Meditation as an effective BCI training protocol for controlling wheeled robots [version 1; peer review: awaiting peer review]

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Abstract

**Background:** Brain-Computer Interface (BCI) systems allow the use of electroencephalographic activities to control devices. As such, it can be an important tool for disabled people since using a BCI does not involve any muscular stimulation. Despite its great potential as an assistive technology, BCI systems are yet scarcely available outside scientific contexts. The main reason is that BCI is still not accurate enough for real world situations. In this paper, we investigated if mindfulness meditation can help BCI users to perform better, particularly on controlling wheeled robots. Controlling wheeled robots must be seen as an important BCI research issue, since disabled people can take the best advantages from assistive wheeled robots.

**Methods:** Case-control study with 30 subjects, meditators and non-meditators, who controlled a simulated wheeled robot using a BCI system.

**Results:** In straight-ahead moves, the robot was 30% faster when controlled by meditators. In stop-and-go moves, the meditators controlled the robot with an accuracy of 66% while the non-meditators’ accuracy was 27%. In rectangular shape moves, meditators also performed better than non-meditators, with an accuracy of 40% against 7% of non-meditators.

**Conclusion:** The results show that meditators performed better than non-meditators. As such, we recommend combining mindfulness meditation with standard BCI training protocols for better control of wheeled robots.
Introduction

Brain-Computer Interface (BCI) systems allows the use of electroencephalographic activities to control devices without using the normal chain of peripheral nerves and muscles. Once the signals have been processed, a BCI detects features that are connected to the mental task being required of the user, then it converts them to commands for external devices. Common BCI mental tasks are Motor Imagery (MI), Event-Related Potential (P300), and Steady State Visually Evoked Potential (SSVEP). According to the mental task, the data processing techniques in the time and/or frequency domain are chosen. BCI aims at four different purposes: communication and control, motor substitution, entertainment, and motor recovery. Particularly, BCI systems can provide new communications and controls that can manage devices dedicated to disabled people.1-3

Despite the progress achieved by researchers over the past years, BCI systems are yet scarcely available outside scientific contexts. Some BCI researchers have admitted that one of the main issues in avoiding the spread of BCI applications outside of research labs relies on the fact that BCIs are not yet creditably accurate to deal with complex real-world situations, such as helping someone, with motor disabilities, to drive an electric wheelchair or to control an assistive robot.4

The accuracy of a BCI system depends on enhancements in three main areas: a) the hardware responsible for signal acquisition; b) the software responsible for signal processing and pattern recognition; and c) the user’s strategies to generate brain patterns recognizable by the system.5 There is much research on “a” and “b”, but scarce research on “c”, even though “c” is as important as “a” and “b” relating to BCI training accuracy. Successful BCI operation requires that the user develop and maintain a new skill, a skill that consists not of proper muscle control but rather of proper control of specific electrophysiological signals.6

The standard BCI training protocol involves the execution of repetitive tasks, in a sort of a-trial-and-error approach. For instance, training the control of an electric wheelchair requires that the user must be sat in the wheelchair, carrying the BCI (already configured), and repeats a series of trials until the success be attained. Although this BCI training protocol is the most adopted, alone it has not been so effective: around 30% of users are unable to control a BCI system at all (BCI Illiteracy) and most of the 70% remaining have reduced performances. Researchers reported that psychological factors such as mood, motivation, and attention span are related to BCI performance.6-8

Meditation can be seen as a set of complex training that involve the regulation of attention and emotions, developed for many purposes, such as keeping well-being and emotional equilibrium. The effects that meditation training has on brain waves have been extensively studied. A major review on this topic covered researches published over a period of 50 years, up to 2005. Through techniques such as electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI), it has been possible to observe the most activated regions of the brain as well as patterns in the meditators’ brain-wave frequency bands. It has been also possible to observe long-term effects on experienced meditators’ brains. That the practice of meditation has beneficial effects on physical and mental health. The regions of the brain activated by meditation are related to a) improvements of meta consciousness; b) body awareness; c) memory processes; d) self-regulation and emotions regulation; e) intra-hemispheric and inter-hemispheric communications.8

On the other hand, few studies have attempted the use of meditation as a method to improve the performance of BCI systems. Some of them reported the existence of distinguishable brain wave patterns on meditators while they were performing MI tasks.9,10 Other studies verified that meditators had better accuracy in using a BCI system to select letters on a computer screen.11,12 All studies evaluated meditation and BCI solving very simple tasks.

We propose to extend BCI and meditation research investigating whether meditation can help BCI users to solve complex tasks, such as to control robots. Particularly, our main interest is the control of wheeled robots through BCI systems. Controlling wheeled robots must be seen as an important BCI research issue, especially when the central objective is to assess intelligent assistive technology. Indeed, disabled people can pragmatically take the best advantages of BCI systems and robotic control developments in their real-life tasks, such as using an assistant wheeled robot to do their housework,13 to control a wheeled telepresence robot to attend a meeting,14 or simply using wheeled mobility assistive devices (WMADs).15 New research and developments involving BCI and robotics are crucial in increasing the independence and the quality of life of people who require assistive technology.

The objective of this study is to investigate if mindfulness meditation can be used as an effective BCI training protocol for controlling wheeled robots. Our hypothesis is that mindfulness meditation is an effective method to improve BCI accuracy.
Methods

Experiment design
The subjects (N = 30) were assigned into a control group (non-meditators) and an experimental group (meditators). Both groups had 15 members. The subjects were required to fill out a questionnaire giving information about their previous experience with BCI, their level of experience with mindfulness meditation, and other additional information. The control group inclusion criteria was healthy individuals over 18 years of age. The control group exclusion criteria was individuals with previous experience with meditation and individuals with previous experience with BCI. The experimental group inclusion criteria was healthy individuals over 18 years of age with previous experience with mindfulness meditation. The experimental group exclusion criteria was individuals with previous experience with BCI. Participants were recruited from the city of Rio de Janeiro, Brazil by reaching out to students and professors from two prominent local universities. In addition to promoting the study within university classes, efforts were also made to raise awareness among meditation groups in the community. The participants ranged in age from 18 to 65 years and consisted of 18 females and 12 males.

Signal acquisition
The subject brain’s signals were gathered through EEG records from the scalp using the Emotiv EPOC+. The Emotiv EPOC+ is a low-cost, portable, and easy-to-configure device (Figure 1), that can be used without a conductive gel; instead of this, the electrodes may be moistened in saline water. Emotiv EPOC+ has wireless connectivity, 14 channels for signal collection (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4) and 128Hz or 256Hz sampling frequency. It is usually sold with a software Control Panel (CP) (Figure 2) and with a software development kit (SDK). Emotiv EPOC+ probably is not as robust as healthcare EEG equipment, however, due to its advantages, it was also used in other research.16–18

Training commands
Emotiv BCI require their users to initially train the commands that will be sent to the system afterwards. In this process, the user gives examples of his brain patterns, performing mental imagery tasks, so that the system adapts itself, through a calibration of its classifier algorithm. In our experiments, the commands were trained using the CP software (Figure 2). First, a baseline referred as Neutral state had to be configured. To do so, the subject was asked to relax, setting free the flow of thoughts, avoiding muscle movements (including facial expressions) for approximately 15 seconds. During this time, the system recorded the subject’s brain signals. Subsequently, the subject trained the commands to be used to control the wheeled robot. To perform this training, the subject focused his thoughts on MI tasks, avoiding real muscle movements (including facial expressions) for approximately 8 seconds. During this time the system recorded the subject brain signals. If it was successful, the subject was able to observe an object moving forward on the CP. The CP also shows the Skill Rating, a numerical value ranging from 0 to 100 that indicates how fine the system recognized the subject’s mental patterns (the training accuracy).

Figure 1. Emotiv EPOC+ headset, electrodes, USB cable, saline, and Bluetooth USB stick.
Wheeled robot simulation

We used the Gazebo to simulate the Turtlebot 3 wheeled robot moving on a virtual environment (Figure 3). To control the robot we used the Robot Operating System (ROS). ROS is a collection of tools, programming libraries, and software design patterns aiming to simplify the elaboration of complex and robust robotic behaviors on a wide variety of robotics’ architectures. We used Emotiv SDK and ROS to develop an interface (Figure 4) that can read subjects’ mental activities and convert them in robot actions. The Emotiv SDK comes with two predefined commands, Push and Pull, plus the Neutral state. We configured the Push command to move the robot forward, the Pull command to spin the robot around itself, and the Neutral state to stop the robot.

Hardware and software

Experiment steps
In the initial step of our experiments the subjects were asked to comfortably sit down in front of a computer screen. Then, the electrodes were moistened in saline water, placed on the subjects’ scalps, and the Neutral state was configured.

After this initial step, the subjects were asked to train commands using MI tasks. To balance performance and available time, they accomplished each command 10 times. The Emotiv’s manufacturer does not indicate an optimum number of times for training a state, although he advises that the more repetitions are performed the greater will be the system’s ability to recognize trained commands. Indeed, this makes sense since there is a classification model supporting the system. The more data are provided the better the model can generalize, as machine learning models demonstrated.

After the Push command training, subjects were asked to guide the robot in the simulated environment through the Emotiv EPOC+. Trained commands were then used to control the wheeled robot.

In Test 1, the subjects tried to drive the robot to cross the virtual environment in a straight line, as fast as possible (Figure 5).

In Test 2, the subjects also tried to drive the robot by crossing the virtual environment in a straight line, but this time they had to stop for 10 seconds at 3 predefined positions (Figure 6).

Figure 4. Emotiv SDK and ROS were used together to develop an interface able to read subjects’ intentions and convert them in robot actions.

Figure 5. Test 1: Crossing the Gazebo simulated environment in a straight line.
In Test 3, the subjects had to train a second command used to move the robot through curves. For that purpose, the Pull command was trained in CP. Then, the subjects were instructed to move the robot to complete a rectangle shape circuit (Figure 7).

Results and discussion

Training accuracy

The subjects trained Push and Pull commands. An unpaired *t*-test\(^*\) was done to compare the sample mean of the training accuracy values achieved by meditators and by non-meditators \((p < 0.05)\).

The result (Table 1) showed that meditators had greater training accuracy than non-meditators for both Push and Pull commands. The training accuracy sample mean for the Push shows to be be greater than for the Pull command. Indeed, the Pull command was trained after the Push command, the classifier had to learn how to distinguish between the two commands. So, it was required that each subject be in two mental states, distinct from each other, thus considerably increasing the difficulty, specially for the command trained later.
**Test 1 - Straight ahead moves**

The subjects tried to traverse the virtual environment straight ahead as fast as possible. The sample mean time (in seconds) required to complete the task was smaller for meditators. An unpaired *t*-test\(^1\) shows that results (Table 2) are statistically significant (*p* < 0.05).

This result indicates that mindfulness meditation can effectively help BCI users, especially in tasks in which it is necessary to maintain focus for a long time. It also shows that mindfulness meditation is positively correlated to concentration skills. To perform the task of crossing the virtual environment straight ahead, a subject had to keep his focus on a single command, maintaining mental focus for as long as possible. Any distraction, like an external noise, or anxiety, arriving at the subject’s mind, may affect his brain waves and, consequently, hinder the recognition of the command by the system. Of course, this may compromise the remaining time to accomplish the task. Therefore, the mindfulness meditation training surely helped the subjects to avoid such distractions while using the BCI system to control the robot.

**Test 2 - Stop and go moves**

The subjects tried to traverse the virtual environment stopping at predefined places. The Barnard exact test on a 2×2 contingency table\(^2\) showed that the results (Table 3) are statistically significant (*p* < 0.05).

These results indicate that mindfulness meditation can also assist BCI’s users in tasks in which it is necessary to switch between different mental tasks. In Test 2, the subjects had to use the Push command to move the robot forward, but also the Neutral state, to stop the wheeled robot (Table 3).

**Test 3 - Rectangular shape moves**

The subjects tried to control the wheeled robot to move throughout a rectangular circuit in the virtual environment. The Barnard exact test on a 2×2 contingency table\(^3\) shows that the results (Table 4) are statistically significant (*p* < 0.05).

### Table 1. Sample mean and standard deviation of training accuracy for Push and Pull commands.

<table>
<thead>
<tr>
<th></th>
<th>Push</th>
<th></th>
<th>Pull</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>X</em></td>
<td><em>S</em></td>
<td><em>X</em></td>
<td><em>S</em></td>
</tr>
<tr>
<td>Control</td>
<td>39.80</td>
<td>26.68</td>
<td>13.80</td>
<td>12.52</td>
</tr>
<tr>
<td>Experimental</td>
<td>62.80</td>
<td>19.76</td>
<td>24.33</td>
<td>15.27</td>
</tr>
</tbody>
</table>

### Table 2. Test 1: sample mean and standard deviation of the time (seconds) required to cross the virtual environment straight ahead.

<table>
<thead>
<tr>
<th></th>
<th><em>X</em></th>
<th><em>S</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>40.20</td>
<td>12.64</td>
</tr>
<tr>
<td>Experimental</td>
<td>30.93</td>
<td>10.44</td>
</tr>
</tbody>
</table>

### Table 3. Test 2 contingency table: a success event indicates that the subject correctly stopped at predefined places.

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Fail</td>
<td>5</td>
<td>11</td>
</tr>
</tbody>
</table>

### Table 4. Test 3 contingency table: a success event indicates that the subject completed the rectangular circuit.

<table>
<thead>
<tr>
<th></th>
<th>Experimental</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Fail</td>
<td>9</td>
<td>14</td>
</tr>
</tbody>
</table>
To complete a rectangular circuit in the virtual environment, the subjects had to control the wheeled robot using two commands, one to move the robot forward and another to make curves. One of the main difficulties faced by the subjects during this test was to mentally alternate between these commands. Indeed, each command is associated with a specific mental pattern and swapping between them involves changing from one mental state to another. However, the subjects take some time to be able to immerse themselves into a particular mental state as they must reach a certain degree of concentration. Therefore, switching between commands to control the robot in real time was a big challenge for the subjects, leaving them, in some cases, to experiment anxiety, fatigue, and frustration, as they have reported in the questionnaires.

A possible explanation as to why the subjects belonging to the experimental group were better than the ones belonging to the control group is that the experience with meditation significantly increases the meditator’s attention control.21 This certainly has helped meditators to stay focused, avoiding external thoughts that would hinder the formation of the desired mental patterns.

Another suitable explanation is that the experimental group took some advantages from the mindfulness meditation experience to develop a more positive attitude when they were facing difficulties. Additionally, negative emotions due to anxiety, fatigue, frustration, etc. can decrease BCI performance because they can hinder the setup of stable mental states. The positive effects of meditation on emotion regulation were extensively discussed in our research.

**Limitations**

Our study is subject to certain limitations that should be considered. Despite implementing anonymous questionnaires, there remains a potential for participation bias that cannot be entirely eliminated. While participation was voluntary, the presence of self-selection bias may restrict the extrapolation of our findings. Additionally, the sample size in our study was relatively small, recruited from a limited geographic area, thereby raising concerns about the generalizability of the results. To enhance the validity of future research, it is crucial to include a larger and more diverse population, encompassing multiple cities or states. Furthermore, it is important to conduct tests involving individuals with motor disabilities, as they represent a significant target audience for BCI technology. In our study, subjects had a restricted time frame for training commands in the BCI system. Further investigation is recommended to verify whether similar outcomes can be achieved with extended training durations.

**Conclusions**

In this study, we investigated if mindfulness meditation can help BCI users to achieve better performance. We carried out an experiment with 30 subjects (15 meditators and 15 non-meditators) who controlled a simulated wheeled robot using a BCI system. The results showed that mindfulness meditators performed better than non-meditators. We recommend combining mindfulness meditation with standard BCI training protocols for better control of wheeled robots.

Regardless of hardware and software advances, operating a BCI system involves the ability to voluntarily shape your own brain patterns. This is a skill that does not come naturally to most people. Developing such a capacity involves training and dedication. Unfortunately, standard BCI training protocols require tedious and repetitive sessions to achieve an acceptable performance. Psychological factors such as mood, motivation, and attention can also influence BCI accuracy. As such, the development of effective psychological training protocols is imperative for mass adoption of BCI technology. It has been shown that meditation practice is related to stress reduction, anxiety reduction, and focus increase. Past research also showed distinguishable brain wave patterns in meditators.

Of the different possible applications for a BCI system, being an assistive technology is undoubtedly the most impactful. Being able to interact with devices without the need for any muscular action can make a big difference in the lives of those who suffer from physical disabilities. Unfortunately, BCI systems are still not accurate enough to be used in real situations, outside of a scientific context. We hope that this study represents a step towards a more accurate BCI and, consequently, contribute to a more inclusive society.

**Ethics and consent**

This study was approved by the Ethics Committee of University Hospital Clementino Fraga Filho of Federal University of Rio de Janeiro at 2020-12-26 under protocol code 114-120. The anonymity of all participants was preserved and respected and there was no discrimination in the selection of individuals. Written informed consent for publication of the participants’ details and/or their images was obtained from the participants.
Data availability

Underlying data

Harvard Dataverse: Meditation as an effective BCI training protocol for controlling wheeled robots, https://doi.org/10.7910/DVN/PT4BRA.22

This project contains the following underlying data:

- rawdata.xlsx (Raw data from both control and experimental group.)
- questionnaire.xlsx (participant questionnaire.)

Data are available under the terms of the Commons Zero “No rights reserved” data waiver (CC0 1.0 Public domain dedication).

References

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