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Alpha rebound improves on-line detection of the end of motor imageries

Cecilia Lindig-León^{1,2}, Laurent Bougrain^{2,1} and Sébastien Rimbart²

Abstract—Limb movement execution or imagination induce sensorimotor rhythms that can be detected in electroencephalographic (EEG) recordings. This article presents the interest of considering not only the beta frequency band but also the alpha band to detect the elicited EEG rebound, i.e. the increasing of synchronization, at the end of motor imageries. From database 2a of the BCI competition IV, it is shown that such phenomenon can be stronger over the alpha than the beta band and it is experimentally demonstrated that the analysis of the alpha band improves the detection of the end of motor imageries. This capacity is useful for self-paced brain-computer interfaces.

I. INTRODUCTION

Brain activity recorded over the primary sensorimotor cortex presents an oscillatory behavior that is of particular interest within two specific frequency bands [1], [2], [3], [4], the alpha (8-13 Hz) and beta (13-25 Hz) bands, as they have been shown to be modulated during and following the preparation and the execution of voluntary movement, passive movement, imagined movement, and even tactile stimulation [5]. This modulation takes two different forms: a reduction in oscillatory power within alpha and beta bands known as event-related desynchronization (ERD) originated over contralateral sensorimotor areas and beginning approximately 2 seconds prior to movement initiation; and an event-related synchronization (ERS) that follows the movement termination and that persists for hundred milliseconds [6]. Although this later modulation is known to be specific of the beta band and is denoted as post-movement beta rebound [7], [8]; in the present study, evidences of the presence of this modulation within the alpha band are exposed again [5]; and, the interest to use the alpha band to detect the end of an imagined movement is reported.

II. MATERIAL

To illustrate this purpose, the database used corresponds to the BCI competition IV, dataset 2a [9] for Continuous Multi-class Motor Imagery provided by C. Brunner, R. Leeb, G. R. Müller-Putz, G. Pfurtscheller, and A. Schlögl and freely available at <http://www.bbcii.de/competition/iv/>. This database contains EEG recordings of nine healthy subjects performing four motor imageries during 2 sessions: left hand, right hand, feet and tongue. For the purposes of this study which are not focused on motor imagery classification but on detection of motor imagery stopping, only 2 classes (left hand and right hand)

were considered. Each session contains 6 runs comprising 12 trials per class, which yields a total of 144 trials per task. Signals are recorded with a sampling rate of 250 Hz over 22 electrodes: Fz, FC3, FC1, FCz, FC2, FC4, C5, C3, C1, Cz, C2, C4, C6, CP3, CP1, CPz, CP2, CP4, P1, Pz, P2 and POz. Fig. 1 shows the timing scheme of the paradigm for each trial, which has an approximate duration of 8 seconds. During the first 2 seconds previous to the cue that indicates the motor imagery to be performed the subject is in a rest state, which allows to observe a period of approximately 4 seconds after the interruption of the motor imagery before that the subsequent trial is starting.

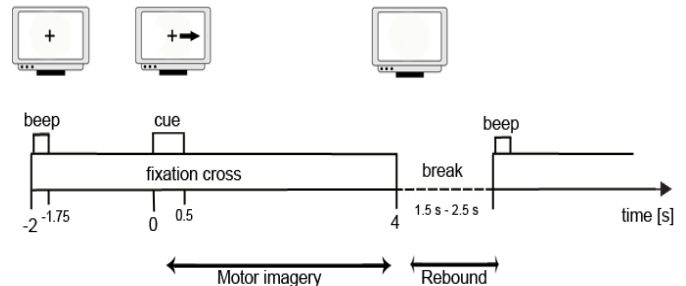


Fig. 1. Timing Scheme of the paradigm. The motor imagery is performed from 0 (cue) to 4s (end of the fixation cross). The duration of the break between trials is variable from 1.5 to 2.5s.

For each session, before runs including motor imageries, the user had to keep eyes open, eyes closed and eye movements for several minutes. These runs have been designed to record eye artefacts and can be used as a baseline.

III. METHOD

The purpose of this study is twofold: first, it prompts that at the end of motor executions or motor imageries an increased synchronization in the alpha frequency band is elicited. The characteristics of this rebound (latency and amplitude) are drawn out and described from the EEG signals comprised in the database 2a of the BCI competition IV. Second, it shows that it is advantageous to take into account a larger frequency range including not only the beta but also the alpha band to improve the online detection of the end of an imagined movement. In this section two preprocessing stages are presented, the first one removes the labeled trials in the used database that were examined by an expert and were found to contain artifacts, so that the neurophysiological phenomenon can be studied as clear as possible without considering unrelated variations (i.e. head muscles activity, electrodes movement, etc.). Then, the preprocessing used to

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detect the end of imagined movements is presented. In this second part, all trials even with artifacts were kept in order to recreate the online measuring conditions to propose a suitable method based on a single trial detection.

A. Quantifying the alpha rebound

A visual inspection over all subjects registers was carried out by an expert who marked trials containing artifacts (see [10], [11] for details). These trials were removed in the present study with the aim to better identify the synchronization in the alpha and beta bands. The remaining N trials were extracted from the database starting 2 seconds before of the corresponding cue and stopping 8 seconds after, thus, each one of them corresponds to a 10s-window over 22 channels (see Fig. 5a). This window size allows to observe the activity up to 4 seconds after the motor imagery was interrupted. The last trial of each run has been also removed due to the fact that the window size used to compute the activity overpasses the length of the run. The next step consists of the filtering of each trial using a 5th-order band-pass Butterworth filter. From this step forward, the described analysis is carried out separately for the alpha and beta bands, which were considered in the ranges [8-13 Hz] and [13-25 Hz] respectively (see Fig. 5b). To quantify the synchronization after the interruption of the imagined movement, the power of each trial was computed by squaring the amplitude of the samples (see Fig. 5c) and then by averaging the power samples across all trials (see Fig. 5d). Finally, the resulting signal was smoothed to reduce variability using a 1s-sliding window with a 100 ms shifting step to compute the mean across samples (see Fig. 5e). This last step differs from [6]. Usually, the mean of the trials' power is normalized using the mean of the power of a baseline window as it is stated in the classic formula $[\text{mean}(\text{power}_{\text{StudiedWindow}}) - \text{mean}(\text{power}_{\text{Baseline}})] / \text{mean}(\text{power}_{\text{Baseline}})$ that leads to ERD/ERS percentages containing information about the evolution of the signal dynamics [6]. Nevertheless, It is known that visual stimuli can reduce the amplitude of the ongoing EEG especially within the alpha band in the visual cortex, thus showing that the model of assuming the baseline as uncorrelated noise does not hold in general. In addition, this study proposes to compare the modulation of the power in the alpha, the beta and both bands specifically after a movement. But, according to Fig. 2, we can see that the power in the alpha band during a 20s-baseline window taken from the run with eyes open is greater than the power of the beta band. So the ERS% will be bigger for beta than alpha. Fig. 3 illustrates this effect: the alpha rebound is bigger than the beta one before the normalization but not after. Thus, here, the ERS is not in terms of percentage with respect to the baseline, but just as a measure of the power of the EEG signals.

B. On-line detection the end of a movement

At this point, it can be observed that both, alpha and beta rebounds, are elicited just at the interruption of the imagined movement (second 4, see Fig. 5e) and that it has

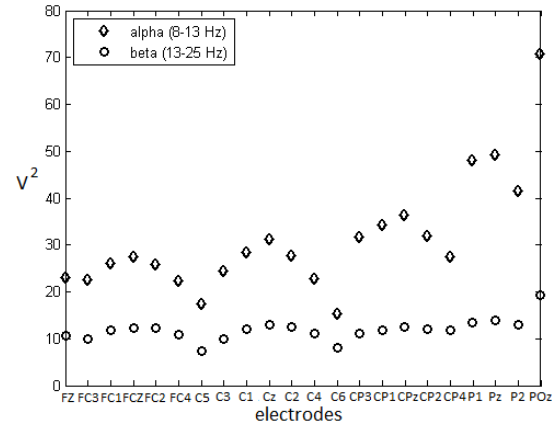


Fig. 2. Average of the power observed in a 20s-window during the baseline for each electrode (for subject 1, session 1).

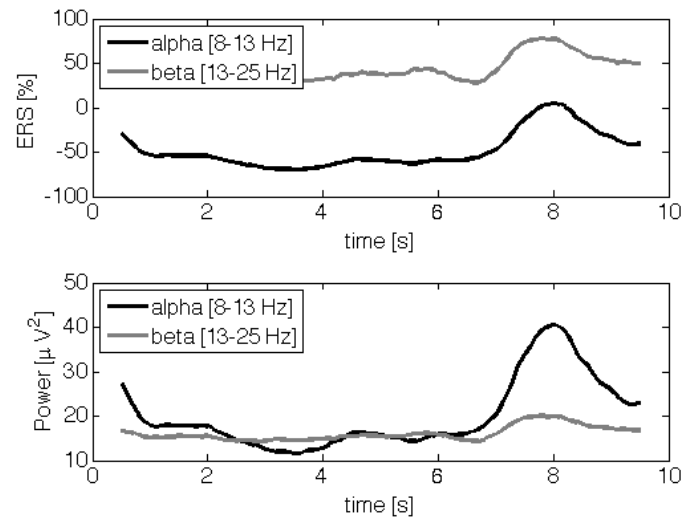


Fig. 3. Effect of a normalization using the mean of the power during a baseline (for subject 3). Because the power in alpha is bigger during a baseline (see 2, computing the ERD/ERS% reduce more the amplitude of the alpha rebound and shift it below. Using the original value of the power keeps the alpha rebound bigger than the beta one.

a latency of 3 seconds approximately. Thus, for the online detection, it has been decided to analyze trials using a 3-seconds sliding window with a 1s-shifting step and to extract from session 1 examples of two classes to bring up a method capable of distinguishing between these two conditions (i.e., segments with rebound and segments without it). Under this scheme, each trial contributes with 7 segments ([-1.5, 1.5 s]; [-0.5, 2.5 s]; [0.5, 3.5 s]; [1.5, 4.5 s]; [2.5, 5.5 s]; [3.5, 6.5 s]), from which the first five are considered as non-target segments and the latest two as target segments. By taking these two classes into account two linear discriminant analysis classifiers (one for left hand and another for right hand) have been trained and tested for each subjects using a 10by10 cross-validation with the first session trials. The second session trials were kept as unseen data in order to evaluate the system performance.

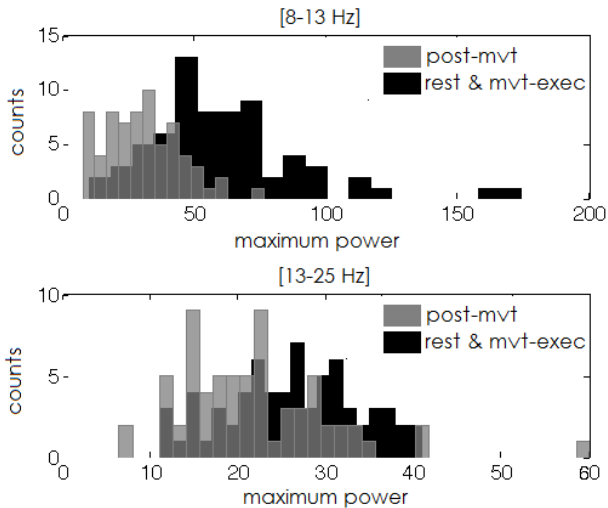


Fig. 4. Histograms of the power observed during a post-movement (dark grey) versus the power of a resting period or a movement execution (light grey), in the alpha band (up) and the beta band (down). Overlapping are reported in a medium grey.

IV. RESULTS

With the aim of quantifying the alpha rebound and comparing it to the beta rebound, we first computed the power during a 20s-window of a baseline period, 1 mn after the beginning of the 2mn-run with eyes open of session 1 and session 2. The power is stable for each electrode between sessions in alpha and beta bands [12]. Moreover, the power of the beta band is almost the same for all electrodes and for all subjects; in contrast, the power for the alpha band is increasing with the distance to the occipital lobe which is known as the region of the processing of visual inputs (see Fig. 2). The power in the alpha band is bigger than in the beta band.

TABLE I

ACCURACIES FOR EACH SUBJECT USING THE UNSEEN SESSION 2.

Subject	Left Hand			Right Hand		
	[8-13]Hz	[13-25]Hz	[8-25]Hz	[8-13]Hz	[13-25]Hz	[8-25]Hz
1	74.46	73.81	78.36	80.12	74.33	80.54
2	72.77	56.25	56.47	73.91	57.56	65.84
3	89.39	81.39	89.61	87.82	81.09	88.87
4	69.01	72.64	72.64	72.71	72.28	78.04
5	73.54	60.89	68.62	71.65	70.78	74.46
6	77.66	70.13	79.22	82.21	76.69	81.20
7	88.62	86.38	90.63	83.98	88.53	85.93
8	79.69	72.54	81.70	83.55	71.00	81.17
9	84.34	81.59	82.42	77.42	73.73	79.95
AVG	78.83	72.85	77.74	79.26	74.00	79.56

Table I shows the accuracy, on the unseen data from session 2, to distinguish a post-movement rebound from a resting period and a movement execution. We report the accuracy for motor imageries of the left and the right hands only. Each LDA has been trained over the data of session 1 filtered on a specific frequency band: alpha alone, beta alone or both bands. For both motor imageries, the accuracies for the beta band are smaller than the accuracies of the alpha band and both bands for almost all subjects. Note the

big difference for subject 2, which shows that the proposed method behaves more stable across different datasets. These results are coherent with the observations made from the amplitude of the (alpha, beta and alpha+beta) rebounds (see Fig. 4 and Fig. 5e).

V. CONCLUSIONS

This paper shows the advantage of analyzing the alpha band in order to detect the post-movement rebound. After computing the power of the EEG signals both, in alpha and beta bands, an improvement of the rebound detection is observed over the alpha band across all subjects that increases the accuracy around 5%. These results show that the proposed online method is feasible for detecting the end of motor imageries; furthermore, it proposes a scheme which does not require to take a baseline for the alpha and beta activities into account to compute the rebound, which is particularly interesting if the period used for the baseline is far away from the online detection.

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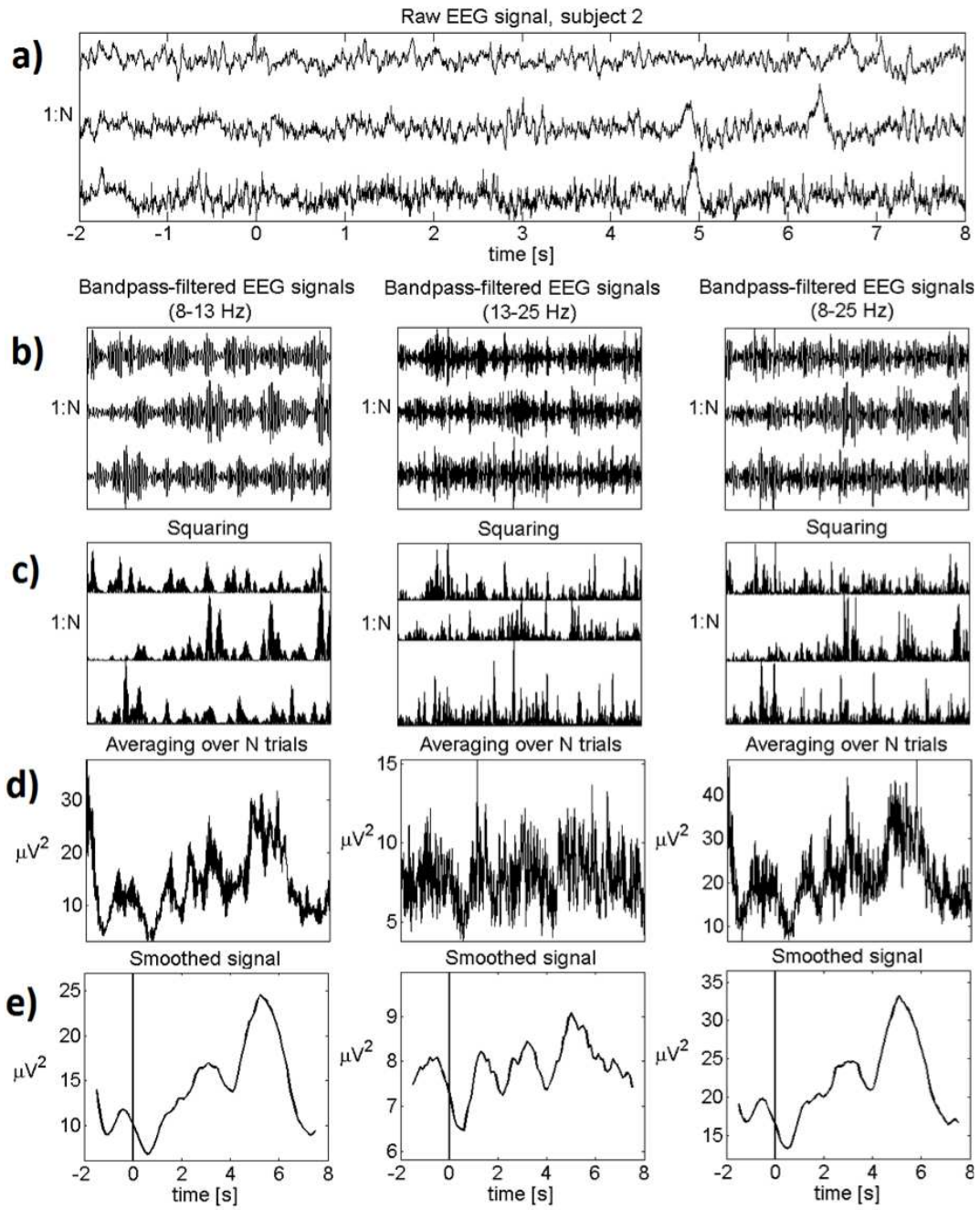


Fig. 5. Processing chain to observe the synchronization of the (alpha, beta and alpha+beta) rebounds after the end of the motor imagery.