Amplitude and latency of beta power during a discrete and continuous motor imageries

Sébastien Rimbert, Laurent Bougrain, Cecilia Lindig-León, Guillaume Serrière

Modulation of beta power in EEG during discrete and continuous motor imageries

Sébastien Rimbert*,†,‡ Laurent Bougrain†,*,‡ Cecilia Lindig-León*,†,‡ Guillaume Serrière*,†,‡

*Neurosys team
Inria
Villers-lès-Nancy, F-54600, France

†Artificial Intelligence and Complex Systems
Université de Lorraine, LORIA, UMR 7503,
Vandœuvre-lès-Nancy, F-54506

‡Neurosys team
CNRS, LORIA, UMR 7503,
Vandœuvre-lès-Nancy, F-54506

***Abstract*—Motor imagery modifies the neural activity within the primary sensorimotor areas of the cortex in a similar way as a real movement. More precisely, beta oscillations (18-25 Hz), which are often considered as a sensorimotor rhythm, show that the amplitude of brain oscillations is modulated before, during, and after a motor imagery. A large number of *Brain-Computer Interfaces* (BCIs) are based on the detection of motor imagery related features in the electroencephalographic signal. In most BCI experimental paradigms, subjects realize continuous motor imagery, i.e. a prolonged intention of movement, during a time window of a few seconds. Then, the system detects the movement based on the *event-related desynchronization* (ERD) and the *event-related synchronization* (ERS) principles. This study shows that a discrete motor imagery, corresponding to a single short motor imagery, would allow a better detection of ERD and ERS patterns than a continuous motor imagery. Indeed, the results of experiments involving 11 healthy subjects suggest that a continuous motor imagery generates a later ERS as well as a more variable and less detectable ERD than discrete motor imagery. This finding suggests an improved experimental paradigm.**

***Index Terms*—Motor imagery, beta band, event-related synchronization, event-related desynchronization, Brain-computer interfaces**

I. Introduction

Electroencephalography (EEG) is a powerful brain imaging technique to detect neuronal activity with millisecond precision by measuring on the scalp the electric potential of the activity of neural populations. According to Hans Berger's observations, EEG signals can be described in terms of neural oscillations i.e. brain rhythms [1]. Oscillatory brain activity is usually divided into several rhythms associated to specific frequency bands: delta (1-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-30 Hz) and gamma (30-70 Hz) [2]. Based on external or internal events, the power of the different rates can vary over time. Hence, it is useful to obtain information on the power of each frequency band in a given time window.

In 1949, Jasper and Penfield showed that the power of brain oscillations in the beta band is modulated during a real movement [3]. Since then, numerous studies have been dealing with the changes arising before, during and after a movement. Indeed, before a movement, compared to a state of rest, firstly there is a gradual decrease of power in the beta band of the electroencephalographic signal, called *event-related desynchronization (ERD)*. Secondly a minimal power level is maintained while the effector is present in the movement. Finally, from 300 to 500 milliseconds after the end of the movement there is an increase of power called *event-related-synchronization* (ERS) or post-movement beta rebound [4] with a duration of about one second. The beta band is not the only one to be modulated during a movement. Indeed, the alpha and gamma rhythms vary as well.

ERD and ERS patterns were not only observed during a voluntary movement. During a passive movement [5], an observation of a movement by a third person [6], a kinesthetic illusion [7], a stimulation of the median nerve [8] or an imagination of movement [9]–[11], also referred as a MI, ERD and ERS patterns are also present. According to Jeannerod [12], MI represents the result of conscious access to the content of the intention of a movement, which is usually performed unconsciously during movement preparation [13]. MI is the ability to imagine performing a movement without executing it [14]. The claim that MI has particularity to access the motor programming processes without the actual movement execution based on the assumption that MI includes the covert stimulation of the movement. MI can be subdivided into two different modes, namely the visual-motor mode and the kinesthetic mode of imagery [15]. Indeed, the imagination of the realization of a movement generates an ERD in contralateral sensorimotor area, which is similar to the one observed during the preparation of a real movement. Although several studies showed an activity uniquely in the contralateral area [16], other studies do not support this hypothesis [17]. After the end of a MI, the activity in beta band recovers faster and the post-movement beta rebound appears.

Emergence of ERD and ERS patterns before, after and during a MI is extensively studied in the *Brain-Computer Interface* (BCI) domain [18] to define detectable commands for the system. Hence a better understanding of these processes can allow to design better interfaces between a brain and a computer system, and can also play an important role in the recovery of the motor capacity after neurological damage. For example MI training is a promising approach in facilitating paretic limb recovery [19]. Another example of disease is amyotrophic lateral sclerosis which involves a steady progressive degeneration of motor neurons leading to an inability of the brain to control movements. In the final stage of this disease, patients become totally paralyzed and are hence unable to communicate. BCIs can be designed to partially recover the lost motor functions. Today, most of the paradigms based on MIs require the subject to perform the movement several times within the predefined time interval. In this study, such a task is commonly referred to as a continuous motor imagery (CMI). However, when the subject realizes the same movement several times, the ERD and ERS patterns are modified. In fact, a simple short MI, referred to this article as a discrete motor imagery (DMI), can be more relevant to detect the ERD and the ERS. Thus, the goal of this study is to analyze and compare the ERD and ERS power of a continuous motor imagery with a discrete one.

In the next section, we present the experimental paradigm. We recorded EEG signals from 11 healthy volunteers who carried out discrete and continuous motor imageries of an isometric flexion movement of the index finger of the right hand. Next, in section III, we present the grand average and individual dynamics of ERDs and ERSs, and perform statistical tests on latency and amplitude of our three conditions: (i) real movement, (ii) imagination of a discrete movement and (iii) imagination of a continuous movement.

II. Material and Methods

Our first objective is to show the differences in terms of latency and amplitude of ERD and ERS between a real movement, a CMI, and a DMI. Our hypothesis is that a DMI could be more visible in EEG signals than the CMI usually used in BCI interaction.

A. Participants

11 right-handed healthy volunteer subjects took part in this experiment (4 men and 6 women, from 19 to 43 years old). They had no medical history which could have influenced the task such as diabetes, peripheral neuropathology, renal insufficiency, anti-depressant treatment or motor problem). This experiment follows the statements of the WMA declaration of Helsinki on ethical principles for medical research involving human subjects [20]. All subjects gave their agreement and signed the information consent before participing.

B. Experimental tasks

Three tasks were proposed to the subjects and all of them concerning an isometric flexion of the right hand index. In the first task, the subjects have performed a real movement. For the second task, they have imagined a single movement. For the third task, they have imagined several continuous movements. The subjects were comfortably resting lying on a thin individual mat with a pillow under their head. Their eyes were closed and their arms lying on sides. Their right index fingers were resting on a computer mouse (Fig. 1).

1) Real movement: The first task consisted of an isometric flexion of the right index finger on a computer mouse. A low frequency beep indicated when the subject has to execute the task. The left-click is recorded as a trigger and has allowed to know exactly when the participant executes the real movement.

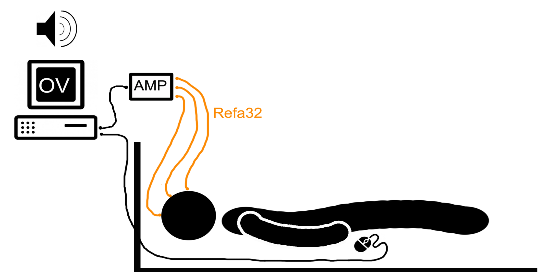

Fig. 1. Schematic representation of the experiment. A low frequency beep indicates the start of the (real or imagined) movement. A high frequency beep indicates the end of the continuous imagined movement. Depending on the experimental setup, the subject presses or imagines to press the button of the mouse. Nine electrodes collect electrical potentials. A Refa EEG acquisition system (AMP) amplifies the signals. The OpenViBE software (OV) records the digitalized potentials.

2) Discrete imagined movement: The second task was a DMI of the previous real movement. A low frequency beep indicated when the subject has to execute the task.

3) Continuous imagined movement: The third task was a CMI during four seconds of the real movement of the first task. More precisely, the subject imagined several (around four) flexions and extensions of the right index finger. This way, the DMI differed from the CMI by the repetition of the imagined movement. For this task, two beeps, respectively with low and high frequencies and separated by a four seconds delay, indicated the beginning and the end of the CMI.

C. Protocol

Each of the three tasks introduced in section II-B corresponds to a session. The subjects completed three sessions the same day. All sessions were split into several runs to avoid fatigue and allow movements. Breaks of a few minutes were planned between sessions and between runs. Before each session, the task was described, and the subject practiced the tasks. At the beginning of each run, the subject remained relaxed for 30 seconds. The data recorded in this period was used as a baseline to compute the percentage of ERD or ERS.

Session 1 corresponding to real movements was split into 4 runs of 25 trials. Sessions 2 and 3 corresponding to discrete and continuous imagined movements, respectively, were split into 4 runs of 25 trials. Thus, 100 trials were realized by subjects for each task.

For sessions 1 and 2, the timing scheme of a trial was the same: one low frequency beep indicating the start followed by a rest period of 12-13 seconds. For session 3, a low frequency beep indicating the start during 4 seconds, followed by a rest period of 10 seconds. The end of the MI is announced by a high frequency beep (Fig. 2).

D. Behavioral data

A custom-written scenario for OpenViBE [21] was designed to automate the generation of beeps, and to record triggers and EEG signals. The triggers corresponding to the left-click allowed us to detect potential behavioral errors. All non

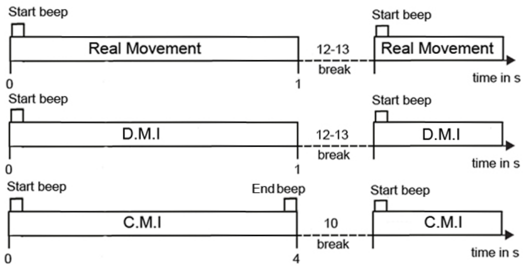

Fig. 2. Timing schemes of a trial for each task: Real Movement (top); Discrete Motor Imagery (middle); Continuous Motor Imagery (bottom).

realized movement were removed from the analysis. For all three tasks, we used a fixed preparatory period duration in which the subjects could anticipate the GO signal. To avoid this, we asked subjects to not anticipate the beep and informed them that their reaction time will not be studied. Nevertheless, all trials in which the reaction time was below to 200 ms were also removed. For each run, we eliminated the first trial because the first time the subjects hear the sound of the beep after the baseline they can be surprised.

E. Electrophysiological data

EEG signals were recorded through the OpenViBE platform with a commercial REFA amplifier developed by TMS International. The EEG cap was fitted with 9 electrodes re-referenced with respect to the common average reference across all channels over the extended international 10-20 system positions. The selected electrodes are FC3, C3, CP3, FCz, Fz, CPz, FC4, C4, CP4. Skin-electrode impedances were kept below 5 kΩ. A matlab code computed the ERD/ERS using the "band power method" [4]. First, the EEG signal is filtered between 18-25 Hz (beta band) for all subjects using a 4th-order Butterworth band-pass filter. Then, the signal is squared for each trial and averaged over trials. Then it is smoothed using a 250-millisecond sliding window with a 100 ms shifting step. We have chosen a specific sliding window because the nature of the real and imagined movement, as well as the components ERD/ERS that underline them, require a short window. Finally, the averaged power computed for each window was subtracted and then divided by the power of the baseline (20 seconds before each run). This transformation is multiplied by 100 to obtain percentages. This process can be summarized by the following equation:

$$ERD/ERS\% = \frac{\overline{x^2} - \overline{BL^2}}{\overline{BL^2}} \times 100 \qquad (1)$$

where $\overline{x^2}$ is the average of the squared signal, $\overline{BL^2}$ is the mean of a baseline segment taken at the beginning of the corresponding run, and ERD/ERS% is the percentage of the oscillatory power estimated for each step of the sliding window. It is done for all channels separately.

ERD and ERS are difficult to extract from the EEG signal. Indeed, the EEG signal expresses the combination of activity from a many neuronal sources. One of the most effective and accurate technique used to extract events is the average technique [22]. This is the technique that we decided to use to represent the modulation of power of the beta rhythm during all three sessions(see Fig. 3).

In addition, we computed the topographic maps of the ERD/ERS% modulations for all subjects (see Fig. 4) and for a specific subject (see Fig. 5).

III. Results

A. Behavioral results

As previously described, we remove from the analysis all the trials where the registered movements occur faster than 20ms, measured from the start sound signal. However, less than 5% of the total amount of trials were removed because the subjects anticipated the starting beep. For sessions 2 and 3, there is no mean to determine the quality of the imagery movement. To tackle this issue, the subjects had to globally evaluate this quality. If the subjective assessment of the session quality was poor the session was performed over again.

B. Electrophysiological results

Once the behavioral answers were treated, ERD and ERS in beta band were computed for each subject. Then, a grand average was done over the 11 subjects. In our analysis we study the following two features: (i) the relative beta power averaged over the time window (is this true) for the electrode C3 and (ii) the topographic map built from the 9 selected electrodes. We compute the beta power for the electrode C3, since it is suitable for monitoring the right hand motor activity. We used a Friedman's test to check that ERD and ERS were significantly and respectively different during the three conditions.

1) Real movement: Fig. 3 (top) illustrates appearance of a small ERD (around 10%) appearing before the end of the movement (i.e. the left-click). After the click, the power in the beta band increases around 80% during 700 ms. The evolution from ERD to ERS is fast (800 ms), and should be linked to the type of movement realized by the subjects. The ERD reaches its maximum one second after the starting beep and returns to the baseline 4 seconds after.

Subject 4 is a subject with an important beta rebound across all three sessions. The subject's topographic map (Fig. 5) shows that in the case of a real movement, the ERS appears in the second after the Start beep. The desynchronization is not visible on the figure. First, because as seen previously, the ERD has a small power, and because it is very short. Then, 2 seconds after the Start beep, the ERS reaches its maximum (80%) and decreases. Finally, the ERS is more important on the area of the electrode C3. The topographic map of the grand average (Fig. 4) shows similar results than for subject 4. It shows that the ERS reaches the maximum 2 seconds after the Start beep. However, the ERS is also there around other electrodes, such as the ipsilateral one.

2) Discrete motor imagery: During a DMI, the desynchronization occurs later (Fig. 3, in the middle). The ERD appears 300 ms after the Start beep. The power is greater than 15%. The synchronization starts 900 ms after the Start beep and

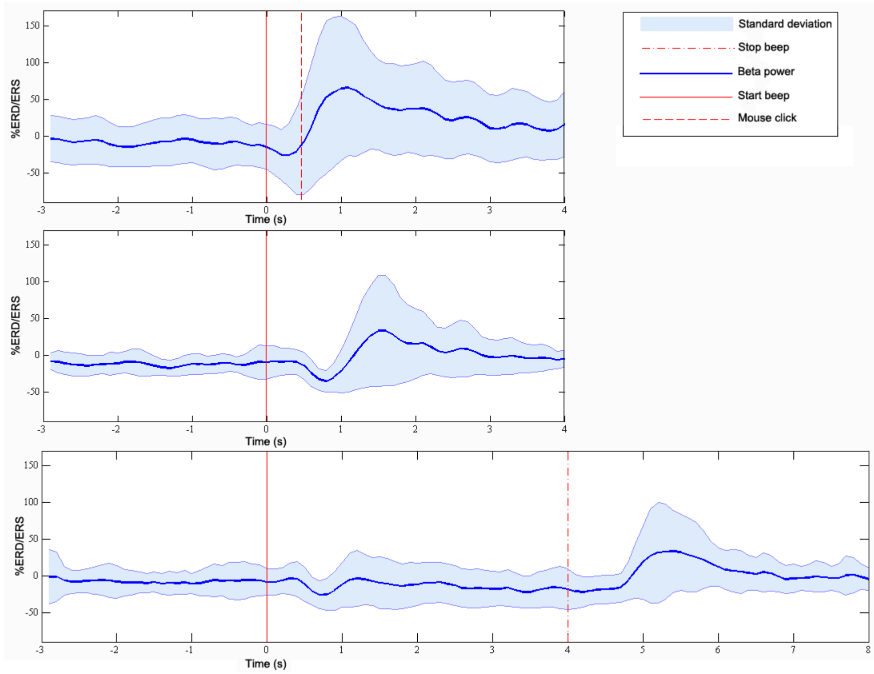

Fig. 3. Grand average (n = 11) ERD/ERS% curves estimated for the real movement (top), the discrete motor imagery (middle) and the continuous motor imagery (bottom) within the beta band for electrode C_3.

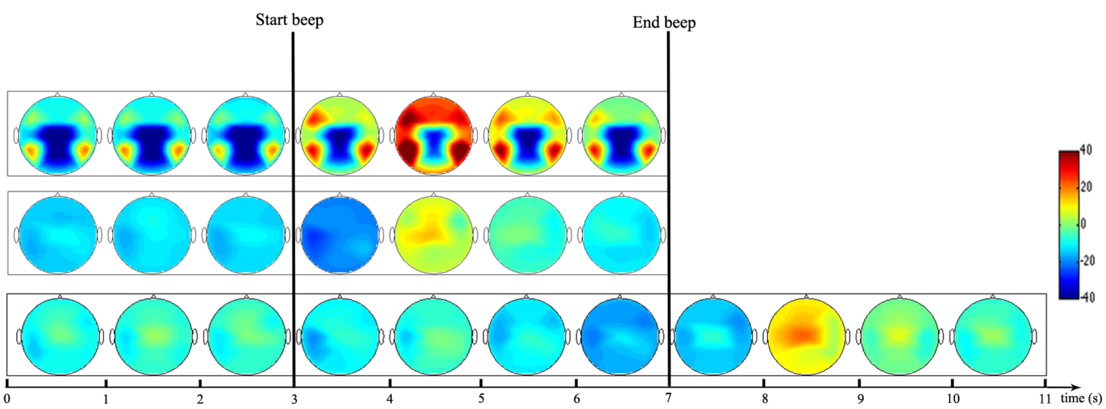

Fig. 4. Topographic map of ERD/ERS% (grand average, n=11) in the beta band during real movement, (top) DMI (middle) and CMI (bottom). Red corresponds to a strong ERS (+40%) and blue to a strong ERD (-40%).

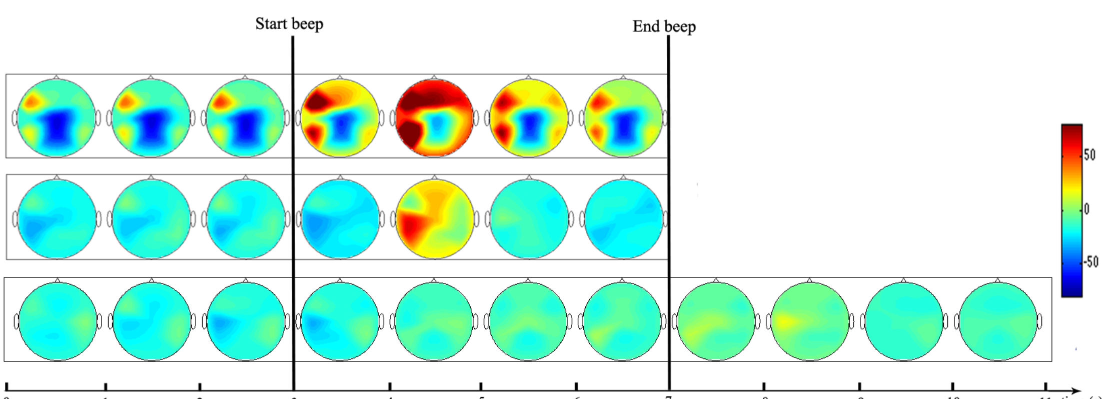

Fig. 5. Topographic map of ERD/ERS% of subject 4 in the beta band during real movement, (top) DMI (middle) and CMI (bottom). Red corresponds to a very strong ERS (+70%) and blue to a very strong ERD (-70%).

the beta rebound is reached 700 ms later. The ERS post-MI reaches 40%, which represents an increase of 65% compared to the desynchronization.

The topographic map of subject 4 (Fig. 5) shows a desynchronization around 20% over the C3 area. One second later, the beta rebound appears, and is more present around the C3 area. The beta rebound is shorter since 2 seconds after the Start beep, the brain oscillations return to the baseline level for all electrodes. The grand average (Fig. 4) shows substantially the same thing. Indeed, the ERD appears one second after the Start beep, then the beta rebound appears one second later. Nevertheless, the rebound is more spread around the central electrodes.

3) Continuous motor imagery: During the CMI, the subjects realized several movements in a time window of 4 seconds. The results of the grand average (Fig. 4) shows a global desynchronization during this time window. However, this ERD can be considered as the concatenation of several ERDs. Indeed, the first ERD (23%) is reached during the first second after the MI. Then the power increases and decreases again, being modulated during 3 seconds. Finally, the ERD lasts during the entire duration of the CMI i.e. 4 seconds. 800 ms after the Stop beep, there is an ERS until the appearance of the beta rebound (36%), around 1300 ms after the end of the CMI.

The topographic map shows that during the first second after the Start beep, an ERD is lightly visible, but then it is difficult to identify a synchronization or a desynchronization. This is particularly true for subject 4 (Fig. 5). It is hard to perceive a continuous desynchronization. Looking at the grand average (Fig. 4), the ERD is stronger but not continuous. In both cases, it is important to notice that the ERD is still there one second after the Stop beep. Then, one second later, the beta rebound appears, still with a stronger presence around the C3 area.

4) Comparison between real movement, discrete motor imagery and continuous motor imagery: If we compare the RM, the DMI and the CMI, we observe that the ERS is stronger for a real movement. Indeed, the beta rebound is 20% larger for a RM than for a MI. Although the ERS is stronger during a DMI than a CMI for some subjects. This result is not statistically significant according to the Friedman test. The ERD of a real movement is not strong compared to the one of a MI. For both DMI or CMI, the ERD is stronger and lasts longer. If we compare the ERD of a DMI and a CMI, the results show that the power of the ERD is greater for a DMI, even if it lasts less. However, this is predictable because during the CMI, the MI lasts during 4 seconds. Finally, the ERD of the DMI is stronger and less variable than the ERD of a CMI.

IV. Discussion

The subjects carried out voluntary movements, DMI and CMI of an isometric flexion of the right hand index finger. Results show that the power of the beta rhythm is modulated during the three tasks. More particularly, the ERD produced by a DMI should be more easily detectable by a brain-computer interface system than the ERD produced during a CMI. However, the comparison between ERSs is not significant, although some subjects have a stronger ERS during a DMI than a CMI.

A. Common average reference

There are several alternatives in the choice of the reference but none is completed. For our study, we used the average voltage of all electrodes. It's well known that a large number of electrodes allows to have a good estimation of the global average potential of the whole head [23]. Although we have no many electrodes, first our results are similar by using the method of the derivation and second the observations correspond to the litterature. The choice of studying C3 without derivation is justified by the fact that we are interested to design a minimal system to detect ERD and ERS.

B. ERD/ERS modulation during real movements

The results are coherent with previous studies describing ERD/ERS% modulations during motor actions. First, we have a quick ERD in C3, starting before the beginning of the movement. Indeed, in most cases, the beta power is modulated one to two seconds before the movement [24]. The weakness of the ERD can be explained because the instruction was to be focused more on the precision than the speed of the movement [25]. However, although some subjects were making efforts to do a voluntary movement, we must consider that an isometric flexion movement on a mouse is a movement setting in the subject's memory. This can have an impact on the low ERD amplitude. We also showed that the beta rebound starts before the click. Since a mouse click, is a really fast movement, we expect that the beta rebound will appear fast as well [26]. However, some studies showed that performing faster movements would not influence the post-movement rebound period.

C. ERS modulation during motor imageries

The results show that the beta rebound is lower after a DMI or a CMI than after a real movement, what has been already been demonstrated previously [27]. Although the beta rebound is stronger after a CMI than DMI for a few subjects. None plausible hypothesis confirm these first results.

D. ERD modulation during discrete motor imageries

When the subjects realized the CMI, the ERD was highly variable during the first 4 seconds. For some subjects, there are some intern-ERD and intern-ERS into this period. Normally, for continuous real movement, the ERD was sustained during the execution of this movement [28]. But, in our data it is possible to detect 3 or 4 ERD during the 4 seconds of CMI where the subject realized 3 or 4 motor imageries. This assumes that the ERD and ERS components overlap in time when we realize a CMI. Several studies already illustrate the concept of overlap of various functional processes constituting the beta components during real movements [29], [30]. Moreover, the beta rebound generated by a median nerve stimulation is reduced when the stimulation is made during different types of real or imagined hand movements [8], [27],

[31]. However, even if the components cancel each other out in the signal, it does not mean that the operation of the underlying processes are similarly affected. This interpretation assumes implicitly that the components are combining each other, which means that the temporal superposition of an ERD and an ERS would result in an intermediate amplitude signal. This could explain why the ERD during a CMI is less detectable and more variable than the ERD during a DMI. To validate this hypothesis, we are planning to realize a new study, to see how two fast-successive movements (or MIs) can affect the signal in the beta frequency band.

V. Conclusion

This article studied the modulation of beta power in EEG during a real movement, a DMI and a CMI. We showed that during a real voluntary movement (e.g. isometric flexion of the right hand index finger) a low ERD appears before the end of the movement, and is followed by a rapid and powerful ERS. Subsequently, we showed that the ERD and ERS components are modulated by both a DMI and a CMI. The ERS is very similar in both cases but the ERD generated by a DMI is easier detectable. The ERD observed during a CMI seems to correspond to a succession of aborted ERDs and ERSs induced by several imagined movements. Thus, in future work, we suggest to ask the subject to perform a DMI. The ERD should be detected easier and faster by a BCI system.

References

[1] H. Berger, "Über das elektrenkephalogramm des menschen." *European Archives of Psychiatry and Clinical Neuroscience*, vol. 87, pp. 527–570, 1929.

[2] R. Salmelin and R. Hari, "Spatiotemporal characteristics of sensorimotor neuromagnetic rhythms related to thumb movement," *Neuroscience*, vol. 60, no. 2, pp. 537–50, May 1994.

[3] H. Jasper and W. Penfield, "Electrocorticograms in man: effect of voluntary movement upon the electrical activity of the precentral gyrus." *Arch. Psychiatry Zeitschr. Neurol.*, vol. 83, pp. 163–174, 1949.

[4] G. Pfurtscheller and F. H. Lopes da Silva, "Event-related eeg/meg synchronization and desynchronization: basic principles," *Clin Neurophysiol*, vol. 110, no. 11, pp. 1842–57, Nov 1999.

[5] G. R. Müller, C. Neuper, R. Rupp, C. Keinrath, H. J. Gerner, and G. Pfurtscheller, "Event-related beta eeg changes during wrist movements induced by functional electrical stimulation of forearm muscles in man," *Neurosci Lett*, vol. 340, no. 2, pp. 143–7, Apr 2003.

[6] P. Avanzini, M. Fabbri-Destro, R. Dalla Volta, E. Daprati, G. Rizzolatti, and G. Cantalupo, "The dynamics of sensorimotor cortical oscillations during the observation of hand movements: an eeg study," *PLoS One*, vol. 7, no. 5, p. e37534, 2012.

[7] C. Keinrath, S. Wriessnegger, G. R. Muller-Putz, and G. Pfurtscheller, "Post-movement beta synchronization after kinesthetic illusion, active and passive movements." *Int J Psychophysiol*, vol. 62, no. 2, pp. 321–327, Nov 2006.

[8] S. Salenius, A. Schnitzler, R. Salmelin, V. Jousmäki, and R. Hari, "Modulation of human cortical rolandic rhythms during natural sensorimotor tasks," *NeuroImage*, vol. 5, no. 3, pp. 221 – 228, 1997. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1053811997902615

[9] C. Neuper and G. Pfurtscheller, *Handbook of electroencephalography and clinical neurophysiology. Event-related desynchronization*. Elsevier, 1999, ch. Motor imagery and ERD, pp. 303–325.

[10] G. Pfurtscheller and T. Solis-Escalante, "Could the beta rebound in the eeg be suitable to realize a "brain switch"?" *Clin Neurophysiol*, vol. 120, no. 1, pp. 24–9, Jan 2009.

[11] K. Nakagawa, Y. Aokage, T. Fukuri, Y. Kawahara, A. Hashizume, K. Kurisu, and L. Yuge, "Neuromagnetic beta oscillation changes during motor imagery and motor execution of skilled movements," *Neuroreport*, vol. 22, no. 5, pp. 217–22, Mar 2011.

[12] M. Jeannerod, "Mental imagery in the motor context," *Neuropsychologia*, vol. 33, no. 11, pp. 1419–32, Nov 1995.

[13] M. Lotze and U. Halsband, "Motor imagery," *J Physiol Paris*, vol. 99, no. 4-6, pp. 386–95, Jun 2006.

[14] L. Avanzino, A. Giannini, A. Tacchino, E. Pelosin, P. Ruggeri, and M. Bove, "Motor imagery influences the execution of repetitive finger opposition movements," *Neuroscience Letters*, vol. 466, no. 1, pp. 11 – 15, 2009. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S030439400901252X

[15] C. Neuper, R. Scherer, M. Reiner, and G. Pfurtscheller, "Imagery of motor actions: Differential effects of kinesthetic and visual–motor mode of imagery in single-trial {EEG}," *Cognitive Brain Research*, vol. 25, no. 3, pp. 668 – 677, 2005. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0926641005002533

[16] G. Pfurtscheller and C. Neuper, "Motor imagery and direct brain-computer communication," *Proceedings of the IEEE*, vol. 89, no. 7, pp. 1123 –1134, Jul. 2001.

[17] S. Fok, R. Schwartz, M. Wronkiewicz, C. Holmes, J. Zhang, T. Somers, D. Bundy, and E. Leuthardt, "An eeg-based brain computer interface for rehabilitation and restoration of hand control following stroke using ipsilateral cortical physiology." *Conf Proc IEEE Eng Med Biol Soc*, vol. 2011, pp. 6277–6280, 2011.

[18] E. W. W. Jonathan Wolpaw, Ed., *Brain-Computer Interfaces: Principles and Practice*. Oxford university press, 2012.

[19] A. J. Butler and S. J. Page, "Mental practice with motor imagery: evidence for motor recovery and cortical reorganization after stroke." *Arch Phys Med Rehabil.*, vol. 87, pp. S2–11, dec. 2006.

[20] A. World Medical, "World medical association declaration of helsinki: ethical principles for medical research involving human subjects." *J Postgrad Med*, vol. 48, no. 3, pp. 206–208, Jul-Sep 2002, kIE: KIE Bib: human experimentation.

[21] Y. Renard, F. Lotte, G. Gibert, M. Congedo, E. Maby, V. Delannoy, O. Bertrand, and A. Lécuyer, "Openvibe: An open-source software platform to design, test and use brain-computer interfaces in real and virtual environments," *Presence : teleoperators and virtual environments*, vol. 10, no. 1, 2010.

[22] R. Quiroga and H. Garcia, "Single-trial event-related potentials with wavelet denoising," *Clinical Neurophysiology*, vol. 114, no. 2, pp. 376–390, 2003.

[23] J.Dien, "Issues in the application of the average reference: review, critiques, and recommendations," *Behavior Research Methods*, vol. 30, p. 34, 1998.

[24] M. van Elk, H. T. van Schie, R. van den Heuvel, and H. Bekkering, "Semantics in the motor system: motor-cortical beta oscillations reflect semantic knowledge of end-postures for object use," *Front Hum Neurosci*, vol. 4, p. 8, 2010.

[25] B. Pastötter, F. Berchtold, and K.-H. T. Bäuml, "Oscillatory correlates of controlled speed-accuracy tradeoff in a response-conflict task," *Hum Brain Mapp*, vol. 33, no. 8, pp. 1834–49, Aug 2012.

[26] L. M. Parkes, M. C. M. Bastiaansen, and D. G. Norris, "Combining eeg and fmri to investigate the post-movement beta rebound," *Neuroimage*, vol. 29, no. 3, pp. 685–96, Feb 2006.

[27] A. Schnitzler, S. Salenius, R. Salmelin, V. Jousmaki, and R. Hari, "Involvement of primary motor cortex in motor imagery: a neuromagnetic study." *Neuroimage*, vol. 6, no. 3, pp. 201–208, Oct 1997.

[28] N. Erbil and P. Ungan, "Changes in the alpha and beta amplitudes of the central eeg during the onset, continuation, and offset of long-duration repetitive hand movements." *Brain Res*, vol. 1169, pp. 44–56, Sep 2007.

[29] B. E. Kilavik, M. Zaepffel, A. Brovelli, W. A. MacKay, and A. Riehle, "The ups and downs of beta oscillations in sensorimotor cortex." *Exp Neurol*, vol. 245, pp. 15–26, Jul 2013.

[30] M. U. Trenner, H. R. Heekeren, M. Bauer, K. Rossner, R. Wenzel, A. Villringer, and M. Fahle, "What happens in between? human oscillatory brain activity related to crossmodal spatial cueing." *PLoS One*, vol. 3, no. 1, p. e1467, 2008.

[31] G. Pfurtscheller, M. Woertz, G. Muller, S. Wriessnegger, and K. Pfurtscheller, "Contrasting behavior of beta event-related synchronization and somatosensory evoked potential after median nerve stimulation during finger manipulation in man." *Neurosci Lett*, vol. 323, no. 2, pp. 113–116, Apr 2002.