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ORIGINAL ARTICLE

Sensorimotor Modulation Assessment and Brain-Computer Interface Training in Disorders of Consciousness

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Abstract

Objectives: To assess awareness in subjects who are in a minimally conscious state by using an electroencephalogram-based brain-computer interface (BCI), and to determine whether these patients may learn to modulate sensorimotor rhythms with visual feedback, stereo auditory feedback, or both.

Design: Initial assessment included imagined hand movement or toe wiggling to activate sensorimotor areas and modulate brain rhythms in 90 trials (4 subjects). Within-subject and within-group analyses were performed to evaluate significant activations. A within-subject analysis was performed involving multiple BCI technology training sessions to improve the capacity of the user to modulate sensorimotor rhythms through visual and auditory feedback.

Setting: Hospital, homes of subjects, and a primary care facility.

Participants: Subjects (N=4; 3 men, 1 woman) who were in a minimally conscious state (age range, 27−53y; 1−12y after brain injury).

Interventions: Not applicable.

Main Outcome Measures: Awareness detection was determined from sensorimotor patterns that differed for each motor imagery task. BCI performance was determined from the mean classification accuracy of brain patterns by using a BCI signal processing framework and assessment of performance in multiple sessions.

Results: All subjects demonstrated significant and appropriate brain activation during the initial assessment, and real-time feedback was provided to improve arousal. Consistent activation was observed in multiple sessions.

Conclusions: The electroencephalogram-based assessment showed that patients in a minimally conscious state may have the capacity to operate a simple BCI-based communication system, even without any detectable volitional control of movement.

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Patients who have disorders of consciousness after brain injury may have very limited consciousness. It may be difficult to quantify their level of awareness or predict recovery. Extensive and prolonged evaluation of each individual is required to resolve basic issues of alertness, attention, visual or auditory capacities, and higher cortical function.[1] Individuals who are in a minimally conscious state or vegetative state may be incapable of providing volitional overt motor responses.

Many consciousness scales are insufficient for complete diagnostic purposes because they require overt motor responses or may provide snapshot measures of activity. The diagnosis of vegetative or minimally conscious state may be probable when there are no overt behavioral responses to external stimuli. However, 43% of patients who receive a diagnosis of vegetative state are reclassified as being minimally conscious after further assessment by clinical experts.[2] A subset of patients with these

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disorders of consciousness can alter their brain activity in response to stimuli or commands. Findings from functional magnetic resonance imaging and electroencephalography (EEG) suggest that some patients who have a diagnosis of vegetative state may have some awareness of themselves and their environment.[2] Therefore, methods are being developed to detect awareness in these patients and enable them to participate actively in decision making. These methods may include equipment that may be incorporated in rehabilitation programs and daily life.

The EEG mu (8−12Hz) and beta (13−30Hz) bands are altered during sensorimotor processing. Oscillations in these bands are known as sensorimotor rhythms.[3-5] Event-related desynchronization is an attenuation of neuronal activity in a particular frequency band and is a decrease in sensorimotor rhythm spectral band power. In contrast, event-related synchronization is an increase in spectral power that is correlated with increased synchronization of neuronal activity. The event-related desynchronization in the mu band and event-related synchronization in the beta band are associated with activated sensorimotor areas, and synchronization in the mu band is associated with idle or resting sensorimotor areas. Event-related desynchronization and synchronization have been evaluated in cognitive studies and provide distinct EEG pattern differences that form the basis of left- or right-hand or foot sensorimotor rhythm-based brain-computer interfaces (BCIs).[3-5] BCIs bypass the normal neuromuscular communication pathways, where the intention of the user is determined from various brain activations measured invasively or noninvasively. Brain responses to external stimuli or voluntary modulation of brain activity may provide intended communication. BCIs have been evaluated in gaming and stroke rehabilitation, and in other people who have limited neuromuscular control because of disease or injury.[6-9] Detection of awareness based on the EEG has followed BCI protocols.[9-12] In EEG-based disorders of consciousness assessment, assessing a person's ability to comprehend and follow instructions to perform two different motor imageries can be achieved by analysis of the event-related synchronization and desynchronization patterns of sensorimotor areas associated with the motor imagery tasks and/or assessing the accuracy in distinguishing one motor imagery from another using only EEG patterns.

Sensorimotor rhythm activations may occur in 19% of subjects who are in a minimally conscious or vegetative state, and some patients are capable of sustained attention, response selection, working memory, and language comprehension.[11] Real-time sensorimotor rhythm feedback in an uncommunicative patient who is in a minimally conscious state may affect the awareness detection protocol, as the patient may become aware that the motor imagery task being performed can affect the position of a sound or visual object presented on a screen, and this may be encouraging or provide an impetus to remain attentive.[9]

Visual and auditory feedback may allow users of a BCI to see or hear the effects of their motor imagery and enable them to modulate or affect something external to their body without movement.[10] Feedback may motivate patients with a spinal cord injury or stroke and increase their performance when learning to control a BCI.[13,14] Real-time feedback may encourage, motivate, and inform the users of the technology that they may be capable of engaging the BCI by intentionally modulating brain activity.

List of abbreviations:

BCI **brain-computer interface**
EEG **electroencephalography**

The purpose of the present study was to perform an EEG-based assessment of awareness in subjects who were in a minimally conscious state and to determine whether response, control, or both, could be achieved with an EEG-based BCI. A secondary purpose was to determine whether feedback could increase the detection of awareness or attentiveness.

Sensorimotor rhythm BCIs teach users to intentionally modulate their EEG through sensorimotor learning. Visual feedback is required in this closed loop system, and this excludes patients who have visual problems. Some patients in minimally conscious or vegetative states have limited gaze control or visual acuity, but visual feedback may be substituted with auditory input.[15,16] Therefore, we compared visual and auditory sensorimotor rhythm feedback in subjects who were in a minimally conscious state to evaluate the effect of stereo auditory musical sensorimotor rhythms feedback on BCI performance. We hypothesized that enabling the subject to experience the potential for BCI in the initial assessment and providing feedback of brain activity, aurally or visually, may improve the assessment.

Methods

Participants

The study included 4 subjects based in Ireland: (1) E, a 27-year-old man who was treated for a juvenile posterior fossa astrocytoma 12 years ago and had postoperative complications that caused severe brain damage and a minimally conscious state (Coma Recovery Scale−Revised score, 4); (2) J, a 53-year-old man who had an anoxic brain injury 4 years ago that caused a minimally conscious state (Coma Recovery Scale−Revised score, 3); (3) P, a 30-year-old man who had severe head trauma 4 years ago that caused a minimally conscious state; and (4) Z, a 31-year-old woman who, 12 months ago, had a subarachnoid hemorrhage and seizure with possible hypoxic brain injury that caused a minimally conscious state (Wessex Head Index Measurement, 26).[16-18] All subjects required full assistance for all activities of daily living. All subjects had an initial EEG-based assessment in a single session. Further BCI training sessions were performed with participants E (13 sessions), J (6 sessions), and P (7 sessions). Initial assessments were performed in the hospital (subjects E and Z), care home (subject P), and family home (subject J). Follow-up BCI training was performed in their family homes (subjects E and J) and care home (subject P). Informed consent was given by the families of the subjects. Ethical approval was granted by the National Rehabilitation Hospital and the University of Ulster Research Ethics Committees.

Study design

For awareness detection, the initial EEG-based assessment involved imagined hand versus toe movement and was performed to activate sensorimotor areas and modulate brain rhythms during 90 trials for each subject. Within-subject and within-group analyses were performed to determine significant activations.

For BCI performance, within-subject analysis was performed in multiple BCI technology training sessions. The training sessions aimed to improve the capacity of the user to modulate sensorimotor rhythms through visual and auditory feedback and to determine whether response reliability could be reached to enable the BCI to be used as a basic communication channel.