Effect of Mindfulness Meditation on Brain-Computer Interface Performance

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Highlights:

- Training in mindfulness meditation (MM) improves ability to control a BCI device.
- Equivalent expectations for improvement are elicited by MM and music training.
- BCI performance is better after MM rather than music training.
- Expectations cannot explain the effect of MM on BCI performance.

Keywords:
Brain-Computer Interface, BCI Performance, Mindfulness', Meditation, Music, Expectation

Abstract

Electroencephalogram based Brain-Computer Interfaces (BCIs) enable stroke and motor neuron disease patients to communicate and control devices. Mindfulness meditation has been claimed to enhance metacognitive regulation. The current study explores whether mindfulness meditation training can thus improve the performance of BCI users. To eliminate the possibility of expectation of improvement influencing the results, we introduced a music training condition. A norming study found that both meditation and music interventions elicited clear expectations for improvement on the BCI task, with the strength of expectation being closely matched. In the main 12 week intervention study, seventy-six healthy volunteers were randomly assigned to three groups: a meditation training group; a music training group; and a no treatment control group. The mindfulness meditation training group obtained a significantly higher BCI accuracy compared to both the music training and no-treatment control groups after the intervention, indicating effects of meditation above and beyond expectancy effects.

1. Introduction

There are more than 100 million potential Brain-Computer Interface (BCI) users in the world, with the majority being stroke and motor neuron disease (MND) patients (Guger, 2008). With BCIs, these individuals can have greater independence and a higher quality of life. They can use BCIs to communicate with the outside world and control devices to perform daily tasks (Pfurtscheller et al., 2003; Vaughan et al., 2006). Any means of improving the effectiveness with which people can use BCI devices could dramatically improve their lives. A candidate is mindfulness meditation because of its claimed ability to lead to better self-regulation (Cahn & Polich, 2006; Sedlmeier et al., 2012), though relatively few studies have compared its effects to an active control treatment of equivalent plausibility (see Jensen, Vangkilde, Frokjaer, & Hasselbalch, 2012, for a recent exception). This paper will explore the use of mindfulness meditation in gaining better control of BCI devices, above and beyond expectation effects. The paper will thus address theoretical issues concerning the nature of mindfulness meditation by way of exploring, for the first time, this possible practical benefit.

An electroencephalogram (EEG) based BCI measures the brain activity at the scalp in a non-invasive manner and the signals are used as inputs to the BCI system. The operation of the BCI is dependent on the effective interaction between the user's brain and the system itself (Wolpaw et al., 2000). One of the biggest challenges faced by the BCI users is to produce consistent and reliable EEG patterns when they operate the BCIs and this is much related to the ability of the users to regulate their mental states. Unstable mental states due to anxiety, fatigue, frustration, or loss of concentration may cause inconsistent EEG patterns. Distraction during the experiment, for instance, caused by feedback presented by BCIs, can modify the EEG and introduce noise to the system (Guger, Edlinger, Harkam, Niedermayer, & Pfurtscheller, 2003; Pfurtscheller & Neuper, 2001). Researchers have been trying to apply different signal processing techniques for BCIs in an attempt to improve the signal-to-noise ratio of the input signal (Bashashati, Fatourechi, Ward, & Birch, 2007). Other studies train users to control their EEG patterns through extensive and resource demanding neuro-/biofeedback training (Hwang, Kwon, & Im, 2009; Neuper, Schlögl, & Pfurtscheller, 1999).

The current study aims to examine the effect of mindfulness meditation training on the ability to control a BCI using motor imagery. Previous cross-sectional studies investigating EEG during hand motor imagery tasks demonstrated that experienced meditators had more distinguishable EEG patterns than the untrained subjects (Eskandari & Erfanian, 2008; Lo, Wu, & Wi, 2004). Thus, mindfulness meditation training may help to reduce "neural noise" and enhance signal-to-noise ratios and thereby facilitate more rapid learning in the use of BCIs (Davidson & Lutz, 2008).

In general, meditation can be categorized into two basic approaches depending on how the attentional processes are directed: concentrative-based meditation and mindfulness-based meditation (Cahn & Polich, 2006). While concentration-based meditation focuses the attention on a single stimulus, mindfulness meditation involves observation of constantly changing internal and external stimuli as they arise (Baer, 2003). Both types of meditation in fact involve mindfulness in the sense of non-judgmental acceptance, but the term “mindfulness meditation” is often used as a contrast to concentration mediation to indicate the difference in emphasis. Mindfulness meditation practice involves non-judgmental observation of sensations, thoughts, feelings, emotions, and environmental stimuli. It is a metacognitive process as it requires both control of cognitive process (i.e. attention self-regulation) and monitoring the stream of consciousness (Bishop et al., 2004; Semmens-Wheeler & Dienes, 2012).

A large body of research has explored the effect of mindfulness meditation training on cognitive abilities. Carter et al. (2005) found that individuals trained in meditation could measurably alter their experience of perceptual rivalry. Furthermore, long-term meditators show higher performance in the domains of sustained attention (Valentine & Sweet, 1999), executive attention (D. Chan & Woollacott, 2007; van den Hurk, Giommi, Gielen, Speckens, & Barendregt, 2010), and attention switching (Hodgins & Adair, 2010) as compared to matched controls. Studies investigating the effect of a 10-day and a 4-day mindfulness retreats respectively (Chambers, Lo, & Allen, 2008; Zeidan, Johnson, Diamond, David, & Goolkasian, 2010) revealed improvement in working memory capacity in meditators following the retreats. The latter study also observed that the meditators increased mindfulness level over an active control group (Zeidan et al., 2010). Moreover, Tang et al. (2007) observed that the people who underwent a 5-day intensive mindfulness meditation retreat showed greater improvement in executive attention, better mood, and decreased stress-related cortisol compared with a control group. Higher attentional control and cognitive flexibility in experienced meditators are correlated with higher self-reported levels of mindfulness (Moore & Malinowski, 2009).

Recent research employing functional magnetic resonance imaging (fMRI) techniques suggests meditation-induced plasticity in the brain areas associated with cognitive control and emotional regulation. Lazar et al. (2005) demonstrated that long-term meditators had thicker cortices than non-meditators in the regions involved in sensory, cognitive, and emotional processing. On the other hand, Hölzel et al. (2011) found that an 8-week Mindfulness-Based Stress Reduction (MBSR) program increased the gray matter concentration within the hippocampus, an area involved in emotional regulation and response control (Corcoran, Desmond, Frey, & Maren, 2005).

The present authors are not aware of any previous randomized controlled trial studies in the field of BCI, except an earlier pilot study conducted by the authors themselves (Tan, Jansari, Keng, & Goh, 2009). BCI experiments are invariably laborious. The present study is an attempt to use a randomized controlled trial design to examine the effects of mindfulness meditation on the BCI performance among a group of meditation-naïve participants.

Many previous studies on mindfulness meditation utilized a randomized two-group design in which a mindfulness meditation intervention group is compared to a no-treatment or wait-listed control group (Baer, 2003). Such a design is limited in that it does not allow the researcher to control for nonspecific treatment effects such as expectancy and demand characteristics. The issues of expectancy and demand characteristic have been explored in consciousness research (Paskewitz & Orne, 1973; Plotkin, 1980) but they have not been clearly addressed in studies involving meditation interventions.

A recent paper (Zeidan et al., 2010) showed that mindfulness meditation increases performance on cognitive tasks. They used the "active control" of listening to the Hobbit being read to them. However, such a control may not elicit the same expectations of improvement in cognitive functioning as meditation. Jensen et al. (2012) found mindfulness based stress reduction compared with non-mindfulness based stress reduction improved selective attention, but it is also not clear whether expectations could account for these results although the control condition is closely matched to the treatment condition. To draw causal conclusions about the effectiveness of an intervention, researchers must compare the treatment condition with an active control and test whether both conditions shared the same expectations (Boot, Simons, Stothart, & Stutts, 2013).We will address this concern.

In the present study, we use a three-group design, similar to Jensen et al. (2012), in which mindfulness meditation is compared not only against a no-treatment control condition but to another mental training condition. For the mental training condition participants received instructions in how to play a classical guitar. This novel control condition is designed on the theoretical basis that learning a musical instrument, like meditation, can be considered as a form of mental training that may be thought by subjects to be as likely to induce neuroplasticity and cognitive transfer among practitioners as meditation (Rabipour & Raz, 2012).

Playing a musical instrument requires a highly sophisticated, multi-modal integration of sensory, motor, and cognitive tasks. Activities that are continuously practiced by the musicians, e.g. pitch perception, attentive listening, musical sight-reading, synchronization between music and movement, composition, emotive transference, manual dexterity, remembering, learning, performing, and receiving multi-sensory feedback activate multiple core brain regions (Janata, Tillmann, & Bharucha, 2002; Levitin & Tirovolas, 2009).

Previous studies comparing musicians with matched non-musicians have found brain structural and functional differences in musically related regions, such as auditory cortex (Bermudez & Zatorre, 2005; Pantev et al., 1998; Schneider et al., 2002), sensorimotor cortex (Gaser & Schlaug, 2003; Hund-Georgiadis & Von Cramon, 1999) and multimodal integration areas (Bangert & Schlaug, 2006; Gaser & Schlaug, 2003; Li, Lai, Luo, Yao, & Yao, 2011; Sluming, Brooks, Howard, Downes, & Roberts, 2007). Studies also found that musicians have performed better than non-musicians on auditory processing (Chartrand & Belin, 2006; Špajdel, Jariabková, & Riečanský, 2007; Strait, Kraus, Parbery-Clark, & Ashley, 2010) and fine motor abilities (Amunts et al., 1997; Hughes & Franz, 2007; Spilka, Steele, & Penhune, 2010).

While effects on musical related domains (near transfer) are relatively common, (Posner, Rothbart, Sheese, & Kieras, 2008) proposed that art training may influence other cognitive processes (far transfer) through the underlying mechanism of attention. Moreover, studies conducted by Rueda, Rothbart, McCandliss, Saccomanno, and Posner (2005) showed that attention training can lead to generalized improvement on other untrained domains. Along with the observations on music related domains, studies also revealed that musicians have greater abilities as compared to non-musicians on more distant domains, such as visual-spatial (Brochard, Dufour, & Despres, 2004; Sluming et al., 2007) and verbal working memory (Brandler & Rammsayer, 2003; A. S. Chan, Ho, & Cheung, 1998; Franklin et al., 2008). In addition, several experimental studies conducted on pre-school children and primary school children had demonstrated the effect of music training on spatial (Bilhartz, Bruhn, & Olson, 1999), verbal (Ho, Cheung, & Chan, 2003), mathematical performances (Graziano, Peterson, & Shaw, 1999), as well as general IQ (Schellenberg, 2004). Importantly, not only does music training have effects on cognitive functioning, people may believe that it does. Thus, we may be able to show that expectations are roughly the same for music and meditation training for enhancing BCI performance. Then meditation rather than music training leading to superior BCI performance would be particularly strong evidence for the claim that the effect of meditation training on BCI performance involves more than an expectancy effect.

2. Material and Methods

2.1 A survey study measuring the expectations on meditation and music interventions

2.1.1 Participants

A questionnaire norming study was conducted on 40 undergraduates from a Malaysian University to measure expectations for how mindfulness meditation and music training would affect BCI Performance. Participants were engineering students between 18 and 22 years old. All participants were Chinese males and had never taken part in any formal meditation or music training.

2.2.2 Design and procedure

Participants were asked to read the paragraphs that describe the scenarios of a) a 12-week mindfulness meditation training and b) a 12-week training on learning to play classical guitar. The order of both scenarios was counterbalanced across participants. In each scenario, the BCI test was explained to the participants. Participants then indicated whether they expect the training would improve, degrade, or cause no change to BCI performance. Participants also rated on a 1 to 10 scale to indicate the strength of their expectation (e.g. How strongly do you believe that the meditation training would make them improve on the BCI test? Give your answer on a 1 to 10 scale, where 1 indicated just guessing and 10 indicated certainty).

2.2.3 Results and Discussions

Results are shown in Table 1 (1A, 1B) and Figure 1.

TABLE 1 (1A & 1B) and FIGURE 1ABOUT HERE

Results showed that the majority of participants expected that both meditation training and music training would improve the BCI performance; a minority thought they would have no effect. Specifically 80% of people thought meditation would improve BCI performance rather than not and 78% of people thought music training would improve BCI performance rather than not (see Table 1A). The odds ratio for these probabilities was 1.1[1], with a 90% confidence interval [0.47, 2.86]. The confidence interval includes 1, indicating no significant association between expectation of change and type of training even at the 10% significance level. Further, the upper limit of the interval indicates that odds ratio in favour of meditation over music could be at most 2.9; e.g. if the probability for expecting a positive change with music was 72% it would be 88% for meditation. Given this is the upper end of the confidence interval, we have established similar expectations of positive change to a high degree of sensitivity[2].

We obtain an even more sensitive demonstration of the equivalence of expectations by looking at the continuous strength of expectation, as shown in Figure 1. There was no significant difference in the strength of expectation for meditation (M = 6.69, SD = 1.86) and musical (M = 6.97, SD = 1.80) training; t(61) = - .61, p = .55, 95% CI on the difference [-1.2, 0.6]. That is, the strength of expectation could only be greater for meditation than music by 0.6 of a scale point, where the scale is 1 (guessing) to 10 (certainty). The data allow only a tiny difference in strength of expectation between the two training conditions.

2.2.4 Conclusion

Both meditation and music trainings elicit clear expectations for improvement in our population, and the strength of expectation is about the same for both.

2.2 Main Study

2.2.1 Participants

Participants of this study were recruited from the engineering faculty of a local university through in campus advertisements and announcements. A total of 76 participants were recruited into the study[3]. Prior to the enrolment of the study, the eligibility of the interested participants was screened through the use of a demographic form and a phone interview. The eligible participants were those who had no previous experience in a formal practice related to mindfulness meditation and had no more music training than the obligatory musical education at primary school. They also did not have any existing or prior history of neurological or psychological disorders and brain injury or brain-related trauma. All the participants recruited were given detailed explanations on the study procedures and were required to complete a written informed consent form before the beginning of the baseline assessment. Participants were randomly assigned to study groups according to a computer-generated random number list. Randomization was conducted after they completed the baseline assessment in order to avoid any of the participants dropping out from the study before the assessment causing unequal sample size between groups. The experimenter was aware of the group allocation of the participants.

2.2.2 Measures

EEG scanning

Imagery of motor tasks are associated with the activation of sensorimotor cortex, but the optimum location of the EEG electrodes to provide the most distinguishable EEG patterns from two different mental task is subject specific. Hence, prior to the BCI test, a scan on the brain signals was conducted in order to identify the optimum locations of the EEG electrodes and the best combination of the mental tasks.

EEG scanning on each participant was conducted using a Nicolet 64-channels EEG acquisition system. Nine electrodes were placed over the sensorimotor cortex area to record the EEG signals produced from three mental tasks: imagine left hand movement (LEFT), imagine right hand movement (RIGHT) and imagine both feet movement (FOOT). The EEG signals of all possible combinations of bipolar EEG channels and mental tasks were analyzed offline. The combination that gave the highest accuracy in the 10x10 fold cross validation analysis was used in the BCI tests.

BCI test

The BCI test started with a 30-minute training phase. Participants were required to perform 60 trials for each of the two mental tasks selected from the EEG experiment. The raw EEG data from each mental task were filtered by using a 5 – 40 Hz elliptic filter. The coefficients of the auto-regressive (AR) model were determined and used to set up a linear-discriminant analysis (LDA) classifier. The classifier was then used to categorize the new EEG signals in the testing phase in real time.

Figure 2 shows a graphical user interface (GUI) that was used in the testing phase. It was designed for selection of 4 options – “A”, “B”, “C”, “D” (Figure 2) and a “RESET” option. The options “A”, “B”, “C” and “D” scroll from left to right. The selection instruction was displayed at the top left corner of the screen. The 4 selection options could be customized to represent the 4 types of hand movements of a prosthetic hand as reported in an earlier study (Goh et al., 2005) or the 4 desired destinations for a wheelchair (Tan, Ng, Ng, & Goh, 2008)

FIGURE 2 ABOUT HERE

To select a particular option, the participant waited for the desired option to scroll into the grey selection box. By imagining the appropriate mental task, the participant moved the cursor to the right (or left depending on the mental task) of the cursor bar. The cursor was to be maintained to the right (or left) during 5 consecutive seconds and repeated a second time for another 5 seconds to confirm and activate the selection of the desired option.

For the purposes of the BCI test, a randomized sequence of selections was provided. Participants were required to make a selection according to the sequence. An example of a randomized sequence of selections is as follows:

Select A → Reset → Select D → Reset → Select C → Reset → Select B → Rest for 30 seconds → Reset → Select C → Reset → Select A → Reset → Select B → Reset → Select D → Rest for 30 seconds → Reset → Select B → Reset → Select C → Reset → Select D → Reset → Select A → Rest for 30 seconds → Reset

If a participant failed to select the desired option in the grey selection box, he waited for the option to return to the selection box after it had scrolled through the next cycle. During the waiting period, no selection should be made. The optimum time to complete a test sequence of selections is 7 minutes. Four types of classification from the BCI test were True Positive (TP), False Negative (FN), True Negative (TN), and False Positive (FP) making a confusion matrix as shown in Table 2.

TABLE 2 ABOUT HERE

The BCI performance is measured by the accuracy (Wolpaw & Wolpaw, 2012) which is defined as

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

2.2.3 Design and procedure

The programs of the study were scheduled according to the university semester timetable. The baseline assessment was conducted before the beginning of the semester. Participants attended an EEG scanning followed by a BCI test at another day. Each session was about 2 hours. Participants were allowed to choose the timeslots from the list given based on their available time. Participants were told to make certain preparations for each test session, for instance having enough sleep (not less than 5 hours), not consuming caffeine or alcoholic beverages, and not performing active exercise for 12 hours prior to the test session. Participants were paid 25 Ringgit Malaysia (equivalent to approximately 8.30 US dollars) for completion of each test session.

Following baseline assessment, participants were randomly assigned into 3 study groups: Group A (mindfulness meditation), Group B (learning to play a classical guitar) and Group C (control group). Intervention programs were started at the beginning of the new semester and ended 12 weeks later. The instructors for mindfulness meditation and music trainings were blind to the content of the assessment.

Participants in Group A attended a mindfulness meditation intervention training that was delivered by a mindfulness meditation instructor who had twenty years of experience of teaching meditation. The training sessions were held once a week for 12 weeks. Each training session was held with groups of 6 to 10 participants and lasted for 1 hour. The participants were taught the concepts and skills of how to practice mindfulness meditation without any spiritual or religious emphasis and how to be always mindful in their daily activities. Each training session included a 20-minute sitting meditation. Participants were guided by the instructor to sit quietly and focus on the flow of their breath, with their eyes closed, and to nonjudgementally become aware of their thoughts, senses, and feelings. They were told to not look for any thought or remain alert waiting for any thought to come but to notice the content of each thought when it arises, accept it, and allow it to go. They were also told to gently focus back on the breath when they noticed that their mind had wandered. As the intervention progressed, the participants were guided with more instructions and details about mindfulness practice. For instance, they were taught to calm down the mind by remaining focused on their breath and to perform a "body scan" – bringing awareness to physical sensations throughout the whole body while nonjudgementally allowing discursive thoughts to simply pass. Sometimes, the participants had additional walking or lying down meditation exercises. Before and after each meditation session, participants were encouraged to share their experience and to ask questions about difficulties while meditating. In addition, participants were assigned to perform 20 minutes home practice per day of mindfulness meditation. They were also encouraged to be aware of the body and mind processes throughout their daily activities.

Participants in Group B learned to play a classical guitar under the guidance of a professional instructor from a local music center. The training sessions were held once a week for 12 weeks. Each training session was held with groups of 5 to 7 participants and lasted for 1 hour. The participants learned various basic techniques of playing a classical guitar, such as understanding the notes, positioning the fingers, pressing strings, tuning, plucking, strumming, and playing the chords and melody. The lesson was conducted based on the syllabus designed by Yamaha Music Foundation (Foundation, 2007). Participants were assigned to perform 20 minutes home practice each day.

Participants in group C were told to not participate in any activities that relate to the mindfulness meditation training or learning a musical instrument during the intervention period.

Each participant was required to submit a log book. Group A and Group B participants were required to record and described their daily practices. Group C participants were required to record and confirm every week that they were not involved in activities that related to the intervention program.

3. Results

3.1 Demographic information

Seventy-six participants were initially recruited for the study and were randomized to either mindfulness meditation training, music training, or a no-treatment control group. Thirteen participants dropped out of the study. The reasons given for dropping out were problems in attending the weekly training sessions or the post-tests due to busy personal schedules and inability to continue to commit to the study. The remaining participants consisting of 23 in the mindfulness meditation group, 20 in the music training group, and 20 in the control group who completed the study. All were Chinese undergraduates with 58 males and 5 females (2 in the meditation training group, 1 in the music training group, and 2 in the control group) majoring in various engineering courses. Their age ranged between 18 and 24 years old (M = 20.10; SD = 1.52) and self-identified as Buddhists (n=56), Christian (n=4), free thinker (n=2) and a Chinese folk religion follower (n=1). Fifty nine were right-handed and four were left-handed.

3.2 Statistical analysis

Means and standard deviation of the BCI accuracy scores across the three groups at baseline and post-test are presented in Table 3.

TABLE 3 ABOUT HERE

A one-way analysis of variance (ANOVA) was conducted on baseline BCI accuracy between the participants from the three groups. In general, the music training group had a slightly higher mean value of BCI accuracy compared to the other two groups but the ANOVA test didn't show a significant difference on the baseline BCI accuracy for the three groups, $F(2,61) = 1.916$, $p > .05$.

Within-group comparisons of our results showed that the participants who underwent meditation training improved their BCI accuracy significantly, $t(22) = -2.28$, $p < .05$, $r = .44$ while both the music training and no-treatment control groups had poorer BCI accuracy at the post-test compared to their baseline scores but the effects were not statistically significant: $t(19) = 1.57$, $p = .13$ and $t(19) = 1.36$, $p = .19$ respectively.

A one-way analysis of covariance (ANCOVA) was conducted to compare the between-group effect on the post-test BCI accuracy, with baseline BCI scores as covariate. Results of ANCOVA indicated that the covariate, baseline BCI accuracy was not significantly related to the post-test BCI scores, $F(1,59) = .29$, $p = .60$. There was a significant between-group effect after controlling for the effect of the covariate, $F(2,59) = 6.30$, $p < .005$. Post hoc comparisons showed that the participants who underwent the meditation training (M = .64, SD = .10) had significantly higher BCI accuracy scores than no-treatment controls (M = .52, SD = .10), $t(59) = 3.39$, $p < .005$, $r = .40$ and the participants who underwent music training (M = .56, SD = .14), $t(59) = 2.45$, $p < .05/2$, after controlling Type I error using sequential

Bonferroni procedure, r = .30. A Bayes factor was conducted on the difference between meditation and music training; this difference, should it exist, was presumed to be plausibly no larger than the difference between meditation and passive control (a difference of .12). Thus to represent the alternative hypothesis (of a difference between meditation and music) a uniform was used between 0 and .12. The Bayes factor (for a sample difference between meditation and music of .08, SE = .033) was 11.45, which is greater than 3 and strong evidence for the alternative over the null. Participants who underwent the music training did not perform any better than the controls, (95% CI [- .043, .107], $t(59) = .87$, $p = .39$), though the data are consistent with the music group being better than the control group by up to 10% .

4. Discussion

The norming study prior to the main study showed that both mindfulness meditation and learning to play a classical guitar elicited clear expectations for improvement on BCI performance with the strength of the expectation being about the same for both. In spite of this positive expectation for improvement, the results of our main study showed that only the mindfulness meditation training group improved in their BCI performance while the music training and the no-treatment control groups did not. The advantage of the meditation over the music group is one of the first demonstrations of the effectiveness of mindfulness meditation in metacognitive regulation above and beyond an expectancy effect.

Considering that many previous studies on music training found plasticity in brain functions, and learning music must involve training in attentional regulation to some degree (Posner et al., 2008), the advantage of meditation is all the more impressive. But it does raise the question of why meditation was so superior.

A possible explanation is that a 12-week music training intervention may not have been sufficient to result in domain transfers that related to the skills required for operating a BCI. Previous studies comparing musicians to non-musicians recruited professional musicians. This population began their practice in childhood thereafter practiced intensely for many years. Researchers have suggested that the differences observed between musicians and non-musicians were related to long-term and intensive practice on a musical instrument (Gaser & Schlaug, 2003; Norton et al., 2005) and early commencement of practice (Amunts et al., 1997; Watanabe, Savion-Lemieux, & Penhune, 2007).

There is also another explanation. Previous studies have reported that unstable mental states due to anxiety, fatigue, frustration, or loss of concentration can affect BCI performance (Guger et al., 2003; Pfurtscheller & Neuper, 2001). In our current study, the baseline tests were carried out at the beginning of the university semester while the post-tests were carried out towards the end of the semester when the students experienced greater stress as they were required to submit their course assignments, and to prepare for their semester tests and examinations. The stress and anxiety levels experienced by the participants during the period of post-tests may have been higher compared to the period during the baseline tests. On the other hand, mindfulness meditation may have enhanced emotion regulation in a way music training did not. The meditators were taught how to non-judgmentally observe their sensations, thoughts, feelings, emotions, and environmental stimuli. This requires both control of cognitive process (i.e. attention self-regulation) and monitoring the stream of consciousness (Bishop et al., 2004). Self-regulation refers to the ability to control the reaction to stress, to maintain focused attention, and to interpret mental states (Fonagy & Target, 2002). Such abilities are particularly important for BCI users to remain focused, calm, and produce consistent EEG patterns. Previous studies have suggested that long-term meditation leads to changes in brain regions important to both cognitive control and emotional regulation (Hölzel et al., 2011; Lazar et al., 2005). People who underwent a short-term meditation training reported better moods (Tang et al., 2007). Future research could disentangle the contributions of attentional and emotional regulation to the ability of mindfulness training to enhance BCI performance.

The current study was not a blind design. The experimenter was aware of the participants' group allocation. Experimenter bias may thus be a possible confound. The participants in the current study were also aware of their group assignment. Of course, it is not possible to blind the participants from their particular group assignment. However, as both intervention groups hold similar expectations for improvement, any difference between the groups on the outcome measure may be attributed to the effect of the treatment.

5. Conclusion

We found in a 12 week intervention study that a mindfulness meditation training group significantly improved their BCI performance compared to a music training group (learning to play a classical guitar) and a no-treatment control group. Both the mindfulness meditation training and music training groups elicited positive expectation and beliefs of improvement in BCI performance and the strength of expectation was about the same for both. The results showed that we have eliminated expectancy effects as an explanation of an objective and useful effect of mindfulness meditation.

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References

Amunts, K., Schlaug, G., Jäncke, L., Steinmetz, H., Schleicher, A., Dabringhaus, A., & Zilles, K. (1997). Motor cortex and hand motor skills: Structural compliance in the human brain. *Human brain mapping, 5*(3), 206-215.

Baer, R. A. (2003). Mindfulness training as a clinical intervention: A conceptual and empirical review. *Clinical psychology: Science and practice, 10*(2), 125-143.

Bangert, M., & Schlaug, G. (2006). Specialization of the specialized in features of external human brain morphology. *European Journal of Neuroscience, 24*(6), 1832–1834.

Bashashati, A., Fatourechi, M., Ward, R. K., & Birch, G. E. (2007). A survey of signal processing algorithms in brain–computer interfaces based on electrical brain signals. *Journal of Neural engineering, 4*(2), R32.

Bermudez, P., & Zatorre, R. (2005). Differences in gray matter between musicians and nonmusicians. *Ann. N. Y. Acad. Sci., 1060*, 395-399.

Bilhartz, T. D., Bruhn, R. A., & Olson, J. E. (1999). The effect of early music training on child cognitive development. *Journal of Applied Developmental Psychology, 20*(4), 615-636.

Bishop, S. R., Lau, M., Shapiro, S., Carlson, L., Anderson, N. D., Carmody, J., . . . Velting, D. (2004). Mindfulness: A proposed operational definition. *Clinical psychology: Science and practice, 11*(3), 230-241.

Boot, W. R., Simons, D. J., Stothart, C., & Stutts, C. (2013). The Pervasive Problem With Placebos in Psychology Why Active Control Groups Are Not Sufficient to Rule Out Placebo Effects. *Perspectives on Psychological Science, 8*(4), 445-454.

Brandler, S., & Rammsayer, T. H. (2003). Differences in mental abilities between musicians and non-musicians. *Psychology of Music, 31*(2), 123-138.

Brochard, R., Dufour, A., & Despres, O. (2004). Effect of musical expertise on visuospatial abilities: Evidence from reaction times and mental imagery. *Brain and cognition, 54*(2), 103-109.

Cahn, B. R., & Polich, J. (2006). Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychological bulletin, 132*(2), 180.

Carter, O. L., Presti, D., Callistemon, C., Ungerer, Y., Liu, G. B., & Pettigrew, J. D. (2005). Meditation alters perceptual rivalry in Tibetan Buddhist monks. *Current Biology, 15*(11), R412-R413.

Chambers, R., Lo, B. C. Y., & Allen, N. B. (2008). The impact of intensive mindfulness training on attentional control, cognitive style, and affect. *Cognitive Therapy and Research, 32*(3), 303-322.

Chan, A. S., Ho, Y. C., & Cheung, M. C. (1998). Music training improves verbal memory. *Nature, 396*, 128.

Chan, D., & Woollacott, M. (2007). Effects of level of meditation experience on attentional focus: is the efficiency of executive or orientation networks improved? *The Journal of Alternative and Complementary Medicine, 13*(6), 651-658.

Chartrand, J. P., & Belin, P. (2006). Superior voice timbre processing in musicians. *Neuroscience Letters, 405*(3), 164-167.

Corcoran, K. A., Desmond, T. J., Frey, K. A., & Maren, S. (2005). Hippocampal inactivation disrupts the acquisition and contextual encoding of fear extinction. *The Journal of Neuroscience, 25*(39), 8978-8987.

Davidson, R. J., & Lutz, A. (2008). Buddha's Brain: Neuroplasticity and Meditation [In the Spotlight]. *Signal Processing Magazine, IEEE, 25*(1), 176-174.

Dienes, Z. (2008). *Understanding Psychology as a Science: An Introduction to Scientific and Statistical Inference*. Palgrave Macmillan Associated website: http://www.lifesci.sussex.ac.uk/home/Zoltan_Dienes/inference/Bayes.htm.

Dienes, Z. (2011). versus Orthodox statistics: Which side are you on? *Perspectives on Psychological Science, 6*(3), 274-290.

Eskandari, P., & Erfanian, A. (2008). Improving the performance of brain-computer interface through meditation practicing. *In Engineering in Medicine and Biology Society, 2008. EMBS 2008. 30th Annual International Conference of the IEEE*, 662-665.

Fonagy, P., & Target, M. (2002). Early intervention and the development of self-regulation. *Psychoanalytic Inquiry, 22*(3), 307-335.

Foundation, Y. M. (2007). *Guitar Course Fundamentals* (26 ed.). Japan: Yamaha Music Foundation.

Franklin, M. S., Moore, K. S., Yip, C. Y., Jonides, J., Rattray, K., & Moher, J. (2008). The effects of musical training on verbal memory. *Psychology of Music, 36*(3), 353-365.

Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. *The Journal of Neuroscience, 23*(27), 9240-9245.

Goh, S. Y., Ng, S. C., Phang, Y. M., Yong, X. Y., Lim, E., Yazed, A. M., & Shuhaida, Y. (2005). A Brain-Computer Interface for control of a prosthetic hand. *Journal of Science and Technology in the Tropics, 1*, 35-41.

Graziano, A. B., Peterson, M., & Shaw, G. L. (1999). Enhanced learning of proportional math through music training and spatial-temporal training. *Neurological Research, 21*(2), 139.

Guger, C. (2008). *Brain Computer Interface*. Paper presented at the Lecture notes in The 4th International Summer School on Emerging Technologies in Biomedicine: Advanced Methods for the Estimation of Human Brain Activity and Connectivity, Applications to Rehabilitation Engineering, Patras, Greece.

Guger, C., Edlinger, G., Harkam, W., Niedermayer, I., & Pfurtscheller, G. (2003). How many people are able to operate an EEG-based brain-computer interface (BCI)? *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 145-147.

Ho, Y. C., Cheung, M. C., & Chan, A. S. (2003). Music training improves verbal but not visual memory: cross-sectional and longitudinal explorations in children. *Neuropsychology, 17*(3), 439.

Hodgins, H. S., & Adair, K. C. (2010). Attentional processes and meditation. *Consciousness and cognition, 19*(4), 872-878.

Hölzel, B. K., Carmody, J., Vangel, M., Congleton, C., Yerramsetti, S. M., Gard, T., & Lazar, S. W. (2011). Mindfulness practice leads to increases in regional brain gray matter density. *Psychiatry Research: Neuroimaging, 191*(1), 36-43.

Hughes, C. M. L., & Franz, E. A. (2007). Experience-dependent effects in unimanual and bimanual reaction time tasks in musicians. *Journal of motor behavior, 39*(1), 3-8.

Hund-Georgiadis, M., & Von Cramon, D. Y. (1999). Motor-learning-related changes in piano players and non-musicians revealed by functional magnetic-resonance signals. *Experimental Brain Research, 125*(4), 417-425.

Hwang, H. J., Kwon, K., & Im, C. H. (2009). Neurofeedback-based motor imagery training for brain-computer interface (BCI). *Journal of neuroscience methods, 179*(1), 150-156.

Janata, P., Tillmann, B., & Bharucha, J. J. (2002). Listening to polyphonic music recruits domain-general attention and working memory circuits. *Cognitive, Affective, & Behavioral Neuroscience, 2*(2), 121-140.

Jensen, C. G., Vangkilde, S., Frokjaer, V., & Hasselbalch, S. G. (2012). Mindfulness training affects attention - Or is it attentional effort? *Journal of Experimental Psychology: General, 141*(1), 106.

Kass, R. E., & Raftery, A. E. (1995). Bayes factors. *Journal of the american statistical association, 90*(430), 773-795.

Lazar, S. W., Kerr, C. E., Wasserman, R. H., Gray, J. R., Greve, D. N., Treadway, M. T., . . . Fischl, B. (2005). Meditation experience is associated with increased cortical thickness. *Neuroreport, 16*(17), 1893.

Levitin, D. J., & Tirovolas, A. K. (2009). Current advances in the cognitive neuroscience of music. *Ann. N. Y. Acad. Sci., 1156*, 211-231.

Li, J., Lai, Y., Luo, C., Yao, L., & Yao, D. (2011). Differences in brain structures between female musicians and non-musicians. *International Journal of Bioelectromagnetism, 13*(4), 274-277.

Lo, P.-C., Wu, S.-D., & Wi, Y.-C. (2004). *Meditation training enhances the efficacy of BCI system control.* Paper presented at the IEEE International Conference on Networking, Sensing and Control, Taipei, Taiwan.

Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and cognition, 18*(1), 176-186.

Neuper, C., Schlögl, A., & Pfurtscheller, G. (1999). Enhancement of left-right sensorimotor EEG differences during feedback-regulated motor imagery. *Journal of Clinical Neurophysiology, 16*(4), 373-382.

Norton, A., Winner, E., Cronin, K., Overy, K., Lee, D. J., & Schlaug, G. (2005). Are there pre-existing neural, cognitive, or motoric markers for musical ability? *Brain and cognition, 59*(2), 124-134.

Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L. E., & Hoke, M. (1998). Increased auditory cortical representation in musicians. *Nature, 392*(6678), 811-814.

Paskewitz, D. A., & Orne, M. T. (1973). Visual effects on alpha feedback training. *Science, 181*(4097), 360-363.

Pfurtscheller, G., & Neuper, C. (2001). Motor imagery and direct brain-computer communication. *Proceedings of the IEEE, 89*(7), 1123-1134.

Pfurtscheller, G., Neuper, C., Muller, G. R., Obermaier, B., Krausz, G., Schlogl, A., . . . Schrank, C. (2003). Graz-BCI: state of the art and clinical applications. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 11*(2), 1-4.

Plotkin, W. B. (1980). The role of attributions of responsibility in the facilitation of unusual experiential states during alpha training: An analysis of the biofeedback placebo effect. *Journal of Abnormal Psychology, 89*(1), 67.

Posner, M., Rothbart, M. K., Sheese, B. E., & Kieras, J. (2008). How arts training influences cognition. In C. Asbury & B. Rich (Eds.), *Learning, arts, and the brain* (pp. 1-10). New York: Dana Press.

Rabipour, S., & Raz, A. (2012). Training the brain: Fact and fad in cognitive and behavioral remediation. *Brain and cognition, 79*, 159-179.

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic bulletin & review, 16*(2), 225-237.

Rueda, M. R., Rothbart, M. K., McCandliss, B. D., Saccomanno, L., & Posner, M. I. (2005). Training, maturation, and genetic influences on the development of executive attention. *Proceedings of the national Academy of Sciences of the United States of America, 102*(41), 14931-14936.

Schellenberg, E. G. (2004). Music lessons enhance IQ. *Psychological Science, 15*(8), 511-514.

Schneider, P., Scherg, M., Dosch, H. G., Specht, H. J., Gutschalk, A., & Rupp, A. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. *Nature neuroscience, 5*(7), 688-694.

Sedlmeier, P., Eberth, J., Schwarz, M., Zimmermann, D., Haarig, F., Jaeger, S., & Kunze, S. (2012). The psychological effects of meditation: a meta-analysis. *Psychological bulletin, 138*, 1139-1171.

Semmens-Wheeler, R., & Dienes, Z. (2012). The contrasting role of higher order awareness in hypnosis and meditation. *The Journal of Mind-Body Regulation, 2*(1), 43-57.

Sluming, V., Brooks, J., Howard, M., Downes, J. J., & Roberts, N. (2007). Broca's area supports enhanced visuospatial cognition in orchestral musicians. *The Journal of neuroscience, 27*(14), 3799-3806.

Špajdel, M., Jariabková, K., & Riečanský, I. (2007). The influence of musical experience on lateralisation of auditory processing. *Laterality, 12*(6), 487-499.

Spilka, M. J., Steele, C. J., & Penhune, V. B. (2010). Gesture imitation in musicians and non-musicians. *Experimental Brain Research, 204*(4), 549-558.

Strait, D. L., Kraus, N., Parbery-Clark, A., & Ashley, R. (2010). Musical experience shapes top-down auditory mechanisms: evidence from masking and auditory attention performance. *Hearing research, 261*(1), 22-29.

Tan, L. F., Jansari, A., Keng, S. L., & Goh, S. Y. (2009). Effect of mental training on BCI performance. *Human-Computer Interaction. Novel Interaction Methods and Techniques*, 632-635.

Tan, L. F., Ng, C. S., Ng, J. Q., & Goh, S. Y. (2008). A Brain-Computer Interface with intelligent distributed controller for wheelchair *IFMBE Proceedings: 4th Kuala Lumpur International Conference on Biomedical Engineering 2008* (Vol. 21, pp. 641-644). Kuala Lumpur, Malaysia: Springer Berlin Heidelberg.

Tang, Y. Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., . . . Fan, M. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings of the National Academy of Sciences, 104*(43), 17152-17156.

Valentine, E. R., & Sweet, P. L. (1999). Meditation and attention: A comparison of the effects of concentrative and mindfulness meditation on sustained attention. *Mental Health, Religion & Culture, 2*(1), 59-70.

van den Hurk, P. A., Giommi, F., Gielen, S. C., Speckens, A. E., & Barendregt, H. P. (2010). Greater efficiency in attentional processing related to mindfulness meditation. *The Quarterly Journal of Experimental Psychology, 63*(6), 1168-1180.

Vaughan, T. M., McFarland, D. J., Schalk, G., Sarnacki, W. A., Krusienski, D. J., Sellers, E. W., & Wolpaw, J. R. (2006). The wadsworth BCI research and development program: at home with BCI. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 14*(2), 229-233.

Watanabe, D., Savion-Lemieux, T., & Penhune, V. B. (2007). The effect of early musical training on adult motor performance: evidence for a sensitive period in motor learning. *Experimental Brain Research, 176*(2), 332-340.

Wolpaw, J. R., Birbaumer, N., Heetderks, W. J., McFarland, D. J., Peckham, P. H., Schalk, G., . . . Vaughan, T. M. (2000). Brain-computer interface technology: a review of the first international meeting. *IEEE Transactions on Rehabilitation Engineering, 8*(2), 164-173.

Wolpaw, J. R., & Wolpaw, E. W. (Eds.). (2012). *Brain-Computer Interfaces: Principles and Practice*. OUP USA.

Zeidan, F., Johnson, S. K., Diamond, B. J., David, Z., & Goolkasian, P. (2010). Mindfulness meditation improves cognition: evidence of brief mental training. *Consciousness and Cognition, 19*(2), 597-605.

Footnotes

[1] If p(med) is the probability that people think meditation will improve BCI performance, and p(mus) is the same for music training, then the odds ratio is: p(med)/(1 - p(med)) divided by p(mus)/(1 -p(mus)). If p(med) and p(mus) were the same, then the odds ratio would be 1 (i.e. no association between expectation and training). For the data, p(med) = 0.80 and p(mus) = 0.775, so odds ratio = 0.80/.20 *.225/.775 = 1.16. For a 2X2 table with cell counts A, B, C, D, the natural log of the odds ratio is normally distributed with squared standard error given by 1/A + 1/B +1/C + 1/D. Putting a confidence interval on an odds ratio allows one to assess the sensitivity of the null result; contrast simply obtaining a non-significant chi square test of association. Note the confidence interval assumes independence of observations, whereas each subject gave an answer for both meditation and music. We did not detect a correlation between the answers for music and for meditation (see Table 1(B)), 90% CI for odds ratio [0.64, 10.64], indicating the assumption of independence was true within broad limits.

[2] Another way of assessing the sensitivity of a non-significant result is with a Bayes Factor, which compares a theory that there is an association with the null hypothesis of no association. A Bayes Factor greater than 3 indicates substantial evidence for the theory; a Bayes Factor less than a 1/3 indicates substantial evidence for the null hypothesis; and a Bayes Factor in between 1/3 and 3 indicates data insensitivity (Dienes, 2011). For the current data, the log odds ratio was 0.1495 with a standard error of 0.547 (see footnote 1). The theory of an association was represented by a half normal scaled assuming a "unit information prior" for each of p(med) and p(mus). That is the standard deviation of the half-normal was calculated assuming one observation worth of knowledge for p(med) and one for p(mus) (i.e. 0.5 observations in each cell); that is, the standard deviation was set to 2.828 (square root of 1/0.5 + 1/0.5 + 1/0.5 + 1/0.5). This is arbitrary but the equivalent of one unit of information is often used as a default for the variance of Bayesian priors in the absence of any other relevant knowledge (see e.g. Kass & Raftery, 1995). In this case the prior amounts to assuming that if there was an association between expectation and training method, in our ignorance we are 95% sure that the odds are between a vanishingly small amount above 1 (no association) up to as large as exp(2*2.828) = 286, i.e. p(med) about 0.95 and p(mus) about .05. The distribution thus reflects our ignorance about the true value of the odds, allowing a wide range, while effectively ruling out very extreme values; it also indicates that odds closer to 1 are more likely than larger values, consistent with the prior notion that music and meditation would both be plausible training methods. The online Bayes Factor calculator associated with Dienes (2008) gives a Bayes Factor of 0.24, strong evidence for the null hypothesis. The relevance of this Bayes Factor needs to be taken only provisionally as the theory was determined not by relevant data but an arbitrary default (Dienes, 2008); contrast Rouder, Speckman, Sun, Morey, and Iverson (2009) who argue for use of default priors). The relevant data for fixing an adequate theory would be those indicating the relation between expectation and BCI performance, which could be used to determine for the BCI improvements we see what expectation differences would be required to account for that difference. Unfortunately we do not have those data. Nonetheless, the confidence intervals for both the categorical and the continuous strength of expectation ratings also demonstrate

the equivalence of expectations for meditation and music training to a high degree of sensitivity.

[3] Originally 32 participants were run and the results indicated insensitivity in distinguishing meditation from the active control. To gain more sensitivity in distinguishing groups, another 44 subjects were run the following year. Note our purpose in running more subjects was not to establish that there was a difference, i.e. to get a significant result, but to establish whether the groups were different or were equivalent. A Bayesian analysis is reported below makes a three-way distinction between difference, equivalence and insensitivity, and thereby obviates the need to consider stopping rule, i.e for the Bayesian analysis, it is perfectly legitimate to top up subjects until sensitivity is reached (see Dienes, 2011). In fact it is in just such a situation that Bayes is especially useful. Note also that the main effect of group reported below is significant by orthodox methods after correction for double testing i.e. using .025 as the criterion for a p-value to indicate 5% significance.