Motor Imagery BCI with Auditory Feedback as a Mechanism for Assessment and Communication in Disorders of Consciousness

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Abbreviations

BCI	Brain-computer interface
MCS	Minimally conscious state
CRS-R	Coma Recovery Scale Revised
VS	Vegetative state
EEG	Electroencephalography
SMR	Sensorimotor rhythms
MI	Motor imagery
DoC	Disorders of consciousness
WHIM	Wessex Head Index Measurement

1 Introduction

Patients with disorders of consciousness (DoC) are difficult to assess both because of their unpredictable fluctuation of awareness and the current adopted scales, which have a poor prognostic reliability [1]. Individuals who are in a minimally conscious state (MCS) or vegetative state (VS), or with unresponsive wakefulness syndrome (UWS), may be incapable of providing volitional overt motor responses. This has resulted in a rate of 43% of patients who were diagnosed as having VS being reclassified as MCS after further assessment [2]. The relatively few patients with these disorders who can alter their brain activity in response to stimuli or

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commands are potentially capable of providing information about their state and condition through direct measures of brain activity using a brain-computer interface (BCI). Such potential may enable adoption of more efficient devices to detect awareness in these patients and enable them to participate actively in decision making. These methods can include equipment that may be incorporated in rehabilitation programs and daily life.

EEG μ (8–12 Hz) and β (13–30 Hz) bands are altered during sensorimotor processing. Oscillations in these bands are known as sensorimotor rhythms (SMR) [3–5]. 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 SMR-based BCIs [3–5]. Brain-computer interfaces 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. Brain-computer interfaces have been evaluated in gaming, stroke rehabilitation, and by other people who have limited neuromuscular control because of disease or injury [6–9]. Detection of awareness based on EEG has followed BCI protocols [9–12]. People who have DoC may achieve comprehension and follow instructions to perform motor imageries by assessing the event-related desynchronization and synchronization patterns or distinguishing motor imageries using EEG patterns. Sensorimotor rhythm activations may occur in 19% of subjects who have an MCS or VS, with some patients capable of sustained attention, response selection, working memory, and language comprehension [11]. Real-time SMR feedback in an uncommunicative patient with MCS may affect the awareness detection protocol, as the patient may become aware that the motor imagery (MI) 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 MI and enable them to modulate or affect something external to their body without movement [13]. Feedback may motivate patients who have spinal cord injury or stroke subjects and increase performance when learning to control a BCI [14, 15]. Real-time feedback may encourage, motivate, and inform the user of the technology that they may be capable of engaging the BCI by intentionally modulating brain activity.

With the present study, we showed for the first time both real-time feedback of SMR in DoC and the use of auditory SMR feedback. Visual acuity and gaze control of many DoC suffers may be insufficient for gaze dependent BCIs; therefore, the presentation of auditory cues and feedback for sensorimotor BCI protocols may be more appropriate for DoC based BCI applications.

In this chapter, we present a method for auditory feedback of SMR during MI using a BCI framework. We present an overview of results of four patients who have DoC, showing the ability of the systems to detect differences in binary MI related rhythms and how feedback may influence a patient's ability to modulate sensorimotor activity over multiple sessions of training with real-time visual and auditory feedback.

2 Methods

2.1 *Participants*

The study included 4 subjects based in Ireland: E, a 27-year-old man who was 12 years after treatment for a juvenile posterior fossa astrocytoma and postoperative complications that caused severe brain damage and MCS(Coma Recovery Scale Revised [CRS-R] score, 4); J, a 53-year-old man who was 4 years after anoxic brain injury that caused MCS (CRS-R score, 3); P, a 30-year-old man who was 4 years after severe head trauma that caused MCS; and Z, a 31-year-old woman who was 12 months after a subarachnoid haemorrhage and seizure with possible hypoxic brain injury that caused MCS (Wessex Head Index Measurement [WHIM], 26), (see Table 1) [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 (19 sessions), J (10 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 and medical teams of the subjects. Ethical approval was granted by the National Rehabilitation Hospital and the Ulster University Research Ethics Committees. A summary of the patient data is shown in Table 1.

2.2 *Study Design*

For awareness detection, initial EEG-based assessment involved imagined hand versus toe movement and was performed to activate sensorimotor areas and

Table 1 Study participants E, J, P and Z summary including gender/age, injury, diagnosis, and post injury period

	Participant E	Participant J	Participant P	Participant Z
Gender/Age	Male, 27	Male, 53	Male, 30	Female, 31
Injury	Juvenile posterior Fossa Astrocytoma with complications after post-operative surgery	Anoxic brain injury	Severe head trauma	Subarachnoid haemorrhage and seizure with possible hypoxic brain injury
Diagnosis	MCS, CRS-R scores 4/23.	MCS, CSR-R score 3	MCS	Unclear, possible MCS, WHIM score 26 (since injury)
Post injury period	12 years	4 years	4 years	11 months

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 SMR 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.

2.3 Data Acquisition

The study included an initial assessment and BCI phase 1 and phase 2 training sessions. In the initial assessment and phase 1 trials, 3 bipolar EEG channels were recorded using a mobile EEG device (g.MOBIlab, g.tec Medical Engineering, Schiedlberg, Austria) as previously described [11]. In phase 2, 16 channels over sensorimotor areas were recorded (g.BSamp, g.tec), digitized (cDAQ 9171, National Instruments, Austin, TX, USA), oversampled at 2 kHz, and average subsampled to 125 Hz. Active electrodes were used (g.GAMMAsys, g.tec). Results from only 3 bipolar channels around electrode positions C3, Cz, and C4 are reported for the majority of sessions. Participant J's final two sessions were conducted with a 16 channel g.Nautilus amplifier. The subjects sat in front of a laptop computer in a wheelchair with the head held upright with a head strap, or sat in the upright position in a bed with the head resting on a pillow.

2.4 Initial Assessment Protocol

The first repetition in the session was similar to a previously described protocol, with MI to squeeze the right hand or wiggle the toes performed in 6 blocks of 15 trials/block (3 blocks for hand squeezing, alternating with 3 blocks for toe wiggling) [10]. Consecutive blocks alternated between hand and toe MI. Each block began with visual and auditory task instructions, which were, "Every time you hear a beep and/or see an arrow on the screen, try to imagine that you are squeezing your right hand into a fist and then relaxing it" or the first part followed "…try to imagine that you are wiggling your toes and then relaxing. Concentrate on the way your muscles would feel if you actually were performing this movement. Try to do this as soon as you hear each beep or see the arrow." After 5 s, the instructions were followed by the binaural presentation of 15 beep tones (each tone, 600 Hz for 60 ms; time between tones, 1 to 2 s, time chosen randomly) synchronized with a cue arrow appearing on the screen (Fig. 1). After 15 trials requesting hand squeeze or toe wiggle imagery, the block concluded with an instruction to relax. The subject rested for 1 to 2 min before the start of the next block (Fig. 1). The protocol differed from the previously reported protocol because instructions and cues currently were

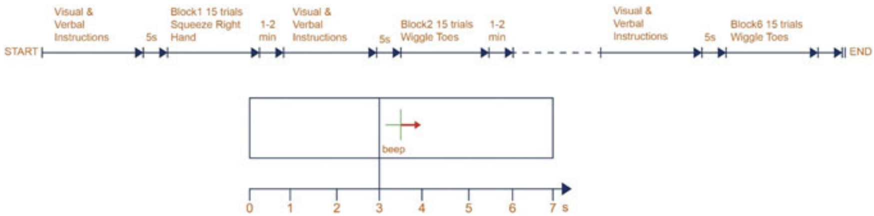

Fig. 1 Initial assessment sessions for subjects with disorders of consciousness. **a** Timing of initial assessment trials. **b** Structure of blocks in initial assessment

presented both aurally and visually [10]. Some participants closed the eyes and may have fallen asleep after the first block. For the remaining rounds a member of the research team observed the subject and provided verbal instructions "imagine squeezing the right hand" (or "imagine wiggling the toes") when the subject appeared to be disengaged or asleep.

2.5 *Real-Time Visual Feedback During Initial Repetition*

Feedback is necessary to improve sensorimotor learning to control a BCI that is based on SMR [14, 15]. Subjects had fluctuating alertness and wakefulness but frequently closed their eyes. Real-time feedback was provided to gain and maintain the attention of the participant. Feedback presented in the form of a game was used in this instance to engage the participant and to add interest to the often tedious task of MI training.

2.6 *Additional Assessment*

After the first repetition of 6 rounds, the EEG data were analysed and subject-specific parameters were selected to enable discrimination of the two MI tasks (hand and toes) using EEG. Subject E participated in feedback experiments using a ball-basket model (See Fig. 2). The experiment included 60 trials in which the subject was asked to direct a ball into 1 of 2 green target baskets that were positioned on the left or right at the bottom of the screen. The ball fell continuously for 3 s and could be directed to the left with imagery to wiggle the toes or to the right with imagery to squeeze the right hand. After a brief rest, another feedback experiment was performed with a spaceship that moved on the screen to the left or right using MI to dodge asteroids that fell from the top to bottom of the screen (See Fig. 2) [19]. Only subjects E and J participated in the spaceship experiment. The subjects were given verbal instructions about how to control the feedback; during the initial 4 trials and periodically during each repetition, attentiveness was encouraged by prompting the subject verbally about the correct MI required.

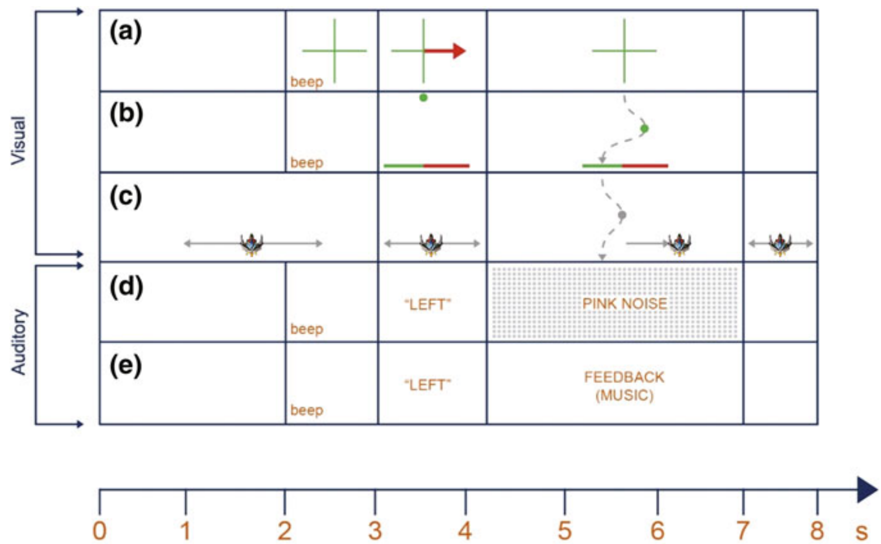

Fig. 2 Trial timing for training sessions with a brain-computer interface. **a** Visual cue training with no feedback. **b** Visual ball and basket feedback. **c** Visual spaceship game training. **d** Auditory feedback with pink noise. **e** Auditory feedback with musical samples

2.7 Follow-up Training Sessions

In follow-up BCI training sessions, subjects were asked to use left or right hand MI to activate sensorimotor areas. Stereo auditory feedback was given as broadband noise (1/frequency or pink noise) or a musical sample. The broadband noise contained cues above and below 1.5 kHz, important in the effective localization of an auditory event. A musical palette included 10 popular musical genres (blues, classical, country, electronic, folk, hip-hop, Irish traditional, jazz, reggae, and rock music). Each genre included an excerpt from a track from each of 3 artists such as Benny Goodman, Charlie Parker, and Miles Davis for jazz music. Auditory feedback was provided with earphones (ER4P, Etymotic Research, Inc., Elk Grove Village, IL, USA). Targets were presented to subjects as a spoken command (left or right), heard in the corresponding ear. Feedback was modulated by continually varying the azimuthal position of the sounds between ±90° using left and right hand movement imagination. Visual feedback was given (subject E only) with the ball-basket and spaceship models. For feedback, the subject was given verbal instruction about how to modulate the feedback signals, and the subject was prompted verbally periodically during visual feedback with the correct MI to perform and ensure awareness of the target during periods of eye shutting or visual acuity degradation. Trial timing was standardized with a cue at 3 s and feedback from 4 to 7 s for all feedback types (See Fig. 2).

Subject E participated in visual and auditory feedback phases. Subjects J and P participated in an auditory feedback phase only. For subject E, the feedback visual phase (visual cues, feedback, and occasional verbal prompts) was performed 6 months after initial assessment. The stereo auditory feedback phase occurred 6 months after the visual feedback phase for subject E, 6 months after initial assessment for subject J, and 8 months after initial assessment for subject P. There were ≤ 8 sessions (1–1.5 h with 2–4 repetitions each; 60 trials/repetition; 8 min/repetition), with 1 to 2 sessions per day (morning and/or evening) in each phase, and each phase was performed during 1 week of intensive sessions.

2.8 Data Analysis

After the initial assessment without feedback, a leave-1-out cross validation was performed on the 6 rounds on each repetition using a BCI signal processing framework that involved the automated selection of subject-specific frequency bands (range, 1–30 Hz) and neural time-series prediction preprocessing using neural networks in conjunction with regularized common spatial patterns. Features were derived from the log-variance of pre-processed or surrogate signals within a sliding window (2 s) and classified using linear discriminant analysis. The operation of the classification step can be simplified as being that of a transform of quantitative input data to qualitative output information [20]. Discriminant analysis and classification are multivariate techniques concerned with separating distinct sets of objects (features or observations) and with allocating new objects (features or observations) to previously defined groups [19, 21–23]. The mean classification accuracy was calculated across the data folds at every sample in the trial to obtain a time course of accuracy across the trial, from imagery onset to completion. Baseline (1000 ms before cue at onset) performance was compared with peak mean classification accuracy. The discrimination accuracy of two baselines before the cued MI period also was assessed. There was no distinction expected in the EEG or correlation with the cue that occurred at 3 s. The two baselines were compared to show that differences between two points of sensorimotor activity with no event-related activation were insignificant, as expected when the subject was not performing MI. These supported the evidence that the observed activations were not obtained by chance. Nonparametric Wilcoxon signed rank test was used to assess the significance of activations. Baseline or chance performance was 50 to 60% for the 2 classes (hand versus toe or left versus right hand movement). During the feedback session, the first repetition in each session used the BCI classifier from the previous day to provide feedback or was a calibration repetition with no feedback; the first repetition each day was used to calibrate a new classifier. In some first repetitions in each session that were earlier in the training phase (i.e., in the first 2–3 sessions), no feedback was given; this enabled the user to focus solely on repeating the imagery to aid in producing a better classifier for the feedback repetitions. In a limited number of cases, if the results of the newly built classifier each day were poor, as a result of poor data quality due to technical problems or subject inattentiveness/engagement in the task during the first repetition, the classifier from the previous day was used for the complete session on that day. In the initial assessment, the 6 no-feedback rounds were used to set up the classifier. Subsequent repetitions included visual feedback or pink noise followed by musical feedback. Analysis was performed for each repetition because different repetitions involved different feedback types, and the level of awareness or engagement was unknown and may have varied for the subjects who had MCS. Many trials were rejected because the head strap occasionally distorted the electrode cap, the subject wheezed, or teeth grinding occurred; the number of trials per repetition after artefact removal by visual inspection was reported. Statistical significance was defined by $P \leq 0.05$.

3 Results

3.1 Initial Assessment

The time course of mean classification accuracy for each subject in the initial assessment, and a feedback repetition with high mean classification accuracy, showed an increase from approximately 50% at baseline (<3 s) toward a peak in the event-related period (Table 2 and Fig. 3). All subjects had significant differences between baseline mean classification accuracy (2 s) and peak mean classification accuracy ($P \leq 0.05$) in all cases where the differences between peak and baseline (peak-baseline) range were between 15 and 45%. In contrast, the difference between 2 baseline points (1000 and 500 ms before cue) for all subjects was not significant in all subjects and repetitions, and the difference between the 2 baseline accuracies ranged from 1 to 18%. The peak mean classification accuracy for all subjects exceeded the 70% criterion level normally used to determine whether a subject was capable of using a 2 class MI BCI [24]. A group analysis comparing baseline and peak accuracies indicated significant brain activation across all subjects (P 0.001). The time at which peak mean classification accuracy was reached was beyond the cue time (3 s) for all subjects, indicating that it was not affected by the cue stimulus during the feedback repetitions. The stimulus response mechanism is normally present between 0.5 to 1 s immediately after the cue stimulus is presented. Although the peak for subject Z was at 3.8 s, this initial assessment did not have different cues for each class of MI (same auditory tone for toe movement and right hand squeeze), so the stimulus responses mechanism should not influence the accuracy in the initial assessment with no feedback. The frequency bands selected to access differences between sensorimotor activation were 8 to 13 Hz (subject E), 8 to 25 Hz (subject J), 12 to 19 Hz (subject P), and 10 to 14 Hz (subject Z), within the normal ranges for detection of differences in SMR oscillations associated with the MI tasks.

Table 2 Results showing the baseline versus peak comparison for the initial assessment and a feedback run (where baseline is the motor imagery discrimination accuracy 1 s before the cued motor imagery period and peak is the peak discrimination accuracy during the motor imagery period). Baseline versus baseline comparisons are also shown (where baselines one and two are the motor imagery discrimination accuracy 1000 and 500 ms before the cued motor imagery period, respectively). *p*-values indicate significant differences between peak versus baseline ($p < 0.05$) with no difference between baseline one versus baseline two ($p > 0.05$)

		No. trials	Peak time (s)	Peak-baseline (%)	Baseline mCA (%)	Peak mCA (%)	Wilcox. p-value	Baseline @ 2 s	Baseline @ 2.5 s	Wilcox. p-value
E	Assessment	38	7.0	21.1	71.1	92.1	0.023	71.1	63.2	0.179
	Feedback run	40	5.0	45.0	42.5	87.5	0.001	42.5	40.0	0.748
J	Assessment	84	4.1	17.9	53.6	71.4	0.011	53.6	54.8	0.841
	Feedback run	50	5.2	20.0	58.0	78.0	0.033	58.0	64.0	0.405
P	Assessment	54	5.7	18.5	51.9	72.2	0.012	51.9	50.0	0.796
	Feedback run	28	5.4	28.6	46.4	75.0	0.046	46.4	28.6	0.096
Z	Assessment	74	3.8	14.9	62.2	77.0	0.008	62.2	67.6	0.206

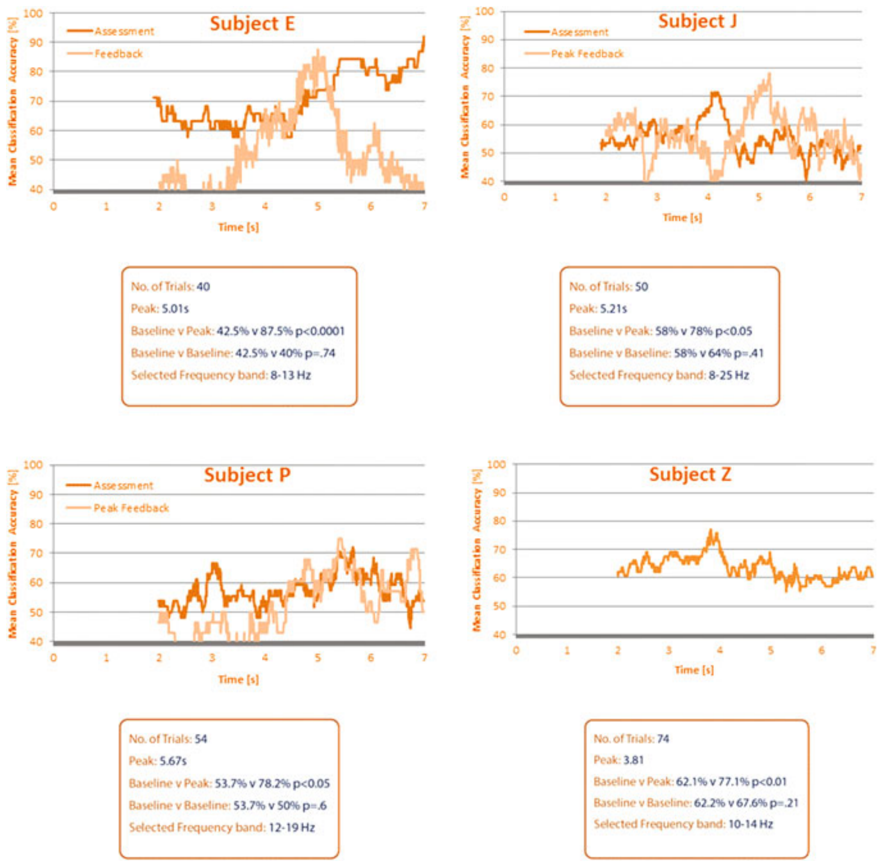

Fig. 3 Relation between mean classification accuracy and time for subjects who had disorders of consciousness and training sessions with the brain-computer interface system. Data shown include the initial assessment and peak auditory feedback repetition (*subject P*, feedback in the initial assessment; *subjects E* and *J*, brain-computer interface training; *subject Z*, no feedback repetition participation)

3.2 Brain-Computer Interface Training Sessions

Subjects E, J, and P participated in BCI training (multiple sessions). Subject E was involved in phases of visual and auditory feedback. Subject J and P had partaken mainly in auditory feedback repetitions because auditory feedback was the most suitable for subjects with MCS. The peak mean classification accuracy in each repetition in each session and the baseline mean classification accuracy, number of trials, and peak-baseline showed that participants E, J and P intentionally activated sensorimotor areas in responses to commands, producing significant differences between baseline and peak mean classification accuracy and (in the majority of repetitions) producing accuracy above the 70% criterion level for two class BCI (See Fig. 4). Many trials were affected by artefacts (subject E, 34%; subject J, 10%; subject P, 2%) and were excluded from the analysis. Labels for the type of feedback (visual: ball, space game, or auditory: pink noise, musical feedback) were noted (See Fig. 4). The plots showed there were SMR activations during feedback with most repetitions showing a statistically significant difference ($P \leq 0.05$) between baseline and peak mean classification accuracy (differences between 2 baselines before cue were not significant in all repetitions except for 1 repetition for subject P [data not shown]). For subject E, the visual and auditory feedback modalities showed similar performance (visual, 80%; auditory, 79% [all repetitions]).

It was important to analyse peak-baseline because of the limited number of artefact-free trials in each repetition. Visual impairment made it unclear whether subjects were aware when the trial was ending using visual feedback, especially for the spaceship game in which the spaceship was on-screen continuously and could be modulated throughout the repetition. In addition to the lack of perceivable visual feedback, visual impairment may have caused reduced baseline versus peak accuracy differences during the visual feedback phase for subject E, but an improvement in accuracy is evident in the auditory feedback phase. Subject J showed consistent activations of sensorimotor areas in all sessions. Subject P was less engaged in the fifth and later than earlier sessions, and a family member noted that he had been physically sick during that period. The results indicated that peak accuracy did not change, but baseline accuracy increased (reason unknown) and caused the detected activation to be insignificant for all repetitions during session 5, 6, and 7 (session 7 was stopped after an initial assessment to determine interest in participating in the session, but the EEG response suggested there was no attempts been made to perform MI). Subject E, who had participated the longest in the study, produced the highest peak performances of all subjects and achieved most results >80% after session 8, suggesting that the subject was improving in performance and sensorimotor learning occurred.

Figure 5 shows topological plots of event related desynchronization/ synchronization ERD/S in the most discriminative frequency band for initial assessment (squeeze right hand versus wiggle toes MI) (all subjects) and for a feedback run (hand versus foot MI) for subject E, J and P. For subject E, there is clear discrimination in the μ band during initial assessment, however ERS during right hand MI appears ipsilateral to the movement, which is unusual. In the later feedback session, there is clear ERD in the μ band in the contralateral hemisphere for right hand movement with slight ERS in the ipsilateral hemisphere. There is slight ERD observable in contralateral hemisphere for left hand movement.

Subject J exhibits clear ERS in higher μ and lower β band contralateral to right hand movement and in central midline for foot movement. ERS in these bands in indicative of activation in regions of the motor cortex that is consistent with other able-bodied studies involving these MI types. During a feedback run, subject J shows clear ERD across μ and lower to central β bands during left hand MI in contralateral motor areas and ERS in these bands in the ipsilateral hemisphere during right arm movement. These findings are again consistent with able-bodied

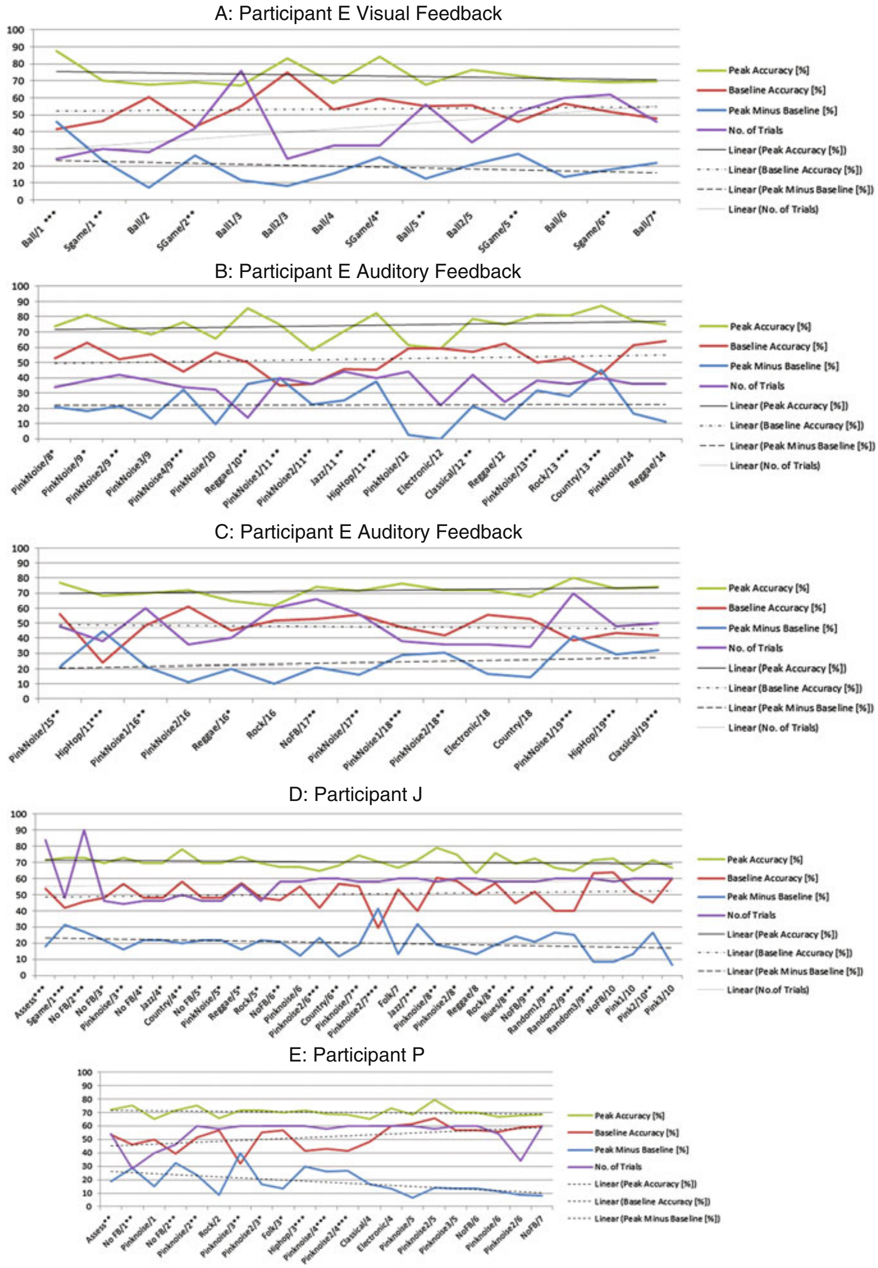

Fig. 4 Relation between baseline and peak mean classification accuracy, peak-baseline accuracy, number of trials and repetitions in subjects with disorders of consciousness and training sessions with the Brain-Computer Interface system. Data include peak, baseline (1000 ms before cue), baseline-peak mean classification accuracy from leave-1-out cross validation, number of trials in each repetition after artifact rejection, and type of feedback presented in each repetition (***$P \leq 0.005$; **$P \leq 0.05$; *$P \leq 0.1$). **a** *Subject E* results from visual feedback sessions; **b** *Subject E* results from auditory feedback sessions; **c** *Subject E* results from auditory feedback sessions (last phase); **d** *Subject J* all sessions; **e** *Subject P* all sessions

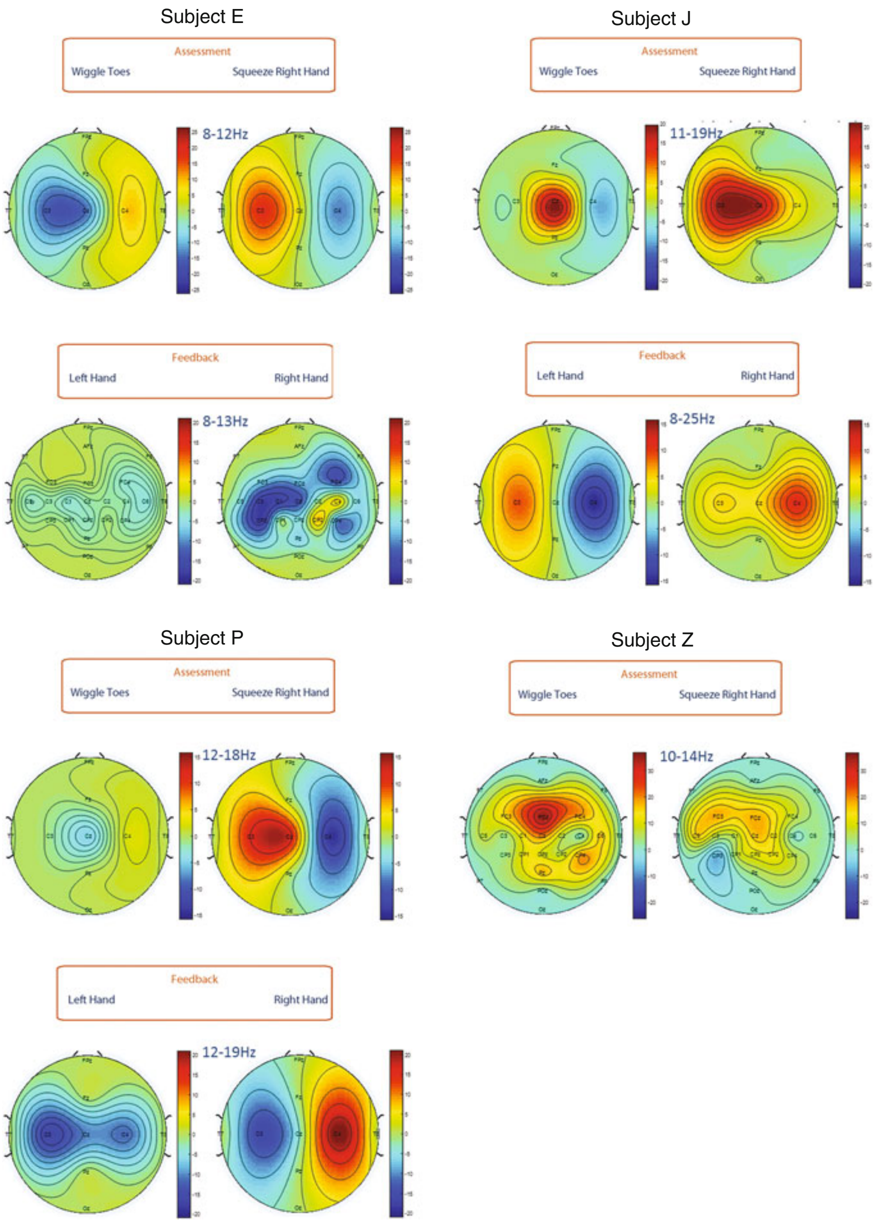

Fig. 5 Topoplots showing event-related desynchronization and synchronization in the most discriminative frequency band for initial assessment (squeeze *right* hand versus wiggle toes motor imagery) (all subjects) and for a feedback run (hand versus foot motor imagery) for *subject E*, *J* and *P*

results and provide clear indication of normal cortical activation in the MCS. Participant P has midline ERD upper μ/lower β during wiggle toes which is normal, with ipsilateral ERD and contralateral ERS in these bands during squeeze hand imagery in the initial assessment which is unusual. However, during later feedback runs, the subject shows upper μ/lower β ERD in the contralateral hemisphere and ipsilateral ERS during right hand MI. Participant J shows contralateral ERD and ERS in the upper μ band in the contralateral hemisphere during initial assessment of squeeze right hand imagery and midline ERS during wiggle toe, which is consistent with expected spatial activation and somewhat consistent with anticipated spectral changes during these MI tasks.

4 Discussion

The evidence obtained from the initial assessment suggests that these subjects who had MCS were aware of themselves and the environment. BCIs use self-directed neurophysiological processes such as the activation of the sensorimotor cortex during MI or attempted motor execution. The results observed in the initial assessment involving a cue, with instructions presented visually and verbally, suggest that subjects had the capacity for sustained attention, response selection, working memory, language comprehension, and visual and/or auditory acuity. The initial assessment results suggest that EEG-based BCI may complement current awareness assessment tests to gain a more detailed understanding of the level of awareness in patients who have a DoC. Attaining information using BCI also may clarify initial diagnosis by complementing existing assessments that involve overt motor responses. The present BCI setup required only 3 EEG channels, mobile data acquisition equipment, and automated analysis and feedback software. Therefore, a bedside assessment may easily be performed in <1 h by a patient's medical team. The EEG recording equipment is decreasing in cost, and medical teams may be easily trained to perform these assessments. After the initial assessment, subjects seemed to realize that they could modulate feedback, and they seemed to increase their attentiveness and level of arousal, which was evident in their demeanour. The realization of the possibility of affecting a visual object or sound external to the body without movement, especially after being unable to do so (for 12 years in subject E), may improve a person's psychological well-being. The subjects were more alert during audio than visual feedback, and audio trial cues were clearer with the musical palette apparently aiding alertness. This was noted anecdotally by researchers and family members of the subjects. The within-subject and between-subject differences in performance during the musical and broadband (pink) noise feedback were insignificant. Therefore, although pink noise is easier to localize than music that includes multiple instruments and vocals, the variety of sounds in the musical feedback did not adversely affect performance. However, the presentation of pink noise may be less appealing than music. The peak performances during auditory feedback for subjects E and J were obtained with musical feedback, which suggests that musical feedback may help increase performance with SMR BCI control. The awareness assessment, MCS baseline versus peak difference, for subjects E and J suggested that their awareness was beyond the MCS and above the 70% accuracy criterion for the discrimination of 2-class MI BCI. The present results confirm the feasibility of using musical stereo audio feedback in SMR BCIs, especially for patients who have visual impairment or DoC, and it may be possible to use sound spatialisation techniques and 3-dimensional sound to improve this experience [25].

The study aimed to assess whether BCIs could provide a communication channel for subjects who have DoC. The results showed that all subjects could be trained to operate a BCI. However, to ensure reliability of the response, the aim is to continue the study in an attempt to train subjects to perform consistently at >85% accuracy prior to introducing a binary ("yes or no") response question system for MCS subjects. The consistent activation of motor areas observed suggests that sensorimotor learning in multiple sessions with auditory feedback may enable communication for users who have DoC. However, 15 to 30% of BCI users may not achieve the criterion level of control (70% accuracy) [26]. In addition, mean EEG amplitude, even in the best trained subjects, may vary over time and between sessions, and consistent performance may be difficult to attain [27]. Therefore, expectations about outcomes with BCI training programs may be guarded [28].

Subjects may become disengaged, as was the case with subject P, and not all repetitions may show significant activations. The experimenter consistently attempted to maintain dialogue and provide encouragement to all subjects and engage family members and/or carers in an interactive discussion to ensure maintenance of subject willingness to improve at using a BCI. At the end of the sessions, it was not possible to detect a consistently reliable single-trial response in all subjects, but it was possible to determine willingness to participate by assessing the data during the repetition or trials. For example, in session 7 for subject P, after no clear observation of activations during sessions 5 and 6, it was decided to ask the subject to perform the MI during the first repetition only, if he wished to continue with the session; when activation was not observed, the session was terminated. Patients who have minimally conscious state may have fluctuations in awareness. The BCI training results may not show activations when subjects are less engaged or aware, and the BCI session may help assess fluctuations in awareness.

4.1 Study Limitations

Limitations in the present study included the limited number of subjects, and there are a limited number of studies that have reported SMR and BCI-based assessment in DoC patients [10, 12]. Family members and care teams for all subjects consented to participate in further BCI training sessions, and we aim to recruit additional subjects for future study. It was difficult to use a consistent format for experiments and obtain useful data because of the new technology available for this study population, resources required, challenges in recording EEG from nonresponsive individuals, and fluctuations in subject awareness. Study subjects were recruited at different stages of the research during the evolution of the BCI training research protocol, based on experiences gained in working with subjects who had DoC. Although the initial assessment was consistent for all 4 subjects, the sequence of BCI training sessions for subjects E, J, and P had subtle differences. Subject E participated in a visual feedback phase before the auditory feedback phase began; subject J and P began BCI training with audio after brief initial visual feedback. In addition, the variation in the type of audio feedback (pink noise or music) limited the identification of the best type of audio feedback. A variety of feedback during training may help attentiveness and interest but may affect the subject's ability to learn from the feedback. In another study of able-bodied individuals, there was no difference in performance when presenting visual and auditory feedback or when presenting different types of audio [16]. Future study may determine the best feedback presentation methods and timing to adapt the BCI classifier [29]. The present study may enable a more consistent approach in future studies that evaluates the effects of audio feedback on BCI performance in DoC and classifier adaptation or calibration.

Another study limitation was the small number of sessions for each subject. Training durations from months to years have been reported for different patient groups, e.g., a tetraplegic patient learned to control a hand orthosis after 62 sessions [30]. In comparison, the results produced by subjects in the present study are promising and consistent with performance of able-bodied subject investigations with similar protocols and number of sessions [16]. Motor imagery strategy may be changed to maximize performance, one approach may not be optimal for all subjects, and modulating sensorimotor cortical rhythms may require motor learning, time, and persistent effort [2]. In the present study, we did not assess the most appropriate MI for each individual or a larger number of electrodes to assess the brain areas that were most activated during MI, and this may be addressed in future studies.

5 Conclusions

In patients who have MCS, the true level of awareness may not be known because the patient may be unable to provide overt motor responses. The present EEG-based assessment showed that subjects attempted to activate sensorimotor areas, and this suggests that these subjects had awareness and cognitive ability. Therefore, diagnosis of these patients may be improved with an EEG-based assessment, and individuals who have DoC may have the capacity to learn how to modulate brain activity and communicate using BCI. Further research may increase the reliability of EEG-based BCI and reduce training times to enable a binary response (yes or no) to questions and enable communication for patients who cannot communicate with gestures such as an eye gaze or thumb movement.

Moreover, a number of testimonies from family members suggests that, as the results of this research provided better evidence of awareness in the patients, this has had an impact on care and treatment plans. These testimonies also indicate that there may be therapeutic values and stimulation gained by patients as they attempt to activate cognitive process during MI and whilst listening or observing feedback based on their efforts. Subjects therefore might benefit from prolonged use of BCI for stimulation and brain engagement as well as communication. With the auditory online real-time feedback setup, evaluated with DoC in research studies preceding this chapter for the first time [10, 13], MI BCIs are broadened to those with visual impairments who may not be capable of seeing targets and feedback presented visually. This is particularly important for DoC based applications of MI BCI, as visual acuity and gaze control capacity is often unknown as the eyes closed condition is prevalent in DoC.

It is recommended that online real-time feedback be provided in studies which involve MI paradigms and DoC patients. In future work, we aim to evaluate SMR BCI in a larger cohort as an assessment tool for use in diagnostic settings and for establishing communication with unresponsive patients. The therapeutic benefits of prolonged training of intentional control by brain activity through motor imagery and stimulation provided by the feedback during the process of learning to modulate SMR will also be investigated.

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