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Effect of mindfulness meditation on brain–computer interface performance

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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

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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 (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,