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Research Report

An investigation of brain processes supporting meditation

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Abstract Meditation is an ancient spiritual practice, which aims to *still the fluctuations of the mind*. We investigated meditation with fMRI in order to identify and characterise both the “neural switch” mechanism used in the voluntary shift from normal consciousness to meditation and the “threshold regulation mechanism” sustaining the meditative state. Thirty-one individuals with 1.5–25 years experience in meditation were scanned using a blocked on–off design with 45 s alternating epochs during the onset of respectively meditation and normal relaxation. Additionally, 21 subjects were scanned during 14.5 min of sustained meditation. The data were analysed with SPM and ICA. During the onset of meditation, activations were found bilaterally in the putamen and the supplementary motor cortex, while deactivations were found predominately in the right hemisphere, the precuneus, the posterior cingulum and the parieto–temporal area. During sustained meditation, SPM analysis revealed activation in the head of nucleus caudatus. Extensive deactivations were observed in white matter in the right hemisphere, i.e. mainly in the posterior occipito–parieto–temporal area and in the frontal lobes. ICA identified 38 components including known baseline-resting state components, one of which not only overlaps with the activated area revealed in the SPM analysis but extends further into frontal, temporal, parietal and limbic areas, and might presumably constitute a combination of frontoparietal and cinguloopercular task control systems. The identified component processes display varying degrees of correlation. We hypothesise that a proper characterisation of brain processes during meditation will require an operational definition of brain dynamics matching a stable state of mind.

Introduction

In the ancient spiritual practice of meditation, the aim is to achieve a special form of awareness. Meditation has been studied due to its potential health benefits (see e.g. Baer 2003; Ospina et al. 2007) and its status as a special form of consciousness, which is uniquely different from both ordinary wake- and sleep states. While a considerable number of studies have been carried out using EEG, only few have used PET, fMRI, SPECT or other neuroimaging methods. Such neuroimaging studies (see e.g. Cahn and Polich 2006 for a recent review) have identified specific brain structures active during meditation (discussed later).

It has been argued that two complementary neural networks may underlie meditation. One network functions as a “neural switch” mediating the shift from normal consciousness to meditation, while the other functions as a “homeostatic threshold regulation mechanism” that maintains the restful state of mind pivotal for meditation (Travis et al. 1999).

In the present study, which was conducted on a large body of subjects, we present a report of an fMRI investigation into the brain processes involved in the initial stages (i.e. the onset) both of meditation and of those supporting sustained meditation.

Meditation

Many different schools and types of meditation exist. Some are connected to formal philosophical systems and/or religious practices (e.g. Hindu, Buddhist, Muslim, Christian etc.), while others are secular (e.g. Mindfulness Meditation, cf. Kabat-Zinn 2003).

The various forms and practices can be seen as variations of concrete operationalisations of meditation. In the present context, and when compared to other states and processes of the mind, these differences may be disregarded as inessential in comparison with the common nucleus that characterises meditation in general.

In Patanjali’s classical analysis of Yoga (see e.g. Hartranft 2003; Haughton-Woods 2003; Sastri 1990; Shearer 1982), meditation is defined as *the control of fluctuations of the mind* that aim to *still the fluctuations (patterning) of the mind*. When the fluctuations of the mind are controlled, the yogi achieves concentration, i.e. meditation (samadhi or Nirvana). *Then, the mind (the self) abides in itself. Pure awareness can abide in its very nature*. This state stands in contrast to a “normal”, uncontrolled state of mind in which, according to Patanjali, *the self (the mind, awareness) identifies itself with the fluctuating patterns of consciousness*.[1]

Patanjali subsequently defines five different types of “fluctuations that together encompass what modern psychology considers the normal mental processes and contents of consciousness. According to Patanjali, they are classified as: (1) *Veridical cognition*: Correct perception based on direct observation, correct inference and verbal communication. (2) *Misconception*: Misperception, false beliefs and erroneous knowledge in conflict with reality. (3) *Conceptualisation*: Imagination derived from words and without contact to real things. (4) *Sleep*: Deep sleep, the perception of nothing (negation of other fluctuations). (5) *Memory*: The retention of past experience (including dreams).

Yoga or meditation is thus twofold defined as a specific form of mastering (eliminating) of such fluctuations and the attainment of a stable concentration of attention and non-attachment to sensory experiences. According to Patanjali, this state may be achieved and stabilised through practice, the repeated and enduring effort of which being aimed at the elimination of (still) fluctuations and mastery of the desire for sensory experiences.

Recently, it has been claimed that a distinction should be made between “concentrative” (focused attention - FA) and “mindfulness” meditation (open monitoring - OM) (Dunn et al. 1999; Lutz et al. 2008). While this may be a productive distinction in some contexts, it is not crucial here.

Concentrative meditation (FA) involves focusing the mind (attention) on an object, a religious or a conceptual symbol, a mantra or some other identifiably material or ideational entity, while simultaneously ignoring all other impressions or recollections, which are considered distractions.

Mindfulness meditation (OM) on the contrary is characterised as “open monitoring” of whatever comes to mind in the moment; i.e. letting sensory impressions, memories and associations pass through the mind without attending

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[1] The citations from Patanjali have been adapted from the referenced translations by the first author.

to any of them in particular. This implies not heeding, evaluating, thinking or in any other fashion reacting to the kaleidoscope of transitory mental experiences.[2]

In both cases, however different they may initially seem, the ultimate aim of the effort is to detect, identify and arrive at the underlying state of the mind, or as described by Patanjali "to still the fluctuations of the mind".

In the concentrative schools of meditation (FA), the object of concentration initially serves as a tool to remove attention from distracting impressions, etc., while the purpose itself is to reach identification with the object; but in advanced stages of meditative training, the object of concentration is in itself considered a distraction (cf. Patanjali). In the mindfulness tradition (OM), the openly monitored events are left to flow by their own accord, while the focus on any particular object or aspect of the experience is deliberately withheld. The attempt is to "ignore" all possible objects of attention and to reach a state in which the "phenomenal features remain in the background, even though there is no contrasting cognitive foreground" (Lutz et al. 2008, p. 164). But as described by Lutz et al. (2008), training in concentration is, at least to some extent, part of the programme in mindfulness meditation and therefore a necessary element (cf. Dunn et al. 1999).

In both cases, the ambition is to surpass the distinction between the observer, the observed and the process of cognition and to ultimately identify with the unformed or formless medium of the fluctuations of the mind; i.e. the mind process itself. Again, in both cases, the aim is to reach a balanced state of mind or "concentration" (cf. Patanjali book I, §41, and §51, Hartranft 2003, p. 77, 98). In this sense, the state Patanjali describes as "concentration" does not differ from the state that Lutz et al. (2008, p. 164) refers to as "the 'effortless' sustaining of an awareness without explicit selection", and in both cases this is synonymous with "meditation".

It may thus be argued that whether a particular concrete meditation carried out by a specific subject in a given situation is best characterised as "concentrative" or "mindfulness" will to a large degree depend on the proficiency of the meditating subject. Although seemingly opposite, a closer inspection reveals that both forms

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[2] In the mindfulness tradition, some aspects of experiences (the content or "fluctuations" of the mind) may be attended to in specific ways during the initial process of training. This is motivated by the therapeutic use of the technique in a western setting, not because this is relevant to the method as a form of meditation in the traditional sense of the word.

in themselves are integral aspects of advanced meditation (cf. Newberg and Iversen 2003). For subjects working in traditions inspired by Zen Buddhism and Tantra, as are the objects of this study, meditation will usually contain some mixture of concentration and open non-evaluative awareness. As e.g. Dunn et al. (1999) has brought attention to, this may create the ground for contradictory and confusing results in studies like the present. This kind of confusion may possibly be avoided by studying only one of these opposed techniques, but in the opinion of the present authors the confusion may possibly be overcome by other means.

Although much more could of course be said about meditation, we propose the hypothesis that meditation may be tentatively characterised as the achievement of a concentrated, non-evaluative and non-discursive state of mind; or, a detachment from the contents of conscious sensory experience and a stable concentration of attention on itself. This attentive awareness has been characterised as a state in which “all things are like the void and cloudless sky. The naked spotless intellect is like unto a transparent vacuum without circumference or centre” (Evans-Wentz 1980, p. 91), and as “mind, suspended in space, nowhere” (Rinpoche 1992, p. 72).

The neural basis of consciousness and meditation

The classical texts on meditation are in fine agreement with modern *systems theoretical approaches to understanding brain processes and consciousness*. Such theories regard consciousness and higher mental processes as a result of integrated activities in local areas of the brain, each contributing specific functions to the global activity pattern (e.g. Anokhin 1974; Bernstein 1967; Buzsáki 2006; Freeman 2000; Luria 1972, 1980; Nieuwenhuys 2001; Swanson 2003; Tononi and Edelman 1998; Vygotsky 1997).

According to these theories the control of behavioural activities, psychological processes and consciousness are realised by reciprocally looping (reentrant) processes organised in *functional systems* (Anokhin 1974; Luria 1972, 1980; Vygotsky 1997) i.e. functional combinations (networks) of processes in anatomically defined “functional blocks”. The functional systems comprise processes in (a) frontal cortical zones, (b) posterior cortical zones, (c) the limbic system, (d) thalamus, (e) basal ganglia, (f) hypothalamus, (g) hippocampus, (h) cerebellum, (i) the mesencephalic formatio reticularis, and possibly other basal structures in the brain and spine (Nieuwenhuys 1996, 2001). The integrative aspect of conscious processes requires the synchronisation of neural activity in these areas (Buzsáki and Draguhn 2004), primarily organised by the so-called thalamo–cortical system (Edelman and Tononi 2000; Tononi and Edelman 1998), but possibly also by the more primitive basic intentional regulating system organised by the hippocampus and the limbic system (Freeman 2000).

The *neurobiological basis of consciousness* may thus be seen as dynamical systemic processes near critical values. Reentrant neural processes among reciprocally connected local anatomical structures in different parts of the brain form functional clusters. A functional cluster which reach a sufficient spatio–temporal extension and which have a sufficient degree of integration as well as differentiation is conceived of as a "functional core" that constitutes the immediate neural correlate of consciousness (Edelman and Tononi 2000; Tononi and Edelman 1998).

In this framework, meditation may be described as a "functional core" of neural processes that is at once maximally integrated and differentiated and that supports a restful but alert attentional state with itself as its object, while only minimally perturbed by external sensory influences (Josephson 1978). By this accord, we would expect this functional core to involve structures in several spatially distributed areas of the brain.

Previous neuroimaging studies

Neuroimaging studies have implicated a number of candidate regions involved in meditation. For reviews see Cahn and Polich (2006), Ivanovski and Malhi (2007) and Neumann and Frasch (2006). However, and for obvious reasons, these reviews do not take into account a number of recent studies.

In these earlier studies, different imaging methods were used, including fMRI, PET and SPECT. Furthermore, the types of meditation investigated, as well as the control tasks, were quite diverse. Differences such as these make comparisons across studies difficult, a fact that should be kept in mind. One of many aspects that varied across studies was the duration of meditation during scanning. This factor is important when making the distinction between the neural switch (onset) mechanism and the process of sustained meditation, the latter of which being the main focus point of the present study.

Concerning meditation onset, some fMRI studies (Farb et al. 2007; Hölzel et al. 2007b) have employed short periods of meditation (<1 min) that displayed increased activity of different frontal cortical areas; either lateral prefrontal cortex

(Farb et al. 2007), or orbital, superior medial and superior frontal parts (Hölzel et al. 2007b). Farb et al. (2007) further found increased involvement in viscerosomatic areas, including insula, secondary somatosensory and inferior parietal regions, whereas Hölzel et al. (2007b) found inferior temporal and cerebellar activity increases. Deactivations as a consequence of meditation onset were placed in medial frontal areas by Farb et al. (2007), and in several frontal, occipital, parietal and cerebellar regions in Hölzel et al. (2007b).

Brefczynski-Lewis et al. (2007) used a somewhat longer meditation duration of 2.7 min on average. They found increased activity in what they regard as attention-related regions, including frontal, parietal and lateral occipital regions, as well as the insula, thalamus, basal ganglia (including putamen) and cerebellum. Deactivations were located in the bilateral anterior temporal lobes (although only for the novice meditation practitioners).

In regard to sustained meditation (6–72 min), neuroimaging studies are more abundant. Compared to varying control states, activations have often been found in prefrontal areas (Guo and Pagnoni 2008; Jevning et al. 1996; Lazar et al. 2000; Newberg et al. 2003; Pardo et al. 1991) - in some cases more specifically located in the dorso–lateral prefrontal cortex (DLPFC; Baron Short et al. 2007; Newberg et al. 2001; Raffone et al. 2007). Some studies also reported activation of parietal (Lazar et al. 2000; Newberg et al. 2003; Pardo et al. 1991) and (mostly anterior) cingulate cortex (Baron Short et al. 2007; Lazar et al. 2000; Newberg et al. 2001; Raffone et al. 2007). With respect to deeper-lying activation sites, some studies have highlighted the role of the hippocampus (Lazar et al. 2000; Lou et al. 1999, 2005) and the striatum (Kjaer et al. 2002; Lazar et al. 2000).

Deactivations can be found in studies of sustained meditation as well, including, somewhat confusingly, in brain regions overlapping the sites of activation found in other studies, including the DLPFC and anterior cingulate cortex (Lou et al. 1999, 2005), as well as parietal regions (Newberg et al. 2001; Newberg and Iversen 2003; Baron Short et al. 2007).

In addition to the functional neuroimaging studies mentioned earlier, a handful of studies have recently investigated the influence of meditation on brain anatomy by using methods such as voxel-based morphometry MRI (Hölzel et al. 2007a; Lazar et al. 2005; Pagnoni and Cekic 2007). Quite remarkably, two of these studies (Hölzel et al. 2007a; Lazar et al. 2005) found an increased size of the right anterior insula in a meditation group compared to controls. They also both revealed increases in structures of the left temporal cortex although not in the same exact structures. The remaining anatomical study on meditation (Pagnoni and Cekic 2007) found that especially the left putamen was larger in a meditation group.

Only one study of meditation employing ICA has been reported. Guo and Pagnoni (2008) found distinct time courses for relevant component brain processes in meditators versus controls.

Hypotheses and aim of the study

In the present investigation, we follow the proposal of Travis and Wallace (1999) that two neural networks may be involved in meditation, i.e. that the rapid voluntarily initiated shift in physiological functioning within the first minute of meditation might be mediated by a ‘‘neural switch’’ in prefrontal areas, which inhibits activity in specific and nonspecific thalamocortical circuits. The resulting ‘‘restfully alert’’ state might be sustained by a threshold regulation mechanism involving tertiary cortical zones, the basal ganglia, the nonspecific thalamic nuclei, nucleus reticularis thalami and the cerebral cortex. This neural loop is hypothesised to then automatically maintain the lower levels of cortical excitability that according to Travis and Wallace (1999) characterise the meditative state.

The proposal that two distinct networks function during onset and sustained meditation serves as the initial hypothesis for the present study. We aim to identify and further characterise both the “neural switch” mechanism, which is used in the voluntary shift from normal consciousness to meditation, and the “threshold regulation mechanism” sustaining the meditative state.

Methods

Subjects

The subjects participating in the *on–off meditations* were 31 individuals belonging to three different schools of meditation. The subjects were 14 females and 17 males (mean age 45, range 24–61). Twenty-eight subjects were right handed, 2 left handed, 1 ambidextrous. Their experience with meditation ranged from 1.5 to 25 years (mean of 11 years). Ten subjects belonged to a school of Zen meditation (Z group), while 21 belonged to one of two Danish traditions of meditation, the M group (13 subjects) and the T group (8 subjects), both of which are inspired by and akin to Yoga and Tibetan Tantric Buddhism. All subjects were scanned twice; generating a total of 60 on–off meditation scans.

The body of subjects participating in the reported *sustained meditation* were 11 females and 10 males (mean age 44.5 years, range 24–61). All subjects belonged to the M group (13 subjects) or the T group (8 subjects). Their level of experience with meditation varied from 1.5 to 25 years (12 years on average), during which they had meditated regularly at least twice daily for between 30 min to more than 2 h per session.

Meditation

The subjects were instructed by their teachers to meditate in accordance with their particular traditions. The subjects in the Z group were counting their respiration from 1 to 10 cycles, after which they would start over again. The M and T groups each employed special imaginative mantras created for the occasion by the respective teachers. Since in both cases the repetition of the mantras was explicitly tied to the respiratory cycle, the meditations were all paced by the subjects individually during the meditation epochs. Since people with extensive experience in meditation tend to start meditating when asked to do nothing, they were instructed that during the baseline-resting state they should not meditate, but let their mind wander, attending to daily matters and experiences, what had happened during the day, or whatever might happen during the rest of the day and the like.

During the on–off meditation, subjects were instructed to start meditating when given a signal consisting of a soft touch on their right ankle, and then 45 s later, when touched again on their right ankle, to stop meditating and instead rest with their eyes remaining closed for another 45 s. This procedure was repeated three times, resulting in three meditation epochs of 45 s interspersed with 45 s resting epochs. The pacing of meditation (and respiration) was left up to the subject within the meditation epochs, whereas the experimenter controlled the initiation and cessation of these epochs.

During the continuous meditation, subjects used the same sort of meditation as during the on–off meditation. They were instructed to rest with their eyes closed during the initial 30 s of the scan, after which they were given a sign (a soft touch on the right ankle) to start the meditation, which in turn lasted for 14½ min at which time the scanner stopped.

Scanning

Scanning during onset of meditation was done using a blocked on–off design with 45 s alternating epochs (meditation = on, normal relaxation = off). A total of 60 scans were obtained.

During continuous meditation, the subjects were scanned for 15 min (14½ min of uninterrupted meditation preceded by ½ min normal relaxation). A total of 21 scans were obtained.[3]

The scans were made on a GE Signa 1.5 T scanner (General Electric Medical Systems, Milwaukee, WI). The sequence used was T2* weighted Gradient Echo EPI, TE = 40 ms, TR = 3.5 s, flip angle = 70º, FOV = 24 cm, slice thickness = 3 mm, with no gap between slices, 64 × 64 voxels per slice, voxel size 4 × 4 × 3 mm. About 32 axial slices (Z group), 34 axial slices (M group) or 35 axial slices (T group) were acquired.

Data analysis

In both the on–off and continuous meditation subsets, the experimental design only contained meditation and rest with no other active conditions. The contrasts were set as meditation versus resting state, which we interpret as revealing “activations” during meditation; and as resting state versus meditation, which we interpret as revealing “activations” during rest, which is synonymous with “deactivations” during meditation (cf. Raichle 1998).

On–off meditation

Data analysis was done with SPM2 (Institute of Neurology, London, UK) running on Matlab version 7 (R14). Data were realigned, normalised to MNI space and smoothed using an FWHM of 7 mm. Experimental effects were estimated with a

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[3] Although the Z group was also scanned during continuous meditation, these data were left out of the present analysis, because the scanning procedure was different for this group, making a combined analysis unacceptable. Data from two additional subjects from the M group was left out due to various unrecoverable deficiencies in the raw data. In the data from 6 subjects in the present set, slice dropouts were discovered in single pictures from the scans. A copy of the immediately preceding or following pictures substituted these pictures. Although this of course introduces disturbances in the data, an examination of trial analyses established that the substitution had only minimal, and actually non-detectable, effect on the results. These scans were therefore included in the group analysis.

general linear model (GLM; Frackowiak et al. 2004; Friston et al. 1994). The data were modelled using a standard haemodynamic response function (HRF) with temporal derivatives and exponential decay in order to compensate for possible minor variations in the timing of the meditation on–off process, and to take account of the fact that the canonical HRF is a theoretical idealisation, which is rarely observed empirically.

Second-level random effects analyses yielded statistical parametric maps. Statistical significance was assessed employing family-wise error (FWE) correction for multiple comparisons (voxel $p < 0.05$, two-sided *t*-test). This analysis was subsequently repeated without correction for multiple comparisons (voxel $p < 0.001$, two-sided *t*-test).

Anatomical localisations were established using the MNI Space Utility (MSU 2005) and the Talairach Daemon (Lancaster et al. 2000, 2007). The MSU was used to find the distributed anatomical localisation of the activated areas, while the Talairach Daemon was used as a supplement in order to localise the local maxima of the clusters after conversion of the coordinates to Talairach space.

Continuous meditation

The analysis of data from continuous meditation involved both SPM GLM and Independent Component Analysis methods and some additional correlation statistics.

Analysis with SPM does not appear relevant for analysis of the data from continuous meditation due to the absence of suitable contrasts in the experimental design. A method like ICA would appear more adequate for the analysis of the continuous meditation data. We did carry out a SPM analysis in order to be able to compare the results with the results from the ICA. We also wanted to test the combination of ICA and SPM analysis. This incentive for the SPM analysis, as should be kept in mind, is the background for choosing the values for some analysis parameters. The chosen parameter values are intended to make the SPM analysis of the continuous meditation data comparable with the ICA of the same data, and not because they should be compared with the SPM analysis of the on–off meditation data.

As mentioned earlier, we do not consider the ICA to be entirely satisfying in order to gain an understanding of brain processes during meditation. We are therefore in the process of searching for other analysis methods that may build on the ICA. Here, we present some of our initial efforts, as well as some concluding speculations inspired by these explorations.

SPM In the SPM analysis, the data were pre-processed (realignment, slice time correction with first slice as the reference, normalisation to MNI space, smoothing 5 mm FWHM) with SPM5 (Institute of Neurology, London, UK; Friston et al. 2007) running on Matlab version 7.3. (R2006b). Fixed effects analyses were carried out on the individual scans, using a "standard" response function for a sustained BOLD effect (Bandettini et al. 1997) with time and dispersion derivatives. Second-level random effects analyses yielded statistical parametric maps. Statistical significance was assessed using statistics uncorrected for multiple comparisons (voxel $p < 0.001$, two-sided t-test).

A spatial smoothing of 5 mm FWHM was employed in order to make the results of the SPM analysis comparable to the results of the ICA, in which 5 mm smoothing was used, and, moreover, to make the combined ICA and SPM analysis possible. The statistical threshold level was also chosen in order to render the results comparable with the ICA.

Anatomical localisations were established along the guidelines described for the on–off meditation.

ICA The data analysis was carried out using probabilistic independent component analysis (FSL 4.0, MELODIC 3.05; Beckmann and Smith 2004, 2005). Preprocessing consisted of motion correction (McFlirt), slice timing correction (reference half way through volume) co-registration to high resolution anatomical scans (using BET, no search, 7DOF), normalisation to MNI-space (no search, 12 DOF), re-sampling resolution 4 mm, noise reduction and voxel-wise de-meaning, normalisation of the voxel-wise variance, and whitening. A spatial smoothing of 5 mm FWHM was employed. The data were then decomposed into components across the temporal-, session/subject- and the spatial domain (maps; Hyvärinen 1999). Estimated component maps were divided by the standard deviation of the residual noise and thresholded at 0.5 (Beckmann and Smith 2005). The group analysis was carried out as a concatenation Group ICA (GICA) with high pass filter cut-off at 250 s.[4] Anatomical localisations were established with the Talairach Daemon after conversion of coordinates to Talairach space.

SPM and ICA combined In addition to the “standard” SPM analysis, we carried out SPM analyses using the component time series produced by the ICA analysis as regressors. For this purpose, the individual time series from all subjects contributing to all components in the GICA were identified and assigned to separate sets for each subject. Each of the time series was then used as regressor in SPM fixed effects analyses (38 analyses of component time series for each of the 21 subjects). This was followed by random effects analyses encompassing the 21 subjects for each of the 38 components.[5] The second-level random effects analyses yielded statistical parametric maps. Statistical significance was assessed using statistics uncorrected for multiple comparisons (voxel $p < 0.001$, cluster $p < 0.01$, one-sided t-test). Anatomical localisations were established using the MNI Space Utility (MSU) and the Talairach Daemon (Lancaster et al. 2000, 2007).

Component correlations The realignment parameters of the SPM pre-processing were further used to characterise the movement-related artefacts among the components from the ICA.[6] The component time series from individuals and their corresponding realignment parameters were therefore correlated in order to exclude movement-related components.

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[4] The following types of parameters for the group analysis were employed in separate analyses: Tensor ICA with Hpf cutoff at 250 s; Concatenation ICA with Hpf cutoff at 250, 100 and 50 s respectively. These analyses produced very similar results, and the present report only takes the results from the Concatenation ICA with Hpf cutoff at 250 s into account. Smoothing with 7 mm FWHM was also used in separate analyses, but resulted in the production of a multitude of extra noise components.

[5] The results of these analyses were surprising, inasmuch as it was only possible to obtain meaningful results for one component (IC 2). In order to filter out movement-related artefacts, we included the realignment parameters in the models of the fixed effects analyses. We subsequently carried out a fixed effects analysis of the data without including the realignment parameters; one analysis including all components, and one analysis including various specifically selected other components and the realignment parameters in the design matrix. None of these analyses could locate more than the same single component. The first analysis was therefore chosen for presentation in the present report.

[6] Because of large variations among the subjects, it turned out to be extremely difficult, in all but a few cases, to find consistent criteria to sort out which components were “noise”, and which might be meaningfully related to the meditation. One complicating factor may be the circumstance that the paces of the subject’s meditation were coupled to their respiratory cycles, as this may cause subtle movements. If all movement-related artefacts were removed, the risk is that some of the meditation-related effects would be removed as well.

The power spectra of the Fourier transforms from the group components were used to exclude components containing frequencies indicating they might be related to Cardiac processes (Cordes et al. 2001).[7]

The components identified with the ICA method were distributed in most of the cerebral space. We therefore hypothesise that the specific characteristics of meditation do not necessarily reside in the location of one or few specific component processes, but may rather be reflected in the causal relationships between the components, or perhaps between some specific components.

Consequently, we wished to analyse the correlations among the components of every subject in order to reveal consistent patterns. This task raises a whole new set of methodological challenges, for which reason we only provide the preliminary findings of these analyses.

Results

Onset of meditation

Major activations during meditation onset (contrast: meditation > rest, FWE corrected statistics, $p < 0.05$, two-sided t-test) were found bilaterally in the mid-ventro–lateral part of putamen extending into the external globus pallidus. Bilateral cortical activations were also found in the supplementary motor area of the medial frontal gyrus (BA 6), the primary somato-motor cortex of the precentral gyrus (BA 4), and in the inferior parietal lobe (BA 40). In the right hemisphere, cortical activation was also found in insula.

Significant deactivations during meditation onset (contrast: rest > meditation, FWE corrected statistics, $p < 0.05$, two-sided t-test) were found mainly in the medial part of the right occipital and parietal lobes, and in the right precuneus, extending into the dorsal posterior cingulate (BA 19, 7, 31). A second cluster of deactivation was found at the parieto–temporal junction in the angular gyrus and superior temporal lobe of the right hemisphere (BA 22, 39).

The activations and deactivations during meditation onset are shown in Figs. 1 and 2, and a list of their localisation is given in Table 1. As may be seen in Fig. 2

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[7] This procedure may not be optimal, but FSL does not give access to the power spectra of the Fourier transforms of the individual time series contributing to the component.

(illustrating results from analysis using uncorrected statistics, voxel $p < 0.001$), the established pattern of activations and deactivations in Fig. 1 may be regarded as core areas in more extensive clusters of activated and deactivated areas, which is relevant in comparison with the results of other investigations.

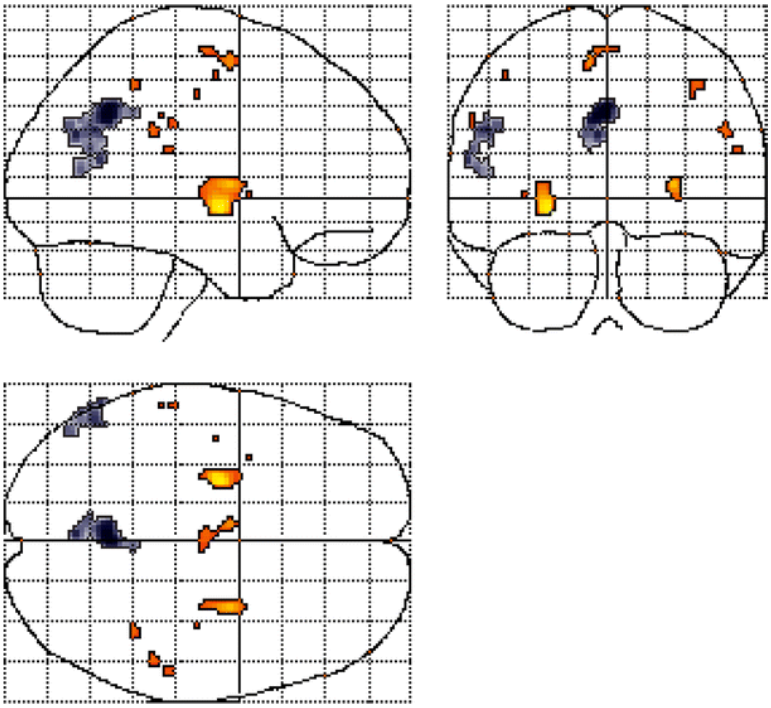

Fig. 1 Meditation onset. Voxels with increased signal during meditation are displayed in red, while voxels with signal reduction during meditation are displayed in blue (SPM2, random effects analysis, FWE corrected, $p < 0.05$) (colour figure online)

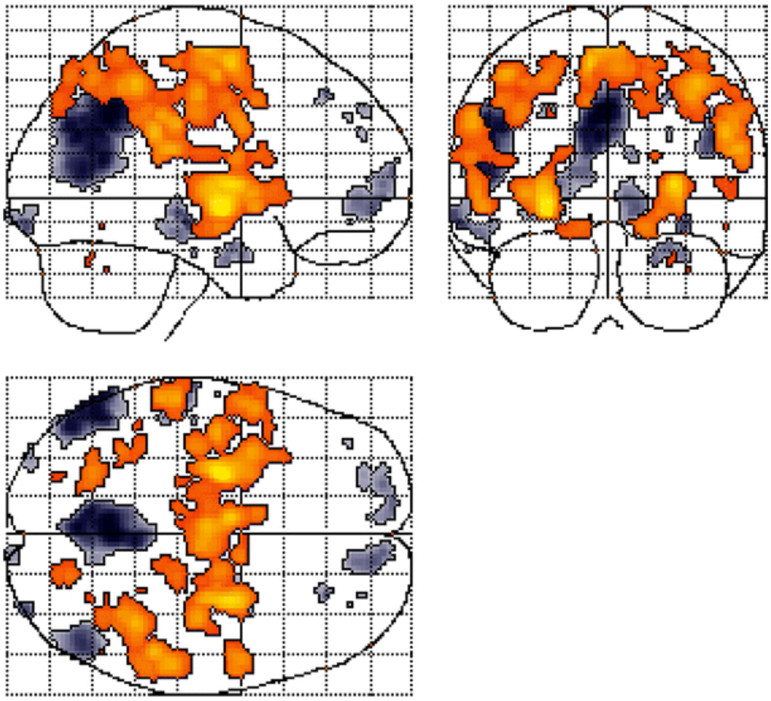

Fig. 2 Meditation onset. Voxels with increased signal during meditation are displayed in red, while voxels with signal reduction during meditation are displayed in blue (SPM2, random effects analysis, statistics uncorrected for multiple comparisons, $p < 0.001$) (colour figure online)

Table 1 Main activations and deactivations during meditation onset

No. of voxels	z Score	Coordinates (xyz)	Lateralisation	Anatomical area
Activations				
121	6.34	26 −8 −4	Right	Putamen (lentiform nucleus)
62	5.79	−28 −4 6	Left	Putamen (lentiform nucleus)
15	5.47	8 −4 58	Right	Medial frontal gyrus BA 6
15	5.18	5 −14 64	Right	Medial frontal gyrus BA 6
	4.93	−4 −16 64	Left	Medial frontal gyrus BA 6
8	5.17	50 −38 28	Left	Inferior parietal lobe BA 40
10	5.17	−38 −46 50	Left	Inferior parietal lobe BA 40
7	5.02	−56 −30 22	Left	Inferior parietal lobe BA 40
3	4.98	58 −28 32	Right	Inferior parietal lobe BA 40
2	4.98	44 −10 54	Right	Precentral gyrus BA 6
2	4.92	−36 −18 44	Left	Precentral gyrus BA 4
1	4.90	36 4 2	Right	Insula
1	4.90	58 −34 36	Right	Inferior parietal lobe BA 40
Deactivations				
201	5.62	4 −56 36	Right	Precuneus BA 7
	5.62	0 −56 38	Interhemispheric	Precuneus BA 7
	5.36	4 −70 28	Right	Precuneus BA 31
	5.17	10 −66 28	Right	Precuneus BA 31
	5.1	−2 −46 38	Left	Cingulate gyrus BA 31
114	5.3	60 −60 16	Right	Superior temporal gyrus BA 22
	5.29	52 −62 30	Right	Angular gyrus BA 39
	5.16	48 −74 32	Right	Angular gyrus BA 39
	5.15	58 −64 22	Right	Middle temporal gyrus BA 39
	5.14	56 −68 12	Right	Middle temporal gyrus BA 39
	5.08	52 −68 34	Right	Angular gyrus BA 39
	5.01	58 −64 14	Right	Middle temporal gyrus BA 19

Statistics FWE corrected for multiple comparisons (voxel $p < 0.05$, two-sided *t*-test)

Continuous meditation

SPM analysis

A random effects analysis (FWE corrected statistics, voxel $p < 0.05$, two-sided *t*-test) found no activations (contrast: meditation > rest), and three small deactivated clusters (contrast: rest > meditation) all located in the right hemisphere, in insula (BA 13), the precentral gyrus (BA 6) and the middle temporal gyrus (BA 20).

Analysis with uncorrected statistics (voxel $p < 0.001$, cluster $p < 0.01$, two-sided *t*-test) uncovered one small cluster located in the head of the left caudate nucleus activated during the continuous meditation (a similar cluster in the right caudate nucleus was too small to survive cluster size correction). Deactivations were more prominent during the continuous meditation condition. About 15 clusters were revealed in the right hemisphere and two in the left hemisphere. Most of the deactivations are reported to be located in white matter (see Fig. 3; Tables 2, 3).

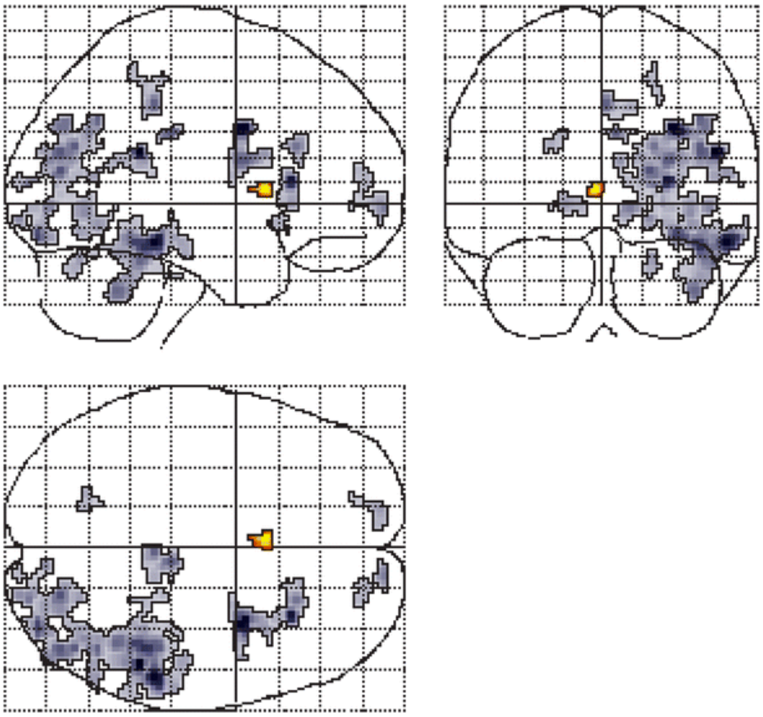

Fig. 3 Continuous sustained meditation. Voxels with increased signal during meditation are displayed in red, while voxels with signal reduction during meditation are displayed in blue (SPM5, random effects analysis, statistics uncorrected for multiple comparisons, $p < 0.001$, two-sided *t*-test, cluster $p < 0.01$) (colour figure online)

Table 2 Main activations and deactivations during continuous meditation

No. of voxels	z Score	Coordinates (xyz)	Lateralisation	Anatomical area	BA
Activations (cluster-level p = 0.035, uncorrected)					
26	4.15	−4 12 6	Left	Caudate head	
			Right	Caudate head	
Deactivations (cluster-level $p < 0.01$, uncorrected).					
139	5.4	48 −42 22	Right	Insula*	BA 13
	3.97	34 −40 18	Right	Insula	BA 13
	3.76	36 −50 18	Right	Superior temporal gyrus	BA 22
236	5.22	32 2 30	Right	Precentral gyrus*	BA 6
	4.51	30 4 18	Right	Claustrum	
	3.97	34 12 20	Right	Insula	BA 13
1,367	5.22	54 −36 −16	Right	Middle temporal gyrus*	BA 20
	4.82	42 −40 −18	Right	Fusiform gyrus	BA 20
	4.56	20 −76 14	Right	Cuneus	BA 18
112	5.05	28 24 10	Right	Claustrum	
	3.94	26 24 0	Right	Claustrum	
	3.73	30 18 −8	Right	Insula	BA 13
147	4.67	32 −86 −14	Right	Middle occipital gyrus	BA 18
	4.07	20 −94 −6	Right	Lingual gyrus	BA 17
	3.72	30 −90 −2	Right	Middle occipital gyrus	BA 18
82	4.43	2 −36 42	Right	Cingulate gyrus	BA 31
	3.75	12 −36 40	Right	Cingulate gyrus	BA 31
71	4.25	22 26 24	Right	WM	
	3.68	14 28 18	Right	Anterior cingulate	BA 24
59	4.27	22 −90 8	Right	Cuneus	BA 17
	4.01	8 −82 18	Right	Cuneus	BA 18
	3.59	10 −94 10	Right	Cuneus	BA 18
33	4.25	12 64 −2	Right	Medial frontal gyrus	BA 10
22	4.12	46 −80 −2	Right	Inferior occipital gyrus	BA 19
36	3.98	54 −60 14	Right	Middle temporal gyrus	BA 19
38	3.94	22 −68 −22	Right	Cerebellum, declive	
58	3.91	−16 62 0	Left	Medial frontal gyrus	BA 10
	3.44	−20 52 0	Left	Superior frontal gyrus	BA 10
30	3.76	−22 −66 26	Left	Precuneus	BA 7
	3.44	−18 −58 24	Left	Precuneus	BA 31
55	3.68	18 56 10	Right	Superior frontal gyrus	BA 10
40	3.68	20 −32 52	Right	Postcentral gyrus	BA 3
	3.63	22 −40 50	Right	Paracentral lobule	BA 5

Localisation of local maxima. Statistics uncorrected for multiple comparisons
(voxel $p < 0.001$, two-sided *t*-test)
Clusters marked asterisks comprise voxels that were significant when using FWE corrected statistics
($p < 0.05$, two-sided *t*-test)

Table 3 Main activations and deactivations during continuous meditation

No. of voxels	z Score	Coordinates (xyz)	Laterali-sation	Anatomical area	BA
Activations , voxel-level $p < 0.001$, uncorrected, cluster-level $p < 0.035$, uncorrected					
26	4.15	−4 12 6	Left	Caudate head/lateral ventricle Bilateral (but mainly left) caudate head/lateral ventricle (40%)	
Deactivations, voxel-level $p < 0.001$, uncorrected, cluster-level $p < 0.01$, uncorrected					
139	5.4	48 −42 22	Right	Insula* Insula (BA 13) superior temporal gyrus (BA 22), inferior parietal lobe (WM 85%),	BA 13
236	5.22	32 2 30	Right	Precentral gyrus* Inferior frontal gyrus (BA 9), precentral gyrus (BA 6), insula (BA 13), claustrum, putamen (WM 83%)	BA 6
1,367	5.22	54 −36 −16	Right	Middle temporal gyrus* Middle and inferior temporal gyrus (BA 20, 21) parahippocampal gyrus (BA 35, 36), insula (BA 13), fusiform gyrus (BA 20, 37), angular (BA 39), middle and superior occipital, and lingual gyrus (BA 17, 18, 19), cuneus (BA 7, 17, 18, 19), precuneus (BA 31), posterior cingulate (BA 30, 31), cerebellum (WM 69%)	BA 20
112	5.05	28 24 10	Right	Claustrum Claustrum, insula (BA 13), inferior frontal gyrus (BA 47) (WM 81%)	
147	4.67	32 −86 −14	Right	Middle occipital gyrus Lingual gyrus, inferior, and middle occipital gyrus, cuneus (BA 17, 18, 19) (WM 61%)	BA 18
82	4.43	2 −36 42	Right	Cingulate gyrus Cingulate gyrus (BA 31), precuneus, paracentral lobe (BA 7, 31) (WM 43%)	BA 31
71	4.25	22 26 24	Right	WM Anterior cingulate (BA 24), WM (100%)	
59	4.27	22 −90 8	Right	Cuneus Cuneus, middle occipital gyrus (BA 17, 18) (WM 88%)	BA 17
33	4.25	12 64 −2	Right	Medial frontal gyrus Medial and superior frontal gyrus (BA 10) (WM 85%)	BA 10
22	4.12	46 −80 −2	Right	Inferior occipital gyrus Middle and inferior occipital gyrus (BA 18, 19) (WM 90%)	BA 19
36	3.98	54 −60 14	Right	Middle temporal gyrus Middle and superior temporal gyrus, occipital lobe (BA 19, 22, 39) (WM 25%)	BA 19
38	3.94	22 −68 −22	Right	Cerebellum, declive	
58	3.91	−16 62 0	Left	Medial frontal gyrus Medial and superior frontal gyrus (BA 10) (WM 98%)	BA 10
30	3.76	−22 −66 26	Left	Precuneus Precuneus (BA 7) (WM 97%)	BA 7
55	3.68	18 56 10	Right	Superior frontal gyrus Anterior cingulate, superior and medial frontal gyrus (BA 10) (WM 95%)	BA 10
40	3.68	20 −32 52	Right	Postcentral gyrus Postcentral gyrus (BA 3), paracentral lobule (BA 5) (WM 98%)	BA 3

Localisation of clusters according to MSU, with relative amounts of white matter (WM) indicated

Clusters marked asterisks comprise voxels that were significant when using FWE corrected statistics ($p < 0.05$, two-sided *t*-test)

In both hemispheres, parts of the superior and medial frontal gyrus (BA 10), and precuneus at the junction of the temporal, parietal and occipital lobes (BA 7) were deactivated. In the right hemisphere, deactivations were also found in the anterior cingulate (BA 24), the inferior frontal gyrus (BA 9, 47), the pre- and postcentral gyri (BA 6, 3), the paracentral lobe (BA 5), areas of insula (BA 13), claustrum, and putamen. Also areas in the angular gyrus, the inferior parietal, the middle and superior temporal lobe (BA 39, 20, 21, 22), the parahippocampal and fusiform gyrus (BA 35, 36, 37, 20) were deactivated, and parts of the posterior cingulate, precuneus, and cuneus, the middle and the inferior occipital gyri as well as the lingual gyrus (BA 30, 31, 7, 17, 18, 19) were involved.

Independent component analysis

The concatenation GICA identified 38 components (IC's) shared by the subjects. A number of the components are easily identified as corresponding to previously established baseline-resting state (BRS) networks (Beckmann et al. 2005), while other components may have functions that can be putatively identified. The anatomical localisations of the BRS network components are tentatively described next.

Component 21 and 27 correspond to an *executive control network* designated as "f" in (Beckmann et al. 2005). IC 21 is located in the left premotor and prefrontal cortex, and it includes areas in the superior, middle and inferior frontal gyri, as well as the right inferior frontal gyrus. IC 27 is located in the anterior and central cingulate cortex, including posterior and central parts of corpus callosum. Parts of the inferior, middle and superior temporal lobes, stretching into the inferior parietal lobe, are involved as well.

Two components, IC 14 and IC 23, correspond to *the sensory-motor system*, designated as "d" in (Beckmann et al. 2005). IC 14 contains areas that represent the face, mouth and throat, while IC 23 contains areas representing the body, torso and limbs.

One component, IC 2, corresponds to network "c" in (Beckmann et al. 2005), where it is described as *the auditory system*. This component comprises the primary and secondary auditory areas in the temporal cortex, as well as language-related areas in the frontal, insular and parietal lobes. Also included are the anterior cingulate cortex and parts of the basal ganglia and thalamus. In addition are areas in the prefrontal, parahippocampal and sensory-motor cortices. While this component network may actually comprise the auditory system, its broad distribution and its inclusion of cingulate, prefrontal and parahippocampal areas, as well as parts of the thalamus and basal ganglia, suggest that audition may not be its only function (see below).

Seven components are related to *visual functions*. Among these, IC's 9 and 30 are concerned with the *basic visual functions* in the primary and secondary visual cortical areas. IC 9 extends over the medial primary visual cortical areas (Designated as “a” in Beckmann et al. 2005). IC 30 incorporates the secondary lateral and dorsal visual areas. This network was designated as “b” in (Beckmann et al. 2005).

Two components comprise *the visuo-spatial system*, which are designated as “e” in (Beckmann et al. 2005). IC 4 encompasses the ventral aspects of the posterior cingulate and the medial prefrontal cortex. The posterior parietal cortex and the occipito–parietal junction are also included. IC 25 includes the dorsal aspects of the posterior cingulate and precuneus. The lateral geniculate is involved, as are areas of the posterior parietal cortex located anteriorly to those in IC 4.

Three components contain *the dorsal visual stream*. The corresponding component networks were designated as “g” and “h” in (Beckmann et al. 2005). IC 17 comprises the right lateral occipital and parietal cortex. IC 5 covers the left lateral occipital and parietal cortex. It also includes the dorsal aspect of the inferior parietal cortex. IC 8 contains the more ventral aspects of the inferior parietal cortex in relation to IC 5.

Other notable components that may represent functional networks or units are IC 7 in the parahippocampal gyrus, IC 16 in the prefrontal and temporal areas, IC 22 in the medial and superior frontal areas, and IC 24 in the thalamus and basal ganglia.

IC 7 in the parahippocampal gyrus may be involved in the space–time integration of sensory information related to intentional activity (cf. Freeman 2000).

IC 16 is found in the posterior ventrolateral prefrontal cortex and anterior parts of the inferior temporal gyrus, as well as in areas of the middle part of the medial and superior temporal gyrus. These areas may serve spatial working memory related to the volitional control of activity. IC 22 is located in the superior and middle frontal gyrus, gyrus frontalis medius and parts of the anterior and middle cingulate gyrus. This component may represent areas involved in more motivationally related executive control of activity (cf. Kopell and Greenberg 2008).

Component 24 covers the thalamus and the basal ganglia, which are known to be involved in the overall integration of cerebral functions.

Movement artefacts Most components are to some degree influenced by movement artefacts. IC 1 is highly correlated with realignment parameters, as are ICs 11–15 and 20–22, 26, 28–29, 31–34 and 36–37 (see Fig. 4). In contrast, IC 2, 4, 17, 27, 38 and 10 appear to be relatively less influenced by movement.

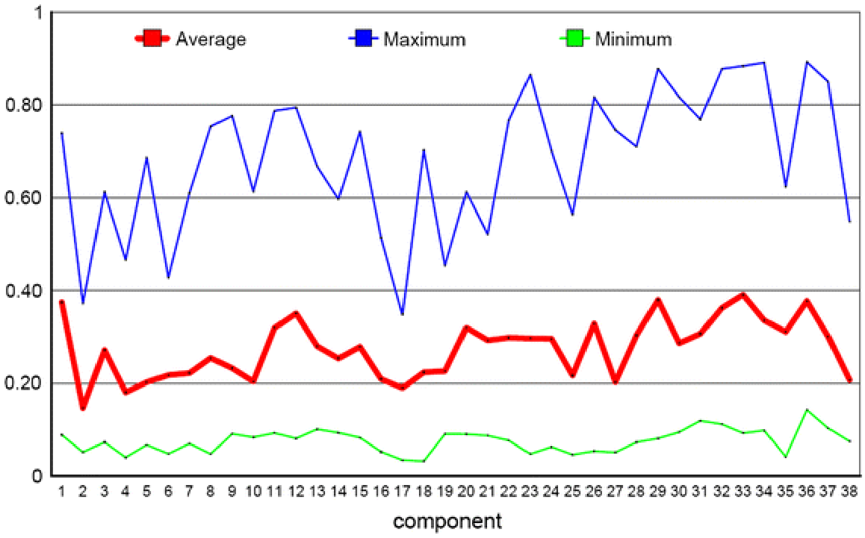

Fig. 4 Correlation of component time series with realignment parameters from SPM preprocessing. On the x axis are the component numbers. On the y axis are correlation coefficients for components versus realignment parameters. The time series of all components from each subject were correlated with the corresponding realignment parameters. Lines show the minimal (green), average (red) and maximal (blue) correlation for all component time series with the corresponding realignment parameters (colour figure online)

One unanticipated and unfortunate consequence of the individual pacing of the meditation was that the temporal progress of the psychological process during meditation is correlated with respiration. Since respiration may result in head movements, some real effects may be removed in the preprocessing by image realignment. The extent of this problem is very difficult to assess.

Components caused by cardiac processes Inspection of the Fourier transforms of components reveal that 70% of the frequencies contributing to IC 10 belong to the bands characteristic for cardiac processes (0.05–0.145 Hz), and consequently this component is most probably caused mainly by such manners of circumstance. Inspection of its anatomical localisation correspondingly reveals that it is located in the cerebral ventricles. Both IC 17 and 21 contain 40% contributions in the cardiac frequency band, while IC 2 contains approximately 30% cardiac frequencies and IC 28, 9, and 4 contain approximately 20% cardiac frequencies. However, the anatomical localisations of these components do not suggest that they should be obvious cardiac artefacts (Fig. 5).

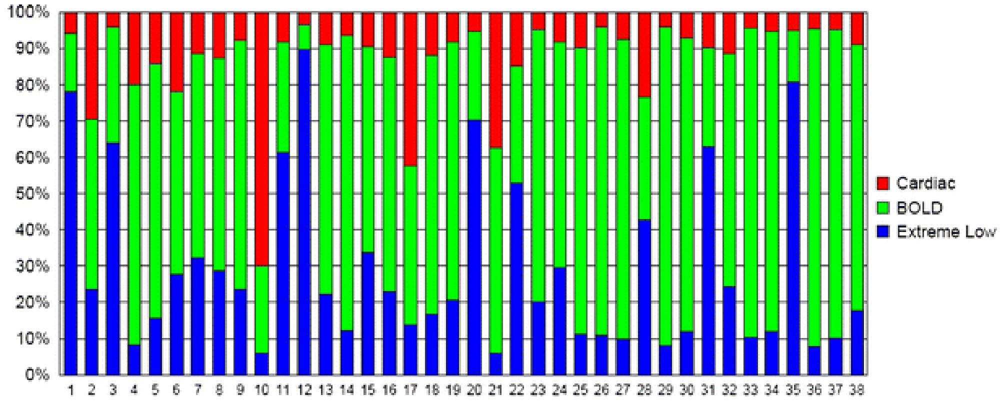

Fig. 5 The contribution of different frequency bands in the Fourier transforms of time series from group components. On the x axis are the component numbers. On the y axis are relative share of the total contributing frequencies in per cent. Bars show the relative contribution of extremely low frequencies (blue), frequencies corresponding to the BOLD haemodynamic response function (green), and corresponding to cardiac processes (red). The frequency bands are determined as Extreme Low: 0.0000–0.0089 Hz. BOLD: 0.01–0.05 Hz, Cardiac: 0.05–0.145 Hz (colour figure online)

In summary, out of the 38 identified components, twelve may be characterised as corresponding to known BRS components (2, 4, 5, 8, 9, 14, 17, 21, 23, 25, 27, 30), four may be putatively identified as other functional networks (7, 16, 22, 24). One component is most probably caused by movements and one by cardiac processes. This leaves 20 components unidentified.

Combination of ICA and SPM

In the combined ICA and SPM analysis, a single component (“component 2”) exceeded the statistical threshold (voxel $p < 0.001$, cluster $p < 0.01$, uncorrected for multiple comparisons; see Figs. 6, 7; Tables 4, 5).

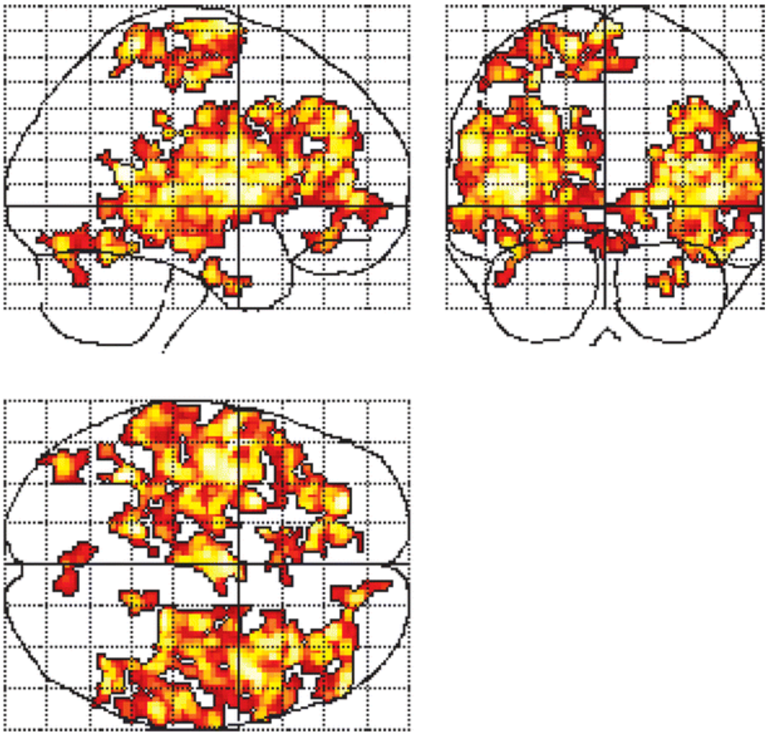

Fig. 6 Combined ICA and SPM analysis of continuous sustained meditation. Voxels in which the signal variations follow the time course of IC 2 are displayed in yellow and red (SPM5 random effects analysis, statistics uncorrected for multiple comparisons, voxel $p < 0.001$, cluster $p < 0.01$, one-sided t-test) (colour figure online)

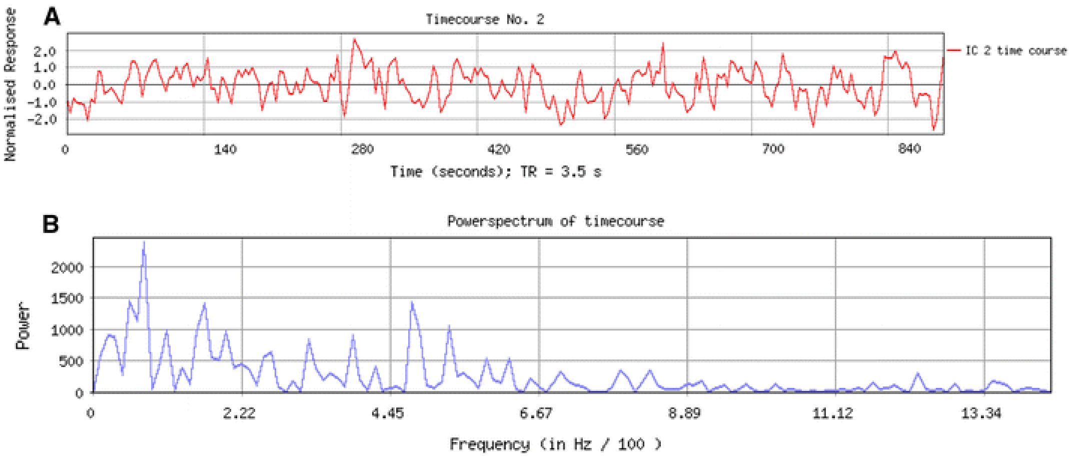

Fig. 7 Time course and Fourier transform of component 2 as identified in the concatenation group ICA. a Time course of activity variations in the brain areas participating in component 2. b Fourier transform of the time series, revealing the relative weight of different contributing frequencies

Table 4 Continuous meditation; component 2 identified from FSL data with the Talairach Daemon after conversion of coordinates to Talairach space

Cluster	Coordinates (xyz)	Lateralisation	Anatomical area
1	−42 −22 4	Left	Insula (BA 13)
	46 −14 4	Right	Insula (BA 13)
	−50 −34 4	Left	Superior temporal gyrus (BA 22)
	66 −34 0	Right	Middle temporal gyrus (BA 22)
	−10 −30 4	Left	Thalamus pulvinar
	14 −58 0	Right	Lingual gyrus (BA 19)
	14 −30 4	Right	Thalamus pulvinar
	22 −38 −4	Right	Parahippocampal gyrus (BA 1)
	−14 −54 −4	Left	Cerebellum anterior lobe culmen
	10 −18 4	Right	Thalamus
	26 −58 −4	Right	Parahippocampal gyrus (BA 19)
	−22 −82 −8	Left	Lingual gyrus (BA 18)
	−26 −66 −8	Left	Fusiform gyrus (BA 19)
	54 18 4	Right	Precentral gyrus (BA 44)
	−26 −82 −16	Left	Cerebellum posterior lobe declive
	22 −78 −4	Right	Lingual gyrus (BA 18)
	58 −46 12	Right	Superior temporal gyrus (BA 22)
	46 22 16	Right	Middle frontal gyrus (BA 46)
2	2 10 8	Left	Caudate caudate body
	2 34 12	Left	Anterior cingulate (BA 24)
	−14 22 4	Left	Caudate caudate body
3	50 −26 56	Right	Postcentral gyrus (BA 2)
	38 −26 60	Right	Precentral gyrus (BA 4)
4	−38 −50 −20	Left	Cerebellum anterior lobe culmen
	−46 −46 −24	Left	Cerebellum anterior lobe culmen
5	−42 −70 −4	Left	Inferior temporal gyrus (BA 37)
6	6 −82 −8	Right	Cerebellum posterior lobe declive
	−6 −82 −8	Left	Cerebellum posterior lobe declive
7	−30 −26 −20	Left	Parahippocampal gyrus hippocampus
8	10 −46 48	Right	Cingulate gyrus (BA 31)
9	−34 38 40	Left	Middle frontal gyrus (BA 8)
10	42 −18 28	Right	No grey matter found
11	22 −10 −28	Right	Parahippocampal gyrus (BA 28)
12	18 6 48	Right	Cingulate gyrus (BA 24)
13	42 38 32	Right	Middle frontal gyrus (BA 9)
14	2 58 28	Left	Superior frontal gyrus (BA 9)
15	50 38 24	Right	Middle frontal gyrus (BA 9)
16	−42 50 20	Left	Middle frontal gyrus (BA 10)
17	−26 −98 −16	Left	Fusiform gyrus (BA 18)
18	−6 −38 60	Left	Paracentral lobule (BA 5)
19	38 −46 60	Right	Inferior parietal lobule (BA 40)
20	22 34 48	Right	Superior frontal gyrus (BA 8)
21	34 30 48	Right	Superior frontal gyrus (BA 8)
22	6 −66 48	Right	Precuneus (BA 7)
23	−30 −78 48	Left	Precuneus (BA 19)
24	−2 −86 40	Left	Cuneus (BA 19)
25	10 6 36	Right	Cingulate gyrus (BA 24)
26	10 −42 36	Right	Cingulate gyrus (BA 31)
27	−42 34 32	Left	Middle frontal gyrus (BA 9)
28	−38 −82 32	Left	Middle temporal gyrus (BA 19)
29	−46 −78 28	Left	Middle temporal gyrus (BA 39)
30	30 62 20	Right	Superior frontal gyrus (BA 10)

Table 5 Continuous meditation; component 2 identified with SPM5

Cluster	No. of voxels	z Score	Coordinates (xyz)	Laterali-sation	Anatomical area
1	176	4.36	−36 −50 14	Left	Superior middle and inferior temporal gyrus (B 18, 22, 39)
2	351	4.27	−26 44 36	Left	Superior middle and medial frontal gyrus (B 9, 10) Anterior cingulum (B 24, 32)
3	3,215	4.22	−50 −2 8	Left	Inferior frontal gyrus and precentral gyrus (B 9, 45, 46, 44, 6, 4) Postcentral and inferior parietal gyrus (B 2, 43, 40) Superior middle and transverse temporal gyrus (B 41, 42, 22, 21, 36) Parahippocampal gyrus (B 27, 28, 35) hippocampus Insula (B 13) claustrum Nucleus ruber Putamen lateral and medial globus pallidus Thalamus: pulvinar ventrolateral nucleus, lateral geniculate
4	406	4.17	0 −6 76	Left	Superior and medial frontal gyrus (B 6)
				Right	Superior and medial frontal gyrus (B 6)
5	252	4.15	−14 −44 66	Left	Pre- and postcentral gyrus (B 6, 1, 2, 3, 4, 5) Superior and inferior parietal gyrus (B 5, 7) Precuneus (B 7)
6	3,415	4.12	46 6 4	Right	Superior middle medial inferior frontal gyrus and Precentral gyrus 4) Postcentral and inferior parietal gyrus (B 40) Superior middle and Transverse temporal gyrus (B 22, 21, 41, 42) Parahippocampal gyrus (B 27, 36) hippocampus Insula (B 13) claustrum Caudate nucleus temporal tail. Putamen lateral globus pallidus Thalamus: pulvinar Ventroposterolateral and ventrolateral nucleus
7	205	3.97	50 44 6	Right	Middle and inferior frontal gyrus (B 10, 44, 45, 46)
8	58	3.97	38 14 44	Right	Middle frontal gyrus, precentral gyrus (B 9, 6)
9	155	3.88	48 −56 −20	Right	Fusiform gyrus, inferior and middle temporal gyrus (B 37, 20)
10	78	3.88	−14 10 38	Left	Anterior cingulum (B 32, 33, 24)
11	134	3.87	−30 −22 52	Left	Precentral gyrus middle and superior frontal gyrus (B 4, 6)
12	138	3.85	14 50 2	Right	Anterior cingulum medial frontal gyrus (B 32, 10)
13	57	3.77	58 −26 −14	Right	Middle temporal gyrus (B 21)
14	92	3.75	32 −12 −28	Right	Uncus parahippocampal gyrus (B 28, 36)
15	116	3.74	−42 −76 −16	Left	Fusiform gyrus inferior and middle occip, gyrus (B 18, 19)
16	102	3.72	−30 30 40	Left	Middle and superior frontal gyrus (B 8, 9)
17	60	3.70	−46 −30 30	Left	Inferior parietal and postcentral gyrus (B 40, 2)
18	253	3.67	−44 22 18	Left	Middle and inferior frontal gyrus (B 45, 46, 9) Insula (B 13) claustrum
19	59	3.64	16 −44 −6	Right	Parahippocampal and lingual gyrus (B 30, 19)
20	94	3.63	−30 38 −12	Left	Middle and inferior frontal gyrus (B 11, 47)
21	64	3.61	−46 −28 54	Left	Postcentral gyrus (B 2, 1, 3)
22	97	3.54	0 −74 −18	Left	Lingual gyrus (B 18)
				Right	Lingual gyrus (B 18)
23	66	3.52	−2 16 2	Left	Caudate nucleus, head
				Right	Caudate nucleus, head

Voxel $p < 0.001$ uncorected; Cluster $p < 0.025$ uncorrected

When identified by SPM, component 2 consists of 23 clusters comprising a total of more than 5,000 voxels located in the medial and lateral parts of the prefrontal cortex, and in the anterior cingulate, basal ganglia, thalamus, insula, parts of the temporal lobe, along with the parahippocampal gyrus and the postcentral, parietal and posterior cingulate areas. Although mainly represented in the left hemisphere, it is largely symmetrical.

A comparison of 52 coordinates describing the localisation of IC 2, as identified by FSL, with 190 coordinates describing the localisation of IC 2, as identified by SPM (uncorrected statistics), reveal that all coordinates from the FSL analysis lie within a distance of 23 mm (94% <20 mm) of the coordinates of the SPM analysis. On the other hand, 60% of the coordinates from the SPM analysis are within 20 mm from coordinates from the FSL analysis, and 87% are within 30 mm distance, and 1% are more than 40 mm away.

As previously mentioned, a component similar to IC 2 has been designated as the “auditive system” resting state network (Beckmann et al. 2005). Its anatomical composition (including dorsolateral and medial prefrontal, anterior and posterior cingulate, and parahippocampal cortices, insula and subcortical nuclei thalamus and the caudate nucleus) suggests it may serve other functions as well. It is interesting to remark that the activated cluster in the head of the caudate nucleus, which was revealed in the SPM random effects analysis, is located within the cluster containing the caudate nucleus in IC 2 in the combined ICA and SPM analysis.

It is noteworthy that IC 2 was the only component, which could be recognised in the SPM analysis. It is also worth mentioning that the pattern of deactivation established in the “normal” SPM analysis appears to some degree complementary to the distribution of areas participating in IC 2, at least in the right hemisphere. Finally it may be noted that the time series of IC2 (Fig. 7a) reveal a general increase of signal level during the “onset” phase of the meditation.

It therefore seems appropriate to give a more elaborate description of this component as depicted in the ICA.

Localisation of component 2

IC 2 encompasses large distributed areas of the brain. One largely bilateral cluster contains numerous areas distributed from the prefrontal lobes to the cerebellum. Some of these areas are only represented in one or the other hemisphere, but in several instances similar areas in the opposite hemisphere are represented in separate clusters.

The large bilateral cluster contains ventrolateral areas in the right middle frontal gyrus (BA 46), the right precentral gyrus (BA 44) and bilateral areas in insula (BA 13). Also included are bilateral parts of the superior temporal gyrus (BA 22), continuing into the right middle temporal gyrus (BA 22), the right parahippocampal gyrus (BA 19), the left fusiform gyrus(BA 19), and bilateral lingual gyrus (BA 18, 19), stretching into the cerebellum. Some areas in the thalamus were involved as well (bilateral in pulvinar and the right medial dorsal nucleus).

One notable cluster is located in the caudate nucleus (body), in the vicinity of the anterior cingulate gyrus (BA 24).

Nine separate clusters are distributed bilaterally in the DLPFC, the middle and superior frontal gyrus (BA 8, 9, 10), in the left hemisphere also (BA 46) and medial areas in the superior frontal gyrus (BA 9). In the right hemisphere, the superior frontal gyrus (BA 8) is represented. Two clusters are located in the right anterior cingulate (BA 24). Three clusters are located in the dorsal parts of the right pre- and postcentral gyrus (BA 4, 2), and medially in the left paracentral lobe (BA 5).

One cluster is located in the left middle temporal gyrus, two in the left parahippocampal gyrus (hippocampus) and the right parahippocampal gyrus (BA 28, 35).

One cluster is found in the right inferior parietal lobe (BA 40), while four clusters are in the posterior part of the left fusiform gyrus (BA 18), the left superior and middle occipital gyri at the junction to the temporal lobe (BA 19, 37).

Five clusters are distributed in the right precuneus (BA 7, 31), the left cuneus and precuneus (B 19) and the right posterior cingulate (BA 31).

Some clusters are found in the cerebellum. As the cerebellum was not scanned in its entirety, they will not be considered here.

Correlations among components

In order to possibly identify networks corresponding to the hypothesised “threshold regulating mechanism”, the mutual correlations among the components were computed. The results are illustrated in Fig. 8 depicting the neural systems concerned and Fig. 9 that shows the correlations among the corresponding component time series from the individual subjects.

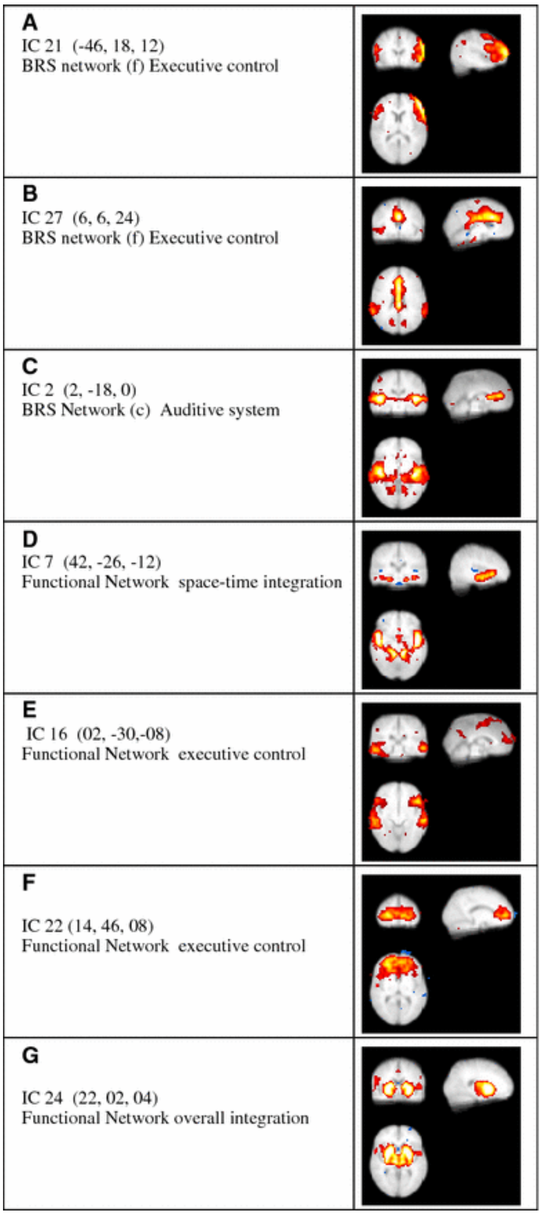

Fig. 8 Selected components identified by ICA of continuous sustained meditation. These components may be related to ececutive control of attention (a–f),and overall integration of neural processes supporting consciousness (g). Components similar to IC 21 and 27 (a, b) have been identified in baseline-resting state investigations and designated as related to executive control. According to their anatomical localisation, IC 7, 16 and 22 (d–f) may also be involved in executive control of attention. Component 2 (c) is identified in this study as being related to the state of meditation, and component 24 (g) encompass the thalamus and basal ganglia which are known to be related to overall integration of cerebral functions

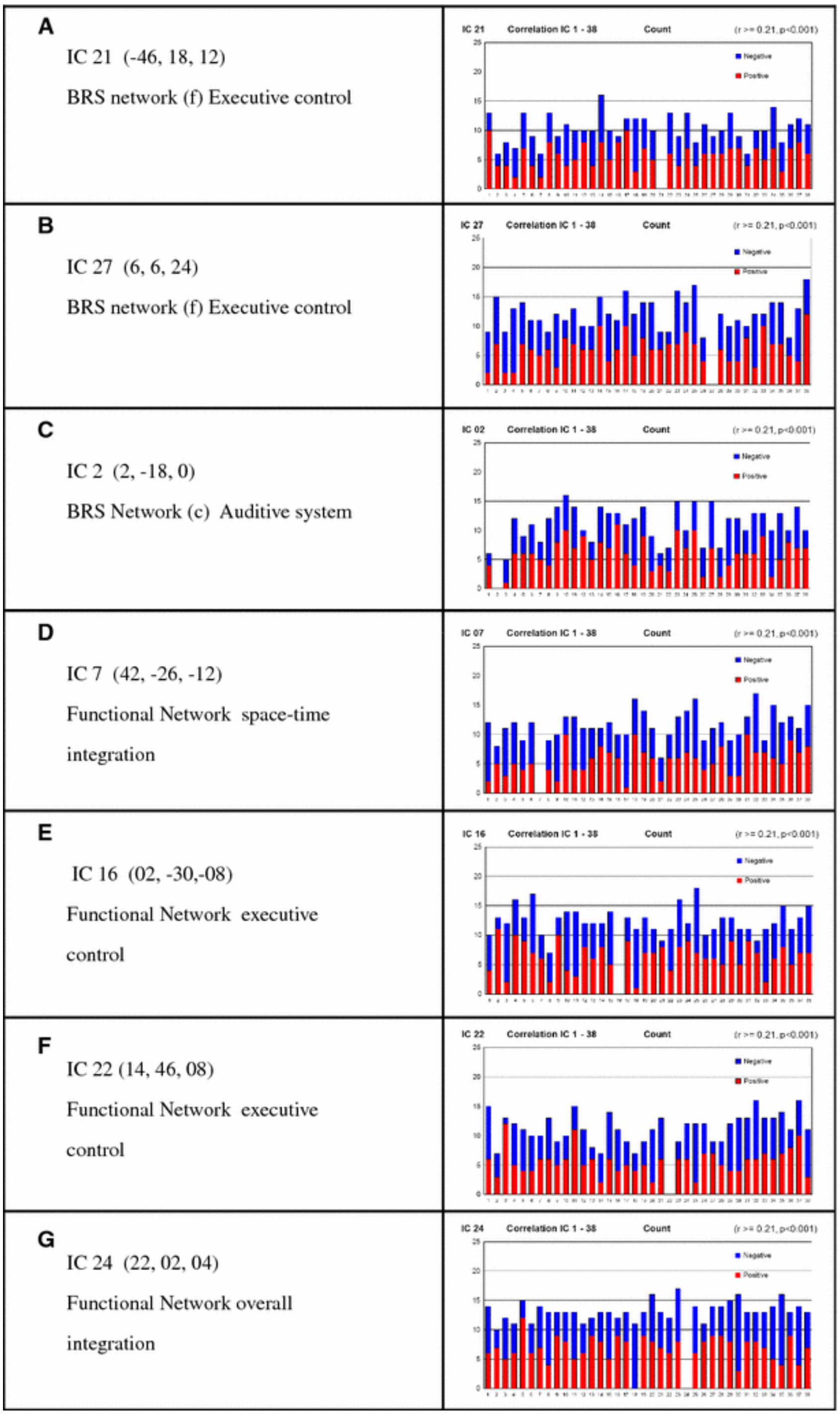

Fig. 9 Correlations among selected components identified by ICA of sustained meditation. The figures show the number of subjects exhibiting positive (red) and negative (blue) correlations among the selected component, and the remaining 37 other components that were identified in the ICA analysis of continuous sustained meditation. On the x axis is the component number (the empty space reveal the position of the selected component). Numbers on the y axis indicate the total number of subjects showing statistically significant correlation coefficients ($df = 255$, $r = 0.21$, $p < 0.001$) (colour figure online)

This analysis reveals that most components show both positive and negative correlations with other components. None of the components in the illustrated subset are either correlated or uncorrelated in all subjects. Even those components that are only correlated in a few subjects are in most cases positively correlated in some subjects while negatively correlated in others. Only one set of components

(IC 24 and IC 18) is exclusively negatively correlated with other components in all cases of observed correlation.

Thus, the 38 components identified in the ICA show a complicated pattern of mutual temporal correlations. The number of statistically significant positive and negative in-phase correlations between component 2 and other selected components is illustrated in Table 6; and, in Figs. 8 and 9 for a smaller subset only comprising components which may be related to executive control.

Table 6 Number of subjects with correlation between component 2 and other components ($df = 255$; $r > = 0.21$; $p < 0.001$)

	Baseline-resting state components											Other functional components			
Component no.	4	5	8	9	14	17	21	23	25	27	30	7	16	22	24
Correlation															
Positive	6	6	4	8	8	6	4	10	10	7	6	5	11	3	7
Negative	6	3	8	6	6	5	2	5	5	8	6	3	2	4	3
Sum	12	9	12	14	14	11	6	15	15	15	12	8	13	7	10

Discussion

During the shift from the resting state to meditation (meditation onset) activations were found bilaterally in the basal ganglia. Bilateral clusters of activations were similarly found in the medial frontal, the precentral and inferior parietal gyri, as well as in the right hemisphere in insula. Deactivations were found medially in the right occipital and parietal lobes, in the right precuneus, the dorsal posterior cingulate, the parieto–temporal junction and, finally, in the superior temporal lobe.

Analysis of the continuous meditation data revealed no activations, and only a few small deactivated clusters located in the insula, the precentral- and the middle temporal gyrus of the right hemisphere. When uncorrected statistics was employed, one cluster was found activated in the head of the left caudate nucleus. The deactivations appeared as peaks in larger clusters, located mainly in the right hemisphere, largely in white matter. They included areas in the frontal, central, parietal, temporal and occipital lobes, the anterior and posterior cingulate, as well as parahippocampal gyrus, and areas of insula, claustrum and putamen.

The independent component analysis identified 38 components in common for the scanned subjects. SPM analyses could only identify one of the 38 components. This component comprises clusters that overlap with the clusters, which are found activated and deactivated in the normal SPM analysis. It incorporates large widely distributed areas in the dorsolateral and medial prefrontal cortex, the anterior and posterior cingulate areas, pre- and postcentral areas, inferior parietal, temporal (incl. parahippocampal) areas as well as clusters in the occipital lobes, the insula, the basal ganglia and thalamus in both hemispheres. Twelve components are similar to the functional components found in studies of the baseline-resting state, while 4 others may be assigned functional roles; two may be identified as artefacts and 20 are as yet unidentified.

Meditation onset

Activations in the medial frontal gyrus, in the DLPFC,[8] and more lateral activations in the inferior frontal gyrus were found in this and comparable studies (Brefczynski-Lewis et al. 2007; Bærentsen et al. 2001; Farb et al. 2007; Hölzel et al. 2007b), although not at exactly identical locations or to the same extent. These areas are presumably implicated in the task-related control of attention (e.g. Dosenbach et al. 2007), which is a common factor in all studies of meditation.

The present study did not replicate the finding of activations in the parts of ACC found in a previous study (Bærentsen et al. 2001), but when using uncorrected statistics a cluster was present in the central cingulate. Although Hölzel et al. (2007b) found activations in the ACC at a more rostral position, and both Brefczynski-Lewis et al. (2007) and Hölzel et al. (2007b) did find some effects in ROI analyses of the ACC when comparing subjects with different amounts of experience in meditation, their findings point in opposite directions. It thus becomes difficult to conceive a straightforward interpretation. Differences may be related to an inverted U-curve effect of training and expertise, in the manner suggested by Brefczynski-Lewis et al. (2007), but may however also be the product of differences in type of meditation, and the amount of intentional effort required in target and baseline tasks.

In agreement with the study by Farb et al. (2007), bilateral deactivations were found in the superior and medial frontal gyri. This is consistent with the change

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[8] When uncorrected statistics were used.

from evaluative to non-evaluative self-monitoring during meditation, which is not stressed in the studies by Brefczynski-Lewis et al. (2007) and Hölzel et al. (2007b).

Activations in the inferior parietal lobes were found in the present study, in our earlier study (Bærentsen et al. 2001) and in the study by Farb et al. (2007), but were not present in studies by Brefczynski-Lewis et al. (2007) or Hölzel et al. (2007b). The different findings may be related to the nature of the experimental tasks. The present study and the study by Farb et al. were both concerned with the "me" versus "I" distinction (cf. Farb et al. 2007), while this was not the case in the studies of Brefczynski-Lewis and Hölzel et al. The activations in the inferior parietal and the deactivation in the parieto–temporal area at the angular gyrus are both located in tertiary sensory association areas, which may be involved in higher order integration of sensory information to meaningful semantic experience (Luria 1972; Nieuwenhuys 2001), and additionally in the regulation of attention (Dosenbach et al. 2007). They may therefore be engaged during the transition to forms of meditation requiring semantic integration, and only to a smaller degree in tasks less demanding in this respect.

Activations in insula that were similar to those observed in the present study have similarly been recorded in other studies (Bærentsen et al. 2001; Brefczynski-Lewis et al. 2007; Farb et al. 2007). This may indicate that the regulation of autonomic and somatic processes is an integral part of meditation (i.e. it is an activity with corporeal aspects, cf. Critchley et al. 2001), but potentially it could also be a reflection of the involvement of insula in executive control (Dosenbach et al. 2007; Sridharan et al. 2008).

Deactivations during meditation were found to be most prominent in posterior areas of the brain. Deactivations similar to those observed by Brefczynski-Lewis et al. (2007) in the anterior temporal lobes were not seen and have not been reported in other investigations. Similarly, the widespread deactivation of areas in most of the cerebrum during mindfulness [reported by Hölzel et al. (2007b) as activation during mental arithmetic] was not seen here and has not been reported in other studies.

The extensive deactivation of PCC was opposite to the activation of similar areas in the Hölzel et al. (2007b), but due to the different contrasting states (rest and mental arithmetic) employed in the two studies, they both imply that regulation of self-related processing in these areas is a significant factor in the transition into meditation. Their absence in the study of Farb et al. (2007) and the

Brefczynski-Lewis et al. (2007) might be explained by the employed contrasts, which did not induce significant differences in the “me-” or self-relatedness of their subjects.

The deactivation of the PCC area corresponds quite closely to findings from studies of “resting state” or the “default mode network” (e.g. Greicius et al. 2003; Raichle et al. 2001; Raichle and Snyder 2007). Although the peaks of the deactivations are at slightly different positions, and the major deactivation site is in the right hemisphere in our study, there is a considerable overlap between the findings. The posterior cingulate deactivation supports the notion that meditation is different from normal relaxation (cf. Raichle et al. 2001; Raichle and Snyder 2007) in the sense that it may indeed match the cessation of self-related thinking, and corresponding attempts towards not being distracted (captured) during meditation by the contents of thoughts and impressions. Deactivations in the anterior cingulate corresponding to those observed in the “default mode” studies were not observed. This suggests that meditation is also different from most cognitive tasks that require attention to task-related aspects of the external spatio–temporal context. During meditation the task-related attention remains focussed on the self in the sense of Patanjali.

Activations in the basal ganglia and thalamus during meditation have also been observed in other studies (Bærentsen et al. 2001; Brefczynski-Lewis et al. 2007). It is interesting to note that the same location in the putamen was found deactivated in a study of the Wisconsin Card Sorting Test (WCST) during the reception of negative feedback and activated during the following attempt at a new matching strategy (Monchi et al. 2001). This suggests that the subjects in our study are attending to the character of their “mental strategy” when they commence meditation.

As in the WCST study - but different from other meditation studies discussed here - we found activations in premotor cortex, although mainly in the supplementary motor area. This again indicates a regulation of attention, which in the case of meditation is directed at the subjects’ own mental and bodily state, while in the WCST it is directed at external stimuli.

The activations in the basal ganglia and thalamus (together with activations in the medial prefrontal cortex) support the proposal advocated by Travis and Wallace (1999) that a network of brain areas effectuate the phasic control associated with the intentional shift from ordinary state of mind into meditation (“the neural switch”). They proposed that this might be centred in the frontal lobes, and that it imposes a general inhibitory influence on physiological functions via the cortico–striato–thalamo–cortical, the cortico–thalamo–cortical and the cortico–ponto–cerebellar–thalamo–cortical loops (cf. Nieuwenhuys 2001). Although we did not find general inhibition of cortical activity, we did find significant deactivations in the PCC area and in other areas of cortex.

Travis and Wallace (1999) also proposed the existence of a “threshold regulation mechanism” affecting a tonic control of cortical excitability, constituted by neural feedback loops centred on subcortical structures, which they hypothesise to be the basal ganglia as involved in basal ganglia-thalamocortical feedback loops. They described these loops as forming a highly structured set of connections sending input from frontal-, temporal-, parietal- and occipital areas of the cortex to the caudate nucleus, from which they are directed via the putamen and globus pallidus to the mesencephalic reticular formation and thalamus, and accordingly influence the cortical tonus and processing.

The two networks proposed by Travis and Wallace are not mutually excluding, but rather the latter forms a subset of the former, and they are differently accentuated, one being centred in the prefrontal cortex, and the other in the subcortical nuclei, most prominently the basal ganglia.

The studies described here are in line with the suggestions made by Travis and Wallace (1999) of a neural switch function that involves extensive cortical–subcortical loops, although the involvement of particular prefrontal and subcortical parts of the brain appears to depend on the nature of the required change of mind. Judging by the mixture of activations and deactivations found in different areas of the brain, it seems doubtful whether the meditative state is actually “relaxed” in the sense of a general lowering of cortical tonus, which was otherwise suggested in the original model proposed by Travis and Wallace (1999).

Whereas Travis and Wallace conceived of meditation as a species of relaxation, involving a lowering of cortical tone, the results from this investigation suggest a more differentiated influence on cortical tonus. We would rather propose that it is not cortical tonus that is down-regulated, but rather the “mental” (narrative, discursive, evaluative) processing of experiences, along the lines suggested by Josephson (1978). Contrary to the suggestions of Travis and Wallace, this may involve the maintenance of a high level of tonus in cortex, and this may be a factor related to the increase of attention and processing power described in several studies (e.g. Carter et al. 2005; Guo and Pagnoni 2008; Jha et al. 2007; Srinivasan and Baijal 2007; Tang et al. 2007; Valentine and Sweet 1999).

In summary, the finding of complex patterns of activations and deactivations during meditation onset in medial and inferior lateral frontal, cingulate and parietal cortex, activations in putamen, posterior premotor and motor cortex, supplementary motor cortex, and insula together support Travis and Wallace's (1999) hypothesis of a cortico–striato–thalamo–cortical loop (Alexander et al. 1986, Graybiel 2008, Kopell and Greenberg 2008) executing a voluntary set shift of attention from external matters to the subjects' own state of mind (and body), according to a previously established rule kept in working memory and effected when the signal to meditate is given.

Continuous meditation

SPM study of continuous meditation

The SPM analysis of continuous meditation found activation in the head of the caudate nucleus. According to the anatomical organisation of connections between the cortex and the basal ganglia (Alexander et al. 1986; Kopell and Greenberg 2008; Nieuwenhuys 2001), it is most probable that this particular part of the basal ganglia connects various lateral and medial areas of the prefrontal cortex; while the question of which areas in particular remains unanswered in the current study, further analysis of the continuous meditation data may help clarify this issue.

Only few investigations have identified activity modulations in the caudate nucleus during meditation. PET studies by Lou et al. (1999, 2005) report decreased activity during meditation, while Kjaer et al. (2002) report increased activity in the ventral striatum. More comparable studies by Lazar et al. (2000) and Tang et al. (2009) report increased activity in nucleus caudatus and the putamen. Findings in the Lou et al. study (1999) are in opposition to findings from other studies. This may possibly be related to the experimental procedure involving prolonged meditation before the experiment in the scanner took place. During the scanning, subjects carried out relaxation and guided imagery activities. The experiment may therefore be interpreted as a post-meditation study.

Concerning the widespread deactivations in the posterior parts of the right hemisphere, which were found in the present study, it is remarkable that reports of deactivations during continuous meditation are relatively few. Some deactivations in the superior frontal and superior parietal areas have been reported by Newberg et al. (2001). Tang et al. (2009) report decreased activity in the right ventrolateral frontal areas (BA 47) as well as in parietal, occipital areas, the angular gyrus, the PCC and in thalamus. While there is some overlap between these findings and those reported here (e.g. in the PCC and the parietal lobe), the findings in the present study are not consistent with those of other studies that, incidentally, are not mutually consistent either.

At a general level, the finding of right hemisphere deactivation appear to support the initial hypothesis of Travis and Wallace (1999), suggesting that meditation entails a lowering of cortical tonus - at least with regard to the right hemisphere. A few points of caution pertain to these findings. The present type of analysis of continuous data with SPM is atypical, which makes comparison with other investigations difficult. Furthermore, the nature of "deactivation" in fMRI is disputed (c.f. Raichle 1998; Gusnard and Raichle 2001). Finally, the possible involvement of white matter activity in neuronal processes is not well known (see e.g. Fields 2004, 2008), and in some cases effects found in cerebral white matter may actually be caused by a fusion of effects in grey matter, e.g. due to smoothing procedures. A further discussion of the white matter effects lies outside of the scope of this article.

Results from ICA and ICA - SPM combined

The ICA identified 38 group components. Some notable components were found located mainly in the dorsolateral and medial frontal cortex, the anterior cingulate, the thalamus and the basal ganglia as well as the posterior cingulate - areas important for the regulation of self-determined attention (Dosenbach et al. 2008). Other components comprise areas in the frontal, temporal, parietal and occipital cortices, hippocampal areas and the insula. Although this is interesting, since most of these components also show up in investigations of normal resting states (Beckmann et al. 2005; Fox et al. 2005; Raichle and Snyder 2007), it still does not reveal any specific characteristics of the corresponding neural processes during meditation.

Inasmuch as it was only possible to recognise one component on the basis of their empirically derived time series, even when employing very liberal statistical significance levels, the SPM analysis using ICA time series as regressors produced a surprising result. In most components, the areas of the brain that were identified appeared as rather random patterns of scattered fragments. This raises the question of how the individual time series from the common components found by the GICA-method maps onto the patterns of activations and deactivations as revealed by SPM.

The component localised in the SPM analysis (IC 2) is interesting by its own merit. It connects nicely to the result of the "standard" SPM random effects analysis, as it contains a nearly identical cluster in the caudate nucleus and thus bears some relation to the SPM analysis of continuous meditation data. The localisation of IC 2 may not be entirely identical when established directly from the ICA data and from the subsequent SPM analysis conducted on the basis of the ICA time series, but in the following discussion, we will not distinguish strictly between them.

In the ICA, we found bilateral areas involved in the dorsolateral prefrontal cortex, as well as more ventral lateral (opercular) regions of PFC, and in midline areas that are comparable to some which have been found active in a number of other studies (Herzog et al. 1990–1991; Jevning et al. 1996; Lazar et al. 2000; Newberg et al. 2001, 2003; Raffone et al. 2007) and, in a ROI study by Baron Short et al. (2007). We also observed the inclusion of areas of the anterior cingulate cortex in the component, which other studies have found to be involved in meditation (Baron Short et al. 2007; Lazar et al. 2000; Newberg et al. 2001; Raffone et al. 2007; Tang et al. 2009), although not in entirely identical locations and by varying degrees (cf. discussion of the on–off meditation studies).

Areas in the dorsal aspects of the right pre- and postcentral gyrus and paracentral lobe are reportedly involved in meditation (Lazar et al. (2000). The right inferior parietal lobe has been attributed various implications in studies by Guo and Pagnoni (2008), Lazar et al. (2000) and Newberg et al. (2001, 2003). The participating areas in the cuneus and precuneus along with areas in the occipital lobe have similarly been implicated differently in other studies (e.g. Tang et al. 2009 and studies mentioned in relation to the on–off meditation).

Also involved in component 2 are areas of bilateral hippocampus observed in studies of meditation by Lazar et al. (2000) and Lou et al. (1999). Areas in thalamus that form part of the component have been observed in activation studies as well (e.g. Brefczynski-Lewis et al. 2007; Newberg et al. 2001, 2003). Modulations of thalamic activity during meditation were correspondingly observed by Orme-Johnson et al. (2006). As previously remarked, activity in the basal ganglia has also been observed in various studies.

Activity in the insula has also been observed in meditation studies (e.g. Lutz et al. 2008, see also section about on–off meditation) and in studies of anatomical effects of meditation (e.g. Hölzel et al. 2007a; Lazar et al. 2005).

The finding that these distributed parts of the brain are involved in one component process during meditation may serve to integrate the variable and disparate observations of the aforementioned studies into a coherent picture. However, this calls for an explanation of the dissimilar results of the different investigations.

As can be seen from the time series of the group component (Fig. 7),[9] the level of activity in the areas constituting component 2 does not invariably increase during the entire meditation, but is rather increased and decreased at various intervals. This may be one of the factors behind the occasionally contradictory results of the meditation studies. The different forms of meditation, as well as the differences in experimental tasks and contrasts, may also be a factor in studies using the contrastive methodology of discovering "activated" areas of the brain.

It is interesting to note that many of the areas of the brain, which are often observed in studies of meditation, may be related to the control of attention (Dosenbach et al. 2007). A component, which is very similar to the one detected here was selected for analysis in a study by Guo and Pagnoni (2008). In this study, they documented the effect of meditation on attention by demonstrating a much closer correlation between the time series of the component and the time series describing the experimental paradigm in meditators compared to subjects without training in meditation.

It is also interesting in this connection, that when we compared 52 coordinates describing the localisation of component 2 with a list of 39 coordinates for ROIs used in a study of attention regulating networks (Dosenbach et al. 2007), we found that all of the 39 coordinates have corresponding locations in IC 2 within a maximum of 30 mm; and, in approximately 80% of the cases within a maximum distance of 20 mm. In a few instances, there is less than 5-mm distance between the coordinates. The same close correspondence is present the other way around except for a few instances of coordinates from IC 2, which are between 30 and 40 mm away from corresponding coordinates in the list describing the attention regulating networks.

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[9] Which is not identical to the time series from the individual scans, but these show at least as much variability.

Considering that in all cases the coordinates from the present study and those reported by Dosenbach et al. (2007) are peaks in more extensive clusters, the close correspondence between them is a clear indication that IC 2 may be considered a manifestation of the attention controlling networks described by Dosenbach et al. It also merits repetition that the only activated cluster we found in the SPM study of continuous meditation is a part of this component.

When the results of the present study are considered in symphony with those from other studies of continuous meditation, some consistency in the results seem to appear. Most studies find areas activated that are related to the regulation of attention. This is hardly surprising given that the meaning of “meditation” is very close to that of “concentration” in the apparently paradoxical sense mentioned in the Introduction. However, meditation is not completely synonymous with either “concentration” or “attention”.

The anatomical localisation of the comprehensive network of involved areas also indicates that meditation depends heavily on neural systems suggested to support basic life sustaining intentional activities in vertebrates; i.e. centred on loops integrating cerebral processes in tertiary association areas, mainly through the parahippocampal formation and areas in the “greater limbic system”, and involving complex cortico–striato–thalamo–cortical loops (Freeman 2000; Graybiel 2008; Nieuwenhuys 1996).

When it comes to the detailed results of the investigations of meditation, some inconsistencies are however evident, and the main question about the nature of the brain processes supporting meditation still appears to be unanswered. The inconsistencies are demonstrated by the very different results regarding deactivations, and to a lesser degree by the conflicting activations obtained in studies using the contrast methodology. The extreme case is the finding of almost opposite patterns of activation and deactivation in the Lazar et al. (2000) study and the study by Lou et al. (1999) or in the study by Brefczynski-Lewis et al. (2007) where no deactivations were visible, while the study by Hölzel et al. (2007b) found deactivations in the encompassed areas distributed throughout almost all of the brain.

It is noteworthy, that the observed effects (activations and deactivations) often are very small and in many cases only detectable in ROI analyses. Although the results of different investigations are more consistent when they have to do with activations, they are still somewhat contradictory and variable.

An obvious explanation is suggested by the proponents of the distinction between "concentrative" and "mindfulness" meditation (Dunn et al. 1999; Lutz et al. 2008), who propose to study either one or the other form in order to get consistent results. Although this may be a viable strategy, it constrains the field of possible investigations and may lead to the loss of essential features of meditation, since meditation is not identical to either form.

When considering the functional–psychological interpretation of the patterns of activation and deactivation that are found in this study, and in other studies that use the contrastive methodology, one must bear in mind that they reveal areas of the brain, where the variation in the local amount and circulation of oxygenated and deoxygenated blood exceeds a statistical threshold. Although it has been firmly established that such variations are correlative with changes in neural processing (especially dendritic input processing; e.g. Logothetis et al. 2001), it has also been shown that these variations are usually just minor fluctuations of approximately 1–5% of the potentially relevant processing taking place in the brain at any given moment (cf. Raichle and Mintun 2006). That some areas are activated during the solution of a specific task does therefore not necessarily entail that the activated areas carry out this task, although these are most likely involved. The realisation of many tasks may require the involvement of (partially) overlapping networks of brain areas (cf. Luria 1972, 1980 a.o.), and for some of these areas the change from being involved in one task to being involved in another may not require neither more nor less neural processing. The shift may consist entirely in the alteration of route and address for the input and output (synchronisation of activity, cf. Buzsáki and Draguhn 2004) as required by the particular activity being realised, and the circumstances under which it takes place.

The present exploratory attempt to find consistent patterns of correlated activity among the component processes during meditation revealed that the mutual relationships among the components is far from simple; in the present case, it is only consistent across the different subjects for one pair of components, i.e. IC 18 and 24 are negatively correlated in all subjects. The modest success of the present attempt to find a consistent pattern of correlated activity suggests that the concept of a stable homeostatic state maintained by a "threshold regulating mechanism", as suggested by Travis and Wallace (1999), does not necessarily mean that this is some sort of "inert" state or stable relationship between any particular set of component processes. On the contrary, it may suggest that what is subjectively experienced as stability is objectively measured as a complicated and highly variable system of changing relationships.

In the original formulation by Travis and Wallace, the tonic regulation of the stable mind during meditation entailed the lowered cortical tone. Rather than to think of meditation as involving decreased cortical tone, it may prove more productive to think of meditation as cognition uncaught by a given attractor (cf. Freeman 2000), as is otherwise the case for the "normal" mind; i.e. a state of mind pertaining to one of the "five types of modifications of the mind" (Patanjali). The stability achieved in meditation may perhaps be conceived as a continuous adaptation and compensation for the disturbances impinging on the subject.

In order to explain what this may imply, the following metaphor in which skiing will take the place of meditation may prove useful. During skiing, the acting subject must focus on the task and keep his balance, while at the same time moving down the slope at a rapid pace. The activity demands instantaneous reactions to various challenges and obstacles. In professional skiing, it may even require the performance of feats that at times seem to defy gravity and could easily injure, or even kill, an untrained novice. However, these fantastic manoeuvres do not become possible because of sorcery or some super-natural manipulation of the laws of nature; quite to the contrary these feats attest an in depth knowledge of such laws, and perhaps more importantly verify the command of the exercising subject over their effect.

During skiing or any other sensory-motor accomplishment, it is crucial to maintain stability in the centre of mass. If this is lost the forces acting on the body may quickly develop beyond the control of the subject, who then risks being overturned by the momentary constellations of forces acting on the body (this is where the novice may be injured). In the case of the skier, maintaining stability will usually require fast flexible adaptations and the mastery of a large variability of postures and movements. By doing so, he/she may counterbalance the dynamically changing conditions and adapt to possible challenges by compensating for the disturbances (cf. Bernstein 1996).

In order for the skier to be successful his/her attention must be maximally focused on the execution of the task, and so he/she must not allow himself/herself be distracted by anything occurring either around or inside him/her. On the other hand, his/her focus must materialise in such a manner that nothing escapes his/her attention, thus allowing him/her to adapt the execution of his/her activity appropriately to rapidly changing circumstances. Ideally, he/she must be maximally focussed and simultaneously completely open minded.

That stability in the achievement of a behavioural goal may require operational variability is not mere speculation and is well documented in a series of studies on marksmanship by Arutyunyan et al. (1968, 1969). They amply demonstrate that the arm postures of expert marksmen were far more variable than those of less skilled pupils undergoing firearms training.

In the progression from novice, to skilled, and finally to expert levels of mastery, the uncontrolled variability present at first likely disappears. During initial phases of training, it may be necessary to constrain the available degrees of freedom. Later when the basics of the behaviour in question have been acquired, the degrees of freedom of movement may in turn gradually be increased, and so the apparent variability of movement increases. This has for instance been shown in studies of infants learning to sit and walk (Thelen and others, see e.g. Bertenthal 2007).

In a general sense, the activity of meditation is not unlike skiing. What matters is the ability to maintain balance during uncontrollable and dynamically changing circumstances. In one case, the stability is maintained in the physical environment and so is directly observable by means of vision. In the other case, stability is maintained in the psychological, or spiritual, sense, why the observation of such may require other means.

If meditation is an activity comparable to skiing, as we believe it is (notwithstanding the obvious differences), and in order to study its underlying brain processes properly, it will be necessary to establish a working definition for the psychological or spiritual concomitant of the “centre of mass” that is stable during skiing. Only when we establish the “centred mind in itself”, including its implicitly necessary mechanisms of stability effectuating variability in response to disturbances, will it be possible to find the involved functional brain systems and shed light on their anatomical identity and localisation.

Conclusion

The patterns of activation and deactivation during the shift from “baseline relaxation” epochs to meditation support the notion that meditation is a state of mind clearly different from both the resting baseline state and the “cognition” related to external tasks. The activations in putamen, posterior premotor and motor cortex, supplementary motor cortex and insula, as well as the patterns of inferior lateral frontal and parietal activations and deactivations summarily support the hypothesis of a “neural switch” (Travis and Wallace 1999) involving a cortico–striato–thalamo–cortical loop (Alexander et al. 1986, Graybiel 2008, Kopell and Greenberg 2008) which executes a set shift of attention from external matters to the subjects own state of mind (and body) according to a previously established rule kept in working memory and effected when the signal to meditate is given.

Results from the study of continuous meditation suggest that this is crucially a matter of attention regulation effected by functional networks of areas distributed in large regions of the brain, involving dorsolateral, ventrolateral prefrontal areas, areas in the gyrus cingulum, inferior parietal lobe as well as areas in the temporal and occipital lobe, the thalamus and the cerebellum.

Although it was possible to some degree to analyse continuous sustained meditation with SPM, and that the results seem to be in a general manner consistent with results from other studies, they still point towards the need for further investigations. The complex issue of the brain processes during continuous meditation (cf. Newberg et al. 2003) necessitates the use of a different methodology than the epoch-related, repeated task experiment employed in the present study.

The present study constitutes an attempt to find new approaches to the study of brain processes during meditation. We made scans of sustained meditation and analysed these data with SPM as well as FSL (ICA). Realising that the results of the ICA have a lot in common with results from studies of baseline-resting state and that any significant differences are hardly detectable, we suggest that in order to properly characterise the brain processes during meditation when compared to normal relaxation, it may be necessary in future analyses not only to consider the anatomical localisation of component processes, but also to analyse the possible dynamical and causal relationships among the components.

The formulation of a viable strategy that aims to elucidate, what it means to reach a stable mind, in which fluctuations are controlled, may call for an analysis of the understanding of stability. When meditation is considered as a real physical somato-motor activity, it is, in principle, not unlike the skier sliding down a slope. In order to maintain a stable balance, the skilled execution of highly variable and often demanding compensatory processes is needed. In the case of meditation, such adaptations are not primarily related to somato-motor activity directed at the environment, but are in essence internal and relate to impressions, recollections, drives etc. and thus not overtly observable. However, compensatory adaptations are likely still essential and warrant some degree of effort in order to accomplish the task in question.

It is necessary to identify the features of the mind that are brought into a stable state, and likewise which features of the mind that might effectuate compensatory adaptations in response to disturbances. Considering the operational implementation of compensatory adaptations, these may well be specific for concentrative versus mindfulness forms of meditation, while we hypothesise that the activity of meditation as such (the stable state) is common to all forms of meditation.

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