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# Effect of mindfulness meditation on brain-computer interface: fMRI perspective

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### Abstract

This study observed the functional changes in brain activity while performing real and imagery movement using functional MRI (fMRI); and to compare the fMRI changes of motor imagery before and after mindfulness meditation (MM) training for correlation with actual brain computer interface (BCI) performance. Thirty-eight participants completed a randomized control trial consisting of 2 groups (MM and non-intervention control groups) to study the effect of MM on BCI performance. The MM group participated in a 4-week MM intervention programme. Out of the 38 cohorts, five participants from the MM group and five from the control group were fMRI scanned for real and imagery movement of right hand, left hand and both feet, before and after intervention. Statistical parametric mapping was used for post processing and analysis of fMRI data. The MM group showed a significant improvement in BCI performance compared to the control group. The fMRI results showed activation of right hand, left hand and both feet motor imagery at fronto-parietal regions before MM training ($p < 0.05$, family wise error). After MM training, the fMRI results revealed a focused activation in 3 out of 4 of the trained subjects during right hand motor imagery, 2 out of 4 of the trained subjects during both feet motor imagery and 1 out of 4 of the trained subjects during left hand motor imagery, compared to the control group. This is also correlated with the improvement of BCI accuracy of the intervention group after MM training. Mindfulness meditation improves BCI performance and is correlated with focused activation of the fronto-parietal region in fMRI during motor imagery.

*Keywords:* Functional MRI, motor imagery, mindfulness meditation, brain computer interface

## INTRODUCTION

A brain–computer interface (BCI) is able to activate electronic or mechanical devices with brain activity alone.[1] BCI is capable of translating human intentions into control signals to output devices. Furthermore, BCIs serve as a communication and control system providing a real-time interaction between the user and the outside world.[1] BCI research is advancing very rapidly and mostly aims at helping patients with severe neuromuscular disorders such as amyotrophic lateral sclerosis[2] lock-in syndrome, cerebral palsy or spinal cord injury, to regain control over their environment and to communicate with their social environment.[3-6] With BCIs, these patients were able to communicate and control devices to perform daily tasks, thus having a reasonable quality of life.[4,7-9]

At present, electroencephalography (EEG) is a commonly used non-invasive method for monitoring brain activity in a practical BCI system.[1] Using motor imagery (MI), which is a mental execution of a movement without any actual movement[10], the changes of the related brain wave - sensorimotor rhythm (SMR) can be detected by the BCI and used to operate the system.[11] As the essential part of the EEG-based BCI systems, the quality of EEG signals that represent the mental imagination is known to have a major effect on the performance of the BCI.[12] EEG patterns are significantly affected by the quality of the mental states, thereby performance

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of EEG-based BCIs is affected not only by the degree of imagined effort but also the quality of mental rehearsal.[11-13] A better BCI performance depends on a better controlled mental state which is able to be more focused during the BCI tests.[14]

Any method to improve BCI performance of those potential users, in which the majority are motor neuron disease (MND) and stroke patients, could improve their quality of life. Mindfulness meditation (MM) is considered as one of the methods because it is believed to have the ability to lead to better self-regulation.[15] MM, commonly referred to in the literature simply as mindfulness, has been described as "bringing one's complete attention to the present experience on a moment-to-moment basis"[16] and as "paying attention in a particular way: on purpose, in the present moment, and nonjudgmentally".[17] MM is a mental practice based on focusing on the sensations of the breath/body while maintaining a relaxed state of mind.[18] Several studies have indicated that MM improves EEG-based BCI performance through mechanisms such as production of more consistent EEG patterns.[14,19]

fMRI studies using the blood oxygenation level dependent (BOLD) response have become a widely used tool for noninvasive assessment of functional organization of the brain. fMRI provides the ability to observe both the structures and also identify which structures participate in specific functions.[20] A growing body of literature has used fMRI to demonstrate that neural systems are modifiable networks and that changes in the neural structure particularly in areas related to attention and response selection, can occur in adults as a result of mindfulness meditation.[21] There is evidence that MM could induce specific 'state' brain modifications and 'trait' brain modifications.[22] Furthermore, a recent study found that regular meditators activated fewer brain regions than non-meditators in order to achieve the same performance during an attentional task, suggesting meditation training can increase brain efficiency, possibly via improved sustained attention and impulse control.[23] Motor imagery is now increasingly being studied using fMRI. A recent study by Hétu *et al*. using activation likelihood estimation (ALE) meta-analysis of 75 papers provides the first quantitative map of the structures activated during MI.[24] MI is demonstrated to consistently recruit a large fronto-parietal network in addition to subcortical and cerebellar regions. Several regions known to involve actual motor execution are included in the motor imagery network.[24,25] Hence, the objective of this study is to compare the fMRI measured brain activity of motor imagery, before and after MM training and; correlate this with changes in BCI performance.

## METHODS

### *The BCI randomized control trials*

#### *Participants*

A total of 53 neurologically healthy, BCI-naïve and mindfulness meditation-naïve (by self-report) undergraduates from a local university were recruited for the study. Prior to the enrollment test, a detailed explanation of the experiment procedure was given, and written informed consent was obtained from all participants.

#### *Method*

The BCI experiment design of the current study is based on the study proposed by Tan *et al*.[14] The study was split into three phases; phase 1 was the pre-intervention test, where an EEG brain mapping and a BCI performance test had been carried out. Phase 2 was the 4-week intervention period. Phase 3 was the post-intervention test, where the tests in phase 1 were repeated to measure the changes of BCI performance. Participants were recruited at the beginning of the academic semester and the entire study was completed by the end of the same semester.

#### *EEG brain mapping*

EEG scanning on each participant was performed using a Nicolet 64-channels EEG acquisition system. Participants performed the different motor execution and motor imaginary tasks of right hand movement, left hand movement and both feet movement. The hand movement comprised of griping in the fist with a frequency of 2Hz. The feet movement comprised of flexing the toes with a frequency of 1Hz.

For the BCI tests, we use the method of motor imagery. Only 9 electrodes are placed in the sensorimotor cortex region (aC3, aCz, aC4, C3, Cz, C4, pC3, pCz, pC4) during both pre and post intervention EEG scanning. This placement of electrodes derives 9 bipolar channels as shown in Table 1. Thirty-six possible EEG bipolar channel combinations are formed as shown in Table 2. For example, the Channelac_C3 (from Region C3) can be used alone or in combination with any other bipolar channels in Region C4 or Region CZ. The

Table 1: The conventions of the names of the derived EEG bipolar channels used in this study.

| | Name of the channel | Electrode Positions |
|---|---|---|
| Region C3 | Channelac_C3 | ac3, c3 |
| | Channelap_C3 | ac3, pc3 |
| | Channelpc_C3 | pc3, c3 |
| Region CZ | Channelac_CZ | acz, cz |
| | Channelap_CZ | acz, pcz |
| | Channelpc_CZ | pcz, cz |
| Region C4 | Channelac_C4 | ac4, c4 |
| | Channel ap_C4 | ac4, pc4 |
| | Channelpc_C4 | pc4, c4 |

combination that gives the highest accuracy in an offline 10x10 fold cross-validation analysis will then be used for both before and after intervention of the BCI performance tests.

For the fMRI tests, focused activation of frontal-parietal regions was found in the MM group subjects who have improved BCI accuracy score at post intervention. Thus, this study suggests that mindfulness meditation improves BCI performance and is correlated with focused activation in motor and other brain regions as observed in the fMRI scanning during motor imagery.

*BCI performance test*

The graphical user interface of the BCI test consisted of 4 alphabets "A", "B'", "C" and "D" at the center of the screen. The four options scrolled from left to right, and instructions were displayed at the top left corner of the screen.

Participants waited for the desired option to scroll into the grey selection box to make a selection. By performing the appropriate motor imagery, the participant moved the feedback cursor to the right (or left, depending on the motor imagery task) of the blue cursor bar, which would trigger a binary selection. Participants were requested to complete 12 selections in 30min. The detail protocol of the BCI performance test was described in the previous study.[14]

*BCI performance test data and analysis*

The results of the binary selection from the BCI test were classified as True Positive (TP), False Negative (FN), True Negative (TN), and False Positive (FP) as shown in Table 3.

The overall BCI performance was measured by the accuracy[26] which is defined as:

$$\text{Accuracy} = \frac{(TP + TN)}{(TP + TN + FP + FN)} * 100\%$$

After completion of pre-intervention test, participants were randomly assigned into meditation group and control group before proceeding to the 4-week intervention period. Between groups effect on post-intervention BCI accuracy was analyzed with ANCOVA using pre-intervention data as a covariate. Statistical analysis was performed using IBM® SPSS® 16.0.

***Mindfulness meditation training***

MM trainings were conducted for 4 weeks, one session per week and 3 hours per session. Under the instruction of a professional meditation instructor, participants were taught to react non-judgmentally to stressful events by focusing on automatic and dynamic stimuli (breath, body, eating, walking). The training procedure involved sitting meditation, self-directed body scans to facilitate the impartial observation of sensation, mindfulness of body, mindfulness of feelings, and working with distraction and difficulties. After the 4-week intervention period, all participants were tested again in exactly the same way and sequence as the pre-intervention tests. Participants in the control group received no particular intervention.

***fMRI study***

*Participants*

Ten participants (5 MM and 5 Control) from the main group participated in the fMRI study. The exclusion criteria were: (1) history of neurological disease, (2) who do not pass MR scanning safety eligibility screen, (3) subjects who are claustrophobic. Written informed consent was obtained from all participants and ethical approval was obtained from the institutional ethics committee (University Malaya Medical Centre Medical Ethics Committee) in November 2011 (MEC Ref. No: 890.16).

**Table 2: Thirty-six possible EEG bipolar channel combinations formed from the 9 bipolar channels**

| No. | Possible EEG bipolar channel combination |
|---|---|
| 1 | channel ac_C3 |
| 2 | channel ac_C3, channel ac_C4 |
| 3 | channel ac_C3, channel ap_C4 |
| 4 | channel ac_C3, channel pc_C4 |
| 5 | channel ac_C3, channel ac_CZ |
| 6 | channel ac_C3, channel ap_CZ |
| 7 | channel ac_C3, channel pc_CZ |
| 8 | channel ap_C3 |
| 9 | channel ap_C3, channel ac_C4 |
| 10 | channel ap_C3, channel ap_C4 |
| 11 | channel ap_C3, channel pc_C4 |
| 12 | channel ap_C3, channel ac_CZ |
| 13 | channel ap_C3, channel ap_CZ |
| 14 | channel ap_C3, channel pc_CZ |
| 15 | channel pc_C3 |
| 16 | channel pc_C3, channel ac_C4 |
| 17 | channel pc_C3, channel ap_C4 |
| 18 | channel pc_C3, channel pc_C4 |
| 19 | channel pc_C3, channel ac_CZ |
| 20 | channel pc_C3, channel ap_CZ |
| 21 | channel pc_C3, channel pc_CZ |
| 22 | channel ac_C4 |
| 23 | channel ac_C4, channel ac_CZ |
| 24 | channel ac_C4, channel ap_CZ |
| 25 | channel ac_C4, channel pc_CZ |
| 26 | channel ap_C4 |
| 27 | channel ap_C4, channel ac_CZ |
| 28 | channel ap_C4, channel ap_CZ |
| 29 | channel ap_C4, channel pc_CZ |
| 30 | channel pc_C4 |
| 31 | channel pc_C4, channel ac_CZ |
| 32 | channel pc_C4, channel ap_CZ |
| 33 | channel pc_C4, channel pc_CZ |
| 34 | channel ac_CZ |
| 35 | channel ap_CZ |
| 36 | channel pc_CZ |

The fMRI scanning was carried out with a Clinical 3.0 Tesla Signa® HDx MR Systems (GE Healthcare, Milwaukee, Wisconsin, USA) equipped with a dedicated 8 channel high definition head coil. Experienced radiographer operated the whole scanning process.

A Blood-oxygen-level dependent (BOLD) – gradient echo, sensitive EPI sequence was used for the whole brain (TR 3s, TE 35ms, 90° flip angle; acquisition timing - matrix 128x128, NEX 1.0, phase FOV 1.0; sampling range – FOV 24cm, slice thickness 3.0mm, spacing 1.0mm). In addition, a sagittal fast spoiled gradient echo (FSPGR) scan was done (TR = 7.9 ms, TE = 3.0 ms, FOV = 25.6 cm, matrix = 256 x 256, thickness = 0.5 mm, image scan time 3 min 48 sec) for structural image fusion with the fMRI.

While lying in the fMRI scanner, participants viewed a projection screen via a mirror mounted on the head coil. Instructions were given to do a series of planned motor execution and motor imagery tasks, alternating them with rest during scanning process. The instructions were projected on the screen using black letters on a white background. Participants were requested to perform the real and imagery motor movement with the same frequency and intensity as in EEG brain mapping and BCI performance test (The hand movement consisted of griping in the fist with a frequency of 2Hz, the feet movement consisted of flexing the toes with a frequency of 1Hz. The participants had to imagine performing the same motor movement during the motor imagery task). Regarding the modality of motor imagery, kinesthetic motor imagery was used instead of visual motor imagery. Participants were asked to imagine performing the movement by themselves, instead of imagining watching themselves or others performing the movement.

Figure 1 shows the fMRI block design. The experiment consisted of three different tasks, which were right hand, left hand and both feet movements. Each task consisted of 5 cycles of repetition where each cycle embodied three conditions lasting a total of two minutes. Each cycle started with a resting baseline period (REST 30s), a motor execution period (REAL 30s), another resting period (REST 30s) and ended with a motor imagery period (IMAGERY 30s). The total experimental run time including all three tasks (right hand, left hand, both feet) was 30 minutes. Participants opened their eyes at all resting, motor execution and motor imagery periods. Through the window of the MRI room, the operator was able to observe and confirm

**Table 3: Classification of binary selection from the BCI test**

| | | Intent. | |
|---|---|---|---|
| | | **Select** | **Do Not Select** |
| Action | Correct response | True Positive (TP) | True Negative (TN) |
| | Incorrect response | False Negative (FN) | False Positive (FP) |

movement executed in the period of REAL and no movement executed in the period of REST and IMAGERY.

### *fMRI Data processing and analysis*

fMRI data processing and analysis was performed using Statistical Parametric Mapping (SPM) 8 software (Wellcome Department of Cognitive Neurology, London, UK) implemented in MATLAB 2011a (Mathworks Inc., MA, USA). The data was first slice-time and motion corrected. Next, the data were spatially normalized to an EPI template in the Montreal Neurological Institute space using the structural images. Subsequently, the normalized data were spatially smoothed using a Gaussian kernel with a FWHM of 6mm, in order to improve the signal-to-noise ratio. 1st level (individual) statistical analysis was carried out using a voxelwise least squares estimation via the general linear model for serially auto-correlated observation. All conditions including REAL and IMAGERY were modelled using the standard hemodynamic response (HDR) function implemented in SPM.

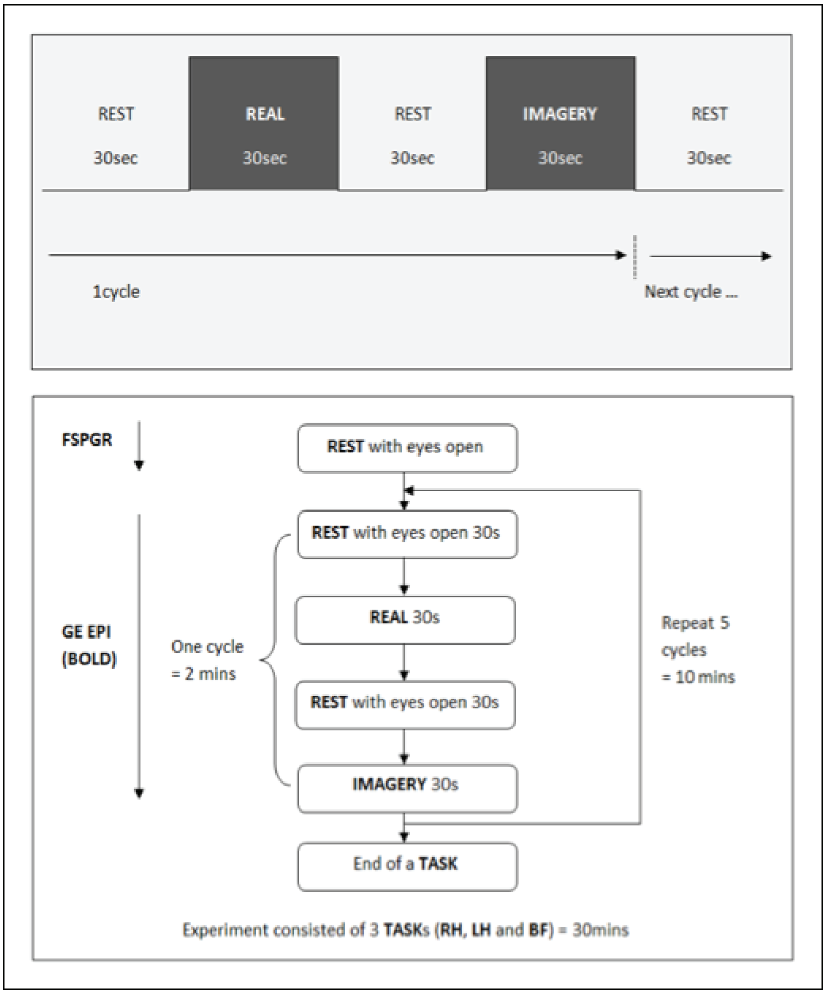


Figure 1. The fMRI block design.

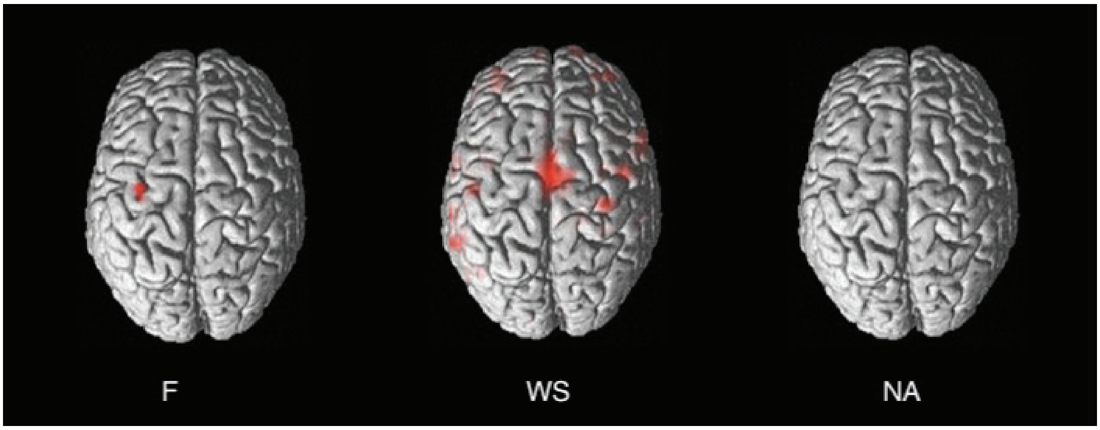


Figure 2. The activation patterns in BOLD signal. F: Focused; WS: Widespread; NA: No-Activation.

Statistical parametric maps were generated to identify regions activated by the respective MI task ($p<0.05$, family wise error [FWE]), specifically the contrast between motor imagery and resting condition (IMAGERY>REST). According to our experimental design, 150s of neural activation (stimulated state) were compared with 300s of normal conditions (resting state) for each motor imagery task.

Fronto-parietal cortical regions activated on fMRI were identified and classified by a neuroradiologist with 12 years' experience and a radiology trainee. Both observers were blinded to the training status and groupings. The Talairach Atlas[27] was used as the anatomy reference for cortical location and classification. The quantitative cortical map of motor imagery by Hétu *et al*.[24] was used as the reference for activation maps of motor imagery. To compare the individual results of the participants that performed the fMRI tests, the fronto-parietal cortical activation patterns were classified into focused (F), widespread (WS) and no-activation (NA). An activation pattern was classified as 'focused' if activation was found confluent to one region of the fronto-parietal cortex. An activation pattern was classified as 'widespread' if activation was found scattered to different regions of the fronto-parietal cortex. If there was no activation in BOLD signal, it was classified as 'no-activation' (Figure 2). The motor imagery parametric maps of each task (right hand, left hand and both feet) in the 1st session (pre-test) and 2nd session (post-test) were compared individually (per subject) using pictorial method.

## RESULTS

### *Demographic and clinical data*

A total of 53 participants were recruited for the MM training study. Fifteen of them withdrew because they disagreed with the group assignment, they had poor attendance at MM training classes, or they were busy with personal schedules. Thirty-eight participants (23 males, 15 females) completed the study with 19 participants in the MM group and 19 participants in the control group. All were undergraduate students of Chinese ethnic background, majoring in various engineering and science degree courses. Their age range was between 19 and 21 (M=19.6, SD=0.8). Mean and standard deviation of BCI accuracy of the meditation and control group were as shown in Table 4.

**Table 4: The mean (standard deviation) of BCI accuracy measured before and after the intervention period for meditation and control group**

| Group | n | Pre-intervention | Post-intervention |
|---|---|---|---|
| Meditation | 19 | 55.1 (11.2) | 64.3 (11.5) |
| Control | 19 | 57.7 (10.5) | 56.4 (9.5) |

The mean accuracy of the meditation group improved 9.2% at post-intervention compared to pre-intervention. The mean accuracy of the control group dropped slightly by -1.4% at post-intervention compared to pre-intervention.

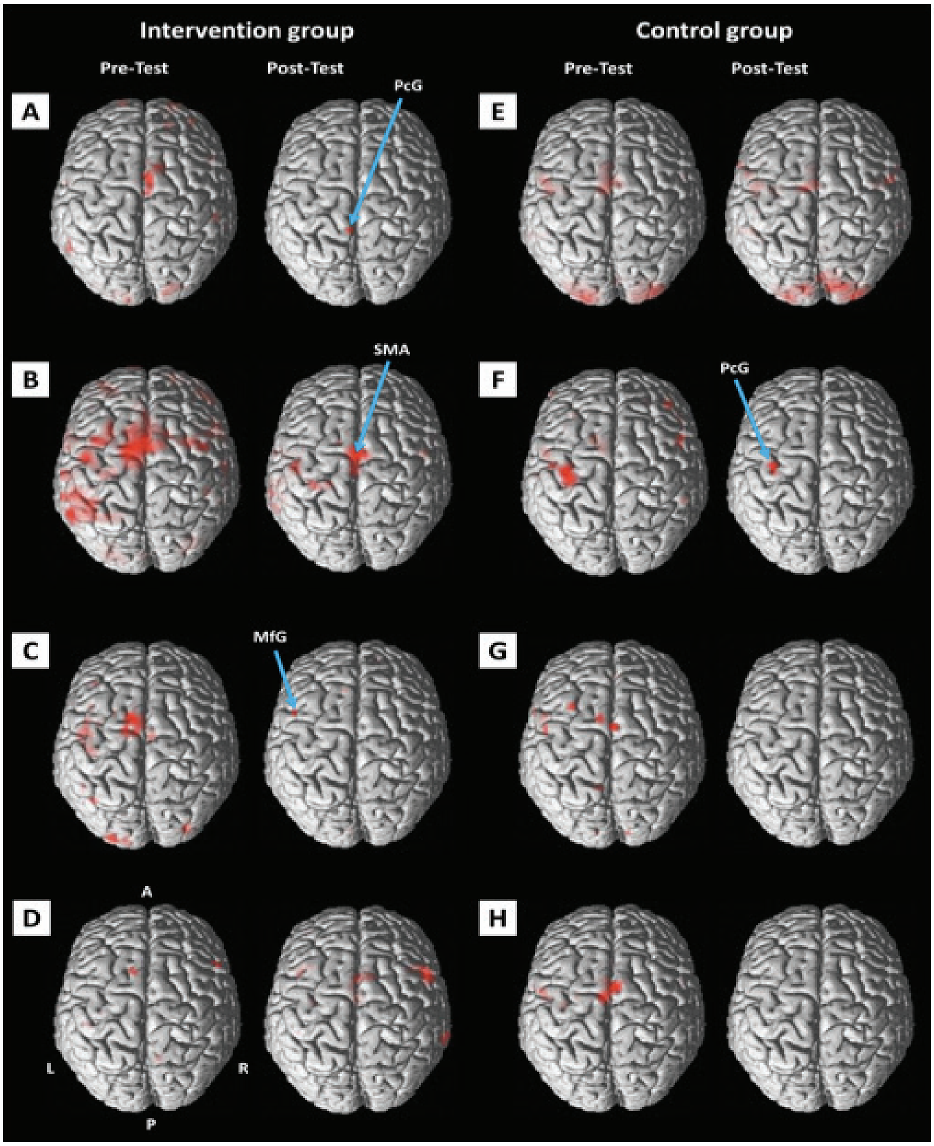

Figure 3. The activation maps of right hand (RH) motor imagery of each subject in MM and control groups before and after intervention.

The effect of MM practice on BCI performance was evaluated using ANCOVA of post-test scores, using pre-test scores as a covariate. Results of ANCOVA on the adjusted mean of post-intervention BCI accuracy for meditation group (M=64.6, SD=10.4) and control group (M=56.0, SD=10.4) indicated that there was a significant between-group effect after controlling for the effect of the covariate, $F(1,35)= 6.372$, $p =.016$, $r = 0.392$. This randomized controlled trial study showed that the MM group significantly improved their BCI performance compared with the no-treatment control group.

Out of the ten participants who completed the fMRI scanning, two participants who used motor imagery tasks (left hand and both feet) that were different from the rest of the participants (motor imagery tasks right hand and both feet), were excluded from analysis. The remaining eight participants consisted of 4 from the MM group and 4 from the control group. They were 5 males and 3 females. Their age range was from 19 to 21 (M=19.8, SD=0.7).

### *fMRI activation maps for motor imagery*

#### *Right hand motor imagery*

Figure 3 shows the activation maps of right

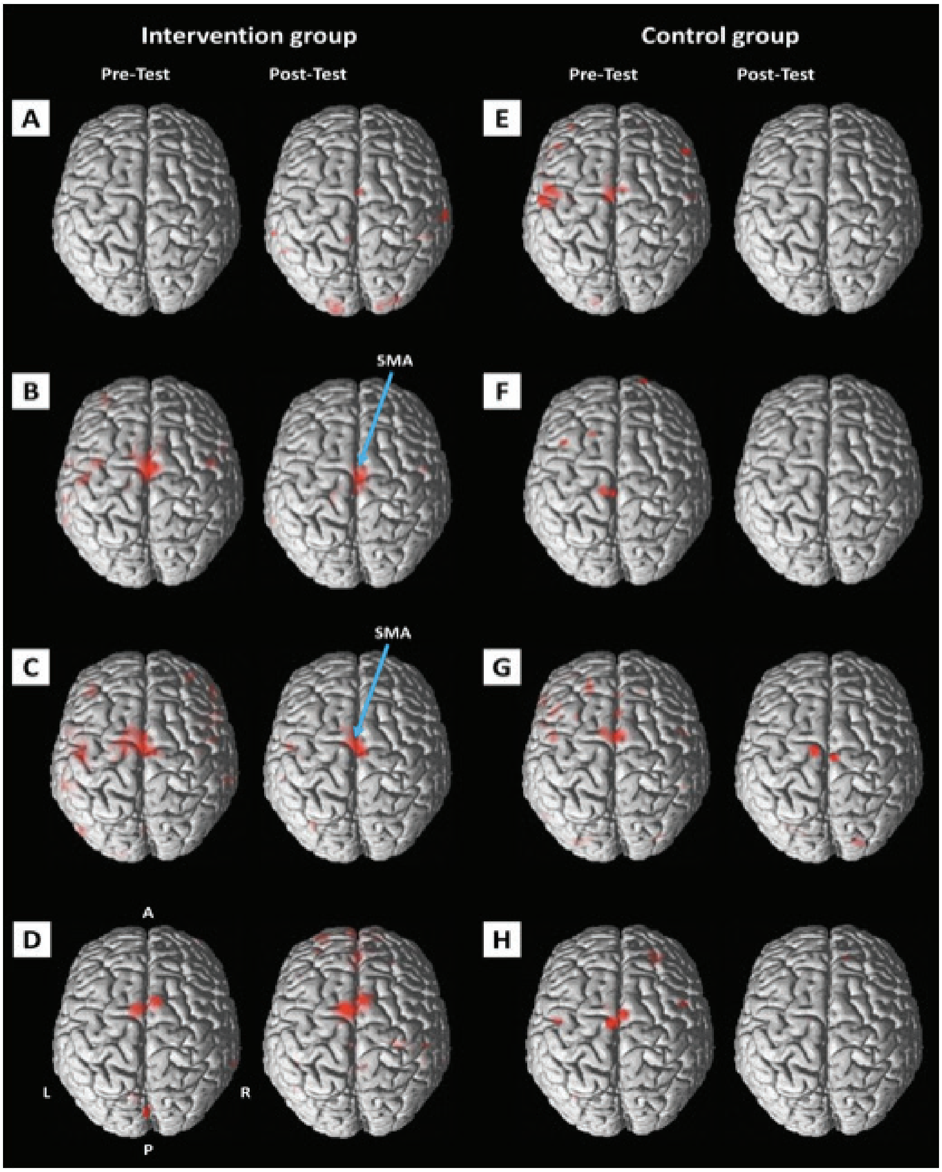


Figure 4. The activation maps of both feet (BF) motor imagery of each subject in MM and control groups before and after intervention.

hand motor imagery of each subject in MM and control groups before and after intervention. All images were threshold at p <0.05, FWE. Focused fronto-parietal activation in subjects A, B, C and F was seen in post-test. After meditation training, activation was found focused to left precentral gyrus (PcG) of subject A, to bilateral supplementary motor area (SMA) of subject B and to left middle frontal gyrus (MfG) of subject C. This was only seen in one subject (F) of the control group post-test, which was focused to left PcG. No post-test fronto-parietal activation was seen in subjects G and H.

***Both feet motor imagery***

Figure 4 displays activation maps of both feet motor imagery of each subject in MM and control groups before and after intervention. All images were threshold at p <0.05, FWE. Focused fronto-parietal activation in subjects B and C was seen in post-test. After meditation training, focused activation was seen in bilateral SMA in two out of four of the trained subjects (i.e. subjects B and C). No similar change post-test was seen in any control subjects. No post-test fronto-parietal activation was seen in subject E and F. Subject H showed pre-test activation in frontopolar cortex,

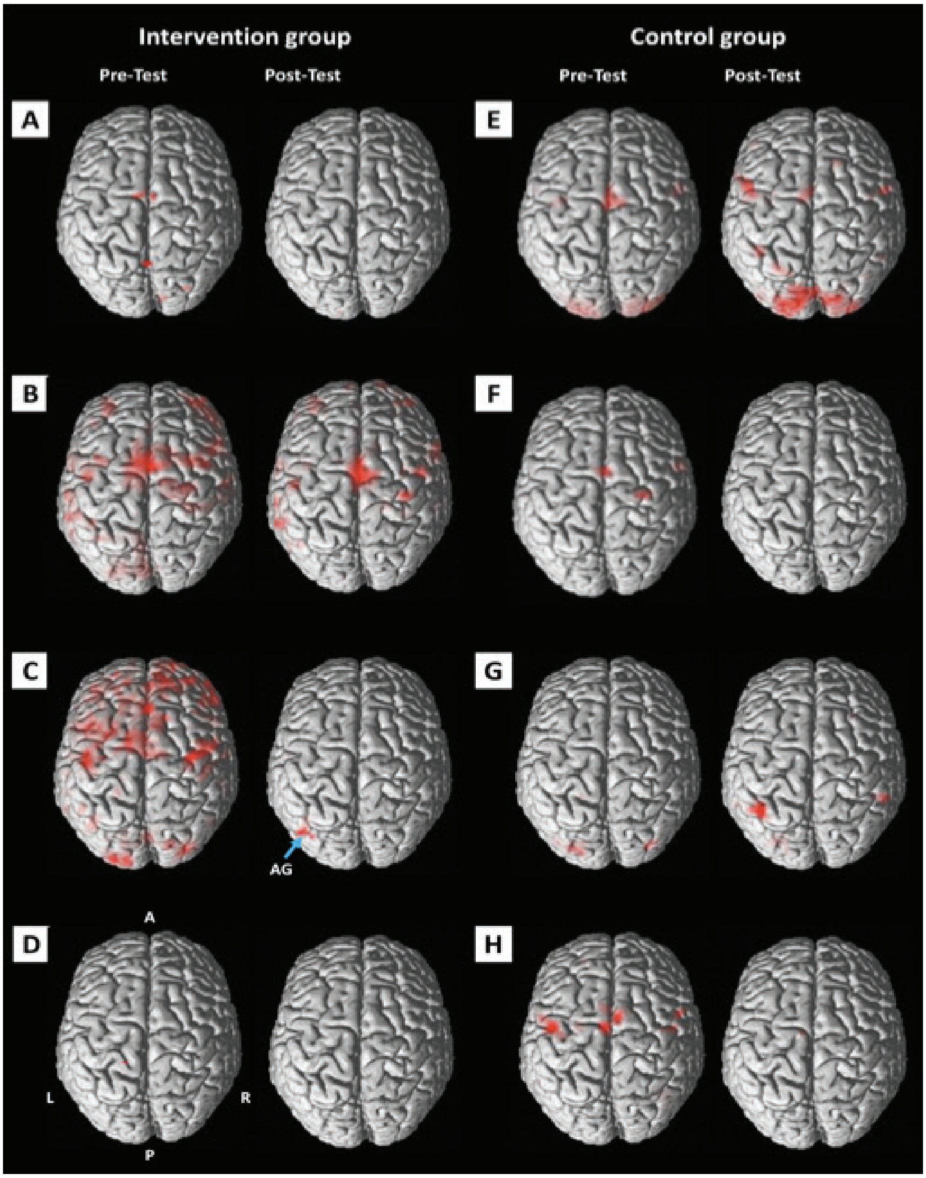


Figure 5. The activation maps of left hand (LH) motor imagery of each subject in MM and control groups before and after intervention.

orbitofrontal cortex and inferior frontal gyrus (i.e. WS).

### *Left hand motor imagery*

Figure 5 shows activation maps of left hand motor imagery of each subject in MM and control groups before and after intervention. All images were threshold at $p < 0.05$, FWE. After meditation training, activation was found focused to angular gyrus (AG) of left inferior parietal lobule (IPL) in subject C. No similar post-test changes were found in the rest of the subjects. No post-test fronto-parietal activation was seen in subjects A, D, F and H (Figure 5).

### *Association of focused activation and improvement of BCI accuracy*

Table 5 presents changes in activation of fronto-parietal network during motor imagery and their correlation with individual BCI accuracy. Overall, focused activation was found more in motor imagery task of right hand and both feet after MM training. In the MM group, right hand motor imagery of 3 subjects (subjects A, B and

**Table 5: Changes in activation of fronto-parietal network during MI and correlation with individual BCI accuracy**

| Group/ Participant | Motor cortex[1] activation on fMRI | | | | | | Changes in BCI accuracy in post-test |
|---|---|---|---|---|---|---|---|
| | Combination of MI tasks chosen for BCI | | | | MI task not chosen for BCI | | |
| | RH | | BF | | LH | | |
| | Pre | Post | Pre | Post | Pre | Post | |
| Meditation | | | | | | | |
| A | WS | F[2] | NA | WS | WS | NA | +14.76 |
| B | WS | F[3] | WS | F[3] | WS | WS | +11.39 |
| C | WS | F[4] | WS | F[3] | WS | F[5] | +25.81 |
| D | WS | WS | WS | WS | WS | NA | +4.44 |
| Control | | | | | | | |
| E | WS | WS | WS | NA | WS | WS | -15.28 |
| F | WS | F[2] | WS | NA | WS | NA | +25.77 |
| G | WS | NA | WS | WS | NA | WS | +3.96 |
| H | WS | NA | WS | WS | WS | NA | +4.72 |

[1] fronto-parietal network; [2] left precentral gyrus; [3] bilateral supplementary motor area; [4] left middle frontal gyrus; [5]angular gyrus of left inferior parietal lobule.
(MI: motor imagery; F: Focused; WS: Widespread; NA: No-Activation)

C) and both feet motor imagery of 2 subjects (subjects B and C) were observed to have these changes. No similar change was found in subject D who also received MM training. The changes in BCI accuracy score of subjects A, B and C were correspondingly better than subject D. The association trend of focused activation and improvement of BCI accuracy was observed here. Only one control (subject F) showed a similar association of focused activation compared to 3 trained subjects, and this control subject also demonstrated a large improvement in BCI accuracy.

## DISCUSSIONS

A previous study by Tan *et al*. showed that MM training group significantly improved their BCI performance compared to the music trained group and a no-treatment control group, indicating effects of MM above and beyond expectancy effects.[14] In that study, the MM training programme was carried out over twelve weeks at one hour per week. In our current study, a shorter MM training programme was carried out over four weeks at three hours per session per week. Our results were similar to Tan *et al*., showing a significant improvement in BCI performance for the MM group compared to a non-intervention control group. Although it has been known that brief MM practice can improve cognitive abilities[18], this is the first time we have shown that a 4-week MM program can improve BCI performance. This will provide a better incentive for BCI users to participate in a MM training program to reap the benefits of improved BCI performance.

The fronto-parietal region had been suggested to form a functional network for attention task[28,29] and during motor imagery.[23] Our fMRI scanning results confirmed this suggestion. The ALE meta-analysis looking at the upper-limb motor imagery showed consistent activations in SMA, PcG and MfG, while lower-limb MI activated SMA region[24] which was consistent with our current fMRI scanning findings.

Our fMRI results also revealed that more MM group participants showed fronto-parietal focused activation than control group participants. In support for this, previous studies had shown meditators can develop the ability of sustained attention during meditation practice.[30-32] fMRI scanning from previous studies found that mental training reduced cortical activities and task effort, suggesting that with meditation, the regulative attention skills invoked less and less frequently, thus reducing the task effort.[30,31] Kozasa *et al*. (2012) reported similar findings where regular meditators were found to activate fewer brain regions than non-meditators in order to achieve the same performance during attentional tasks.[23]

In conclusion, mindfulness meditation improves BCI performance and is correlated with focused activation of the fronto-parietal region in fMRI during motor imagery.

## DISCLOSURE

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Conflict of interest: None

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