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Differential engagement of anterior cingulate and adjacent medial frontal cortex in adept meditators and non-meditators ☆

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Abstract

This study investigated differences in brain activation during meditation between meditators and non-meditators. Fifteen Vipassana meditators (mean practice: 7.9 years, 2 h daily) and fifteen non-meditators, matched for sex, age, education, and handedness, participated in a block-design fMRI study that included mindfulness of breathing and mental arithmetic conditions. For the meditation condition (contrasted to arithmetic), meditators showed stronger activations in the rostral anterior cingulate cortex and the dorsal medial prefrontal cortex bilaterally, compared to controls. Greater rostral anterior cingulate cortex activation in meditators may reflect stronger processing of distracting events. The increased activation in the medial prefrontal cortex may reflect that meditators are stronger engaged in emotional processing.

Keywords: Meditation; Mindfulness; Anterior cingulate cortex; Medial prefrontal cortex; Emotion regulation; Attention regulation

Meditation has recently gained increasing interest as a way of training the mind [2]. However, considering the diversity of meditation techniques, there is no simple answer to the question "What is being trained while meditating?". During self-guided meditation, concentration is typically focused on a specific object (e.g., a mantra, an image, body sensations, or one's own breath) while distracting events are disregarded. Meditation is thereby a state of intense concentration or heightened awareness and differs from daydream-like resting [6]. Therefore, the task of meditation is characterized by two general cognitive conditions: (a) the disregard of distracting events and memories that interfere with the task and thus create conflict, and (b) the absence of mind wandering.

A review of neuroimaging studies on meditation by Newberg and Iversen [13] points out that volitional, self-guided types of meditation usually involve an activation of the prefrontal cortex (e.g., [10]), as well as the anterior cingulate cortex (ACC) [1,10]. The ACC is generally involved in detecting the presence of conflicts emerging from incompatible streams of information processing [18]. During meditation, distracting external events as well as memories represent conflicting events to task goals. In this case, ACC activation may contribute to the maintenance of attention by alerting those systems directly implementing top-down regulation to resolve this conflict [18].

Meditators report that regular meditation practice enables them to focus their attention on a single object for an extended period of time [2], and that distractions disturb this focus less frequently. Consequently, brain activation patterns should differ between experienced meditators and persons without meditation training. On one hand, it seems plausible that the repeated ACC activation during meditation training might lead to an increased ACC activation for experienced meditators compared to people who are not trained in disregarding distractions. On the other hand, it is equally possible that the increased ability to disregard distractions might cause a diminished need for ACC activation. As presented at the 2004 Society for Neuroscience (SfN) meeting, Brefczynski-Lewis et al. [3] found increased ACC activation in meditation only for novice meditators, but not for experienced meditators. The authors assume that experienced meditators are typically less distracted and better enabled

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to sustain attentional focus. Greater ACC activation in controls reflects "greater error proneness (i.e., distraction) and conflict monitoring in the controls than in the adepts; the conflict would be between the instruction to focus and the difficulty of complying with such instructions" [11]. While trained meditators are continuously able to keep their attention on the object of meditation, non-meditators presumably switch between the task and a daydreaming-like resting, or default state. The "default mode" is considered an organized mode of brain function that is present as a baseline and attenuates during specific goal-directed behaviors [7]. It is characterized by activity in midline areas within the medial prefrontal cortex (MPFC), the posterior cingulate cortex (PCC), and the precuneus [16]. Activity in these regions is assumed to indicate spontaneous self-generated mental activity, i.e., streams of thoughts and episodic memories. Resting state structures are thought to be functionally affected by long-term meditative practices [11]. The study by Pagnoni et al. [14], presented at the SfN meeting in 2005, found a marked reduction of activation in the default mode network during a meditative task in meditators compared to controls, suggesting that meditation training may reduce the activity in the default mode network.

One technique used for cultivating concentration in Buddhist mindfulness meditation (*Vipassana*) is mindfulness of breathing. Sensations around the nostrils and above the upper lip that arise due to breathing are observed with a mindful attitude; without judging or analyzing [8]. Whenever the focus of attention is lost, trainees are required to redirect their attention to these sensations.

The aim of the present study was to investigate the effects of the training of cognitive functions by meditation practice. We therefore compared cerebral hemodynamic responses of well-trained meditators and participants without prior meditation experience during mindfulness of breathing. Meditators are trained to disregard distractions during meditation. Following the results of Brefczynski-Lewis et al. [3], we predicted them to show less ACC activation than non-meditators. In addition, as meditators are trained to refrain from mind wandering, we expected less activation in the default mode structures dorsal MPFC, PCC, and precuneus. Our sample included meditators, who might habitually practice meditation when not engaged in a different task. Therefore, a mental arithmetic task was chosen as the control condition to ensure the participants would not meditate.

Thirty healthy, right-handed subjects participated in the study; fifteen meditators (mean age: 33.8 years; standard deviation (S.D.): 4.6 years) and fifteen non-meditators (mean age: 33.4 years; S.D.: 5.6 years). Participants in the two groups were matched for sex, age, and level of education. Each group consisted of twelve male and three female participants. Written consent was obtained after the experiment had been explained. Meditators were recruited in a Vipassana Center in Germany, where meditation is taught in the tradition of S.N. Goenka [8]. Inclusion criteria were a regular meditation practice for at least two years, a daily meditation practice of 2 h, and the participation in a minimum of four 10-day courses (see [8]). The actual duration of meditation practice ranged between 2 and 16 years with a mean of 7.9 years (S.D.: 5.1 years). All meditators have implemented mindfulness of breathing (*anapana sati*) into their daily practice. Controls had no previous experience with meditation or similar practices.

In the block design, participants performed three different tasks: (a) In the mindfulness of breathing (*mindfulness*) condition, they had to observe the sensations evoked by breathing in the area below the nostrils and above the upper lip. Whenever the focus was lost, the attention should patiently be redirected to the sensations in the relevant face area. (b) For the mental arithmetic (*arithmetic*) condition, ten numbers between 0 and 20 were successively presented on a screen; these had to be added up by the participants. A screen with three different results was presented and participants had to choose the correct answer by pressing the appropriate button. (c) The so-called *button* condition resembled the *mindfulness* condition; additionally, participants had to press a button with every first sensation they encountered when inhaling. It is mentioned here for the sake of completeness only; results will not be presented in this paper.[1] Participants were asked to keep their eyes closed during the *mindfulness* condition. A sound marked the end of each phase and information on the next phase could be read on screen.

In order to apply a sensitive high-pass filter, the blocks were kept as short as possible while still allowing participants to get into a meditation-like state, which requires a certain length of concentration without interruption. Thus, *mindfulness* and *button* condition lasted 1 min, the condition *arithmetic* lasted 30 s. In one half of the experiment, six blocks of the conditions *mindfulness* and six blocks of *arithmetic* alternated, while in the other half, *button* and *arithmetic* took turns (six blocks each). To counteract serial effects, the order of the two halves was balanced. Altogether, the duration of the three conditions was 6 min each.

Following the scanning, participants rated their subjective experiences during the *mindfulness* condition. They were asked to give the percentage of time they had kept their attention on the task. Additionally, they rated their subjective difficulties with the task, tiredness, boredom, relaxation, happiness, and well-being on a Likert-type scale from zero ("not at all") to ten ("very much").

A total of 481 scans were obtained using a Siemens Symphony 1.5 T scanner with a standard head coil. Volumes were registered using a T2*-weighted gradient echo-planar imaging sequence (EPI) with 30 axial slices covering the whole brain (field of view 192 mm, flip angle 90°, thickness 4 mm, gap 1 mm, descending, 64×64 pixels, TR = 3 s, echo time 50 ms). The orientation of the axial slices was parallel to the AC-PC line.

Preprocessing and statistical analyses were conducted using SPM2 (Wellcome Department of Cognitive Neurology, London) implemented in Matlab (Mathworks Inc., Natick, MA, USA, release 12), which is based on the general linear model (GLM) approach. Preprocessing consisted of realignment, slice-time correction, normalization to the standard space of the Mon-

[1] We included the button condition as a further control condition hoping it would facilitate the maintenance of attention by giving an external task. Under the button condition, however, subjects reported very diverse subjective experiences. We, therefore, found data not comparable and excluded it from further analyses.

treal Neurological Institute brain (MNI-brain), and smoothing (9 mm). The voxel-based time series were high-pass filtered with a cutoff of 256 s. Movement parameters were considered covariates.

The conditions were individually modeled using the canonical hemodynamic response function and contrasts were calculated in the first level analysis. These were then used in second level random effects analyses. Exploratory voxel intensity analyses were inspected at an α level of 0.05, corrected for the entire volume (correction according to family wise error).

For definition of the regions of interest (ROI), the anatomical parcellation of the normalized brain (single-subject high-resolution T1 volume of the Montreal Neurological Institute) was used [17]. Masks were created using the MARINA software [20] based on the assignment between anatomical structures and voxel coordinates.

ROI analyses (threshold: $p = 0.001$, uncorrected; $\alpha = 0.05$, family wise error corrected for ROI; cluster size >10 voxels) were calculated for the ACC, the dorsal MPFC (medial part of the superior frontal gyrus), the precuneus, and the PCC in both hemispheres for all contrasts.

A significant group difference in the percentage of time in which participants kept their attention on the task (meditators: $M = 83.5\%$; S.D. = 13.1%; controls: $M = 57.7\%$; S.D. = 24.5%; $t = 3.6$; $df = 28$; $p = .001$) indicated that meditators experienced more concentration during mindfulness than controls. The group difference was also significant for boredom (meditators: $M = 0.13$; S.D. = 0.35; controls: $M = 2.77$; S.D. = 2.18; $t = -4.62$; $df = 14.7$; $p < .001$). Though not significant, controls reported to have encountered more difficulties with the task (meditators: $M = 2.23$; S.D. = 1.94; controls: $M = 3.77$; S.D. = 2.53), more tiredness (meditators: $M = 1.3$; S.D. = 2.05; controls: $M = 2.83$; S.D. = 2.28), less happiness (meditators: $M = 3.97$; S.D. = 2.97; controls: $M = 3.37$; S.D. = 2.32) and less well-being (meditators: $M = 6.00$; S.D. = 2.39; controls: $M = 5.87$; S.D. = 2.42). There was no difference in the experienced relaxation (meditators: $M = 6.47$; S.D. = 2.50; controls: $M = 6.40$; S.D. = 2.32).

First, exploratory analyses are reported for the contrasts between the conditions for the whole sample. Activations greater in *mindfulness* than in *arithmetic* (contrast *mindfulness* > *arithmetic*) are displayed in Table 1. Default mode structures and ACC failed significance. However, when choosing a lower threshold (uncorrected, $p = .001$) and correcting for small volume, the left precuneus (18 voxels; $t = 3.88$; $p = 0.069$; *x, y, z*: −6, −54, 27), the left PCC (5 voxels; $t = 3.74$; $p = 0.016$; *x, y, z*: −3, −54, 27), right MPFC (88 voxels; $t = 7.45$; $p < 0.001$; *x, y, z*: −9, 63, 6), left MPFC (56 voxels; $t = 6.84$; $p < 0.001$; *x, y, z*: 12, 66, 6), left ACC (37 voxels; $t = 4.81$; $p = 0.004$; *x, y, z*: −3, 30, −9), and right ACC (20 voxels; $t = 4.75$; $p = 0.004$; *x, y, z*: 3, 27, −9) showed activations.

The contrast *arithmetic* > *mindfulness* showed a large cluster of activation (18827 voxels), covering almost the entire brain. Activation peaks occurred in the occipital lobe. Regions of activation within the cluster and respective percentages for those regions are displayed in Table 2.

We also inspected the contrast *mindfulness* > *arithmetic* separately for the two sample groups. For either of the groups, one significant cluster was found in the left inferior temporal lobe (meditators: 51 voxels; $p = .004$; $t = 9.76$; *x, y, z*: −48, −21, −30; controls: 13 voxels; $p < .001$; $t = 11.73$; *x, y, z*: −51, −6, −39).

For testing the postulated hypotheses, we compared the groups of meditators and controls in the contrast *mindfulness* > *arithmetic*. Neither in the exploratory nor in ROI analyses did controls show enhanced activations compared to meditators for the contrast *mindfulness* > *arithmetic*. Yet, greater activation was observed for meditators than for controls in ROI analyses in the bilateral ACC and dorsal MPFC (Table 1; Fig. 1). Enhanced ACC activation was located at rostral sites.

Additionally, activation patterns are reported for the *mindfulness* condition for the whole sample in Table 3. In order to better detect activations, the threshold was set to an uncorrected p-value of 0.0001 (cluster size >20 voxels). Activations occurred in the right rolandic operculum, bilateral parahippocampal region, left cerebellum, left inferior temporal gyrus, and bilateral postcentral gyri. When contrasting activations of the two groups during mindfulness, no significant activations were found in either of the contrasts. However, when lowering the threshold to a p-value of 0.001 and correcting for small volume, there was a tendency for significance at the left MPFC (16 voxels; $t = 4.345$; $p = 0.084$; *x, y, z*: −27, 36, 27) and right MPFC (47 voxels; $t = 4.45$; $p = 0.071$; *x, y, z*: 24, 39, 24) for meditators > controls. There were no group differences during the *mental arithmetic* condition.

To investigate the effect of meditation training, the cerebral hemodynamic response during mindfulness of breathing, contrasted to mental arithmetic, was compared between experienced meditators and participants without previous meditation experience. In contrast to our expectations, greater activation was observed for meditators than for controls in the bilateral ACC and the dorsal MPFC in both hemispheres. We did not find effects in the PCC and the precuneus.

Contrary to the results of the present study, Brefczynski-Lewis et al. [3] found greater ACC activation for novices than for experienced meditators. This difference was attributed to greater error proneness and conflict monitoring in the novices than in the adepts [11]. The exact location of ACC activation in the study by Brefczynski-Lewis et al. was not reported. In the present study, the difference in the activation between the two groups has its peak at rostral ACC sites. Within the ACC a major parcellation between dorsal and rostral-ventral regions can be made based upon cytoarchitecture and connectivity [4]. Cognitive tasks consistently activate the dorsal division, while the rostral-ventral division is activated by affect-related tasks, which require emotional processing [4]. The significant difference in brain activation in the rostral ACC in our study suggests that meditation training leads to more cortical processing of emotional conflict during mindfulness. Self-report data indicates that meditators have kept more continuous attention on the task, felt less bored, and have encountered less difficulties with the task than non-meditators. This suggests that meditators were more successful in attention regulation. Consequently, it seems that greater subjective expertise in attention regulation goes along with greater ACC activation, rather than supporting the explanation of compensatory ACC activation in novices. Vogt et al.

Table 1
Exploratory analyses for the whole sample and regions of interest analyses for meditators > controls in the contrast *mindfulness* > *arithmetic*; *p*-values were family wise error corrected for the total brain respective for regions of interest

Region	Analysis	Hemisphere	*x*	*y*	*z*	*t*	Cluster size	*p*-corr
Whole SAMPLE								
Inferior temporal	Expl	Left	−51	−3	−42	13.43	359	0.000
Inferior orbital frontal	Expl	Left	−45	36	−21	8.26	22	0.000
Cerebellum Crus 2	Expl	Right	36	−84	−42	7.98	69	0.000
Rectus	Expl	Right	15	21	−21	7.92	102	0.000
Cerebellum Crus 2	Expl	Left	−24	−93	−36	7.73	16	0.001
Superior medial frontal	Expl	Left	−9	63	6	7.45	51	0.001
Superior frontal	Expl	Right	15	66	6	6.98	19	0.002
Meditators > controls								
ACC	ROI	Left	−12	42	12	5.11	83	0.002
ACC	ROI	Right	9	48	9	3.97	19	0.025
Dorsal MPFC	ROI	Left	−12	45	15	4.48	11	0.017
			0	48	39	4.20	40	0.031
Dorsal MPFC	ROI	Right	6	51	3	4.36	31	0.017
			3	48	39	4.10	23	0.029

Coordinates *x, y*, and *z* are given in Montreal Neurological Institute space.

Table 2
Regions of activation (lobes and hemispheres) and percentage (for those greater than 5.0) within the 18827 voxel cluster of activation for the contrast *arithmetic* > *mindfulness* for the whole sample

Lobe	Hemisphere	%	Structure
Occipital	Left	15.47	Middle (24.5%), lingual (17.52%), calcarine (17.26%), superior (12.41%), fusiform (11.70%), inferior (8.66%), cuneus (7.95%)
Occipital	Right	15.28	Lingual (20.22%), calcarine (17.80%), middle (18.00%), superior (13.74%), fusiform (13.61%), inferior (9.03%), cuneus (7.59%)
Frontal	Right	6.38	Middle (57.84%), inferior opercular (22.26%), inferior triangular (19.91%)
Cerebellum	Right	5.04	Lobule 6 (48.61%), Crus 1 (31.55%), lobule 8 (19.84%)
Cerebellum	Left	5.75	Crus 1 (40.52%), Lobule 6 (39.13%), lobule 8 (20.35%)
Parietal	Left	5.51	Inferior (39.02%), superior (38.66%), precuneus (22.32%)

Percentages for the structures in parenthesis are related to the overall activation within the respective lobe and hemisphere.

[19] suggest an alternative parcellation of the cingulate cortex, and found that the rostral (perigenual) ACC is activated during happy emotions. Greater rostral ACC activation in meditators might thus correspond to greater well-being and happiness.

The majority of previous studies in the field found that self-guided types of meditation involve ACC activation [13]. The results of our study confirmed that rostral ACC activation was greater for the mindfulness than the control condition, though at a lower threshold. Most of the studies which showed increased ACC activation during meditation (e.g., [1,10]) did not include a control group, and consequently do not allow inference on the effect of meditation training on ACC activation. The results of our study contradict the data by Brefczynski-Lewis et al. [3] and the interpretation that greater ACC activation corresponds to successful conflict resolution in meditation still remains tentative. Further studies are required to test the alternative explanations.

Also contrary to our expectations, meditators showed significantly more activation in the dorsal MPFC than non-meditators (contrast: *mindfulness* > *arithmetic*). No group effects were found for the precuneus and PCC, indicating that the difference between the two groups cannot generally be subsumed under what is known as default mode activation.

The MPFC is known to be commonly activated in emotional processing [15]. It might thereby be involved in the cognitive

Table 3
Exploratory analysis for the condition *mindfulness* for the whole sample ($N = 30$); *p*-values were uncorrected; $p < .0001$ (cluster size >20)

Region	Hemisphere	*x*	*y*	*z*	*t*	Cluster size	*p*
Rolandic operculum	Right	63	6	9	7.22	143	0.002
Parahippocampal region	Right	54	−6	−36	7.10	258	0.003
Cerebellum	Left	−18	−57	−54	6.42	42	0.017
Inferior temporal	Left	−54	0	−39	6.39	134	0.019
Postcentral gyrus	Left	−24	−30	72	6.31	22	0.023
Postcentral gyrus	Left	−60	3	15	6.13	74	0.037
Parahippocampal region	Left	−27	−18	−30	6.00	55	0.050

Coordinates *x, y*, and *z* are given in Montreal Neurological Institute space.

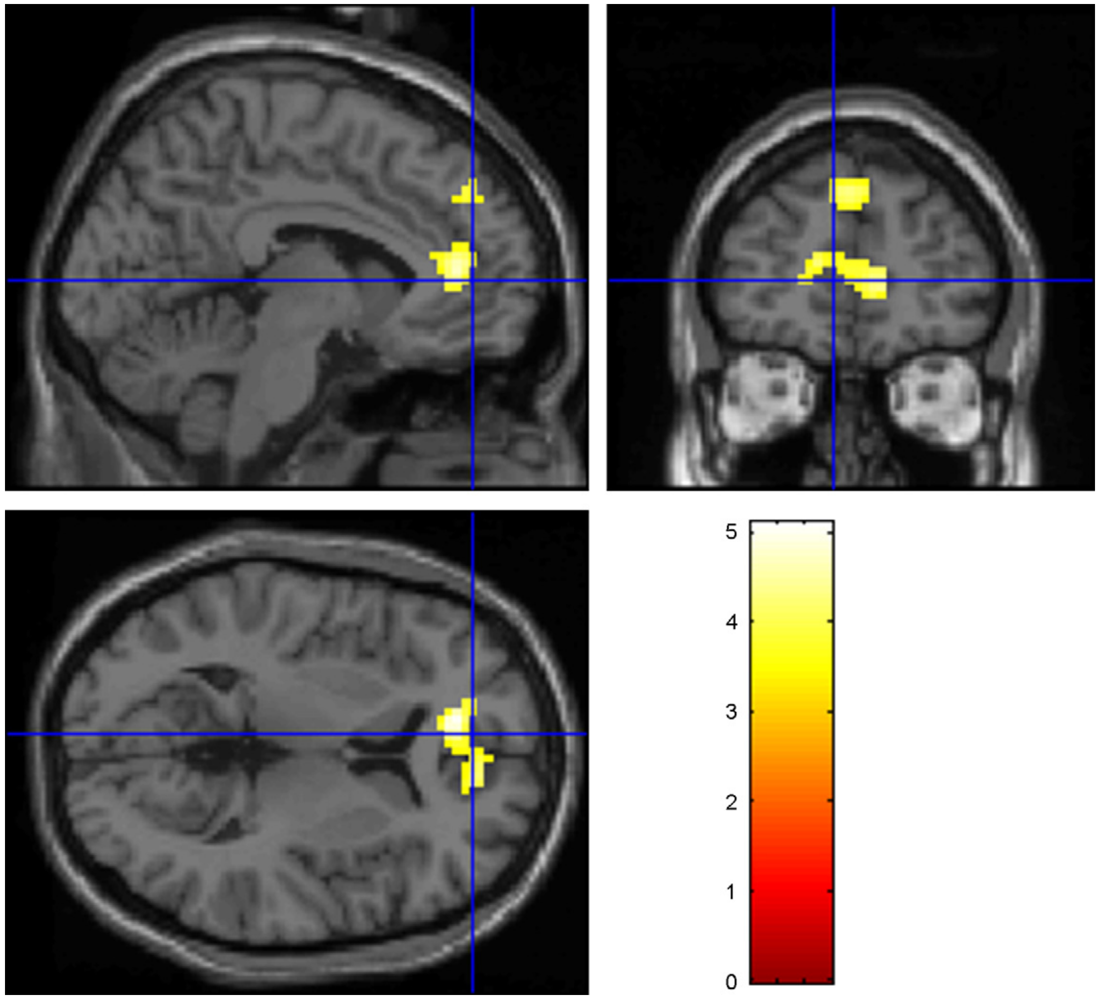

Fig. 1. Stronger brain activation in the rostral anterior cigulate cortex and medial prefrontal cortex in meditators than controls for the contrast *mindfulness* > *arithmetic* (threshold: $p = 0.01$, extend threshold >5 voxels; MNI coordinates: $x = -6$; $y = 48$; $z = 6$; color bar indicates T-values).

aspects of emotional processing, such as paying attention to emotion or the identification of emotions. Thus, it is engaged when subjects internally attend to their emotional state [9]. We assume that stronger MPFC activation in meditators implies that they are more strongly engaged in emotional processing, reflecting their improved ability for emotion regulation.

Aside from testing the hypotheses of the present study, we investigated the activation during mindfulness of breathing (anapana sati) across the whole sample on an exploratory basis. Activations occurred in the postcentral gyri, extending into the rolandic operculum, as well as temporal, parahippocampal and cerebellar regions. Neuroimaging studies localized the sensory representation of the lips at the base of the pre- and postcentral gyri [12]. The adjacent rolandic operculum was shown to be active in oro-pharyngeal somatosensory sensitivity [5]. Activation here obviously corresponds to the sensory aspect of anapana sati.

In the present study, we responded to the shortcomings of earlier studies on meditation by using a rather large sample and investigating a well-defined and precisely described meditation technique [8]. The participants were not randomly assigned to the groups, but rather self-selected by their meditation training. Therefore, differences between the groups cannot be clearly attributed to the meditation training alone, but may have already existed beforehand. Longitudinal studies are required to clearly attribute the differences to the training in meditation itself. In order to apply a sensitive high-pass filter, we kept periods of meditation as short as possible. However, meditation phases of 1 min do not allow meditators to reach deep meditation.

The control task, mental arithmetic, differs from the meditation condition not only in regard to the meditative state, but also in respect to several other aspects, such as the external (versus internal) focus, open (versus closed) eyes, preparation for response (versus maintaining quiet). Thus, differences between the conditions are attributable to factors other than the meditative state. However, we did not investigate the difference between the conditions, but group differences within this contrast. As the mental arithmetic task should be comparable for both groups, the group comparison on the contrast mindfulness > arithmetic is considered an appropriate way to test the training effect of meditation. Differential MPFC activation, though at a lower threshold, was observable for the mindfulness condition, but not for the arithmetic condition, confirming that the group difference at the contrast can strongly be attributed to mindfulness.

Still, the confounding effects of the difference between the conditions have to be kept in mind. A challenge for future studies is to find a control condition that differs from the experimental condition only in the meditative state.

In summary, the present study shows that meditators have stronger activation in the rostral ACC during mindfulness of breathing, compared to controls. This group difference is attributed to stronger processing of distracting events in meditators. Furthermore, meditators showed stronger activation in the dorsal MPFC than controls, suggesting that meditators are more engaged in emotional processing during meditation. Mindfulness training leads to increased activation of structures known to be relevant for attention and emotion regulation.

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