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Meditation training increases brain efficiency in an attention task

Elisa H. Kozasa [a,b,*], João R. Sato [c,d], Shirley S. Lacerda [a], Maria A.M. Barreiros [a], João Radvany [a,e], Tamara A. Russell [f], Liana G. Sanches [a], Luiz E.A.M. Mello [g,1], Edson Amaro Jr. [a,d,1]

[a] Instituto do Cérebro, Instituto Israelita de Ensino e Pesquisa Albert Einstein, São Paulo, Brazil
[b] Department of Psychobiology, Universidade Federal De São Paulo, São Paulo, Brazil
[c] Universidade Federal do ABC, Santo André, Brazil
[d] Instituto de Radiologia, Universidade de São Paulo, São Paulo, Brazil
[e] Department of Imaging, Hospital Israelita Albert Einstein, São Paulo, Brazil
[f] Institute of Psychiatry, King's College London, London, UK
[g] Department of Physiology, Universidade Federal de São Paulo, São Paulo, Brazil

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ABSTRACT

Meditation is a mental training, which involves attention and the ability to maintain focus on a particular object. In this study we have applied a specific attentional task to simply measure the performance of the participants with different levels of meditation experience, rather than evaluating meditation practice *per se* or task performance during meditation. Our objective was to evaluate the performance of regular meditators and non-meditators during an fMRI adapted Stroop Word-Colour Task (SWCT), which requires attention and impulse control, using a block design paradigm. We selected 20 right-handed regular meditators and 19 non-meditators matched for age, years of education and gender. Participants had to choose the colour (red, blue or green) of single words presented visually in three conditions: congruent, neutral and incongruent. Non-meditators showed greater activity than meditators in the right medial frontal, middle temporal, precentral and postcentral gyri and the lentiform nucleus during the incongruent conditions. No regions were more activated in meditators relative to non-meditators in the same comparison. Non-meditators showed an increased pattern of brain activation relative to regular meditators under the same behavioural performance level. This suggests that meditation training improves efficiency, possibly via improved sustained attention and impulse control.

Introduction

Meditation is a mental training of attention. This involves the selection of goal-relevant information from the array of inputs that bombard our sensory systems (Slagter et al., 2007).

Behavioural and neurophysiological studies have shown that meditation improves attentional performance (Lutz et al., 2009; Tang et al., 2007). Five days training (20 min of meditation per day) improved conflict scores on the Attention Network Test relative to a relaxation control group (Tang et al., 2007). Meditation experience is associated with reduced interference during the Stroop task (Chan and Woollacott, 2007), and meditators have a better attentional performance in the Stroop task compared with a meditation-naïve control group (Moore and Malinowski, 2009). These findings suggest that meditation training results in increased efficiency of networks recruited during the attention and impulse control requirements of the Stroop task.

Proper performance of the Stroop Word-Colour Task (SWCT) requires both attention and impulse control. The priming of colour naming through the simultaneous presentation of a written word stimulus will therefore facilitate (when the colour and word stimuli are congruent, e. g., "blue" written in the colour blue) or interfere (the incongruent Stroop trial, e.g., "blue" written in red) with colour naming. The task involves circuits subserving attention, working memory, response selection and inhibition, motor planning and motor response among others (Peterson et al., 1999).

A number of recent studies have suggested that meditation training may change brain morphology and function, particularly in areas related to attention and response selection (Hölzel et al., 2011; Jang et al., 2011). Long-term meditation practice was associated with increased cortical thickness in subjects who practice Insight meditation, which involves focused attention on internal experience. In that study, prefrontal cortex and right anterior insula areas associated with attention, interoception and sensory processing, were thicker in meditators than matched controls (Lazar et al., 2005). Areas showing increased gray matter concentration within the left hippocampus, the

* Corresponding author at: Instituto do Cérebro, Instituto Israelita de Ensino e Pesquisa Albert Einstein, Av. Albert Einstein, 627/701, CEP 05601-901, São Paulo, SP, Brazil.
E-mail address: ehkozasa@gmail.com (E.H. Kozasa).
[1] These two authors share the last authorship.

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posterior cingulate cortex, the temporo-parietal junction, and the cerebellum were identified in a controlled longitudinal study investigating the effects of 8-week Mindfulness Based Stress Reduction (MBSR) compared with controls (Hölzel et al., 2011).

An fMRI study using a simplified meditative condition interspersed with a lexical decision task compared regular Zen meditators and matched control subjects (Pagnoni et al., 2008). Zen meditators displayed a reduced duration of the neural response linked to conceptual processing in regions of the default network, suggesting that meditative training may foster the ability to control the automatic cascade of semantic associations triggered by a stimulus and, by extension, to voluntarily regulate the flow of spontaneous mentation. In a previous study, we found an increased activation in the attention network after one week of intensive meditation practice (which is much more than the habitual pattern of meditation practice even for the regular meditators) when the participants were performing the incongruent task of the SWCT (Kozasa et al., 2008).

Among meditation practices, there are two categories: focused attention meditation (FA), which entails the voluntary focusing of attention on a chosen object, such as mindfulness of breathing and mantra meditation; and, open monitoring meditation (OM), which involves non-reactive monitoring of the content of experience from moment to moment such as “zazen”, the *Zen* traditional sitting meditation. FA and OM are often combined, whether within a single session or over the course of a practitioner's training (Lutz et al., 2008). Regular meditators usually have different levels of expertise in both categories.

In this neuroimaging study, we were probing attention task performance in regular meditators and non-meditators outside the formal practice. Participants are not, as in most other studies, meditating or instructed to meditate during the probe. We hypothesize that regular meditators will complete the more demanding incongruent trials with better efficiency, represented by a reduced activation of the attention network.

Materials and methods

Participants

Regular meditators and non-meditators answered a validated questionnaire for mental disorder screening, the SRQ-20 (Self-Report Questionnaire) (Mari and Willians, 1986). A psychologist and a neuropsychiatrist supervised the screening and when necessary interviewed participants. The participants of this study did not present any diagnosed mental disorder or history of neurological diseases.

We selected 20 right-handed regular meditators (with at least three years of practice, three times a week) and 19 non-meditators (with no practice or who practice less than once a week) matched by age, years of education and gender. There were 8 and 9 males respectively in each group. The average number of years of practice for the regular meditators was 8.53 years (s.d. of 4.07), with a variety of OM or FA practices such as “zazen”, mantra meditation, mindfulness of breathing, among others. Participants mean ages were 46.39 and 43.80 years (s.d. of 9.30 and 9.35) for the regular meditators and non-meditators respectively. 77.8% of the regular meditators were university graduates and 22.2% were educated as far as post graduate level; 10% of the non-meditators were educated up to secondary level, 65% were graduates and 25% were post graduates.

Stroop Word-Colour Task

Participants were familiarized with the task before fMRI sessions. In the fMRI sessions only single words were presented (Carter et al., 1995). They were instructed to communicate the colour (red, blue or green) of these single words presented in three conditions (congruent, neutral and incongruent) by pressing the respective button. In the SWCT congruent condition, word and colour are the same, with the word “blue” written in the colour blue (for example). In the neutral condition, words unrelated to any colour (e.g., stone) are coloured red, blue or green. In the incongruent condition, word and colour are not the same. For example, if the word “blue” appears in red then the correct answer is red. The colours were represented by 3 buttons respectively and the participant had to select red, blue or green when answering with the use of one of three fingers on their right hand. Each word stimulus was presented for 1 s. These stimuli were interspersed by the appearance of a fixation cross for 1 s. Each trial was presented in blocks of 10 trials in the sequence congruent-neutral-incongruent 6 times (180 trials).

Image acquisition

Performance was evaluated during an fMRI adapted SWCT task using a block design. Image acquisition (3.0T MR system—Siemens Tim Trio, 12ch head coil), visual stimuli presentation (via goggles), and subject response were synchronized (NNL systems, www.nordicneurolab.com). The fMRI acquisition was based on T2*-weighted echo planar (EPI) images for the whole brain. The acquisitions parameters were EPI GRE T2–BOLD PACE: TR = 2000 ms, TE = 50 ms, 32 slices, 3.3 mm of slice thickness, 0.5 mm of interslice gap, FOV = 200 mm and matrix 64 × 64, 3 mm^3 voxels, with 180 volumes, discarding the first 4 volumes, relate to the signal decay, necessary for the MR signal to reach steady state.

Image processing

The fMRI data processing was carried out using FSL (www.fmrib.ox.ac.uk/fsl/;Smith et al., 2004). The volumes were processed by movement correction (MCFLIRT), spatial smoothing (FWHM = 5 mm) and spatial normalization to standard space (affine, 12 DoF). The activation maps were produced using the general linear model (GLM) using FILM routines, which is based on semi-parametric estimation of residuals autocorrelation (Woolrich et al., 2001). The group activation maps and groups comparisons were obtained using the mixed-effects model, in order to include the within-subject variances of parameters estimates. The significance was set to 1% at single-voxel level and 5% (corrected) at mass-cluster level for group analyses.

We determined brain regions more active in the incongruent relative to the congruent tasks in non-meditators compared with regular meditators (i.e.: the contrast of HRF (haemodynamic response function) betas estimates for regular meditators (incongruent–congruent) > non-meditators (incongruent–congruent) and non-meditators > regular meditators.

Results

Behavioral data

Behavioural data can be found in Table 1. Significant differences in reaction time between the conditions were observed for both groups (congruent < incongruent), indicating the presence of a Stroop effect. There were no differences in the Stroop task interference effect between the groups. However, regular meditators did not show any significant decrement in accuracy (range 0–10) related to the congruent versus incongruent conditions, yet this was present in non-meditators (incongruent < congruent).

fMRI data

Non-meditators compared to meditators activated the right medial frontal gyrus, middle temporal gyrus, lentiform nucleus, precentral gyrus and postcentral gyrus (Figs. 1 and 2; Table 2). The first three regions belong to one cluster with a local maxima (spatial

Table 1
Comparison between groups (regular meditators versus non-meditators) and condition (congruent versus incongruent): ^{t}—Independent-Samples T test; ^{MW}—Mann–Whitney test; ^{tp}—Paired-Samples T test; ^{W}—Wilcoxon signed Rank test; Stroop C–reaction time = Stroop task congruent condition–reaction time; Stroop I–reaction time = Stroop task incongruent condition–reaction time; Stroop I–C effect (reaction time) = comparison between Stroop C and Stroop I reaction time; Stroop C–correct answers = Stroop task congruent condition–number of correct answers (scoring from 1 to 10); Stroop I–correct answers = Stroop task incongruent condition–number of correct answers (scoring from 1 to 10); Stroop I–C effect (correct answers) = comparison between Stroop C and Stroop I correct answers.

	Regular meditators	Non-meditators	Significance between groups
	N = 20	N = 19	
Stroop C–reaction time in milliseconds	728.03 ± 87.62	721.82 ± 138.00	0.868 ^{t}
Stroop I–reaction time	823.64 ± 97.66	809.62 ± 152.25	0.736 ^{t}
Stroop I–C effect (reaction time)	**p < 0.001** ^{tp}	**p < 0.001** ^{tp}	
Stroop–interference effect[a]	1.13 ± 0.10	1.12 ± 0.09	0.754 ^{t}
Stroop C–correct answers[b]	9.74 ± 0.35	9.76 ± 0.27	0.789 ^{MW}
Stroop I–correct answers[b]	9.50 ± 0.51	9.43 ± 0.73	0.954 ^{MW}
Stroop I–C effect (correct answers)	p = 0.833 ^{W}	**p = 0.003** ^{W}	

[a] Stroop–interference effect = Stroop task incongruent condition–reaction time/Stroop task congruent condition–reaction time.
[b] Correct answers were presented as the average score of the 6 blocks of 10 incongruent or congruent conditions.

coordinate with maximal statistical value) corresponding to the lentiform nucleus. The last two regions belong to another cluster with a local maxima in the precentral gyrus.

Because we determined brain regions more active in the incongruent relative to the congruent tasks in non-meditators compared with regular meditators, some typically activated regions in a Stroop task did not appear in Figs. 1 and 2 and Table 1. They are presented in Fig. 3 (supplementary material) with all participants in the contrast incongruent versus congruent.

Fig. 2 shows the amplitude of bold responses in the lentiform nucleus, medial frontal gyrus, middle temporal gyrus and precentral gyrus during the incongruent and congruent conditions in meditators and non-meditators.

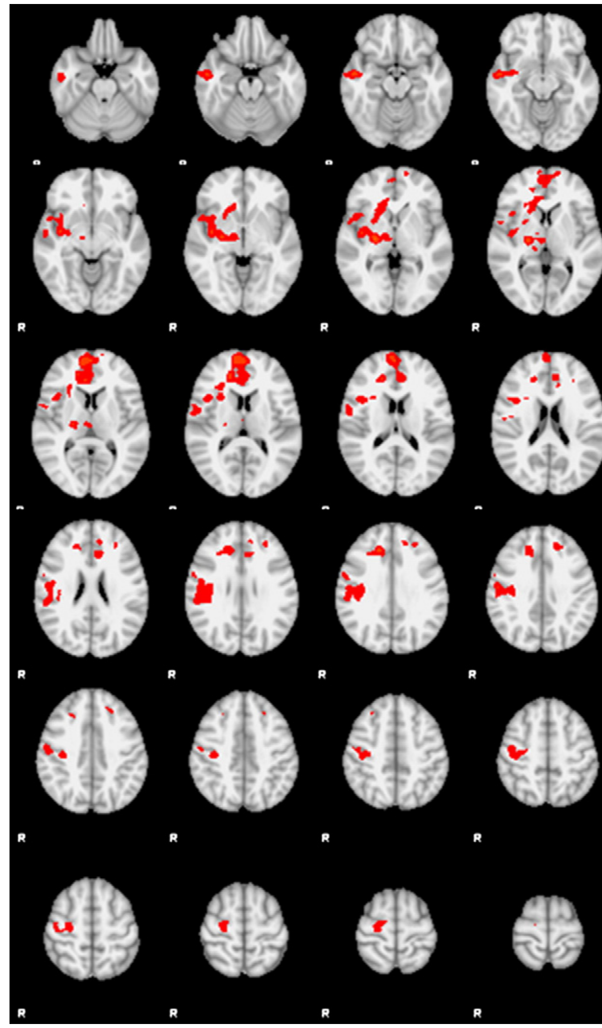

Fig. 1. Brain regions with significant differences for the contrast (incongruent > congruent conditions) between non-meditators and regular meditators: right medial frontal gyrus, middle temporal gyrus, lentiform nucleus (cluster1), precentral gyrus and postcentral gyrus (cluster 2).

Discussion

We sought to determine brain regions more active in the incongruent relative to the congruent SWCT in non-meditators compared with regular meditators. We recognize that different practices might engage different brain networks but common to all meditative practices is the necessity to train attention. Regular meditators usually have some level of expertise in OM and FA meditation (Lutz et al., 2008). It is this attention process that is of interest in our study. This would allow us to examine any possible differences in attention abilities between regular meditators and non-meditators. Although the regular and non-meditator groups were matched on the majority of behavioural outcomes, differences in brain activation were seen.

Stroop task interference effects were present in both groups. However, only among the regular meditators there were no within-group differences in the number of correct answers across the incongruent and congruent conditions (Table 1). The small difference in the behavioural results between the two groups can be related to ceiling effects in this highly educated sample. However we have found a large effect size when analyzing differences in the brain activation.

In the incongruent condition there is a conflict between colour naming and reading. The requirement for conflict resolution makes the incongruent task more difficult and slower than the congruent task (the Stroop task interference effect). Egner and Hirsch (2005) have suggested that the conflict resolution in Stroop tasks arises as a result of cortical amplification of task-relevant information, in this case, colour naming. In previous studies (Chan and Woollacott, 2007; Moore and Malinowski, 2009), results have shown that meditation experience was associated with reduced Stroop task interference effects on paper-and-pencil Stroop tasks. This suggests that meditation produces long-term increases in the efficiency of the executive attentional network. It is possible that meditation training has facilitated the neural pathways related to maintaining attention on the task-relevant information, amplifying what is relevant. Since many meditative techniques tend to foster the ability to control the automatic cascade of semantic associations triggered by a stimulus (Pagnoni et al., 2008), it could be also hypothesized that a weakening of the automatic mental reading response when presented with a visual–verbal stimulus increases the probability for the "colour channel" to win the competition for the response, without having to resort as much to the activation of additional neural circuits exerting impulse control. This interpretation seems in fact to be supported by the ROI data plots (Fig. 2), where meditators show less of an increase than controls, when processing

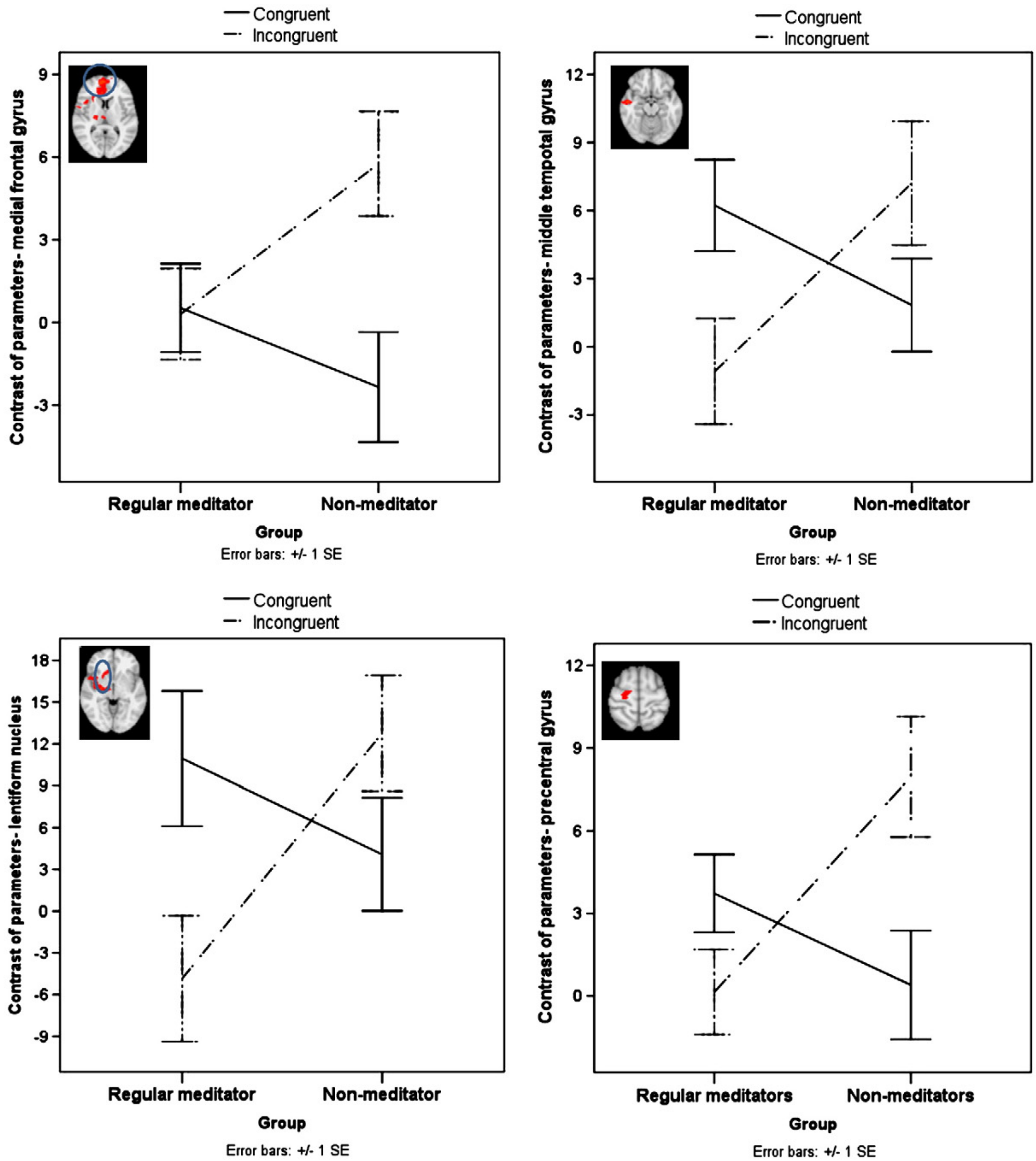

Fig. 2. Figure shows the amplitude of bold responses in the right medial frontal gyrus, middle temporal gyrus and lentiform nucleus (mean and standard-error bars) in regular meditators and non-meditators in congruent and incongruent conditions.

Table 2
Statistical information of clusters highlighted when comparing the BOLD response of regular meditators and non-meditators in the regions more activated in the incongruent task compared with the congruent task.

Group	Side	Region	BA	MNI coordinates			*p* values
				X	Y	Z	
Non-meditator > regular meditator	R	Lentiform nucleus		24	−14	0	<0.001 (cluster 1)
	R	Lentiform nucleus		22	−16	4	
	R	Medial frontal gyrus	10	6	62	12	
	R	Middle temporal gyrus	21	54	−6	−16	
	R	Medial frontal gyrus	10	16	42	12	
	R	Medial frontal gyrus	9	16	32	32	
	R	Precentral gyrus	6	38	−14	30	<0.032 (cluster2)
	R	Precentral gyrus	4	54	−14	38	
	R	Postcentral gyrus	2	40	−26	28	
	R	Middle frontal gyrus	6	22	−18	66	
	R	Precentral gyrus	6	26	−16	60	
Regular meditator > non-meditator	No activations						

incongruent compared with congruent stimuli in the cluster containing the medial prefrontal region which has been classically linked to impulse control (Boes et al., 2009).

In the contrast (incongruent>congruent conditions) in non-meditators compared with regular meditators, non-meditators showed greater activation in brain regions related to attentional circuits and motor control. This included the right medial frontal gyrus, middle temporal gyrus, lentiform nucleus, precentral gyrus and postcentral gyrus (Figs. 1 and 2; Table 2). Other authors have shown that the fMRI Stroop task is associated with BOLD responses found in the medial frontal gyrus, more specifically the anterior cingulate, and the prefrontal cortex—and these areas are reported as key areas in the cognitive control of the task (Carter et al., 1995; MacDonald et al., 2000). Other areas related to the motor control of the task are also cited (Peterson et al., 1999). Similar areas are more active during the meditation condition than in a rest condition (Brefczynski-Lewis et al., 2007).

This is the first demonstration of differences in the attention network elicited by the Stroop task in the comparison of regular meditators and non-meditators. We suggest that the meditation training has enhanced the ability to both maintain attentional set and control impulses allowing this group to complete the task with less activation. We speculate that meditators may have maintained the focus in naming the colour with less interference of reading the word and consequently have to exert less effort to monitor the conflict and less adjustment in the motor control of the impulses to choose the correct colour button.

In support for this, Brefczynski-Lewis et al. (2007) have shown that experienced meditators presented less activation in the medial frontal region than non-meditators in meditation practice compared with the rest. This region, especially the anterior cingulate cortex (ACC), is implicated in conflict monitoring in the engagement of cognitive control, promoting adjustments in behavior (Kerns et al., 2004) such as the inhibition of motor actions during a task (Sharp et al., 2010). In this case, the medial frontal region is involved in the conflict monitoring of the SWCT conditions and adjustments when choosing one of the buttons during the task (which represents the selection of one of the colours). The middle temporal gyrus is associated with planning volitional movement (Caffarra et al., 2010). Motor control includes the ability to inhibit a planned movement if it is identified as incorrect or inappropriate. The lentiform nucleus is part of the gateway to the basal ganglia and is related to the motor control and the activity of the primary motor cortex (the precentral gyrus) (Kreitzer and Malenka, 2008).

Fig. 2 suggests that regular meditators tend to have “higher” activation levels, compared to non-meditators, for congruent stimuli, and lower activation levels for incongruent stimuli. It seems that regular meditators, unlike non-meditators, tend to process incongruent and congruent stimuli quite similarly (and this is partially supported by the lack of a congruency effect for the number of errors in the task).

Experienced meditators can develop the ability of sustained attention during meditation practice (Brefczynski-Lewis et al., 2007; Lutz et al., 2009; Tang et al., 2007). Here we are suggesting that this ability can also be generalized for attention tasks outside formal meditation practice. If this is the case, meditation can have sustainable effects in brain circuitry and behaviour related to attention abilities. This observation may support reports that meditation training develops the ability of keeping attention to execute an attention task with less interference from distracters (Brefczynski-Lewis et al., 2007). Moreover, meditation could also have an effect of reducing the necessity of impulse control (in this case the motor control required to press the right button).

Regular meditators activated fewer brain regions than non-meditators in order to achieve the same performance during an attentional task. This is evidence that meditation training can increase brain efficiency in attention and impulse control.

Supplementary materials related to this article can be found online at doi:10.1016/j.neuroimage.2011.06.088.

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