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Daily training with realistic visual feedback improves reproducibility of event-related desynchronisation following hand motor imagery

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HIGHLIGHTS

- Event-related desynchronisation (ERD) value enhanced after daily training with visual feedback.
- Realistic feedback produced the high reproducibility of ERD with the small inter-trial variance.
- Realistic feedback training is a suitable method to acquire the skill to control an ERD-based brain-computer interface system.

ABSTRACT

Objective: Few brain–computer interface (BCI) studies have addressed learning mechanisms by exposure to visual feedback that elicits scalp electroencephalogram. We examined the effect of realistic visual feedback of hand movement associated with sensorimotor rhythm.
Methods: Thirty-two healthy participants performed in five daily training in which they were shown motor imagery of their dominant hand. Participants were randomly assigned to 1 of 4 experimental groups receiving different types of visual feedback on event-related desynchronisation (ERD) derived over the contralateral sensorimotor cortex: no feedback as a control, bar feedback with changing bar length, anatomically incongruent feedback in which the hand open/grasp picture on screen was animated at eye level, and anatomically congruent feedback in which the same hand open/grasp picture was animated on the screen overlaying the participant's hand.
Results: Daily training with all types of visual feedback induced more robust ERD than the no feedback condition ($p < 0.05$). The anatomically congruent feedback produced the highest reproducibility of ERD with the smallest inter-trial variance ($p < 0.05$).
Conclusion: Realistic feedback training is a suitable method to acquire the skill to control a BCI system.
Significance: This finding highlights the possibility of improvement of reproducibility of ERD and can help to use BCI techniques.

1. Introduction

Sensorimotor rhythms (SMR), including the arch-shaped mu rhythm (8–13 Hz) and the central beta rhythm, are observed over the sensorimotor cortex using scalp electroencephalogram (EEG). Two types of SMR pattern changes are observed in the sensorimotor process: event-related desynchronisation (ERD), which is characterized by SMR amplitude attenuation, and event-related synchronization (ERS), which is characterized by SMR enhancement (Pfurtscheller and Lopes da Silva, 1999). ERD is observed during motor execution, and its spatial pattern is clearly different for finger and foot movement (Pfurtscheller et al., 2000a), each corresponding to the location of the respective somatosensory and motor areas. In addition to actual motor behaviour, mental motor imagery can alter neural activity in the sensorimotor cortex and result in ERD (McFarland et al., 2000; Neuper and Pfurtscheller, 2001; Neuper et al., 2005). Such brain potential changes can be used as communication signals with electronic devices, as in brain–computer interface (BCI) (Wolpaw and McFarland, 2004; Birbaumer, 2006; Nijholt and Tan, 2008). Although ERD during motor imagery has been successfully applied in BCI (Pfurtscheller

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et al., 2000b), large inter-subject variability limits the practical use of BCI (Hashimoto et al., 2010a). Therefore, training users to control a BCI will help achieve a high classification accuracy (Neuper et al., 1999; Wolpaw et al., 2002; Hwang et al., 2009).

Visual feedback may be an effective tool for accomplishing these objectives. For instance, there is some evidence that a rich visual representation of the feedback signal, such as in a 3-dimensional video game or virtual reality environment, enhances the learning process in a BCI task (Pineda et al., 2003; Leeb et al., 2007; Hashimoto et al., 2010b). This suggests that realistic and engaging feedback scenarios closely related to a specific target application assist users in motor imagery (Neuper et al., 2009). Thus, it seems plausible to expect that use of different types of visual feedback may improve the controllability of BCI.

The goal of the present study was to explore which types of visual feedback promote robust ERD in ERD feedback-regulated motor imagery training. In this experiment, we prepared three types of visual stimuli; bar feedback (BAR) with changing bar length on the screen, anatomically incongruent feedback (INCONGRUENT) in which the hand open/grasp picture was animated on the screen in front of the participant, and anatomically congruent feedback (CONGRUENT) in which the same hand open/grasp picture was animated on the screen overlaying the participant's hand. A motor imagery task with no feedback (NONE) was used as a control. We investigated the difference in ERD value and reproducibility among the feedback types after 5 days of training. This study has implications in the understanding the influence of feedback type on BCI performance and the reactivity of sensorimotor rhythms during the complex interplay between motor imagery and feedback processing.

2. Methods

2.1. Participants

A total of 32 (22 men and 10 women, aged 21–35 years, mean 26.6 years, all right handed) in good health with no history of neurologic disease participated in an experimental session conducted daily for five consecutive days. Participants were experimentally naïve, and also had no history of similar motor-imagery experience in exercise and sports. They gave informed consent after the experimental procedure was explained to them. The experimental protocol used in the study was in accordance with the Helsinki Declaration and was approved by the ethical committee of Keio University.

2.2. EEG recording

EEG was recorded with seven sintered Ag/AgCl scalp electrodes placed over the centroparietal areas (Fig. 1A). The closely spaced electrodes with distances of approximately 2 cm were placed in a configuration including the electrode positions C3, C4, and Cz of the international 10–20 system. The channels placed anterior to C3 and C4 were called C3a and C4a and posterior were called C3p and C4p. Electrode impedance was kept lower than 10 kΩ throughout the experiment. The EEG signals were amplified and bandpass filtered between 2 and 100 Hz using Neuropack (Nihonkohden, Tokyo, Japan) and then sampled at 256 Hz. Participants were instructed to keep their arms and hands relaxed during the recordings.

2.3. Experimental paradigm

Participants sat in a comfortable armchair. Each participant performed in a series of two experimental sessions: one screening and

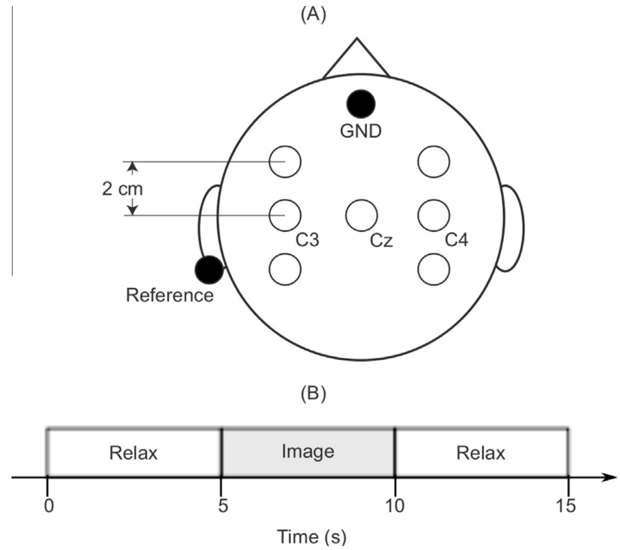

Fig. 1. Experimental design. (A) Electrode setup. (B) Time course of a single trial of the feedback session.

one feedback session. In the screening session, participants were asked to imagine grasping with their right hand following a fixed repetitive time scheme (Fig. 1B). The trial was initiated with the presentation of the word 'Relax' on the monitor, and a 5-s countdown was presented at the bottom of the monitor. The word and countdown disappeared after 5 s, and the participants were asked to imagine a movement. After 5 s of EEG feedback exposure, the participants were asked to relax for 5 s. This 15-s trial was repeated 20 times. The EEG montage and frequency band for deriving ERD in the subsequent BCI feedback session were determined from the ERD results in this screening session (see also EEG Analyses section below). This protocol was followed because EEG results are dependent upon the participant's current mental state; the exact positions of the electrodes shifted from day to day, although they were set as precisely as possible according to the code of the international 10–20 system. The methods used in this study have been previously published (Neuper et al., 1999; Wolpaw and McFarland, 2004).

In the feedback session, the time course of the trial was the same as in the screening session. ERD was calculated during motor imagery by a 1-s window of the EEG every 100 ms (see also EEG Analyses section below). During the right hand motor imagery, the feedback stimulus depending on ERD value was displayed in the centre of the monitor. The coupling of ERD to the resulting feedback action was determined. Participants generally achieved ERS via passive relaxation and ERD via a continuous grasping movement imagery with the right hand. Participants were randomly assigned to 1 of 4 experimental groups of different types of visual feedback as described below.

2.3.1. NONE

The monitor was placed approximately 1 m in front of the participant at eye level and no stimulus was presented during the feedback period. Such paradigm has been used in previous BCI studies (Pfurtscheller et al., 1997; Pfurtscheller and Neuper, 2001).

2.3.2. BAR

The monitor was placed approximately 1 m in front of the participant at eye level. A bar was presented on the monitor. This bar lengthened toward the right of the monitor with increasing ERD and shortened with decreasing ERD (Fig. 2A). BAR feedback