4 Brain–Computer Interfaces for Motor Rehabilitation, Assessment of Consciousness, and Communication

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Abstract

Brain–computer interface (BCI) technology has recently been extended to help patients with disorders of consciousness (DOC) and stroke. These two promising new directions focus on new patient groups and new applications for these groups. First, patients diagnosed with a DOC might benefit from new BCI-based systems that can help assess (or reassess) their consciousness, allow communication and even outcome prediction, and guide rehabilitation. Second, patients with motor disabilities resulting from stroke might use BCIs to facilitate rehabilitation to recover lost motor functions more quickly and completely than conventional therapy alone. Both of these directions have advanced well beyond the initial proof-of-concept stage, with dozens of publications from numerous different groups that validate methods and devices with patient groups in real-world settings. However, broader studies with patients are still needed. We briefly review these two new directions, describe the mindBEAGLE and recoveriX systems that are based on them, and present examples of results from real-world applications with patients.

4.1 INTRODUCTION

Early review articles focused on brain–computer interface (BCI) research correctly noted that the BCI research community was primarily focused on providing communication and control for patients who were unable to communicate through conventional means owing to severe motor disability. These target users included patients with late-stage amyotrophic lateral sclerosis and others with locked-in syndrome (LIS), meaning that they have little or no reliable voluntary muscle control (Wolpaw et al. 2002; Kübler et al. 2001). However, in the last few years, review and commentary articles have shown a different trend: helping new patient groups with BCI technology (Allison et
al. 2013; Wolpaw & Wolpaw 2012; Brunner et al. 2015). Two of the most promising extensions aim to help persons with disorders of consciousness (DOC) and stroke.

4.2 PATIENTS WITH DOC

Patients with DOC include persons in a coma, vegetative state (also called unresponsive wakeful state or UWS), or minimally conscious state (MCS) (Giacino et al. 2012). Like patients with LIS, these patients do not have sufficient voluntary muscle control for communication, even with typical assistive technologies designed for people with limited movement control. However, unlike LIS patients, patients diagnosed with DOC are also considered incapable of the cognitive activity necessary for communication. That is, the disorder of consciousness prevents them from understanding and remembering new information, developing new messages or commands, and executing the mental activity necessary to communicate. Thus, reassessment of their cognitive abilities, and especially the development of a communication system for these unique patients, is a major challenge.

However, the clinical observation at bedside results in diagnostic errors in up to 42% of patients, since awareness may coexist with insufficient motor control (Giacino et al. 2012). By collecting objective measures of awareness, a BCI system that does not require the patients to see may improve dramatically the diagnostic accuracy of the DOCs and, depending on the residual cognitive functioning, also enable these patients to communicate. The same approach can be used to assess awareness and allow communication for complete LIS (CLIS) patients, who are unable to communicate by any means, including visual-based BCIs (Marchetti & Priftis 2014; Guger et al. 2017). To meet the special requirements of DOCs and CLIS patients, nonconventional BCI modalities are needed, based on their residual capacity to understand instructions, perceive auditory and vibrotactile stimuli, and perform mental tasks, despite their visual impairment.

Some groups have shown that a minority of persons diagnosed with DOC are able to communicate using BCI technology (Brunner et al. 2015; Risetti et al. 2013; Schnakers et al. 2009; Lugo et al. 2014; Lulé et al. 2013). This indicates that, even if patients seem unconscious during behavioral assessment, these patients could show signs of consciousness during reassessments with a BCI.

Different approaches to consciousness assessment have been used. One of the challenges is that many patients suffer from visual deficits, and therefore conventional BCI approaches have to be adapted to be independent from visual stimuli. This means that patients must be able to understand task instructions, stimuli, and feedback even though they cannot see. To date, the auditory and tactile modalities have been employed.

Below, we introduce the mindBEAGLE system. This is a complete hardware and software platform for real-time biosignal analysis designed especially for DOC patients to assess the level of consciousness and provide communication (see Figure 4.1). It includes a laptop with preinstalled software, 16-channel EEG cap, amplifier, earbuds, and vibrotactile stimulators. All task instructions are presented auditorily in the user’s native language, either through the earbuds or the experimenter’s voice.

![FIGURE 4.1](image_url)

Left: the mindBEAGLE system including a biosignal amplifier, computer, EEG cap, in-ear phones, and vibrotactile stimulator. Right: in usage with a patient.
This system can use four approaches for assessment:

The “Auditory Evoked Potential” or AEP approach is designed to elicit event-related potentials (ERPs) through auditory stimuli. mindBEAGLE uses two types of tones that are presented for 100 ms: rare target stimuli (1000 Hz) and more probable standard stimuli (500 Hz). Target tones, which are only one out of eight stimuli, are randomly interspersed among the standard tones. The user is instructed to silently count each target stimulus while ignoring other stimuli. Successful task performance will elicit an ERP with a P300 to target stimuli only.

Figure 4.2 shows an example of a UWS patient (P1) and an MCS patient (P2). The MCS patient shows a clear P300 response and an improving classification accuracy.

Figure 4.3 shows the AEPs and classification accuracy of a CLIS patient and the classification accuracy of a healthy control in sham condition. Of special interest is that the CLIS patient shows a strong ERP and perfect classification accuracy after five target tones. The accuracy looks like a healthy control person, while the EPs show a smaller amplitude and later peak compared to healthy controls. Additionally, the figure also shows the accuracy achieved with a healthy control in sham condition (in which tactors were not fixed to the arms).

The “Vibrotactile-2” or VTP2 approach uses tactile stimuli instead of auditory stimuli, although instructions are still provided through earbuds. Vibrotactile stimulators are placed on each wrist, and the user is instructed to silently count each time the right wrist stimulator vibrates. Then, the two stimulators intermittently vibrate for 50 ms. Like the auditory paradigm, 1/8 of the stimuli are deviant stimuli (right wrist vibrations), and the stimuli are presented in random order. Thus, the VTP2 approach is also a classic oddball paradigm designed to elicit distinct ERP components that reflect the user’s decision to silently count deviant stimuli.

Figure 4.4 shows the VTP2 responses and classification accuracies of P1 and of P2. There is a clear difference between the ERPs of the UWS and MCS patient. The MCS patient reached a median accuracy of 100%, while the UWS patient showed 0% accuracy.

The “Vibrotactile-3” or VTP3 approach enables the patient to communicate in a binary fashion and differs from the VTP2 approach as follows. First, the system uses three vibrotactile
stimulators, with the third “deviant” stimulus placed on the right ankle or chest. Second, the proportion of stimuli is different: in each sequence of eight stimuli, one is delivered to the right wrist, one is delivered to the left wrist, and six are delivered to the right ankle, in pseudorandom order. Third, the subject is instructed to silently count the stimuli to the left or right wrist, corresponding to the left or right cue. The deviant stimulus is never the target.
Last, the subject hears a cue before each sequence of pulses with the word “left” or “right.” This VTP3 approach is a more complex variant of the oddball paradigm that can assess advanced cognitive function. Indeed, if the patient is performing well and above chance level during the training phase of the classifier, this paradigm can be used to test communication. The patient now does not get a cue instructing which hand is the target and instead needs to concentrate on the left hand to say yes and on the right hand to answer no.

Figure 4.5 shows the VTP3 results for a patient that seemed UWS on the behavioral level for two sessions. In the first session, no ERP was found and the average classification accuracy was 25%. However, in the second session, the patient was able to communicate successfully, and the average classification accuracy increased to 75%. This improvement was observed in the P300 amplitude elicited by left hand stimuli.

**FIGURE 4.5** VT3 responses and classification accuracy of patient P3 for two different sessions. An improvement of the ERP and accuracy is observed from the first to the second session. Interestingly, the patient was not able to communicate during the first session, yet during the second session, the patient was able to communicate successfully. Here is an example during which the patient answered no, as shown by the higher P300 amplitude elicited by left hand stimuli.
accuracy was only 40%. The calculated classifier could not be used successfully to establish communication. In the second session, the patient was able to improve performance and a significant ERP was found, resulting in a classification accuracy of 80%. Then, the classifier was used to perform a communication run by asking yes/no questions. This patient could successfully answer 9 out of 10 questions. Figure 4.5 shows an example of a question where the known answer is NO (for which a higher-amplitude P300 is found over the left hand contralateral hemisphere) and another example for YES.

A communication run using the classifier from session 2 was employed as well (see Figure 4.6). During this session, the patient was able to answer 9 out of 10 questions correctly.

The “Motor Imagery” or MI approach, unlike the three preceding approaches, does not rely on the P300 and other ERPs. Instead, like most other MI BCIs, it relies on changes in EEG power in specific frequency bands that occur when a person imagines movements. These changes, called event-related (de-)synchronization or ERD/S, are typically present in the 8- to 13-Hz band over sensorimotor areas. Its specific characteristics may change in patients with brain injury. The user is instructed to imagine either left or right hand movement in response to cues that instruct “left” or “right” and a starting tone. Another cue, the word “relax,” instructs the user to stop performing motor imagery. This cue occurs after eight seconds, providing eight seconds of motor imagery data.

These four assessment modes are designed to target assessment of command following and communication and to provide different approaches in case one approach is not effective. This leverages the concept of a “hybrid BCI” that can use different types of BCIs to provide the communication protocol that works best for each user (Pfurtscheller et al. 2010). If a user is successful with one or more assessment modes, then the four modes can also be used for communication. Indeed, since some DOC patients may fade in and out of command following, it seems best to switch to the communication mode as soon as the assessment reveals potential for communication. The AEP and VTP2 modes support a “quick test” of basic brain functions, while the VTP3 and MI modes support more in-depth communication options. However, mindBEAGLE can still only provide yes/no communication. We are therefore currently developing new hybrid BCI options to improve nonvisual communication.

The hybrid BCI approach may be especially important to improve the diagnostic accuracy in DOC patients, in which “BCI inefficiency” may be higher than typical patients. In a typical BCI, “BCI inefficiency” does not convey much useful information about the cognitive abilities of the user and the BCI’s inability to discern relevant brain signals reflects a challenge for the system designer. However,
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if a DOC patient shows to be unable to follow commands in repetitive BCI sessions, the system might be working as expected, confirming that the patient is unaware and cannot communicate through any mechanism. Importantly, this is not the only conclusion that should result from these situations.

Two very recent developments merit attention here. First, a new publication (http://www.cnn.com/2017/06/15/politics/otto-warmbier-north-korea/index.html) showed that persons with CLIS can use BCI technology to communicate. This provides further hope for extending BCI technology to new patient groups, particularly those with the greatest need. Second, during June 2017, the popular media (such as http://www.cnn.com/2017/06/15/politics/otto-warmbier-north-korea/index.html) announced that an American student returned from North Korea with a DOC and that further details of the type of DOC were not clear. Sadly, the student died a few days after returning to the United States. If he had survived longer, might BCI technology have helped to further assess his condition, and perhaps enable him to provide information about how he was injured?

4.3 STROKE PATIENTS

While stroke can have many effects, we focus here on the impairment of motor function. These impairments can affect hand and arm function, speech, gait, and other motor abilities. Although stroke is very prevalent, and improved stroke treatment methods are potentially impactful and profitable, therapy outcomes remain poor. Most people who participate in therapy improve only modestly, at best.

In typical therapy, patients are asked to perform or imagine specific movements. They may receive assistance from an orthosis or functional electrical stimulator (FES) to help them complete the movements. These systems are active whenever the patient is told to perform the desired mental activity or imagery.

However, if patients are not performing the motor imagery when expected—throughout each and every trial—then the feedback they receive may often be uncorrelated with the required brain activity. Patients receive rewarding feedback when they should receive no feedback, or cues to perform the task differently. The expected pairing between brain activity and peripheral activity does not reliably occur, which violates foundational assumptions in feedback and the underlying principle of Hebbian learning (Neuper & Allison 2014). BCI technology could provide a new way to close the feedback loop by monitoring motor imagery (even if patients cannot actually move) and triggering feedback only when users are imagining movement.

This new principle, called paired stimulation (PS), has been used in recent publications (Xu et al. 2014; Pichiorri et al. 2015; Belda-Lois et al. 2011; Ortner et al. 2012). The recoveriX system (Figure 4.7) is designed to couple real-time indices of motor imagery with different types of feedback, including FES activation and the movement of a virtual avatar. By providing feedback only while

FIGURE 4.7 The left image depicts the closed-loop feedback in recoveriX, including a 16-channel wireless system. The right image shows a patient using a recoveriX prototype to restore hand function. The system includes EEG electrodes, a biosignal amplifier, a computer, and an FES.
the user performs the expected mental activities, recoveriX creates a much more effective closed-loop paradigm that increases compliance and user engagement.

Figure 4.8 shows a 65-year-old stroke patient who began recoveriX training 3 months post-stroke. The stroke affected the functions of his left arm. A nine-hole PEG test was used to measure the time to put nine pegs into holes of a board in front of the patient. The recoveriX training was performed a total of 24 times for 30 min each (80 left hand movement imaginations, 80 right hand movement imaginations). The patient needed between 25 and 26 s to perform the task with his right hand. With the left hand, he could not do the test within the first nine sessions. Then, he improved the time of the left hand from 1 min 30 s continuously to 52 s.

Figure 4.9 shows the BCI classification error rate across 24 sessions. The patient started with a minimum error rate of 12.5% and was able to reduce the error rate to only 1.3% in session 13. Curiously, while the error rate remained low after session 13, it was always above 1.3%.

Figure 4.10 shows the changes of the common spatial pattern (CSP) filter applied to the 64 EEG electrodes. In session 2, the patterns are very fuzzy, but in session 23, clear spots around C3 (right hand representation area) and C4 (left hand representation area) can be seen.

**FIGURE 4.8** Left: Patient P5’s residual arm movement before the recoveriX training (he could not lift the arm higher). Right: the same patient’s arm movement after nine recoveriX sessions.

**FIGURE 4.9** Classification error rate during the 24 recoveriX training sessions of P5.
recoveriX is designed to work with different movements, and we present one example based on right wrist dorsiflexion. A patient who can no longer perform this movement would typically be asked to imagine it while an FES or other mechanism tried to complete the effort by stimulating or manually manipulating relevant areas of the arm, wrist, and hand. recoveriX can add crucial information to this system: real-time measures of imagined wrist dorsiflexion based on ERD/S maps. Unlike conventional therapy, the patient would always know when dorsiflexion imagery is correctly performed. Aside from creating a more effective feedback loop during recoveriX usage, this approach is also useful for verifying compliance to therapists and doctors, who otherwise have no objective way to confirm that their patients are both trying to perform the imagined task and succeeding in their effort. Initial results have been promising, even with post-acute patients, and further research and development is ongoing.

4.4 CONCLUSION

The two new directions presented here could lead to new hope for patients affected by DOC and stroke. Table 4.1 summarizes the benefits that BCIs could provide, extending the classical goal of BCI research (communication for patients with LIS) with these new directions.

![FIGURE 4.10](image)

**FIGURE 4.10** Brain plasticity from session 2 to session 23. The figure shows two CSPs used to weight each electrode according to its importance for the discrimination task. Top: two most important CSP filters in session 2. Bottom: CSP filters in session 23.

### TABLE 4.1
How Different Patient Groups Might Benefit from BCI-Based Technology

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Reliable Communication without a BCI?</th>
<th>Reliable Communication with a BCI?</th>
<th>Might Need BCI (re-)Assessment of Consciousness?</th>
<th>Might Benefit from BCI Rehabilitation?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Most disabilities</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Depends on disability</td>
</tr>
<tr>
<td>LIS</td>
<td>Usually</td>
<td>Yes</td>
<td>No</td>
<td>Being studied</td>
</tr>
<tr>
<td>CLIS</td>
<td>Very few options</td>
<td>See (Guger et al. 2017)</td>
<td>In some cases</td>
<td>Being studied</td>
</tr>
<tr>
<td>MCS</td>
<td>No</td>
<td>Depends on cognitive functioning</td>
<td>Yes—could lead to communication</td>
<td>Being studied</td>
</tr>
<tr>
<td>UWS</td>
<td>No</td>
<td>Depends on cognitive functioning</td>
<td>Yes—could lead to communication</td>
<td>Being studied</td>
</tr>
<tr>
<td>Coma</td>
<td>No</td>
<td>No</td>
<td>Yes—could help confirm diagnosis</td>
<td>No</td>
</tr>
<tr>
<td>Stroke that affects voluntary movement</td>
<td>Usually; depends on disability</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Note: Some patients are misdiagnosed, and BCI technology can provide further information.*
Table 4.1 presents nascent efforts that could inspire broader systems and applications, such as other kinds of rehabilitation (e.g., cognitive, sensory, or emotional) and extensions to other target groups (such as patients with disabilities resulting from other causes). Assessment and rehabilitation also create the new challenge of outcome prediction. Can we predict a user’s likelihood of communicating with a specific approach and/or achieving a certain rehabilitation goal? How long might these challenges take, and what parameters are optimal? There are a myriad of opportunities for future development, and substantial research, development, innovation, and validation with patients will be required to see which directions are the most beneficial to different groups.

REFERENCES


