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Source-space EEG neurofeedback links subjective experience with brain activity during effortless awareness meditation

Remko van Lutterveld[a], Sean D. Houlihan[a,c], Prasanta Pal[a], Matthew D. Sacchet[b], Cinque McFarlane-Blake[a], Payal R. Patel[a], John S. Sullivan[a], Alex Ossadtchi[d,e], Susan Druker[a], Clemens Bauer[a,c], Judson A. Brewer[a,c,*]

[a] Center for Mindfulness, University of Massachusetts Medical School, Worcester, MA, USA
[b] Neurosciences Program and Department of Psychology, Stanford University, Stanford, CA, USA
[c] Department of Brain and Cognitive Sciences, MIT, Cambridge, MA, USA
[d] Centre for Cognition and Decision Making, National Research University Higher School of Economics, Moscow, Russian Federation
[e] Laboratory of Control of Complex Systems, Institute of Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia

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ABSTRACT

Background: Meditation is increasingly showing beneficial effects for psychiatric disorders. However, learning to meditate is not straightforward as there are no easily discernible outward signs of performance and thus no direct feedback is possible. As meditation has been found to correlate with posterior cingulate cortex (PCC) activity, we tested whether source-space EEG neurofeedback from the PCC followed the subjective experience of effortless awareness (a major component of meditation), and whether participants could volitionally control the signal.

Methods: Sixteen novice meditators and sixteen experienced meditators participated in the study. Novice meditators were briefly trained to perform a basic meditation practice to induce the subjective experience of effortless awareness in a progressively more challenging neurofeedback test-battery. Experienced meditators performed a self-selected meditation practice to induce this state in the same test-battery. Neurofeedback was provided based on gamma-band (40–57 Hz) PCC activity extracted using a beamformer algorithm. Associations between PCC activity and the subjective experience of effortless awareness were assessed by verbal probes.

Results: Both groups reported that decreased PCC activity corresponded with effortless awareness ($P < 0.0025$ for each group), with high median confidence ratings (novices: 8 on a 0–10 Likert scale; experienced: 9). Both groups showed high moment-to-moment median correspondence ratings between PCC activity and subjective experience of effortless awareness (novices: 8, experienced: 9). Both groups were able to volitionally control the PCC signal in the direction associated with effortless awareness by practicing effortless awareness meditation (novices: median % of time = 77.97, $P = 0.001$; experienced: 89.83, $P < 0.0005$).

Conclusions: These findings support the feasibility of using EEG neurofeedback to link an objective measure of brain activity with the subjective experience of effortless awareness, and suggest potential utility of this paradigm as a tool for meditation training.

Introduction

Mindfulness meditation programs have beneficial effects on a number of psychiatric conditions. For example, mindfulness has been shown to have similar treatment-related effect sizes for anxiety and depression as antidepressants, but without the associated toxicities (for a recent review and meta-analysis see Goyal et al., 2014). However, learning to meditate may not be straightforward. Unlike activities such as yoga or football, no immediate feedback to students is possible in meditation as there are no easily discernible outward signs of performance. In addition, a teacher's feedback may be biased. Bias may come from the teacher's ability to interpret students' verbal descriptions, which may be further influenced by several factors, including the ability of a student to describe internal states (Van Lutterveld and Brewer, 2015). Real-time neurofeedback based on signals that are associated with effective meditation practice may provide a possible solution to this issue.

A recent study found that meditation is associated with decreased activity in the default mode network (DMN) (Brewer et al., 2011). In

* Corresponding author at: Center for Mindfulness, University of Massachusetts Medical School, Worcester, MA, USA.
E-mail address: Judson.Brewer@umassmed.edu (J.A. Brewer).

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addition, mind-wandering and self-referential processes, which may be considered the opposite of meditation, have been associated with increased activity in this network (Mason et al., 2007; Whitfield-Gabrieli et al., 2011). Building on these findings, a recent fMRI neurofeedback study showed that activity in a major hub of the DMN, the posterior cingulate cortex (PCC), correlated negatively with the subjective experience of increased effortless awareness, (which is a major component of meditation and consists of the factors "concentration", "observing sensory experience", "not 'efforting'" and "contentment"; Garrison et al., 2013a) and positively with mind-wandering and self-referential processes (Garrison et al., 2013a). These results illustrate that activity in the PCC may provide an ideal target for neurofeedback training during meditation, as information in either direction (increased or decreased activity) relates to the quality of practice. However, fMRI is expensive and impractical to use. Moreover, its temporal resolution is relatively poor, making it challenging for participants to interpret the feedback. In contrast, electroencephalography (EEG) is relatively inexpensive, portable and has excellent temporal resolution. Given the recent advances in spatial source-estimation for targeting specific brain regions, EEG neurofeedback from the PCC may provide a scalable methodology to facilitate individuals in identifying and fostering specific cognitive states associated with meditation practice. As electro- and magnetoencephalographic studies have shown task-related gamma-band power suppression in the PCC (Brookes et al., 2011; Jerbi et al., 2010; Ossandon et al., 2011), and pilot testing showed that the best results were found for low gamma (40–57 Hz) in a symptom–capture approach, we will focus on this frequency band.

Based on the above reviewed fMRI findings, in this proof-of-concept study we hypothesized that 1) local desynchronization of PCC activity (decreased PCC activity), as presented via source-space EEG real-time neurofeedback, would correspond with the subjective experience of effortless awareness, and that 2) the participants can volitionally control the PCC feedback signal in the direction of increased effortless awareness. To test this prediction, novice meditators performed a basic meditation practice to induce the subjective experience of effortless awareness while being provided EEG real-time neurofeedback in a double-blind, step-wise protocol. Furthermore, neurofeedback was provided to experienced meditators who performed a self-selected meditation practice to induce effortless awareness as this population has extensive practice in introspection related to the subtle cognitive states of this state.

Methods and materials

Participants

Sixteen novice meditators (defined as having no meditation practice in the previous year and < 20 entire lifetime hours) and 16 experienced meditators (defined as meditating ≥ 30 min per day for at least 5 days per week over the past 5 years) were matched for age, gender and handedness. The exclusion criteria for both novice meditators and experienced meditators were: (i) any neurological condition, including head injury or head trauma, (ii) any serious psychiatric, cognitive or medical disorder which could interfere with completion of the study (anxiety and depressive disorders in remission were not considered exclusion criteria), (iii) not being on a stable dose for the last 6 months if using anxiolytic or antidepressant medication, (iv) alcohol abuse, specified as drinking more than 14 alcoholic drinks per week at any one time or more than 4 drinks at any one time for a male, and drinking more than 7 alcoholic drinks per week at any one time or more than 3 drinks at any one time for a female, and (v) illegal or recreational drug use in the past 6 weeks. Additional exclusion criteria for the novice meditators were (vi) practicing any meditation practice or yoga, Tai Chi or Qigong in the last year or over 20 h ever in life, attendance of a meditation or yoga retreat, and participation in any meditation course. The demographics for both groups are shown in Table 1. The participants were paid 30 dollars for their participation in the study. The study was approved by the University of Massachusetts Medical School Institutional Review Board and all the participants were provided a fact sheet before participation in the study.

Effortless awareness

All the participants were first taught the concept of effortless awareness. Effortless awareness is a major component of meditation practice and consists of the factors "concentration", "observing sensory experience", "not 'efforting'" and "contentment" (Garrison et al., 2013a). Novice meditators were taught "noting practice" meditation, which is theoretically thought to support and train effortless awareness. During noting practice, novices were instructed to silently label the sensory experience that was most predominant from moment-to-moment (i.e. seeing, hearing, feeling or thinking) (Fronsdal, 2008). Before the experiment, the novices performed a short noting practice session (~ 30 s) in which they verbalized the noting practice out loud to confirm that the participants understood the instructions. Next, they completed a short silent practice session (~ 30 s). The exact instructions for the noting practice and the practice session are provided in Supplementary Text S1. To provide the novice meditators with the highest temporal resolution of feedback, the novice meditators performed noting practice with their eyes open. The experienced meditators performed the meditation practice in which it was the easiest for them to foster effortless awareness. The exact instructions for the experienced meditators are provided in Supplementary Text S1. In pilot experiments it was found that for experienced meditators who did not regularly meditate with their eyes open, doing so interfered with their sense of effortless awareness. For this reason, the experienced

Table 1
Demographics. Differences in gender were tested using the chi-square test. As the assumptions of the chi-square test did not hold for work status, marital status and race, these variables were tested using Fisher's exact tests. Highest completed level of education was tested using the Mann–Whitney test. Differences in age were tested using an independent samples t-test after testing for normality.

	Novice (N = 16)	Experienced (N = 16)	Test statistics	P
Gender (male/female)	11/5	10/6	0.139	0.710
Age (mean with standard deviation in parentheses)	51 (14)	53 (12)	− 0.521	0.606
Handedness (right/non-right)	13/3	13/3	0.000	1.000
Highest level of completed education (college or university/graduate school)	6/10	1/15	88.000	0.035
Work status (full-time/part-time/homemaker/retired/unemployed)	9/3/1/2/1	11/3/0/2/0	2.276	0.926
Marital status (never married/married/living in permanent relationship/divorced)	1/11/2/2	2/9/4/1	1.681	0.706
Race (White/African American/Asian)	13/1/2	16/0/0	2.865	0.226
Meditation practice (Theravada/Vajrayana/Zen/Theravada, Zen and Vajrayana/Vedanta and Mindfulness/Zen and Catholic Contemplative/Theravada, Zen and Mindfulness)		5/6/1/1/1/1/1		
Lifetime meditation practice hours (median, range)		6164 (1527–50,978)		