

# A $^{15}\text{O}\text{-H}_2\text{O}$ PET Study of Meditation and the Resting State of Normal Consciousness

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**Abstract:** The aim of the present study was to examine whether the neural structures subserving meditation can be reproducibly measured, and, if so, whether they are different from those supporting the resting state of normal consciousness. Cerebral blood flow distribution was investigated with the  $^{15}\text{O}\text{-H}_2\text{O}$  PET technique in nine young adults, who were highly experienced yoga teachers, during the relaxation meditation (Yoga Nidra), and during the resting state of normal consciousness. In addition, global CBF was measured in two of the subjects. Spectral EEG analysis was performed throughout the investigations. In meditation, differential activity was seen, with the noticeable exception of V1, in the posterior sensory and associative cortices known to participate in imagery tasks. In the resting state of normal consciousness (compared with meditation as a baseline), differential activity was found in dorso-lateral and orbital frontal cortex, anterior cingulate gyri, left temporal gyri, left inferior parietal lobule, striatal and thalamic regions, pons and cerebellar vermis and hemispheres, structures thought to support an executive attentional network. The mean global flow remained unchanged for both subjects throughout the investigation ( $39 \pm 5$  and  $38 \pm 4$  ml/100 g/min, uncorrected for partial volume effects). It is concluded that the  $\text{H}_2^{15}\text{O}$  PET method may measure CBF distribution in the meditative state as well as during the resting state of normal consciousness, and that characteristic patterns of neural activity support each state. These findings enhance our understanding of the neural basis of different aspects of consciousness. *Hum. Brain Mapping 7:98–105, 1999.* © 1999 Wiley-Liss, Inc.

**Key words:** meditation; imagery; frontal-subcortical loops; cingulate gyrus; striatum; caudate nucleus; cerebellum; occipital cortex; V1; attention; awareness; consciousness



## INTRODUCTION

Regional neural mechanisms supporting meditation have not previously been investigated. The aim of the present work was to examine whether this can be done reproducibly with the  $^{15}\text{O}\text{-H}_2\text{O}$  PET method, and if so,

whether the neural activity of meditation differs from the resting state of normal consciousness. If this is the case the data might contribute to the understanding of the neural mechanisms of consciousness. There are two major aspects of consciousness [Flanagan, 1991] which seem complementary: consciousness of our sensory world, and the equally important consciousness of action, or the fact or illusion of voluntary control. Yoga Nidra is a meditative state in the Yoga tradition where these aspects are dissociated: the mind “withdraws” from wishing to act, it is not associated

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with emotions, nor the power of will. The meditator becomes a neutral observer. He experiences the loss of conscious control and an enhancement of sensory quality [Janakanda, 1992; Ballantyne and Deva, 1990]. These experiences seem to be common to a number of meditation techniques. In a factor analysis on the subjective accounts of 940 persons performing a variety of relaxation techniques, Smith et al. [1990] concluded that meditation, within or outside the Yoga concept, was characterized by a “profound willingness to let go of personal goals and concerns, and an intense absorption of attention” to the sensory world. A related dissociation is in psychoanalysis as noted by Epstein [1988]: “Thus Freud proposed an optimal attentional stance or state of mind characterized by two fundamental properties: the absence of critical judgement or deliberate attempts to select, concentrate, or understand; and an even, equal and impartial attention to all that occurs in the field of awareness.”

In the present study we compare the global and regional CBF to the spectral analysis of EEG, and relate these to the subjective experience during the resting state of normal consciousness and the Yoga Nidra relaxation meditation. Thus the activity patterns of consciousness for action and consciousness of our sensory world may be separated in order to obtain information on the neural pattern meditating these two main aspects of consciousness.

## SUBJECT GROUP AND METHODS

The present study, reported preliminarily in abstract form [Kjaer et al., 1997], involved nine normal, yoga practitioners. Three were females, and the age range was 23–41 years. Each had more than 5 years of experience with Kria Yoga, Yoga Nidra, and other Yoga techniques. The study was approved by the local Ethical Committee and informed consent obtained for each participant.

### PET scanning and CBF recording

PET scans were carried out on an Advance PET scanner (GE, Milwaukee, WI) operating in 3D mode with collimating septa retracted, producing 35 image slices with a distance of 4.25 mm. The total axial field of view was 15 cm with an approximate in-plane resolution of 5 mm [DeGrado et al., 1994]. Each subject was exposed to an initial 10 min transmission scan followed by eight intravenous injections of 200 MBq  $^{15}\text{O-H}_2\text{O}$  (or 300 MBq—see below), two during the normal resting state, two during the normal state with

auditory stimulation, and four during meditation, induced and maintained by similar auditory stimulation. The tracer was administered by an Automatic Water Injection System (AWIS) via the left brachial vein over 30 sec followed by 10 ml of isotonic saline for flushing. Data acquisition was triggered by total count rate build up and began approximately 40 sec after start of the AWIS and lasting for 90 sec. Between repeated emission scans there was an interval of at least 10 min to allow for isotope decay.

In two subjects global CBF was quantified. Arterial input curves were drawn at a flow rate of 8 ml/min and continuously sampled each second. These two subjects received 300 MBq tracer and the data acquisition periods were split in two 45 sec frames. Quantitative flow images ( $n = 2$ ) were calculated using the autoradiographic rCBF tool delivered with the scanner software. The algorithm corrects the arterial input curve for delay and dispersion by fitting it to a whole-FOV coincidence-counts curve recorded at 1 sec intervals [Meyer, 1989]. Afterwards flow images are calculated using a lookup-table which is generated from the first frame only. Then, whole-cerebrum regions of interest were drawn and analyzed. For regional statistical analysis, the two frames were averaged to reflect the count distribution over 90 sec.

For detection of activated areas, the datasets were transformed to a standard stereotactic three dimensional space as defined by Talairach and Tournoux [1988]. The spatially normalized images were smoothed with an isotropic Gaussian filter (FWHM 13 mm). Foci of activated areas were assessed voxel-by-voxel by calculating Z-scores with the appropriate contrasts between scan conditions. The omnibus significance threshold was  $P < 0.001$  ( $Z > 3.09$ ) comparing the expected and observed number of pixels above the threshold [Friston et al., 1991]. Changes are reported in Z-scores (number of standard deviations) after transforming the statistical maps to the unit Gaussian distribution. The cerebral structures were identified by their Talairach coordinates. During the PET examination, the eyes were covered with pads to prevent visual stimulation and to minimize eye movement. The examination room was quiet, with subdued light. Earphones were plugged into both ears.

### Meditation and EEG

The subjects practiced an intense form of concentration meditation (Tantric Kriya Yoga) for 2 hr before arriving at the PET center. Kriya Yoga is experienced as an exercise which detaches the mind from thoughts and preoccupations of daily life and makes the mind

more susceptible to relaxation meditation [Janakanda, 1992; Ballantyne and Deva, 1990]. This general experience was shared by the subjects in the present study who testified that initial Kriya Yoga greatly facilitated subsequent relaxation meditation (Yoga Nidra). At the time of onset of the first measurement, the subjects were awake and no longer in meditation, but ready for a subsequent meditation session with detached attention. Relaxation meditation (Yoga Nidra) was performed by running a tape for 45 min with a voice inducing relaxation meditation through different stages. The subjects were familiar with and trained in responding to this particular tape by relaxation meditation. For each subject EEG was continuously monitored in a 10–20 montage (Cadwell spectrum 32) with spectral analysis of 16 channels. Eight PET examinations were carried out in the following sequence of conditions:

- 1) In the normal conscious state before Yoga Nidra, without sensory stimulation (Silent control I).
- 2) Six minutes after initiation of Yoga Nidra: Verbal guidance to the experience of the weight of individual body parts.
- 3) Sixteen minutes: Verbal guidance to the experience of joy and happiness in abstract form (i.e., not related to external events or facts).
- 4) Twenty-six minutes: Verbal guidance to the visual imagination of a summer landscape with forests, streams, and meadows with cattle.
- 5) Thirty-eight minutes: Verbal guidance to the abstract perception of the self: symbolized with a golden egg.
- 6) Fifteen minutes after end of tape and cessation of meditation (Silent control II).
- 7) Twenty-five minutes after cessation of meditation: Listening to the beginning of the tape, with the same voice and the same monotonous prosody giving factual instructions on the meditation to follow and to avoid motor behavior: “Rest, make sure you are comfortable and the phone plug is out” etc. (Auditory control I).
- 8) Thirty-five minutes after end of meditation: As 7 (Auditory control II).

The sequence of measurements was not counterbalanced, as it was decided to begin with a resting flow measurement without verbal stimulation to minimize the risk of inducing meditation prematurely. The silent controls flanked the meditation sequence, and each of the four control measurements was compared with the combined measurements of meditation to test for any order effect.

## RESULTS

### Subjective experience

After termination of the PET measurements, the subjects confirmed that the control situations had been experienced as normal, alert resting states without meditation. They had been listening to the tape with factual instructions in a state of normal conscious control of behavior. They also stated that the meditation sequence had been satisfactory, with the experience of reduced conscious control of attention and behavior, relaxation, and “loss of will,” and, on the other hand, an intense sensory experience. They had been passively following the instructions on tape as they were used to. The present study thus involved two subjectively distinct states of consciousness.

### EEG

Also objectively, documented by the EEG measurements, the two states were clearly different as the theta band (4–8 Hz) had increased power ( $\mu\text{V}^2/\text{sec}$ ) in all derivations ( $P < 0.03$ ) by a mean of 11%, in accordance with the subjective experience of reduced control [Stigsby et al., 1981]. In addition, the meditative state was distinctly different from light sleep (stage 1), as the alpha band (8–12 Hz) was essentially identical with the alpha band in normal consciousness (an insignificant decrease of 2%, compared to >50% decrease in stage 1 sleep) [Rechtschaffen and Kales, 1968].

### CBF

Global CBF, uncorrected for the ventricular system and partial volume effects, remained unchanged throughout the experiment for both subjects ( $39 \pm 5$  ml and  $38 \pm 4$  ml/100 g/min). Regional activity supporting meditation was identified by subtracting the pattern of the resting state of normal consciousness with verbal stimulation (mean of two measurements) from each of the four measurements of meditation with different contents (Table I, Fig. 1), and from these four measurements in combination (Table II, Fig. 2). As expected, the activity pattern of meditation differed according to the meditative content. Meditation on sensations of weight of limbs and other body parts, presumably related to “motor attention” (i.e., the supplementary motor area) [Martin et al., 1996], was supported mainly by parietal and superior frontal activity; abstract sensation of joy by left hemisphere parietal and superior temporal (Wernicke area) activity; and visual imagery by strong activation of the

TABLE I. Meditative stages vs. normal consciousness, with auditory stimulation

	Talairach coordinates (maxima of significant differences of flow distribution for each region)			Z score
	x	y	z	
<b>Bodily sensations</b>				
Postcentr. gyrus	-38	-32	40	5.53
Sup. front. gyrus	4	-16	68	4.85
Parahippoc. gyrus	-32	-26	-28	4.93
Sup. par. lobule	-16	-70	36	3.76
	32	-54	60	4.12
Cingulate gyrus	14	-8	40	3.97
Inf. occ. gyrus	-28	-98	4	3.87
Inf. front. gyrus	36	36	-16	3.61
Sup. occ. gyrus	20	-84	22	3.52
Ling. gyrus	-4	-84	-2	3.46
	22	-94	-16	3.39
<b>Abstract sense of joy</b>				
Parahippoc. gyrus	-32	-26	-26	4.62
	34	-26	-30	4.78
Postcentr. gyrus	-18	-34	62	4.65
	6	-14	60	4.06
M. temp./m. occ. gyrus	22	-56	18	4.63
Inf. front. gyrus	-48	18	-8	3.84
Sup. temp. gyrus	-48	-12	12	3.73
Inf. temp. gyrus	-58	-70	-58	3.77
Sup. occ. gyrus	6	-94	32	3.80
<b>Visual imagery of landscape</b>				
Parahippoc. gyrus	18	-56	-8	4.97
	-32	-22	-24	4.69
Postcentr. gyrus	-6	-24	62	4.45
	40	-30	52	3.79
Occ. inf. gyrus	-28	-96	-6	4.92
	38	-96	4	4.65
Fusiform gyrus	32	-26	-32	4.14
<b>Symbolic representation of the self</b>				
Par. inf. lobule	-46	-32	62	4.08
Par sup. lobule	34	-58	62	3.61
Post. centr. gyrus	-30	-12	34	3.44

Negative X coordinates, left hemisphere; positive, right. Z score > 3.09.

occipital lobe with sparing of the V1 region, and the parietal lobe. Meditation on symbolic representation of the self was supported by bilateral parietal activity. Common to most meditative situations was a strong bilateral hippocampal activation. This was also apparent in the combined meditation measurements (the

meditative state) which in addition was characterized by activity in parietal and occipital sensory and association regions, again with the exception of V1.

The combined brain activity pattern of the meditation sequences (with auditory stimulation) was then subtracted from the mean of the two measurements of the resting normal consciousness, with similar auditory stimulation, to identify regions which differentially supported the resting state of normal consciousness. This revealed a bilateral group of regions with sustained, "tonic" activity: orbital and dorsolateral prefrontal, anterior cingulate, temporal, inferior parietal lobule, caudate nucleus, thalamus, pons, and cerebellar vermis and hemispheres (Fig. 2, Table III). These structures could be identified by examination of each of the four resting states of normal consciousness separately, thereby ruling out an order effect on these findings.

## DISCUSSION

The study confirmed that CBF distribution could be determined reproducibly during meditation. Thus information has been obtained for the first time on the neural structures underlying the meditative state. It has also been confirmed that the resting state of normal consciousness is subserved by a pattern of neural activity which is reproducible.

Meditation on the weight of the limbs and other body parts was found to activate the supplementary motor area (SMA) strongly. Such a task may involve motor planning and attention with SMA activation as seen with the mere demonstration of tools [Martin et al., 1996]. Also parietal and occipital activation was noted. During abstract meditation on joy and happiness, activation is almost exclusively limited to the left hemisphere, including the Wernicke region, perhaps due to the abstract verbal nature of the task. The differential activity of meditation with visual imagery is centered upon the visual cortex, except for the V1, and the parietal cortex. These regions are very similar to those regions which have been shown to be active in voluntary visual imagery [Kosslyn et al., 1993]. One important difference is, however, the apparent lack of prefrontal and cingulate activity during meditation, possibly due to less volitional, motivational, and emotional control during relaxation meditation. It also shows important similarities to the activation pattern during REM sleep and dreaming [Braun et al., 1997], with the remarkable omission of differential activity in the anterior cingulate during meditation. This again is probably related to the paucity of emotional experience during meditation compared to dreaming. The



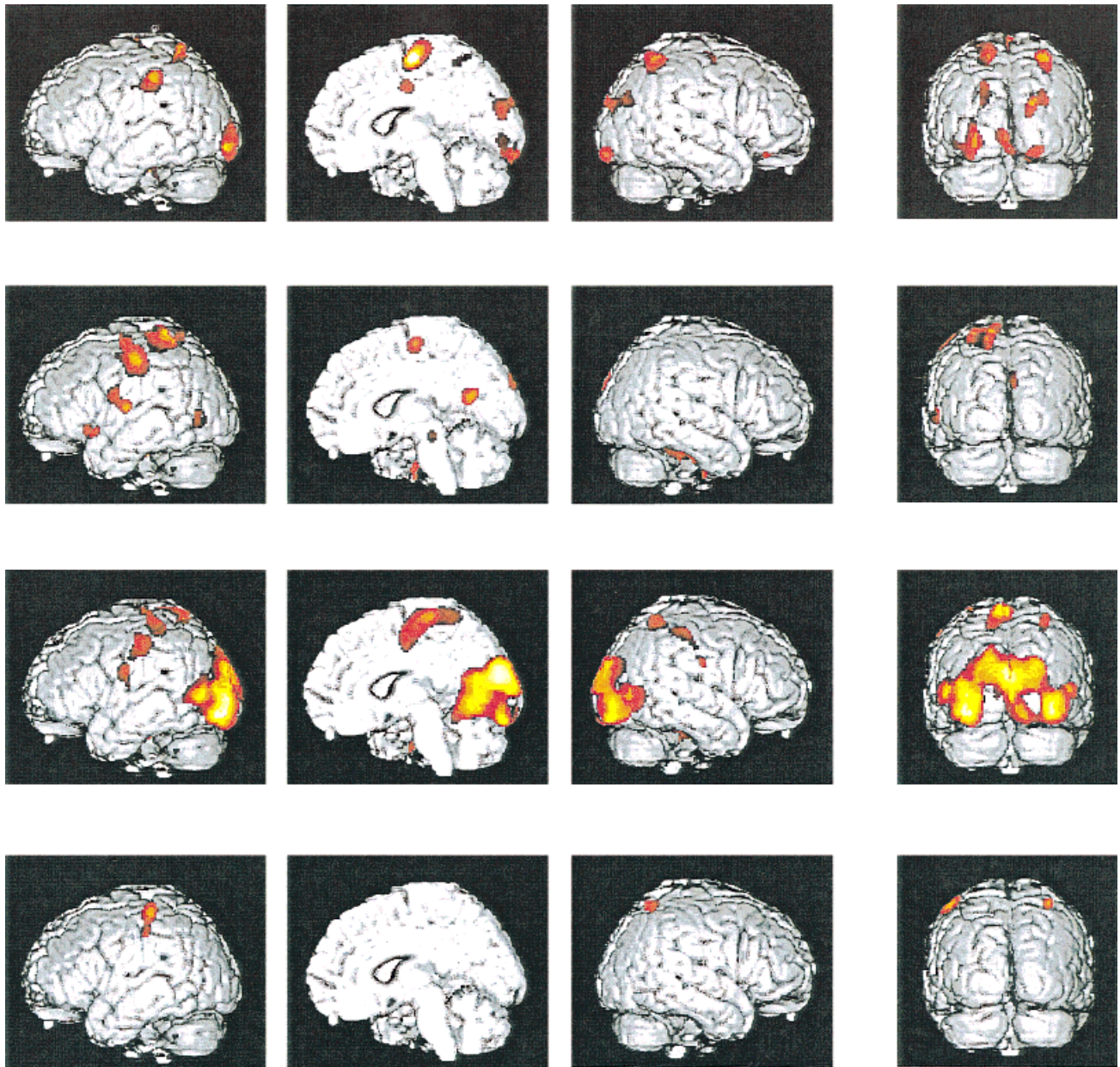


Figure 1.

Cerebral activity pattern of four stages of meditation vs. normal consciousness (all with auditory stimulation). The experience of emotional and volitional detachment is combined with meditation on weight of body parts (upper row), abstract perception of joy (second row), visual imagery (third row) and symbolic representation of the self (lower row). Characteristic differential flow

activities are supplementary motor area and parietal, left parietal and Wernicke, visual (except V1) and anterior parietal, and parietal respectively. In addition, focal hippocampal activity is prevalent (poorly seen in the perspectives chosen). Normalized values,  $P < 0.01$ , mean of nine subjects.

lack of activity in the V1 supports a recent hypothesis of Crick and Koch [1995] according to which V1 activity is not part of the neural substrate of visual awareness. During symbolic meditation of the self, bilateral parietal activity was noted, in accordance

with the role attributed to these regions in bodily representation [Adair et al., 1995].

The resting state of normal consciousness is characterized by differential activity in prefrontal, striatal, thalamic, temporal, parietal, and cerebellar regions

TABLE II. Combined meditative stages vs. normal consciousness, both with auditory stimulation

	Talairach coordinates (maxima of significant differences of flow distribution for each region)			Z score
	x	y	z	
Fusiform gyrus	-32	-26	-26	5.28
	34	-26	-30	4.92
Sup. occ. gyrus	22	-82	24	4.73
Middle occ. gyrus	-30	-90	28	4.61
Postcentral gyrus	-40	-30	42	4.73
Inf. frontal gyrus	4	-16	64	4.87
	-26	4	-18	3.34
	38	36	-18	3.54

Negative X coordinates, left hemisphere; positive, right. Z score > 3.09.

when compared to meditation. This state therefore seems to be differentially subserved by structures known to subserve attention in its so-called executive form: ablation of each structure, with the exception of the cerebellum, may induce neglect in the contralateral hemisphere [Mesulam, 1985]. Prerogatives of

the dorso-lateral prefrontal cortex are working memory and preparation for voluntary motor activity [Goldman-Rakic, 1995]. Relinquishing the latter is one of the hallmarks of the meditative state. The anterior cingulate seems to have a particular role in the motivation and resolution of conflict by selection among competing processing alternatives on the basis of some pre-existing internal conscious plan [Pardo et al., 1990]. Other functions attributed to the anterior cingulate are maternal behavior, visceromotor and skeleto-motor control and executive attention. The structure is, hence, involved in emotionally controlled effects or executive functions. All these functions are experienced as reduced during meditation [Ballantyne and Deva, 1990]. The striatum is important for context analysis in space and time, and for the selection of cortical activity in preparation for actions [Posner and Rothbart, 1994], and the thalamus for regulation of cortical input [Cummings, 1993]. In slow wave sleep decreased activity has been noted in a similar set of regions: the anterior cingulate gyri, prefrontal cortex (especially orbito-frontal), basal ganglia and brain stem. It has been proposed that the one characteristic of all sleep stages is the lack of dorso-lateral frontal activity [Maquet et al., 1997], just as we see it in this study of meditation. Functionally, this would correspond to the

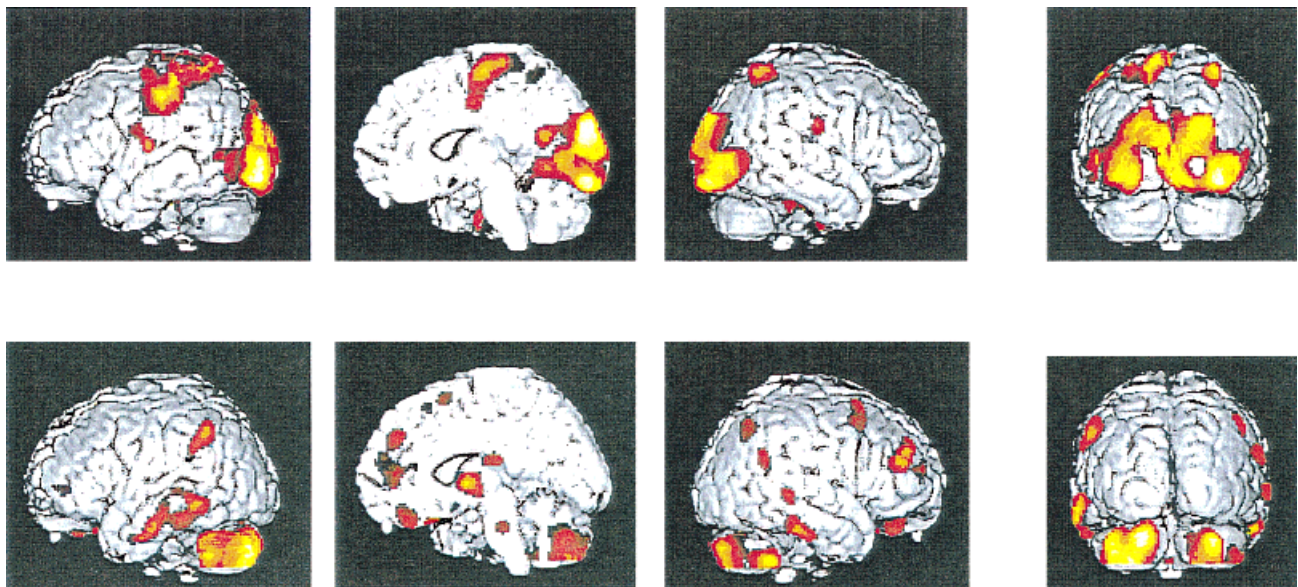


Figure 2.

Cerebral activity patterns of combined meditative stages vs. normal consciousness (upper row) and conversely (lower row). Both conditions with auditory stimulation. The meditative state has differential activity mainly in anterior parietal and occipital regions (except V1). The experience of conscious control of actions is

accompanied by high perfusion bilaterally in dorso-lateral orbital and cingulate frontal regions, posterior parietal region, temporal region, and the caudate nucleus, thalamus, pons, and cerebellar vermis and hemispheres.



**TABLE III. Normal consciousness vs. combined meditative stages, both with auditory stimulation**

	Talairach coordinates (maxima of significant differences of flow distribution for each region)			Z score
	x	y	z	
Sup. front. gyrus	-8	20	56	4.43
Middle front. gyrus	-24	44	2	4.39
	34	46	28	4.64
Inf. front. gyrus	-38	40	12	3.28
Med. orbital gyrus	-2	16	-26	4.92
Cingulate gyrus	-24	44	2	4.39
	8	44	20	3.10
Middle temp. gyrus	60	-28	-28	4.48
Inf. temp. gyrus	-60	-48	-8	4.23
Inf. parietal lobule	-50	-52	40	4.35
Caudate nucl.	12	-22	20	3.56
Thalamus	-24	-32	6	3.89
	8	-6	0	3.83
Red. nucl.	-8	-24	-4	3.59
Pons	4	-28	-28	3.63
Cerebellum, vermis	2	-50	-50	3.65
Hemispheres	-16	-80	-28	5.69
	32	-78	-36	4.71

Negative X coordinates, left hemisphere; positive, right. Z score > 3.09.

decreased executive activity common to both conditions. Finally, the cerebellum, perhaps the most surprising constituent of this pattern of neural activity, has recently been shown to participate in a number of cognitive functions, including attention and the prediction of future events [Allen et al., 1997]. This concept is based on functionally as well as anatomical connection which places the cerebellum in cortico-subcortico-cortical loops regulating behavior, just as has been proposed lately for the basal ganglia and thalamus [Middleton and Strick, 1994].

To summarize, the meditative state is characterized by activity in the hippocampi and posterior sensory and associative systems known to be activated by imagery, and the resting state of normal consciousness is, when compared to meditation, characterized by activity in the so-called executive attentional system and the cerebellum. These two functions are closely related to two complementary aspects of consciousness: The conscious experience of the sensory world and the fact or illusion of voluntary control, with self regulation. Consciousness and attention/awareness are, however, not identical. According to Tart [1975]

consciousness may be seen as a more complex process, defined as awareness modulated by the mind. In the present investigation the individuals experienced two states of consciousness: the resting state of normal consciousness with the experience of conscious control, and the meditative state with the experience of rich imagination, and loss of conscious control. No attempt was made to limit the activity of the mind during these conditions, and the very different neural patterns subserving each of these conditions were accordingly quite extensive. It is therefore reasonable to assume that the states were characterized by different states of consciousness rather than its simpler constituent, awareness. Thus we may conclude that the two neural patterns do, indeed, seem to constitute the differential foundations of the two complementary aspects of consciousness.

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