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Short-lived brain state after cued motor imagery in naive subjects

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Abstract

Multi-channel electroencephalography recordings have shown that a visual cue, indicating right hand, left hand or foot motor imagery, can induce a short-lived brain state in the order of about 500 ms. In the present study, 10 able-bodied subjects without any motor imagery experience (naive subjects) were asked to imagine the indicated limb movement for some seconds. Common spatial filtering and linear single-trial classification was applied to discriminate between two conditions (two brain states: right hand vs. left hand, left hand vs. foot and right hand vs. foot). The corresponding classification accuracies (mean ± SD) were 80.0 ± 10.6%, 83.3 ± 10.2% and 83.6 ± 8.8%, respectively. Inspection of central mu and beta rhythms revealed a short-lasting somatotopically specific event-related desynchronization (ERD) in the upper mu and/or beta bands starting ~300 ms after the cue onset and lasting for less than 1 s.

Introduction

There is strong evidence from functional magnetic resonance imaging studies that motor execution and mental imagery of the same action (motor imagery, MI) activates overlapping and/or similar neural networks in primary motor and related areas (Gerardin *et al.*, 2000; Ehrsson *et al.*, 2002). Concerning self-paced (at free will) motor execution, one has to differentiate between the preparatory and the execution phases. During unilateral hand movement, the preparatory phase is associated with a contralateral mu and central beta event-related desynchronization (ERD) that appears 1–2 s prior to movement onset and becomes bilaterally symmetrical in the execution phase (Stancak and Pfurtscheller, 1996a,b; Derambure *et al.*, 1999). In the case of the imagination of such a unilateral hand movement, however, the contralateral ERD is preponderant during the whole imagery process (Pfurtscheller & Neuper, 1997; Pfurtscheller *et al.*, 2006c), similar to what is observed during the preparation of a self-paced hand movement. These observations indicate that similar neural structures in primary sensorimotor areas become activated in the course of preparation of a motor action and during the mental simulation of the same action without its execution (Jeannerod & Decety, 1995). In the case of foot MI, very often a midcentrally localized ERD simultaneous with a bilateral event-related synchronization (ERS) can be observed (Pfurtscheller *et al.*, 2006c). Summarizing, it can be stated that mu and/or beta components display a somatotopically organized activation (ERD) pattern, and both the pre-movement ERD and the imagination-related ERD appear to reflect a similar type of short-lived brain state in premotor and motor areas that represents the preparation for a movement, regardless of whether it will be performed or just imagined (Neuper & Pfurtscheller, 1999).

Sensorimotor rhythms such as mu and central beta can be modified not only by executed, imagined or observed movement (Jasper & Penfield, 1949; Salmelin & Hari, 1994; Leocani *et al.*, 1997; Pfurtscheller & Neuper, 1997; Derambure *et al.*, 1999; Neuper & Pfurtscheller, 1999; Alegre *et al.*, 2002; Muthukumaraswamy & Johnson, 2004; Pineda, 2005), but also after presentation of a semantic stimulus, as shown by Müller-Gerking *et al.* (2000). The latter authors reported for the first time a short-lasting ERD of sensorimotor rhythms during the presentation of a visual cue indicating an upcoming limb movement (right or left finger or foot) that was followed (2 s later) by an acoustic stimulus to which the subject should react with the proper movement. Applying pairwise discrimination functions to the electroencephalography (EEG) signals, they were able to discriminate between the three types of movement during a short-lasting period within the first second after visual cue presentation. The best results were obtained with a running classification window of 250 ms. This discrimination was interpreted as indicating that there are distinct short-lasting EEG patterns (short-lived brain states) associated with the three types of movement that were performed afterwards.

In this study, we addressed for the first time the question of whether short-lasting ERD patterns, characteristic of short-lived brain states, are induced in able-bodied subjects without any experience in mental simulation of a motor task (MI) when a cue signifying one of three imagery tasks (right hand, left hand and foot MI) is presented. We investigated further whether the type of MI has an impact on the discrimination between two brain states. Similar to the study of

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Müller-Gerking *et al.* (2000), we used the common-spatial patterns (CSPs) algorithm (Fukunaga, 1990) together with a running classifier to distinguish between two brain states at a time (two-class discrimination problem).

Materials and methods

Subjects and experimental task

Ten right-handed healthy subjects with a mean age of 28.1 ± 10.3 years (median age 24.5) participated in this study. The study was approved by the local ethics committee of the Medical University of Graz, and all subjects provided their written consent to participate in the experiment. Each subject sat in a comfortable armchair in an electrically shielded cabin viewing a 17-inch monitor from a distance of about 1.2 m. Each trial began with the presentation of a fixation cross at the centre of the monitor, followed by a short warning tone at second 2. At second 3, an arrow pointing left, right or down, representing one of three different MI tasks (left hand, right hand and both feet, respectively), appeared on the screen for 1.25 s. After that, the fixation cross was presented again until the end of the trial at second 8 (Fig. 1B). A blank screen followed until the beginning of the next trial. This inter-trial period varied randomly between 0.5 and 2.5 s. Subjects were required to execute the indicated MI task up to

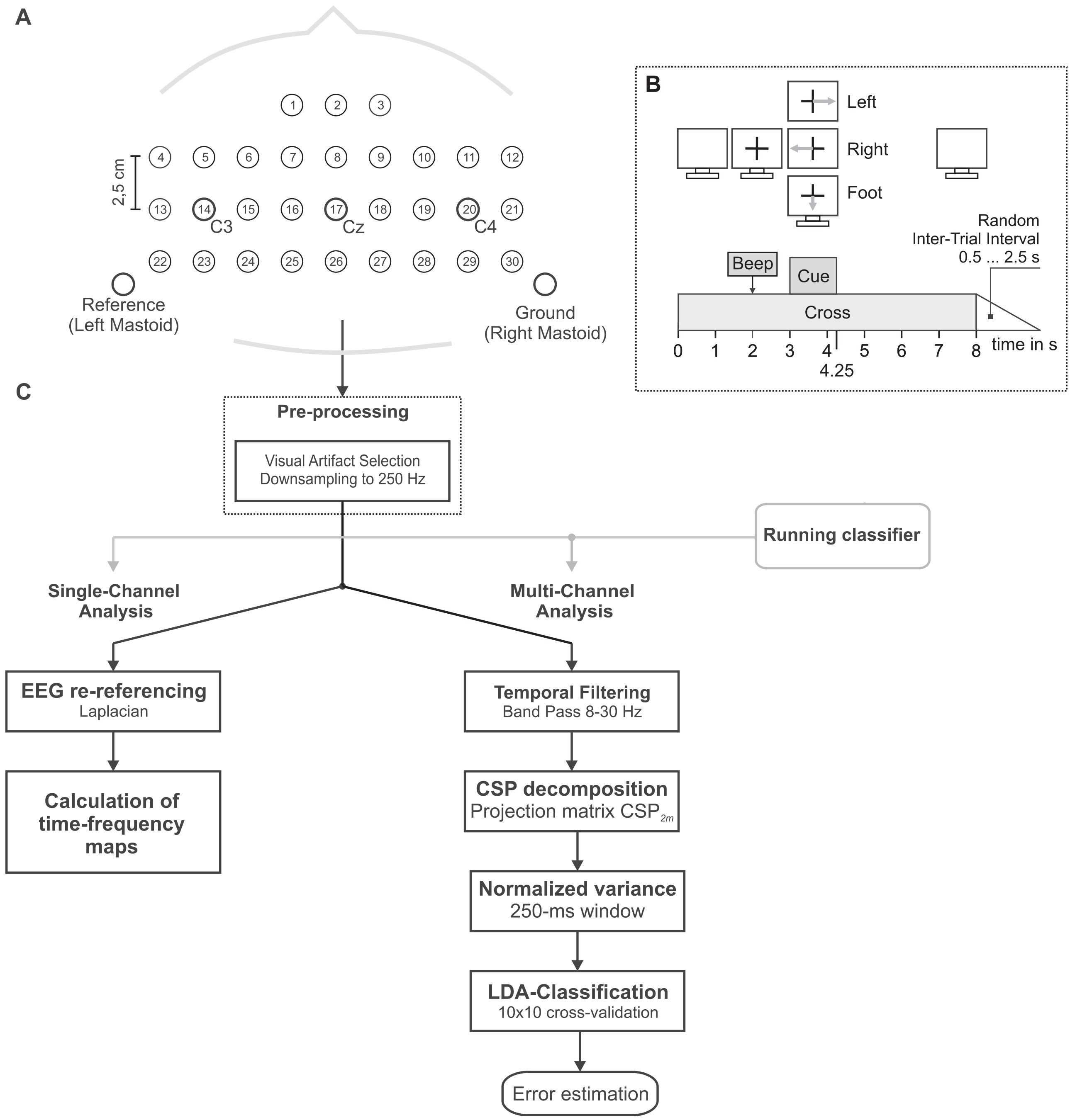

FIG. 1. Electrode positions (A), timing and cue-based experimental paradigm (B), and flow diagram of the data analysis (C). CSP, common-spatial pattern; LDA, linear discriminant analysis.

second 8. They were told to perform kinaesthetic MI and avoid movement and blinking during the imagery task. The experiment was divided into eight runs, each consisting of 10 trials of each MI task. Within each run, the tasks were performed in a random order to avoid adaptation.

EEG and electromyography recording

Continuous EEG signals were recorded from a grid of 32 Ag/AgCl scalp electrodes (Easycap, Germany) referenced to the left mastoid with the ground on the right mastoid. The closely spaced electrodes at distances of approximately 2.5 cm were placed in a configuration including the electrode positions C3, C4, Cz and Fz of the international 10-20 electrode system (Fig. 1A). The signals were acquired with a Syn/Amps amplifier (NeuroScan, USA) filtered between 0.05 and 200 Hz. An additional 50-Hz notch filter was used. The data were sampled at 1000 Hz.

The electromyograph was recorded from three bipolar channels over the left/right finger extensor at the forearm and the right musculus tibialis, respectively, using a bipolar amplifier (g.tec; Guger Technologies, Graz, Austria). Filter settings were set at 0.5 Hz for high pass and 1000 Hz for low pass, and sensitivity was set to 2 mV. The data were digitized with 3000 Hz and stored for further analysis.

Data analysis

The CSP method and Fischer's linear discriminant analysis (LDA) classifier were used to discriminate between any two classes. The CSP method projects multichannel EEG data into a low-dimensional spatial subspace in such a way that the variances of the filtered time series are optimal for discrimination. The projection matrix, consisting of the weights of the EEG channels, is sorted in descending order of the eigenvalues. Relevant for classification are filter pairs consisting of the m largest eigenvalues and the m smallest eigenvalues. In this study, $m = 2$ was selected (Müller-Gerking *et al.*, 2000; Ramoser *et al.*, 2000). The structure of data processing is presented in Fig. 1C. Before applying CSP and LDA, the EEG recordings were visually inspected for electro-oculography and electromyography artefacts, downsampled from 1000 Hz to 250 Hz, and filtered between 8 Hz and 30 Hz. To get a good generalization of the classifier, a 10×10 cross-validation procedure was adopted. The EEG data from each trial were divided into time segments 250 ms in length (63 samples) overlapping by half of their length. For segments with the same time lag, individual LDA classifiers were trained and tested.

Calculation of time–frequency maps

To enhance local oscillations, orthogonal source derivations (Laplacian) were calculated (Hjorth, 1975). After triggering the data, trials of 8 s duration were obtained, including 3 s before the cue. The quantification of ERD/ERS was carried out in four steps: bandpass filtering of each trial, squaring of samples, and subsequent averaging over trials and over sample points. The ERD/ERS is defined as percentage power decrease (ERD) or power increase (ERS) in relation to a 1-s reference interval before the warning tone (Pfurtscheller & Lopes da Silva, 1999). ERD/ERS values corresponding to 2-Hz frequency bands ranging from 6 to 40 Hz (with an overlap of 1 Hz) were calculated. All values for one EEG channel were subsequently used to construct time-frequency maps (ERD/ERS maps). The statistical significance of the ERD/ERS values was verified by applying a t-percentile bootstrap statistic to calculate confidence intervals with $\alpha = 0.05$. For further details about time–frequency map calculation, see Graimann *et al.* (2002).

Results

Discrimination between two different brain states during visual stimulation (cue) associated with different instructions

The power of discrimination between two different brain states is indicated by the classification accuracy of single EEG trials analysed within 250-ms time windows. As an example, the discrimination between left and right hand MI of all subjects is displayed as a function of time in Fig. 2. Each diagram displays about 50% accuracy prior to visual stimulation (second 3), followed by a fast increase to an initial peak about 1 s after cue onset. This early peak is indicative of a short-living brain state found in the majority of subjects. Some of the subjects (s0, s4, s5 s7 and s8) displayed a more or less pronounced second discrimination peak during the few seconds following the cue. The discrimination time courses for epochs of 1.5 s for all task combinations (right vs. left hand, left hand vs. feet and right hand vs. feet) are shown in Fig. 3. The maximal classification accuracy of the first peak together with the corresponding latency, measured from cue onset, is summarized in Table 1. A latency (delay) of 1000 ms means that in the processing window from 750 to 1000 ms, the highest classification accuracy was present. The mean accuracies (± SD) were 80 ± 10.6% (left vs. right hand MI), 83.3 ± 10.2% (left hand vs. feet MI) and 83.3 ± 8.8% (right hand vs. feet MI), respectively. Three subjects displayed a classification accuracy of more than 90%. For statistical analyses, ANOVAS for repeated measures were computed. The calculations revealed no significant differences between the peak classification accuracies, but a significant difference ($F_{2,18} = 4.43$, $P < 0.05$) in the latency of the peak when right hand vs. feet MI and left hand vs. right hand MI were compared. For right hand vs. feet MI, the mean latency (+ SD) of the peak was significantly longer 1.25 + 0.20 s) than for right hand vs. left hand MI (1.00 + 0.28 s). To give an impression of the spatial features that were identified by the spatial filters, the four patterns (two for the largest and two for the smallest eigenvalues) obtained are displayed in Fig. 4. These patterns correspond to the maximal classification accuracy of the first peak as indicated in Table 1. The maxima and minima, respectively, were found very frequently at electrode positions overlying right and left hand representation areas. Especially in maps with feet MI, frontal electrodes overlaying foot representation and supplementary motor areas were also of importance.

The initial short-lasting peak provides evidence that the EEG activity pattern that appears for about 500 ms within the first second after the visual cue contains significantly different features that depend on the movement imagined according to the visual cue. This initial peak was presented in all subjects studied with more or less dominance, and is therefore a very frequent and stable phenomenon. A second long-lasting discrimination peak with a delay of some seconds was less dominant and showed larger inter-subject variability (see example in Fig. 2).

Somatotopically specific desynchronization (ERD) patterns of sensorimotor rhythms during visual cue presentation

Although the discriminations of any two different brain states were based on the analysis of 32 EEG signals recorded over premotor and motor areas, clearly different patterns were found in spatially filtered (Laplacian) recordings over the primary motor areas (electrode positions C3 and C4). For illustration, time–frequency maps (ERD

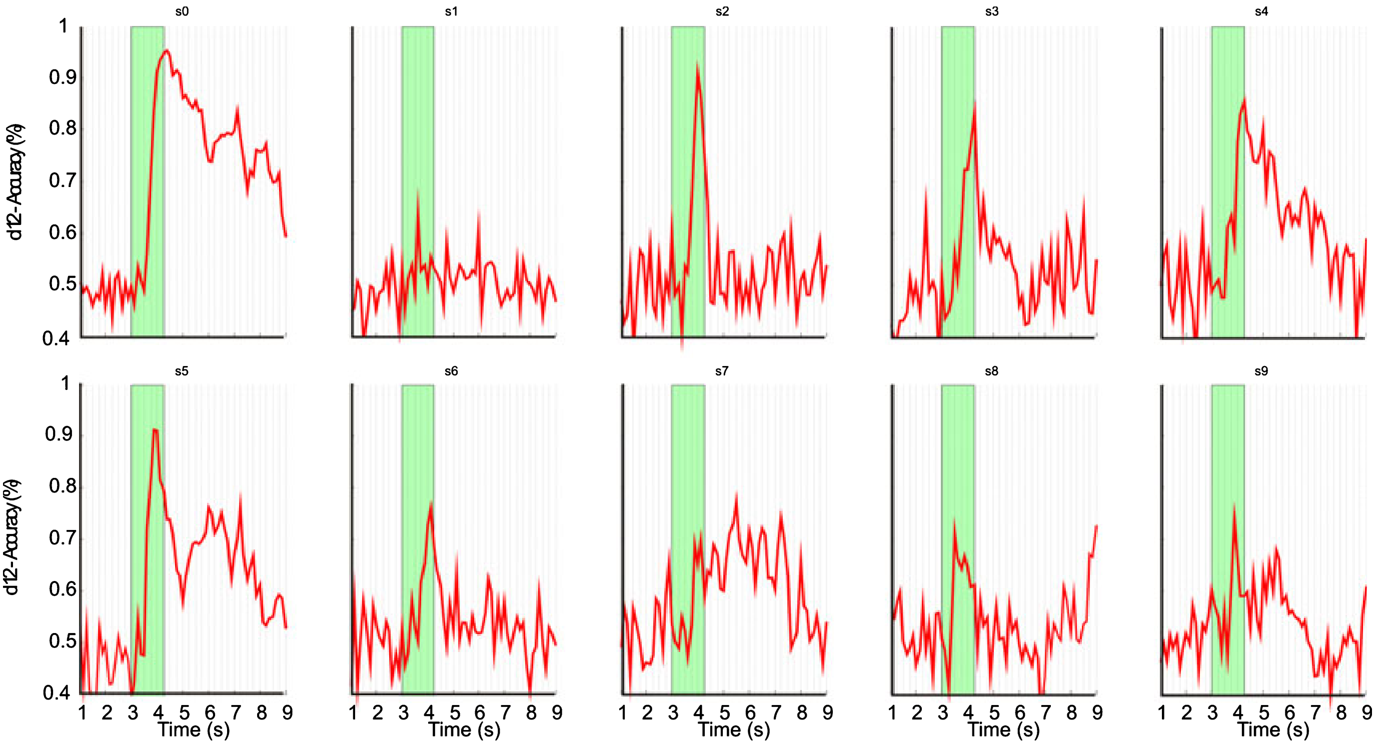

FIG. 2. Discrimination time courses documenting the separability between two brain states (right vs. left hand motor imagery) obtained with a 250-ms window. The time of visual cue presentation is indicated by a green bar. Classification accuracy from 40% to 100% is shown on the *y*-axis, and time from 1 s to 9 s appears on the *x*-axis. The data were collected from 10 naïve subjects without any motor imagery experience.

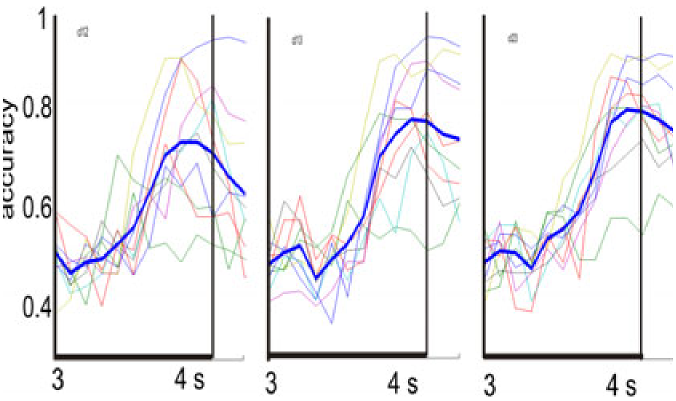

FIG. 3. Discrimination time courses for a length of 1.5 s after cue onset. The duration of cue presentation is indicated by a horizontal bar and a vertical line. Data from all subjects and all three brain states compared: right vs. left hand motor imagery (left panel), left hand vs. feet motor imagery (middle panel), and right hand vs. feet motor imagery (right panel).

TABLE 1. Classification accuracy of the initial peak and its latency (delay) after cue onset for all 10 subjects and all combinations

	Left vs. right hand		Left hand vs. foot		Right hand vs. foot	
Subject	Accuracy (%)	Delay (s)	Accuracy (%)	Delay (s)	Accuracy (%)	Delay (s)
s0	95.29	1.375	96.71	1.250	92.69	1.375
s1	63.70	0.625	62.55*	0.625	63.94	1.375
s2	90.83	1.000	83.39	1.000	88.11	1.000
s3	82.99	1.250	76.71	1.250	82.46	1.375
s4	85.58	1.250	91.46	1.250	82.01	1.250
s5	91.16	0.875	94.03	1.375	92.76	1.000
s6	75.92	1.125	76.72	1.125	75.10	1.250
s7	69.80	1.125	89.91	1.250	89.79	1.625
s8	71.39	0.500	80.66	0.875	81.74	1.125
s9	73.70	0.875	81.06	1.250	84.57	1.125
Mean	80.04	1.000	83.32	1.125	83.32	1.250
Median	79.46	1.063	82.23	1.250	83.52	1.250
SD	10.62	0.283	10.19	0.228	8.76	0.195

*Within chance level [$P < 0.05$; see Müller-Putz *et al.* (2008) for more details].

maps) of two representative subjects are displayed in Fig. 5. In subject s2, the initial discrimination peak was limited to cue presentation. This peak is caused by the different reactivity patterns induced by the visual cue indicating either right or left hand MI. Both the short-lasting upper mu ERD (10–12 Hz) and beta ERD (20–24 Hz) displayed a significant power decrease ($P < 0.05$) starting approximately 300 ms after cue onset at the contralateral electrode position (C3 or C4) in the right and left hand MI condition, respectively (indicated by stippled elipses).

A completely different ERD pattern was observed in subject s5, with an initial discrimination peak of 90.8%, followed by a longer-lasting classification accuracy of about 75% during the next seconds. In this subject also, two reactive frequency bands could be differentiated over the hand representation area: 10–12 and 21–25 Hz. In contrast to subject s2, both the upper mu and central beta ERD were present over several seconds with a clear contralateral preponderance. This ERD started first in the contralateral hemisphere, and with a delay of about 500 ms in the ipsilateral side. The temporally limited, short-lasting ERD during cue presentation was also dominant during feet MI. Examples of ERD maps calculated at electrode Cz in three

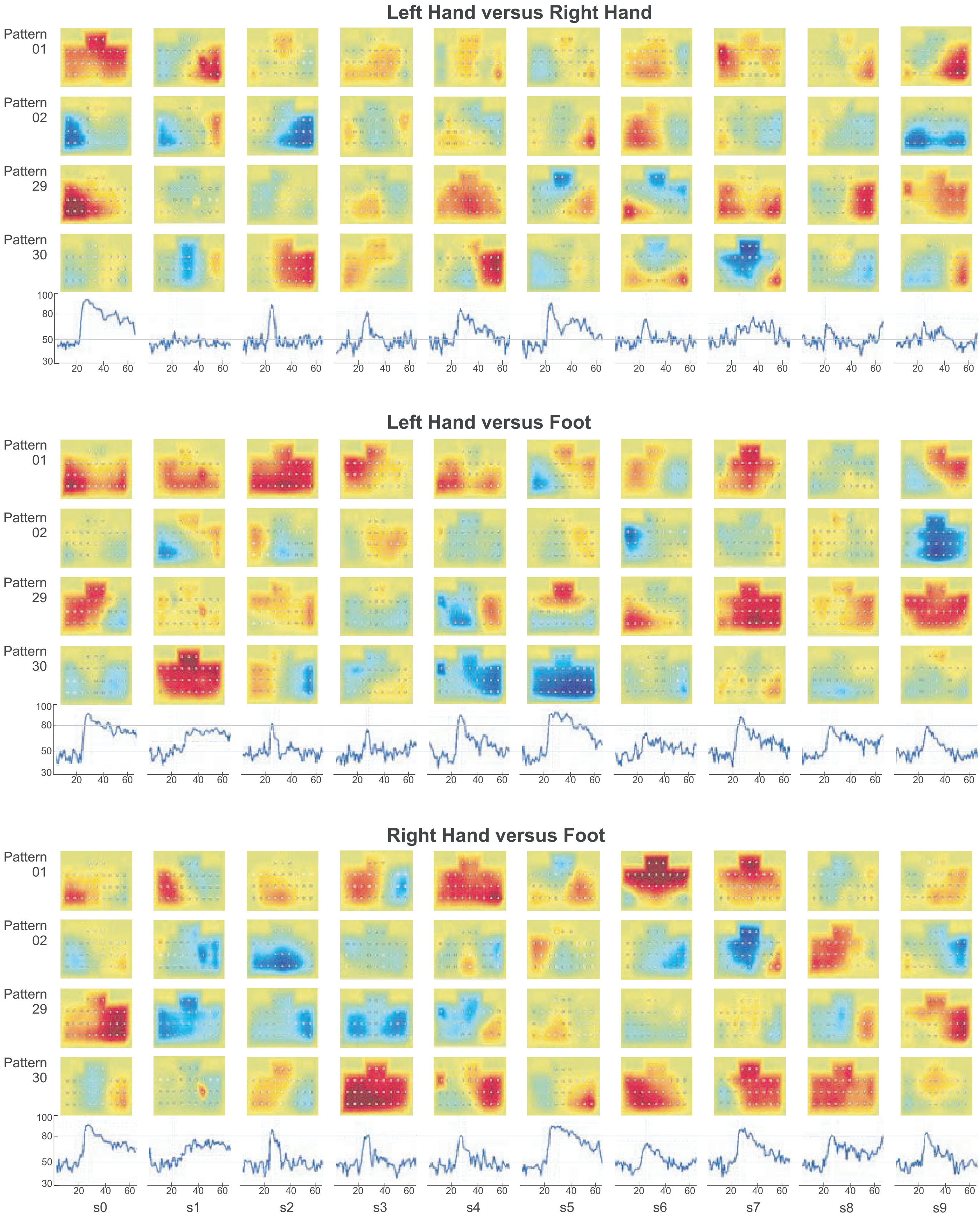

FIG. 4. Common spatial patterns for each pair of motor imagery conditions and all subjects. In addition, the corresponding discrimination time courses (for details see Fig. 2) are displayed. The maps are calibrated for the maximum (red) and minimum (blue) of all maps calculated.

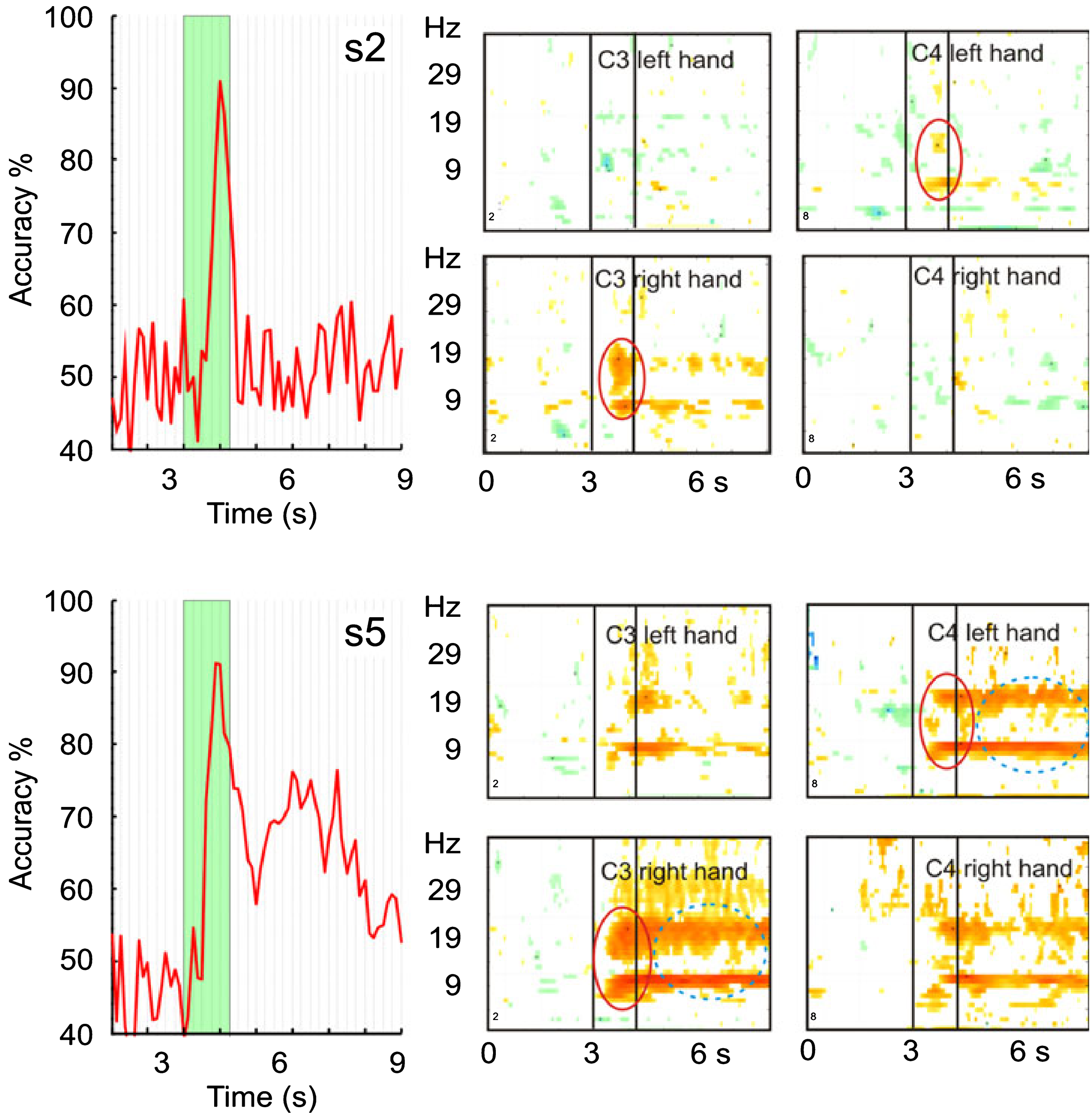

FIG. 5. Discrimination time courses (left side, for further explanation see Fig. 2) and time–frequency maps calculated at electrode positions C3 and C4 [right side: upper maps, left motor imagery (MI); lower maps, right MI] of two characteristic subjects (upper panel, s2; lower panel, s5). Reactive mu and beta components displaying significant event-related desynchronization and responsible for the discrimination between two brain states are marked by ellipses (solid for classification of short-lived brain states and stippled for classification of brain states during conscious MI in s5). Vertical lines in the time–frequency maps mark the window of cue presentation.

subjects are displayed in Fig. 6. Clearly visible are the phasic beta ERD patterns during cue presentation in each of the subjects.

Discussion

The main finding of the present study is that there are distinct EEG patterns occurring during the short-lived mental state when a subject imagines different movements of hands and feet. In the present study, we applied a classification procedure to multichannel, single-trial EEG data recorded during classical brain–computer interface training sessions with three MI tasks: right hand, left hand and feet movement (Pfurtscheller *et al.*, 2005). One method suitable for studying temporal aspects of brain activation using multichannel EEG recordings consists of computing CSPs (Koles, 1991; Müller-Gerking *et al.*, 2000). This CSP method leads to spatial filters that are optimal in the sense that they extract signals that maximally discriminate between any two conditions. A subsequent linear classification of these extracted signals results in a good recognition rate. With the CSP method, it was possible to study the separability between two conditions (two brain states), with a high time resolution. In the majority of subjects, it was found that the recognition rate had a clear initial peak within the first second after the start of cue presentation, with a fast increase of the recognition rate starting about 300 ms after stimulation (Fig. 3). Such an initial recognition peak after visual cue presentation has already been reported in the case of situations where a subject had to perform a movement after a cue (Müller-Gerking *et al.*, 2000). The present findings show that similar short-lasting brain states are also seen in an MI task. This gives support to the interpretation that similar neural networks are responsible for both conditions: execution and imagination of a movement.

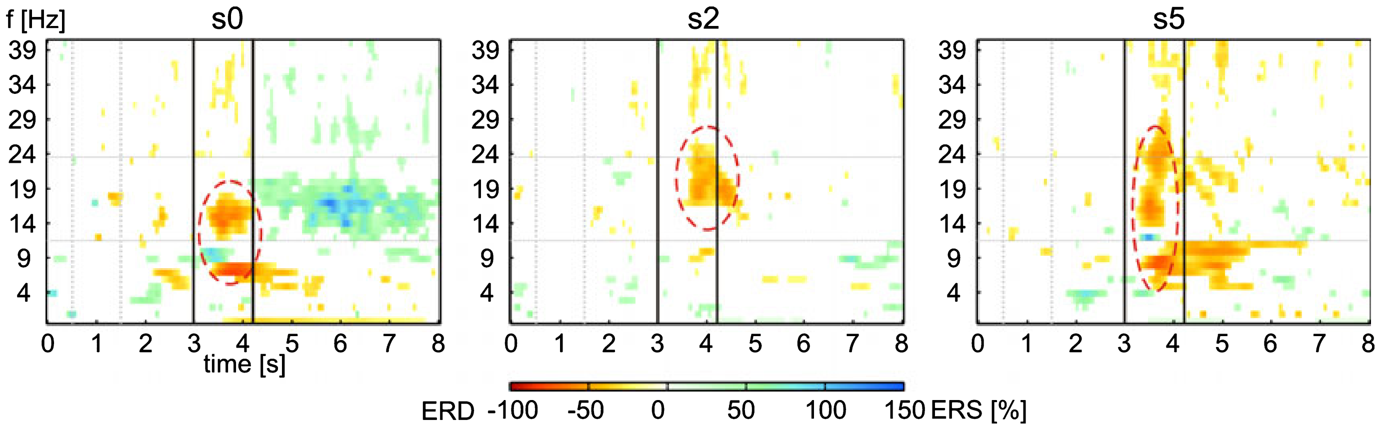

FIG. 6. Examples of time–frequency maps calculated at the vertex (electrode position Cz). Data of three subjects (s0, s2 and s5). In each map, a significant beta event-related desynchronization (ERD) (marked by a stippled ellipse) is observed, limited to the time window of cue presentation when feet motor imagery was indicated. For further explanation see Fig. 5. ERS, event-related synchronization.

The initial, short-lasting separability peak indicates that in a short time window of about 500–750 ms, the EEG signals display different spatiotemporal patterns in the investigated imagery tasks. The robustness of these findings among different subjects allows us to conclude that in nearly every subject, such a somatotopically specific activation (ERD) pattern can be induced by the cue stimulus; or, in other words, the cue can induce a short-lived brain state as early as about 300 ms after cue onset. It is possible that this process is only partially consciously experienced and may be interpreted as a kind of priming effect.

Conscious experience is necessary, however, to induce specific long-lasting brain patterns during the imagery process. The latter process corresponds to the second discriminating peak, which is variable in shape, long-lasting over some seconds, and may even be missing in some subjects. This peak very probably depends on the mental strategy used (e.g. visual vs. kinaesthetic motor imagery) (Neuper *et al.*, 2005), the vividness of the imagery process, the mental effort, and other psychological factors (e.g. motivation and attention). Even in one subject, the same mental MI strategy can result in completely different ERD patterns (and different reactions in heart rate as consequence), depending on the degree of imagined efforts (Pfurtscheller *et al.*, 2006a,b).

It is relevant to relate the present findings obtained using scalp EEG recordings with data obtained by means of direct recordings from single neurons in the motor cortex. Thus, neurons of the monkey's motor cortex can discharge about 60–80 ms after occurrence of a visual cue, indicating the direction of the upcoming movement (Georgopoulos *et al.*, 1982). Preparatory changes in neural activity before the execution of a movement have been documented in monkey primary motor and premotor cortex with a short latency of about 100 ms after the occurrence of the preparatory visual cue signal (Riehle & Requin, 1995). These studies show that the motor cortex is engaged as early as about 100 ms in the chain of events that are triggered by the occurrence of the cue that leads to the target movement. We hypothesize, therefore, that the short-lived brain state that we identified in the present study reflects this premovement motor cortical activity corresponding to the motor programme for the type of the upcoming MI task and is the result of the visual cue-triggered 'motor memory'. It has been suggested that such 'motor memories' are stored in cortical motor areas and the cerebellum motor systems (Naito *et al.*, 2002), and play a role when, during the MI process, memory information related to previous experiences is retrieved (Annett, 1996).

One point needs discussion, namely the slightly higher (but not significant) classification accuracy in connection with feet MI as compared to right vs. left hand MI and their longer peak latencies. This can be interpreted to mean that the short-lived brain state induced by feet MI is better discriminable from the brain state associated with either left or right hand MI. One reason for this could be the antagonistic behaviour of the upper mu ERD and ERS during MI, known as 'focal ERD/surround ERS' (Pfurtscheller & Lopes da Silva, 1999; Suffczynski *et al.*, 2001). Feet MI results not only in a midcentrally focused mu and/or beta ERD but very often also in a bilateral mu ERS over the hand representation area (Pfurtscheller *et al.*, 2006c). These authors reported on a much larger difference in band power changes (ERD, ERS) in the 10–12-Hz frequency band when different (hand vs. foot MI) and not homologous (right vs. left hand MI) limbs were compared.

In conclusion, we demonstrated that somatotopically specific desynchronization patterns (ERD) in the electroencephalogram can be induced not only through planning of a specific limb movement (pre-movement activation) (Stancak and Pfurtscheller, 1996a,b) or imagination of such a movement without its execution (Pfurtscheller *et al.*, 2006c), but also with a visual cue indicating a specific MI task. In the latter case, a short-lasting brain state is induced starting approximately 300 ms after cue onset and lasting for less than 1 s. It is remarkable that such a brain state can be induced in naive subjects without any experience in MI and previous training. This property may be relevant in planning brain–computer interfaces.

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Abbreviations

CSP, common-spatial pattern; EEG, electroencephalography; ERD, event-related desynchronization; ERS, event-related synchronization; LDA, linear discriminant analysis; MI, motor imagery.

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