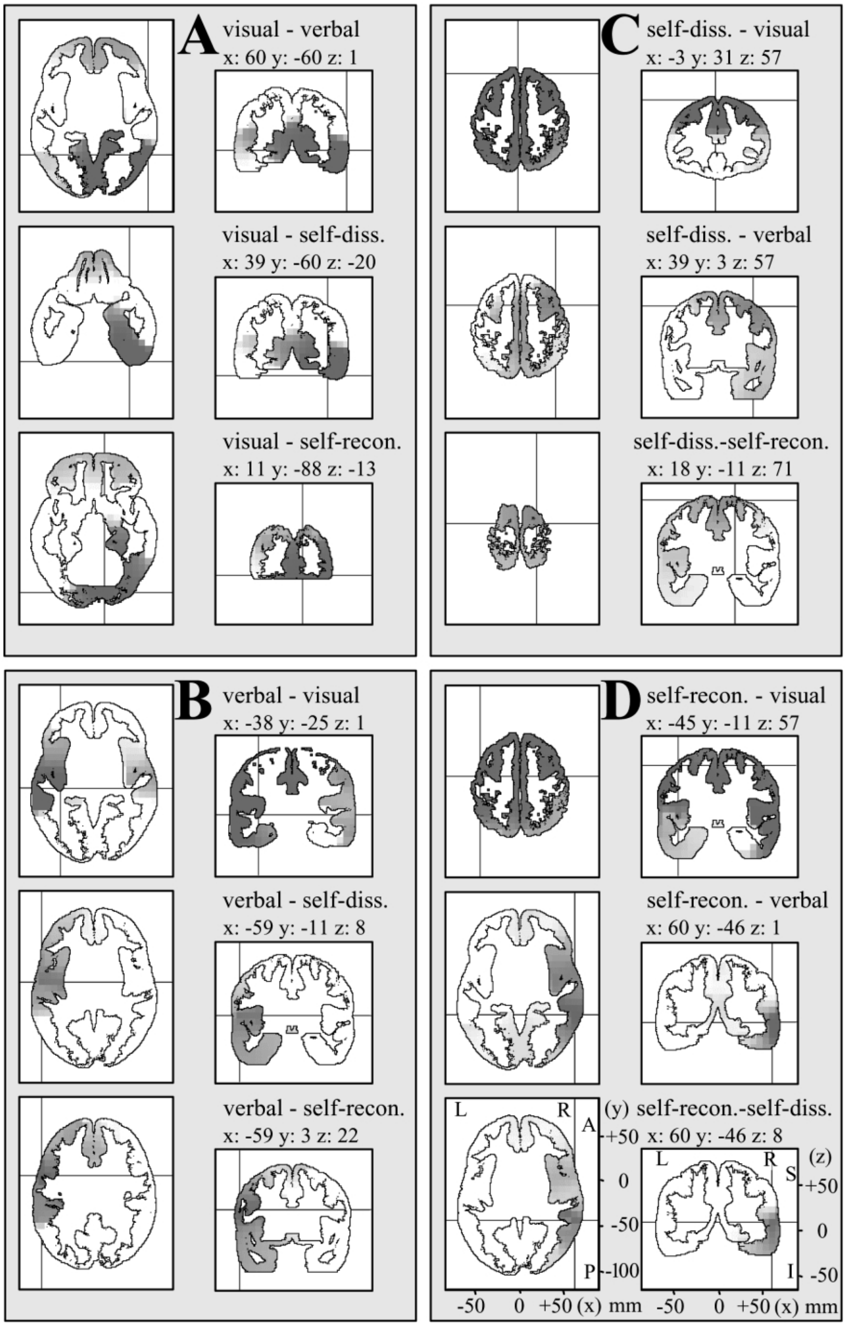

Fig. 2. LORETA *t*-test images. Each panel shows in coronal (left) and transverse (right) views (L-left; R-right) the three brain slices that contained the maximal *t*-values (see Table 1) when testing the LORETA results during the visualization meditation ('visual', panel A), the verbalization meditation ('verbal', panel B), the self-dissolution meditation ('self-diss.', panel C) and the self-reconstitution meditation ('self-recon.', panel D) vs. the other three meditations. Higher *t*-values-darker grey; hairline crossings aimed at maximal *t*-value in each panel. The Talairach coordinates of the slices are listed in millimeters.

Table 1
Statistical comparisons between the 35–44 Hz LORETA functional images during the four meditations: voxels with maximal *t*-values

Compared meditations	Corrected $P < 0.05$ threshold[a]	*t*-value[a]	Brodmann area and anatomical structure[b]	Side[b]	Talairach[b]		
					x	y	z
(A) Visualization							
vs. verbalization	3.12	14.19	21; middle temporal gyrus	R	60	−60	1
vs. self-dissolution	3.12	12.73	37; fusiform gyrus	R	39	−60	−20
vs. self-reconstitution	3.11	10.57	18; lingual gyrus	R	11	−88	−13
(B) Verbalization							
vs. visualization	3.12	24.40	13; insula	L	−38	−25	1
vs. self-dissolution	3.16	7.50	22; superior temporal gyrus	L	−59	−11	8
vs. self-reconstitution	3.21	12.88	6; precentral gyrus	L	−59	3	22
(C) Self-dissolution							
Vs verbalization	3.12	14.83	6; superior frontal gyrus	(M)	−3	31	57
Vs. verbalization	3.16	6.38	6; middle frontal gyrus	R	39	3	57
vs. self-reconstitution	3.20	5.91	6; superior frontal gyrus	R	18	−11	71
(D) Self-reconstitution							
vs. visualization	3.11	11.18	4; precentral gyrus	L	−45	−11	57
vs. verbalization	3.21	11.25	21; middle temporal gyrus	R	60	−46	1
vs. self-dissolution	3.20	8.43	21; middle temporal gyrus	R	60	−46	8

[a] $P < 5\%$ *t*-value thresholds corrected after Holmes et al. (1996) and maximal observed *t*-values.

[b] Locations give Brodmann area, brain structure, side [Right, (Midline), Left] and Talairach coordinates in mm (x − from left to right; y − from posterior to anterior and z − from inferior to superior; see also Fig. 2), answering the question at which voxel the largest strength difference was found (e.g, ‘visualization vs. verbalization’ means: where was the activity during the visualizing meditation maximally stronger than during the verbalizing meditation?).

states of consciousness are associated with different patterns of brain activation depending on the content of consciousness. Recent PET studies have started elucidating the neural substrates associated with meditative and hypnotic states (Lou et al., 1999; Maquet et al., 1999; Rainville et al., 1999; Kosslyn et al., 2000). For instance, meditative states characterized by detached attention (loss of conscious control and enhancement of sensory quality) but focusing on different contents-elicited content-specific activation (body sensations: parietal and superior frontal activation; visual imagery: occipital and parietal activation; Lou et al., 1999).

The different meditations were consciously self-induced, volitionally generated by the subject without systematic input of external origin. The visualizing and verbalizing meditations with their

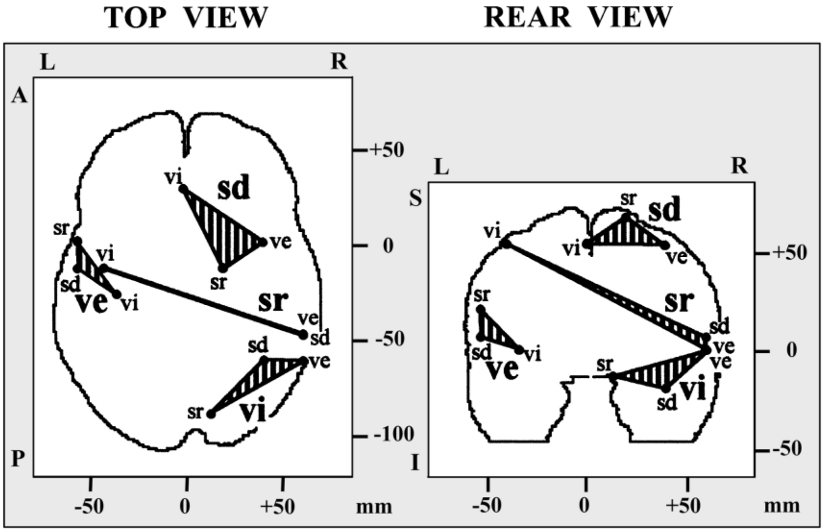

Fig. 3. Locations of maximal t-values extracted from the LORETA t-test images in Fig. 2. The locations of the maximal values were embedded into a translucent head and are shown in coronal (left) and transverse (right) views as in Fig. 2 (L-left; R-right; A − anterior; P − posterior; I − inferior; and S − superior). Meditations: vi − visualization; ve − verbalization; sd − self-dissolution; and sr − self-reconstitution.

clearly different right posterior and left central gamma sources might well reflect mechanisms of imagery of visual and linguistic nature, respectively. On the other hand, the two meditations which concerned the experience of the self are not obviously related to perceptual (or motoric) modalities, while their EEG gamma band source localizations differed from each other and from the visualizing and verbalizing meditations.

In terms of content or modality, the visualizing meditation ('Buddha in front of me') clearly involves visual imagery. Within the conceptual framework of EEG gamma band activity playing a crucial role in the execution of consciousness- or attention-associated functions, our localization findings support visual imagery functions. The gravity center, as well as the maximal LORETA differences of the EEG gamma band activity during this meditation, was more posterior and more to the right compared with the other three meditations that appeared to involve lesser degrees of visualization. The observation is in agreement with other reports that indicated right posterior activation as brain substrate of spontaneous visual imagery (Lehmann et al., 1998, as opposed to task-executing imagery — for review see Kosslyn et al., 1995). In general, early visual areas (Kosslyn et al., 1999) have been found to be activated during visual imagery. Furthermore, ventral occipital lobe activation has been reported during content-specific (faces, colors, objects) visual imagery or hallucination that reflected the functional specialization of this brain region (ffytche et al., 1998; Howard et al., 1998; O'Craven and Kanwisher, 2000).

The 100-syllable mantra obviously involves linguistic, verbalizing, possibly auditory activity. In agreement with the generally known left-sided, anterior and temporal brain functional topography of active language functions (for review, Cabeza and Nyberg, 2000), the gamma band gravity center and the maximal LORETA differences during this meditation were more to the left than in the other three meditations, and more anterior than in the visualizing meditation. The cognitive modes of these meditations that involved mental visualization and verbalization patently are not unusual in everyday life.

On the other hand, experiences of dissolution and reconstitution of the self do not occur commonly in normal, awake conditions, even though they are occasionally observed in normal hypnagogic hallucinations. Our findings appear especially important for neuropsychiatric research, because disturbances of the concept of self, its boundaries and definitions, are a basic feature in psychoses and in disorders associated with depersonalization and derealization. The brain activities during the meditations concerning self-dissolution and self-reconstitution were separated by different locations of maximal gamma band activity in the LORETA analysis although they overlapped in the gravity center analysis. We note that during the discussion of the planned experimental procedure, the meditator had stated that these two meditations actually formed a whole, as the latter would naturally emerge from the former, and that they could not be reversed in sequence. Nevertheless, they were experienced as subjectively different, and indeed were separated in the LORETA results. Compared with the other two meditations, their gamma band gravity centers were more on the right than for the verbalizing 100-syllable mantra meditation and more anterior than for the visualizing meditation. The more right-sided gravity center of the conceivably non-visualizing experiences may be related to the putatively more holistic nature of processing in the right hemisphere (Galin and Ornstein, 1972). LORETA clarified that the self-dissolution meditation maximally activated more superior and anterior regions (predominantly on the right in the superior frontal gyrus) than the self-reconstitution meditation. Involvement of the right prefrontal cortex in the meditative state of self-dissolution is intriguing in light of recent evidence from functional neuroimaging and human lesion studies indicating an important role of this region in self-consciousness (see also Vogeley et al., 1999). Right prefrontal activation has been reported during tasks involving self-recognition, autobiographical retrieval and self-evaluation (Fink et al., 1996; Craik et al., 1999; for review, see Keenan et al., 2000). Also, lesions to the right fronto-temporal cortex led in some cases to the experience of cognitive detachment from self (for review, see Wheeler et al., 1997), cannabinol-induced depersonalization has been found to be associated with right anterior frontal activation (Mathew et al., 1999; Sierra and Berrios, 1998), and comparable results have been reported in psychiatric depersonalization experiences and passivity phenomena (delusion of alien control, detachment, 'non-belongingness'; Cutting, 1989; Spence et al., 1997). The present result of preponderant predominantly right-sided anterior activation during a voluntarily altered state of consciousness characterized by dissolution of the self also brings to mind the observed right-sided prefrontal activation during conflict between intended self-generated movement and sensory information (Fink et al., 1999) and the assumed role of the right frontal region in reality testing (Knight and Grabowecky, 1995; Rainville et al., 1999). Compared with self-dissolution, the self-reconstitution meditation had a more posterior localization; it might have involved more of the body schema functions that are typically ascribed to right parietal areas (Cassady et al., 1998).

The relations between our volitionally induced dissolution and reconstitution of the experience of the self on one side, and pathological phenomena on the other side, are currently unclear, but it is intriguing that subjects with depersonalization disorders, who typically experience an altered familiarity of the self and the environment, showed decreased metabolic activity in right middle and superior temporal cortices (Brodmann areas 21 and 22; Simeon et al., 2000).

The question arises whether the 35–44 Hz gamma band activity might conceivably be a technical harmonic of 18–21 Hz beta-2 band activity, thus generated by the same neural population. When testing this hypothesis, we found the gamma source gravity center significantly more anterior, more right and more inferior than that of beta-2. Thus, the neural source populations involved in the production of gamma and beta-2 activity were different.

The present single-case study reports the activation of different neuronal assemblies during different meditations; it did not address the putative general differences between non-meditation and meditation states that were the topic of several articles (Banquet, 1973; Hebert and Lehmann, 1977; Lou et al., 1999). Further studies will have to determine whether the differences between meditation modes that were found in our single subject are comparable over subjects that use the same meditations.

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