Chapter 4

Motor Imagery with Brain-Computer Interface Neurotechnology

Christoph Guger∗, Christoph Kapeller1, Rupert Ortner1 and Kyousuke Kamada2
1g.tec medical engineering GmbH, Guger Technologies OG, g.tec medical engineering Spain SL, g.tec neurotechnology USA Inc., Sierningstrasse, Schiedlberg.
2Department of Neurosurgery, School of Medicine, Asahikawa Medical University, Hokkaido, Japan

Abstract

A brain-computer interface (BCI) analyzes brain activity in real-time to convey information or control an external device. BCI systems often consist of a biosignal amplifier for EEG data acquisition, parameter estimation, and classification to make decisions in real-time. Many BCIs are controlled via motor imagery (through imagined movements), which modulates the EEG in certain frequency bands and regions. Motor imagery based BCIs are used for various applications like cursor control,

∗ guger@gtec.at
robotic and avatar control, stroke rehabilitation, cognitive assessment, training, and communication.

This article presents key scientific experiments and applications, including some of the newest results.

**Keywords:** Brain-computer interface, BCI, motor imagery, event-related desynchronization, ERD, rehabilitation, assessment, control applications

### Introduction

**What Is a BCI?**

Brain-computer interfaces typically use the Electroencephalogram (EEG) or the Electrocorticogram (ECoG) to generate a control signal in real-time. Figure 1 illustrates the basic components of such a system. EEG based systems can easily be used with healthy subjects or patients, since the EEG is measured with active surface electrodes placed on the head, which may be dry electrodes or require electrode gel, saltwater, or other materials to ensure a good contact with the scalp. ECoG based BCI systems are mostly used with patients undergoing brain surgery or invasive brain mapping, which use implantable electrode grids or strips that usually have 64 to 256 channels.

The EEG/ECoG electrodes are connected to a biosignal amplifier to magnify the signals, which are transmitted to a computer for real-time analysis. This processing system performs parameter extraction algorithms such as: (i) bandpower estimation; (ii) calculation of adaptive autoregressive parameters; (iii) variance estimation; and many other techniques. Afterwards, these calculated parameters are classified with classification algorithms like (i) linear discriminant analysis (LDA) or (ii) support vector machines (SVM). Finally, these algorithms produce an output which allows control of an external device in real-time. This control could entail spelling, moving a cursor on a monitor, or using a robotic device. Critically, the BCI user must be able observe the object being controlled. This provides feedback reflecting whether the intended task was executed successfully. Different publications have shown that this feedback loop helps to improve the accuracy and speed of a BCI system (Guger et al., 2001, 2003, 2012a; Neuper and Allison, 2014).
BCI Principles and Applications

BCI systems could use: (i) evoked potentials like the P300 or N200; (ii) steady-state evoked potentials (SSEPs); (iii) motor imagery; and/or (iv) slow waves. Slow wave based systems use just a few channels and require substantial training. They are inaccurate, allow very limited bandwidth, and are highly vulnerable to noise. Steady-state based systems often use visual stimuli with specific frequencies to generate brain activity at corresponding frequencies when users view them.

These systems primarily use electrodes over the visual cortex, and can yield high accuracies with minimal training (Guger et al., 2012a). Speed and accuracy can be further improved if, instead of a constant stimulation frequency, a certain code is embedded in the stimulation by switching an LED on or off in a specific pattern. This code-based VEP or c-VEP approach has another advantage over SSVEP: c-VEP can be used with epilepsy patients without inducing seizures (Kapeller et al., 2014). SSVEP/c-VEP based systems are perfectly suited for continuous control of external devices. BCIs with evoked potentials often use an oddball paradigm, in which an unlikely event is embedded in likely events, producing a P300 and other components in the EEG. P300 based systems also require very limited training time, with high accuracy and robustness (Guger et al., 2012b). P300 based system are used for goal-oriented control applications like smart home control, spelling, painting, and some online tasks (Edlinger et al., 2011).
Motor Imagery BCI Applications, Including Accuracy and Performance

Motor imagery based systems usually entail the imagination of right hand, left hand or foot movement. This produces an event-related desynchronization/synchronization (ERD/ERS) over the sensorimotor cortex, which the BCI can analyze to infer user intent. Therefore, the electrodes are placed over sensorimotor regions, and people are trained with feedback paradigms to gain control. In the case of EEG based systems, the BCI system uses either bipolar derivations over the motor cortex (Guger et al., 2001) or a whole grid of electrodes over the sensorimotor cortex analyzed with common spatial patterns or CSP (Guger et al., 1999). Ortner showed that the grand average accuracy after 20 minutes of training for the CSP based system is around 80% (Ortner et al., 2015, accepted). If 2 bipolar derivations are used, about 6% of the population reach 90% accuracy or better (Guger et al., 2003).

Motor imagery BCIs that include ECoG electrodes can also use task-related high-gamma activity. In this case, the ECoG grids are implanted over the sensorimotor cortex by a neurosurgeon. Standard grids have (for example) 64 electrode contacts with a center-to-center distance of 1 cm. High-density grids have 256 channels with a center-to-center distance of only a few mm, yielding a higher resolution. The first task for an ECoG based BCI system is the identification of the electrodes coding the necessary information. This can be done with a high-gamma functional mapping system within a few minutes (Brunner et al., 2009, Prückl et al., 2013; Kapeller et al., 2015, Schalk et al., 2008). Another approach is to train a spatial filter (CSP) to automatically weight each electrode according to the BCI classification task. This spatially filtered signal, or the selected electrode, can be used to directly control motor movements of a virtual or robotic avatar.

Advantages of Motor Imagery BCIs for these Applications

Motor imagery BCIs require more training time than P300 or SSVEP based systems, but can also yield high accuracies. They can be used for continuous control applications or detection of motor movements. This article will detail three applications: (i) motor rehabilitation after stroke; (ii) assessment of patients with disorders of consciousness; and (iii) avatar control to increase embodiment with (for example) a robotic avatar. For motor rehabilitation, the system can detect motor commands from the
brain in real-time, which can be used to trigger a functional electrical stimulator (FES) or an avatar immediately after the movement imagery. This approach guarantees a close relationship between the movement imagery and other system activities (Daly, 2013, Mrachacz-Kersting, 2013, Thompson, 2013).

Figure 2. System components of a BCI system for rehabilitation.

Figure 3. Left: Overview of motor and cognitive functions for different patients. Patients near the bottom of this figure have limited or no motor control, and may be unable to communicate (or even participate in assessments) without a BCI. Right: Electrophysiological test battery for assessment of cognitive functions for patients without adequate motor control.
For assessment purposes, the patient with DOC (see Figure 3) can be instructed to repeatedly imagine a certain motor movement. The BCI system calculates a certain classification accuracy that reflects the patients’ cognitive processing capability (Guger, C. et al., 2014, Kotchoubey, B. et al., 2005, Kübler, A. et al., 2007, Laureys, S. et al., 2010).

Avatar control can be realized by directly mapping motor imagination onto real motor actions of a robotic avatar or a virtual representation. Motor imagery based BCIs guarantee a high embodiment with the artificial avatar. An important aspect for such applications is also the restoration of sensation of the prosthetic limb (Pisotta et al., 2014).

**Methods**

**EEG/ECoG Recording Setups**

Figure 4 shows the principal setup of a fully equipped EEG based BCI research lab. Normally, a person is seated in a comfortable chair with a headrest to reduce artifacts. The person wears an electrode cap with 8-256 EEG electrodes, depending on the application, connected to the biosignal amplifier. Wireless technology allows the person to move around during the experiment or during breaks. The biosignal amplifier sends the data to the real-time processing BCI system that controls either: (i) a head-mounted display for stereoscopic effects; (ii) a computer monitor; or (iii) a Virtual Reality system to provide feedback to the user. Electrical stimulation, tactile stimulation or auditory stimulation can also be presented, and activity from microphones, eye-trackers and switches/buttons can be synchronized with the EEG data. The output of the BCI system can also be sent to a movement computer controlling an exoskeleton or a rehabilitation device. All of these components must communicate with each other in real-time to fully automate the experimental setup.

ECoG based BCI systems are typically used with patients who are seated in a bed in front of a computer screen or Virtual Reality system (see Figure 5). The ECoG electrodes are implanted by a neurosurgeon, and the electrode cables are connected to the 64-256 channel amplifier system. The data are transmitted to the BCI system, which has to deal with much more data because of the higher sampling frequency. This system can be synchronized with more or less the same components as the EEG system.
Figure 4. Laboratory plan of a complete EEG based brain-computer interface.

Figure 5. Laboratory plan of a complete ECoG based brain-computer interface.
System Setup for Each Application

Motor Rehabilitation with BCI

Figure 6 illustrates the experimental setup for motor rehabilitation with a 64 channel BCI system. The 64 channel cap uses active electrodes for quick EEG cap preparation and clean, artifact free data collection. These electrodes are connected to the biosignal amplifier g.Hlamp (g.tec medical engineering GmbH, Austria) with 24 Bit resolution and 256 Hz sampling frequency. The amplifier is connected to the computer running all the real-time analyses. The patient is also equipped with bipolar stimulation electrodes on both arms, which can move the hands when the BCI system detects a movement imagination.

Figure 6. Setup of a motor imagery based BCI system for stroke rehabilitation with FES. Left: The patient imagines a left hand movement, which is detected and translated into a control signal with the BCI in real-time. This activates the FES and thereby moves the left hand. Right: Right hand movement imagination with right hand stimulation.
The system starts with an instruction arrow pointing either to the right or left side of the screen and by moving the avatar’s hand (see Figure 7). This indicates the supposed motor movement imagination that the user should perform for 4 seconds. In total, the user has to imagine 80 left and 80 right hand movements, which requires about 25 minutes. During this procedure, the EEG data are acquired and the BCI system is calibrated. In the next run, the user can already control the avatar’s arms or legs with the BCI's real-time output, thus creating closed-loop feedback.

Figure 7. Experimental instructions are shown to the patient with right and left arrows indicating the site of hand movement imagination. The virtual hand moves if the BCI system detects the corresponding movement type. Left: Hand rehabilitation with first person view; Middle and Right: foot rehabilitation via a mirror to allow the patient to see his or her legs.

**EEG DOC Assessment**

To provide cognitive assessment for DOC patients, the user is prepared for recording with a cap with 16 EEG electrodes overlaying the sensorimotor cortex. Then, the user is instructed via the loudspeaker to imagine moving the left or right hand, and a short beep later indicates the termination of this movement imagination. This is repeated 60 times for each hand to keep the measurement time short. After an initial EEG acquisition run, the BCI system can be calibrated to give feedback in the next session. In this application, the feedback is for the experimenter and physician to investigate the success of motor control on the fly.

**ECoG Avatar Control**

In the case of ECoG based avatar control, the user is seated in front of the computer screen that cues which hand movement should be imagined (see Figure 8). The implant with 60 channels is connected to the BCI system, and the BCI controls an avatar’s prosthetic hand in real-time, so that the user can directly see its movement. The tasks in this example were to imagine a fist, to make a peace sign or to straighten all fingers (each 20 times).
Signal Processing and Classification

In all three applications, the acquired EEG data from the first run are used to calculate a common-spatial pattern (CSP) filter. This filter has all EEG channels as inputs, and weights each channel according to its importance for the discrimination task. It also maximizes the difference between the classification tasks. Then, the variance with a certain forgetting window is estimated for the most important filtered channels. These parameters are normalized, and finally a linear discriminant analysis is trained on the data. This results in a user-specific classifier that can be used to give feedback or to control an object in the next run.

Results

Motor Rehabilitation

Figure 9 shows both the mean and minimum classification error rates across 21 training sessions for one patient. The patient started with an error
rate of 12.5% and improved to 3.8% after 13 sessions. The minimum error rate was never above 21.6%. Figure 9 (middle) also shows the 4 most important CSP filters for sessions 1 and 13. In both cases, the right and left finger regions (around C3 and C4) are the most important centers for the BCI classification.

Figure 9. Classification accuracy, common spatial patterns (CSP) maps and cursor movement time for one subject, with classification accuracy over time. The mean error rate is calculated for the interval 2-4 seconds after the cue indicating the movement type. The minimum error rate is the minimum of the whole period after the cue (5 seconds).

The bottom line of Figure 9 shows the output of the LDA classifier for left and right movement imagery. In session 1, the difference between left and right hand imagery is much smaller than in session 13. Furthermore, the time course of the error rate over the movement imagination trials is shown. In session 13, the error drops more quickly and is ultimately lower than earlier sessions.

Table 1 summarizes performance in a 9-hole PEG test that the patient performed during the 21 BCI training sessions. This test of hand motor control
requires users to put objects into holes, and the completion time and error rate is measured. The patient initially needed 31 seconds for the left (non-affected) hand, and 1 min 5 seconds for the right hand, which was affected by stroke. After the 21 BCI training sessions, the patient could complete the task within about 30 seconds for both hands.

Table 1. Results with a 9-hole PEG test, repeated 8 times for each hand. “Falls” reflects the number of times that a peg was dropped, reflecting an error

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Assessment of Cognitive Functions with Motor Imagery

Figure 10 presents the ERD/ERS maps for right and left hand movements over channels C3 and C4, and shows clear ERD and ERS activity. The bottom curve shows the classification accuracy over trial time for all movement imagination. The user reached a mean classification accuracy of 99.2%.

Avatar Control

Figure 11 shows a high density electrode grid with 60 channels implanted in an epilepsy patient at Asahikawa Medical University over the sensorimotor
cortex. The other grid and strip electrodes are not used for the analysis presented here, since they are not located above the motor cortex.

Figure 10. Top: ERD maps for electrode positions C3 and C4 for left and right hand movement imagination. Bottom: BCI classification accuracy over time.

Figure 11. Brain mapping results from cortiQ indicating the ECoG electrodes responsible for motor movements. Left: ECoG grid locations superimposed on the brain. Right: CSP maps (fist, peace sign and fingers straight) on a high density grid for the 4 most important CSP filters.
Figure 11 (right) shows the 4 most important CSP filters for the three types of motor movement imaginations. The red and blue circles around the electrodes indicate important electrodes for a certain movement task (bigger diameter = more important).

Figure 12 shows the classification error rate over 120 movement repetitions across the trial duration. The patient reached a minimum error rate of 0%.

Discussion

Motor imagery based BCI systems are important for motor rehabilitation, cognitive assessment and avatar control to increase embodiment. This chapter has reviewed relevant technology, and shown how it is used in certain experimental approaches.

Advantages/Disadvantages of EEG based BCIs

EEG based systems have the major advantages of being easy to prepare and use, without requiring the costs, risks, and other challenges associated with neurosurgery. New technologies such as active electrodes, 24 bit
resolution and high oversampling to reduce noise have made these systems much easier in real-world applications. Within about two minutes, a user can be prepared for recording with a cap using 16 EEG channels, which can be adequate for motor rehab and cognitive assessment. Therefore, this procedure can easily be done on a regular basis. Another important advantage is that the active EEG electrodes can be mounted without abrading the skin, which makes the procedure much more comfortable for the patient and therapist. Additionally, water based gel don't cause skin irritation or itching, and the gel may disappear a few hours after the EEG cap is removed.

Advantages/Disadvantages of ECoG based BCIs

The implanted ECoG grids have the big advantage of high spatial resolution, which allows BCIs to discriminate individual finger movements, a task which is impossible with EEG based systems. Furthermore, the signal-to-noise ratio of an ECoG system is much higher, which makes it easier to capture a good control signal, quickly identify the important electrodes and establish reliable communication and control. Critically, the ECoG based BCI system does not produce many false positives, which allows the system to reliably stop the avatar or hand movement if the user is done with the control task. This “zero-class problem” is especially difficult with EEG based systems. However, the zero-class problem is not relevant for the two presented applications: (i) motor rehabilitation and (ii) cognitive assessment.

Advantages/Disadvantages of BCIs for assessment and rehabilitation

BCI systems for cognitive assessment have the major advantage of providing a very objective measure of each patient’s task performance. If the BCI accuracy is 0%, then it is very likely that the patient cannot perform the task; if the accuracy is 100%, then the patient was able to perform the task very well. This informs the therapist whether the patient is still able to follow conversations and understand instructions.

In the case of motor rehabilitation, the BCI classification informs the therapist whether or not the patient is correctly performing the task. This allows the therapist to influence the training and motivate the patient. The
paired stimulation with motor imagery also produces motor movement, which further motivates the patient to perform the training.

**Future Outlook**

In the future, a combination of these systems will be important. Motor rehabilitation systems will also be used for patients with DOC, while cognitive assessment systems will be used for patients with motor disabilities. The full body avatar could provide the perfect closed-loop feedback device in the future, and will open many new applications like self-feeding with your own avatar (Figure 13).

![Figure 13. A BCI user controlling his avatar to give him a Coke from Abderrahmane Kheddar (CNRS-AIST JRL) (Petit et al., 2015).](image-url)
References


