CHAPTER 14

ERD/ERS patterns reflecting sensorimotor activation and deactivation

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Abstract: Oscillations in the alpha and beta band (<35 Hz) show characteristic spatiotemporal patterns during sensorimotor processing. Whereas event-related desynchronization (ERD) during motor preparation, execution, and imagery can be seen as a correlate of an activated cortical area, event-related synchronization (ERS) of frequency components between 10 and 13 Hz may represent a deactivated cortical area or inhibited cortical network, at least under certain conditions. Induced beta rhythms (13–35 Hz, beta ERS) can be found in sensorimotor areas following both voluntary movement and somatosensory stimulation. In a recent study we used different tasks involving execution and imagery of movements of the upper and lower limb to produce activation vs. deactivation/inhibition of the sensorimotor hand area. Sensorimotor interference, as a function of the activation level of the motor cortex, was studied by the use of repetitive median nerve stimulation (MNS) (ISI 1.5 s) in 12 healthy volunteers during the following task conditions: (i) cube manipulation between thumb and fingers of one hand, (ii) imagined cube manipulation, (iii) continuous foot rotation movements, and (iv) imagined foot movements. EEG was recorded from hand and foot representation areas and processed time-locked to MNS (ERD/ERS). In addition, task-related band power changes (TRPD/TRPI) were analyzed. We found a clear-cut suppression of the stimulation-induced beta ERS (indicating an enhanced activity state of the sensorimotor areas) during active cube manipulation and a weaker suppression during cube imagery. Mental imagination of foot movement led to an increase of the hand area mu rhythm, but did not interfere with stimulation-related effects on beta ERS. These findings support that interfering sensorimotor activation and deactivation is reflected in graduated changes of induced mu and beta oscillations.

Keywords: mu rhythm; beta oscillations; event-related desynchronization (ERD); event-related synchronization (ERS); voluntary movement; motor imagery; median nerve stimulation

Mu synchronization and desynchronization in voluntary movement and motor imagery

Voluntary movement is the overt basis of human behavior: without movement we cannot walk, communicate, or interact with others. According to the present view, the brain processes involved in generating and controlling movements are accomplished through parallel distributed processing in multiple motor areas (for a review, see Dum and Strick, 2005). The study of oscillatory EEG signals in the sensorimotor and related cortical areas provides a window to how the information processing in multiple neuronal networks may be realized.

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It is well established that preparation, execution, and also imagination of movement produce an event-related desynchronization (ERD) over the sensorimotor areas, with maxima in the alpha band (mu rhythm, ∼10 Hz) and beta band (∼20 Hz) (Jasper and Penfield, 1949; Chatrian et al., 1959; Pfurtscheller and Aranibar, 1977; Neuper and Pfurtscheller, 1999). The mu ERD is most prominent over the contralateral sensorimotor areas during motor preparation and extends bilaterally with movement initiation. ERD during hand motor imagery is very similar to the pre-movement ERD, i.e., it is locally restricted to the contralateral sensorimotor areas (Neuper and Pfurtscheller, 1999). Since ERD of alpha band and beta (<30 Hz) frequency components can be viewed as an electrophysiological correlate of an activated cortical network, prepared to process information with an increased excitability of cortical neurons (Lopes da Silva and Pfurtscheller, 1999; Pfurtscheller and Lopes da Silva, 1999), the pre-movement ERD and the ERD during motor imagery may reflect a similar type of readiness or presetting of neural networks in sensorimotor areas (Neuper and Pfurtscheller, 2001a).

During movement preparation and execution, desynchronization of alpha band (mu) activity at a specific cortical location may be accompanied by an increase of synchronization (ERS) in the 10-Hz band over areas not engaged in the task (Pfurtscheller and Neuper, 1994; Pfurtscheller et al., 1996b, 2006). ERS can also be observed after the movement, over the same areas that had displayed ERD earlier (Toro et al., 1994). Because the mu rhythm typically occurs in the absence of processing sensory information or motor output, it was conceived to reflect a cortical “idling” or “nil-work” state (Mulholland, 1995). Therefore, it has been hypothesized that the 10-Hz ERS is produced by deactivated cortical areas and may represent idling or inhibitory cortical activity (Pfurtscheller et al., 1996b). This may be the case in cortical areas representative for another modality and in neighboring areas that correspond to the same modality as well. For example, in a movement task a central ERD is accompanied by an occipital ERS and in a visual task an occipital ERD is found in parallel with a central ERS (Pfurtscheller and Neuper, 1994). Other examples are execution and imagination of foot movement; in both cases very often an ERD close to the foot representation area is accompanied by a synchronization of the hand area mu rhythm (Neuper and Pfurtscheller, 2001a). This observation, ERD and ERS occurring at the same moment in time in different scalp locations, was named “focal ERD/surround ERS” (Suffczynski et al., 1999) and interpreted as a type of lateral cortical inhibition of networks not directly involved in a specific task (see also Chapter 2, this volume). More recently, it has been shown that mu ERS likely reflects more than an idling state (for a review, see Pineda, 2005). Exemplarily, a task-related alpha power increase (TRPI) has been found to be related to context-dependent inhibition of extended sensorimotor networks (Hummel et al., 2002; see also Chapter 15, this volume).

**Beta rebound following movement and somatosensory stimulation**

Besides the mu rhythm, the central beta rhythms may be indicative for the activity state of neural networks in the sensorimotor cortex. The general finding is that beta oscillations are desynchronized during preparation, execution, and imagination of a motor act (Pfurtscheller, 1981; Stancák and Pfurtscheller, 1996; Neuper and Pfurtscheller, 1999). After movement offset, the beta band activity recovers very fast (<1 s) and short-lasting beta bursts appear. These beta oscillations, described also as post-movement beta ERS or “beta rebound” (Pfurtscheller et al., 1996a), display a high degree in somatotopical specificity (Salmelin et al., 1995; Neuper and Pfurtscheller, 1996; Brovelli et al., 2002). Recently, Pfurtscheller et al. (2005) reported a distinct spatial distribution of beta ERS after different types of motor imagery. The occurrence of a beta rebound related to mental motor imagery implies that this activity does not necessarily depend on motor cortex output and muscle activation.

A number of experiments have also shown beta oscillations to be sensitive to somatosensory stimulation (Salmelin and Hari, 1994; Salmius et al.,
1997; Neuper and Pfurtscheller, 2001b) and passive movement (Cassim et al., 2001). Resembling to voluntary hand movement, stimulation of the median nerve can elicit short-lasting bursts of beta oscillations that are localized predominantly in the contralateral hand sensorimotor cortex (Salenius et al., 1997). In general, electrical median nerve stimulation (MNS) above the sensory threshold can generate two types of cortical responses, a phase-locked (evoked) response localized in the postcentral somatosensory cortex (Baumgartner et al., 1991) and a non-phase-locked (induced) response in the form of beta oscillations in the precentral motor cortex. The latter appears within 1 s after the delivery of the stimulus and follows a short-lasting ERD immediately after stimulation. Beta ERS has been reported in response to median/tibial nerve stimulation (Hari et al., 1996; Neuper and Pfurtscheller, 2001b; Brovelli et al., 2002), functional electrical stimulation (FES) producing wrist extension (Müller et al., 2003), and even mere tactile stimulation of the finger tip (Pfurtscheller et al., 2001; Cheyne et al., 2003; Gaetz and Cheyne, 2006).

Figure 1(A) shows the topographical display of beta band ERD/ERS time courses comparing voluntary index finger movement and MNS (Neuper and Pfurtscheller, 2001b) and Fig. 1(B) shows topographic maps of one representative subject with beta ERS obtained in three different conditions: mechanical finger stimulation, electrical nerve stimulation, and voluntary finger movement. In all conditions the focus of beta ERS was found over the contralateral primary sensorimotor cortex. Of interest is the observation that sensory stimulation can elicit short-lasting bursts of beta oscillations, irrespectively whether it is accompanied by a visible motor response or not.

![Figure 1](image-url)

Fig. 1. (A) Topographical display (nose on top) of grand average ERD/ERS curves comparing movement vs. stimulation of the hand (mean frequency band: 15–20 Hz). The horizontal line marks the level of reference power and the vertical line movement-offset/stimulation. Band power increase (beta ERS) is indicated by upward deflection, band power decrease (beta ERD) by downward deflection. (B) Topographical maps of one subject, each representing an interval of 125 ms, showing the distribution of beta ERS (16–20 Hz) following tactile stimulation of the index fingertip (electrode positions are marked), median nerve stimulation, and index finger movement. “Black” indicates beta power increase (ERS). (C) Electrode montage (modified from Neuper and Pfurtscheller, 2001b).
This means that sensory stimulation alone can change the ongoing activity of beta oscillatory networks in the motor cortex (see also Chapter 16, this volume).

The stimulation-related beta ERS can be suppressed by various tasks involving motor cortex activation, e.g., exploratory finger movements (Salenius et al., 1997; Pfurtscheller et al., 2002), motor imagery (Schnitzler et al., 1997) or even movement observation (Hari et al., 1998). From these studies we can conclude that not only the post-movement beta ERS, but also the beta ERS induced by somatosensory stimulation, reflects aspects of the functional state of the primary motor cortex. More specifically, these central 20-Hz oscillations have been interpreted to reflect a short-lasting state of deactivation or inhibition of motor cortex networks (Salmelin et al., 1995). Further support for this assumption comes from studies using transcranial magnetic stimulation (TMS), in which it was shown that the excitability level of motor cortex neurons was significantly reduced within the first second after termination of finger movement (Chen et al., 1998) and after MNS as well (Chen et al., 1999).

Effects of interfering sensorimotor activation and deactivation on mu ERD and beta ERS

In a recent study we used repetitive peripheral nerve stimulation to investigate the activity state of motor cortex networks during sensorimotor interference. Starting from the hypothesis that the excitability of motor cortex circuitry is modulated by movement execution and motor imagery, the aim of this study was twofold: first, we sought to corroborate previous magnetoencephalographic (MEG) findings that activation of the motor cortex, by performing or imagining manipulatory finger movements, desynchronizes the central mu rhythm and suppresses stimulus-induced beta oscillations (cf. Salenius et al., 1997; Schnitzler et al., 1997). Second, we wanted to extend the previously reported results and evaluate the hypothesis that inhibition of the hand area network, assumedly produced by foot movement or foot motor imagery (Pfurtscheller and Neuper, 1994; Neuper and Pfurtscheller, 2001b), results in a synchronization of the mu rhythm and an enhancement of the beta ERS. The idea was to utilize overt motor behavior and motor imagery of upper vs. lower limb to produce a state of activation vs. deactivation/inhibition, respectively, of neuronal networks in the sensorimotor cortex.

In order to evaluate how the activation of the sensorimotor hand area depends on concomitant short-lasting (i.e., stimulation-induced) vs. long-lasting processes (i.e., movement execution and motor imagery), we used in this study a combined approach of (i) ERD/ERS time frequency analysis (Graimann et al., 2002) and (ii) analyses of task-related power decreases/increases (TRPD/TRPI; Gerloff and Hallett, 1999). Even though ERD/ERS and TRPD/TRPI follow the same rationale, i.e., the analysis of regional changes in oscillatory brain activity in relation to a certain event, they differ in that ERD/ERS focuses on spectral power changes time-locked to a single stimulus, whereas TRPD/TRPI concentrates on changes with steady-state processes related to continuous movement execution or mental imagery (for a discussion of “event-related” vs. “task-related” analysis of oscillatory activity, see Chapter 15, this volume).

Subjects and experimental paradigm

Twelve healthy right-handed volunteers (six men and six women, aged 19–32 years) participated in the study. Periodic MNS was delivered at the right wrist in four different experimental conditions, each of which lasted about 3 min:

**CUBE**

MNS and cube manipulation: The subjects performed continuous finger movements by manipulating a small cube between thumb and fingers of the right hand.

**I-CUBE**

MNS and cube manipulation imagination: Participants were instructed to imagine continuously the movement of condition CUBE.
FOOT MNS and foot movement: The subjects performed a continuous movement of the right foot in form of a circle with the heel resting on the floor.

I-FOOT MNS and foot movement imagery: Subjects were instructed to imagine the foot movement they had to perform in condition FOOT.

Bipolar ball electrodes with 2.5 cm interelectrode distance were used for stimulation of the right median nerve. Stimulation was performed with constant current pulses of 0.2 ms duration every 1.5 s. Before the experiment started, the adequate stimulation intensity for stimulating the median nerve (at the wrist) was adjusted to evoke a slight visible thumb twitch without causing discomfort. Each experimental condition was preceded by a 3-min resting period, during which MNS was repetitively applied without any additional task. Besides the specific task instructions, the participants were asked to sit relaxed with eyes open and resting arms, and to avoid any movements other than requested.

Data recording and processing

The EEG (bandpass between 0.5 and 30 Hz) was recorded with four electrodes positioned at positions 2.5 cm anterior and posterior to C3 and Cz, respectively (C3a, C3p, Cza, and Czp), sampled at 2 kHz, and converted into bipolar by calculating the difference for the electrode of interest (C3 = C3a–C3p, Cz = Cza–Czp). All data were visually controlled for artifacts before further processing.

Figure 2 illustrates the influence of periodic median nerve stimulation on rhythmic EEG activities (single EEG trials) in the contralateral hemisphere (C3) during a rest condition. The mu rhythm is attenuated following the stimuli and resynchronizes slowly. Examples of post-stimulus beta bursts (ERS) can be observed within a few hundred milliseconds after stimulation.

Because of interindividual variability in reactive frequencies, subject-specific frequency bands were used for subsequent analysis. To this end, ERD/ERS time–frequency maps were calculated for all conditions (for a description of ERD/ERS map calculation, see Graimann et al., 2002), and on the basis of the stimulation-related ERD/ERS values obtained for electrode position C3 the reactive frequency bands were determined for each participant. In the alpha range, the mean center frequency displaying the largest ERD was 11.4 Hz ± 0.8 (mean ± SD); in the beta range, the largest ERS was found about 19.3 Hz ± 1.9 (mean ± SD).

ERD/ERS time curves were calculated for both, the subject-specific alpha and beta bands, using the intertrial variance method (Kalcher and Pfurtscheller, 1995). In the subject-specific alpha band, the maximum alpha ERD with respect to the reference interval (250–0 ms before the trigger) was measured; in the beta band, maximum synchronization (ERS) was quantified for further analysis.

Task related power decrease/increase (TRPD/TRPI) for the different task conditions was determined by calculating the variance. For this purpose the trials of each condition were bandpass filtered in the two subject-specific frequency bands, and the overall variance of each condition was calculated from these filtered data. In order to estimate the task-related power increase/decrease, each condition with motor or mental task was related to the preceding resting condition.

Stimulation-related band power changes

In Fig. 3 the averaged (thick line) and subject-specific (thin lines) ERD/ERS curves are displayed for all subjects and conditions. Comparing the alpha band (upper panel) and the beta band (lower panel) activity, it can be noticed that the beta band shows a faster time behavior than the alpha band (mu rhythm) and results in a clear beta rebound that declines back to the baseline before the next stimulus is delivered (< 1.5 s).

We evaluated whether the stimulation-related ERD/ERS response during the investigated motor and imagery tasks differed significantly from the corresponding (preceding) rest conditions. Interestingly, the mu rhythm ERD yielded significant
results only for the cube manipulation task at electrode position C3 (paired t-test, $t = -3.346$, $df = 11$, $p < 0.01$). No significance was found for the other conditions (see box plots in Fig. 4, upper panel) or for the electrode position Cz. This result indicates that continuous hand movement (cube manipulation) significantly reduced the stimulation-induced mu rhythm changes, specifically over the corresponding hand sensorimotor area.

Analysis of the post-stimulus beta ERS showed a highly significant power suppression during cube manipulation ($t = 3.091$, $df = 11$, $p < 0.01$) over electrode C3. A tendency was detected in the data for cube manipulation imagination ($t = 1.967$, $df = 11$, $p < 0.075$), whereas both foot-related conditions did not alter the beta ERS (compare box plots in Fig. 3, lower panel).

**Task-related power decrease/increase**

The task-related band power (TRPD/TRPI) changes of the mu rhythm, referenced to the preceding resting condition, yielded a highly significant band power decrease for both the cube manipulation ($t = 6.795$, $df = 11$, $p < 0.01$) and the cube movement imagination task ($t = 4.608$, $df = 11$, $p < 0.01$). Foot movement imagination, in contrast, led to a significant mu power increase ($t = -2.215$, $df = 11$, $p < 0.05$). Unexpectedly, the performed foot movement apparently did not change the alpha power over C3 (Fig. 5, upper panel).

Figure 5, lower panel, shows the box plots for referenced beta band power measurement, which yielded a highly significant decrease for cube manipulation ($t = 8.496$, $df = 11$, $p < 0.01$) and foot
movement ($t = 5.241$, $df = 11$, $p < 0.01$). Still a significant difference was found for cube manipulation imagination ($t = 2.370$, $df = 11$, $p < 0.05$). Only foot movement imagination failed to produce a statistically noteworthy result over C3.

**Correlation of mu rhythm ERD and beta ERS**

The analysis of the relationship between the magnitude of the mu ERD and the beta ERS across subjects and conditions gave significant results for cube manipulation ($r = 0.6$, $p < 0.05$) and foot movement ($r = -0.654$, $p < 0.01$) over electrode C3. The positive correlation between alpha band ERD and beta ERS in the cube manipulation task indicates that a stronger mu rhythm ERD is associated with a smaller beta ERS. With foot movement, in contrast, a negative relationship emerged, in the sense that a stronger mu rhythm ERD appeared in connection with an enhanced beta ERS. Over Cz, no significant correlation between mu rhythm ERD and beta ERS could be found.

**Discussion and conclusions**

**Suppression of stimulation-related ERD/ERS by cube manipulation**

In agreement with previous findings (cf. Salenius et al., 1997; Neuper and Pfurtscheller, 2001b), the oscillatory brain activity with components in the 10- and 20-Hz bands showed the characteristic reactivity pattern to periodic median nerve stimulation (during rest), i.e., each stimulus was followed by a transient desynchronization (ERD) and a subsequent rebound (ERS). As noted before, it was anticipated that complex finger manipulation...
as well as the mental simulation of this task would result in activation of the hand motor cortex and, therewith, desynchronize the central mu rhythm and suppress stimulus-induced beta bursts. In fact, continuous finger movement, in comparison to the resting condition, reduced the stimulus-related mu ERD. The beta ERS was completely abolished during cube manipulation, and there was also a tendency found for the cube imagination task.

This is in line with previously reported MEG data showing that imagination of manipulatory finger movements attenuates the 20-Hz activity to a lesser extent than actually executed finger movements (Schnitzler et al., 1997).

The picture of sensorimotor interference becomes even clearer when changes of steady-state processes also are considered, i.e., based on the band power decreases/increases during the whole time periods of task performance (TRPD/TRPI; Gerloff and Hallett, 1999). Compared to the

Fig. 4. Box plots indicating the distribution of the obtained values for the maximum mu ERD (upper panels) and the maximum post-stimulus beta ERS (lower panels) for electrode position C3 for all conditions (from left to right: rest 1, cube movement; rest 2, foot movement; rest 3, cube manipulation imagination; rest 4, foot movement imagination). Each box represents the mean 50% between the lower and upper quartile values; the median is indicated by a line. Significant differences are marked by a double arrow.

Fig. 5. Box plots indicating the distribution of the obtained values for the referenced band power of mu (upper panels) and the referenced task-specific beta band power change (lower panels) for electrode position C3 for all conditions (from left to right: rest 1, cube movement; rest 2, foot movement; rest 3, cube manipulation imagination; rest 4, foot movement imagination). Each box represents the mean 50% between the lower and upper quartile values; the median is indicated by a line. Significant differences are marked by a double arrow.
preceding resting condition, the band power in the reactive alpha and beta bands decreased substantially during active cube manipulation, but also, to a smaller degree, in the cube movement imagination task. This observation confirms that the mentioned task conditions resulted in a long-lasting activation (i.e., enhanced activity state) of neuronal networks in sensorimotor areas, especially in the case of active cube manipulation. Furthermore, the ongoing desynchronization (blocking) of alpha band activity gives an explanation for the reduced stimulus-related mu-rhythm ERD during cube manipulation. Similarly, the reduced level of ongoing beta band activity during task performance may facilitate the suppression of the stimulation-induced beta ERS.

The clear-cut suppression of the stimulation-induced beta ERS during sensorimotor interference indicates that at least two processes may play a role for the magnitude of the beta ERS (elicited by median nerve stimulation of constant intensity): a central mechanism increasing the level of activation in the primary motor cortex (e.g., the generation of a motor command, and the involvement of cortico-cortical or cortico-subcortical circuits) and the modulation of the afferent input from the limb (e.g., by a gating mechanism at the thalamocortical level, e.g., Brunia, 1993, or Fu et al., 2001). The former is expected to result in activation of the motor cortex, irrespective of whether the motor behavior is really executed or only imagined. The latter may account for the complete suppression of the beta ERS during active movement (cube manipulation). Gating of attention during the active motor task can reduce the sensory input from the peripheral nerve stimulation or the awareness thereof (cf. Cheron and Borenstein, 1987; Brunia, 1993; Mima et al., 1998) and, thereby, further attenuate the beta ERS (Pfurtscheller et al., 2002).

Enhancement of the hand area mu rhythm by foot motor imagery

Starting from the concept termed “focal ERD/surround ERS” (Suffczynski et al., 1999, 2001), which emphasizes the idea of simultaneous activation and deactivation/inhibition of locally restricted cortical regions, the present study contrasted the effects of directing the focus of attention onto the upper vs. lower limb, thus drawing on distinct sensorimotor cortical areas. Concentration on foot movement as well as foot motor imagery was expected to activate the cortical foot area along with a deactivation/inhibition of the hand area network, since the latter is presumably not involved to perform the task (Pfurtscheller and Neuper, 1994; Neuper and Pfurtscheller, 2001a). Consequently, we expected a synchronization of the mu rhythm over the hand area, while subjects concentrated on the foot.

Although neither foot movements nor foot motor imagery had an impact on the reactivity patterns of ERD/ERS computed time-locked to median nerve stimulation, in the task-related band power significant changes occurred. The foot imagery task led to a significant increase of the hand area mu rhythm, but the actually performed foot movements did not change the alpha band power over the hand area. Of interest is, that the 10-Hz synchronization during foot motor imagery was only significant for the hand area (C3), but not found for the midline scalp location (Cz), which probably overlies the foot area localized in the mesial cortex.

The distinct reactivity patterns, i.e., decrease (ERD) vs. increase in synchrony (ERS), associated with (mental) concentration on the hand vs. foot, respectively, provide further support for the “focal ERD/surround ERS” phenomenon (Suffczynski et al., 1999, 2001), which was simulated by an extended version of the lumped model initially proposed by Lopes da Silva et al. (1974). The antagonistic ERD/ERS pattern may be interpreted in the light of a thalamocortical mechanism to facilitate focal cortical activation (“focal ERD”) by a simultaneous deactivation or inhibition of surrounding cortical areas, which are outside the focus of attention (“surround ERS”). In this respect the demands of the task may be of importance. It can be assumed, for instance, that actual executed foot movements became habitual over time during task performance and, therefore, required less attention than the motor imagery task. Given the distractive input from the repetitive stimulation of the median nerve, foot motor
imagery probably requires more mental effort to avoid disturbance. As a result, stronger mu enhancement, as expression of top–down processes, is more likely.

A very interesting aspect is that the reactive alpha (mu) components are found in the upper alpha band with a center mean frequency above 11 Hz. Upper alpha or mu components typically show a movement-specific and locally restricted desynchronization during voluntary limb movement (Pfurtscheller et al., 2000), in contrast to the more widespread ERD of lower alpha components. It was reasoned that the upper alpha frequency components reflect a mechanism responsible for selective attention to a motor subnetwork. This effect of selective attention to one motor subnetwork (e.g., foot area) may be accentuated when other motor subnetworks (e.g., hand area) are “inhibited.” This is in agreement with more recent studies showing that especially the frequency band 11–13 Hz displays ERS in the hand area, when the subject is engaged in another motor task (i.e., execution or imagination of foot or tongue movements; see Pfurtscheller et al., 2006), or withholds pre-learned finger movements (Hummel et al., 2002). On the basis of a combined approach of EEG task-related power and TMS cortical excitability analysis, Hummel et al. (2002) substantiated that the enhanced 11–13 Hz mu components in the hand representation area are instrumental for inhibitory control at the cortical level (see also Chapter 15, this volume).

Both mu and beta responses showed in principle the same patterns with an initial ERD followed by a rebound in the form of an ERS. The mu ERD had the greatest magnitude about 400 ms after stimulation, whereas the beta ERS displayed a maximum about 600 ms after stimulation. The degree of reactivity of mu and beta rhythms (magnitudes of the mu ERD and beta ERS to somatosensory stimulation) was correlated, but showed differential effects dependent on the task. In the cube manipulation task (focus of attention onto cube manipulation and therewith activation of the hand motor cortex), a stronger mu rhythm ERD was associated with a smaller beta ERS. When the stimulus-induced beta ERS is associated with a short-latency deactivation (inhibition) of the motor cortex, it can be expected that a long-lasting activation of the motor cortex should not only desynchronize the mu rhythm, but also counterbalance the short-lasting inhibition and suppress the beta ERS (Hari et al., 1998; Pfurtscheller et al., 2002).

During foot movement, however, a stronger mu rhythm ERD was correlated with an enhanced beta ERS. Since alpha and beta power changes usually have the same direction, this finding requires an explanation. One reason could be that the foot movement task in this study presumably did not implicate deactivation of the hand area. Previous studies reported, on the one hand, a relatively widespread mu rhythm ERD during self-paced foot movement, covering also the hand representation area (Arroyo et al., 1993; Toro et al., 1994; Pfurtscheller et al., 2000). On the other hand, an increase (ERS) of the upper alpha band (10–13 Hz) or mu activity over the hand area was observed, when foot movement was only one possible behavioral response, to be executed in dependence of a cue stimulus, indicating the requested type of movement (Pfurtscheller and Neuper, 1994). Comparable effects, in terms of hand area mu rhythm enhancement, have been reported, when the subjects imagined foot movements and “suppressed” imagery of hand movements, respectively (Neuper and Pfurtscheller, 2001a). This task-related aspect may further explain that in the present study, only the more demanding foot motor imagery task, but not the execution of continuous foot movements, resulted in an increase of the hand area mu rhythm. Another point to consider is that beta ERS over the motor cortex hand area was not only found related to movement, imagery, or stimulation of the contralateral hand, but was further observed to be co-activated during toe and lip stimulation (Gaetz and Cheyne, 2006). These examples raise the possibility that, independent of the somatotopic representation, the hand area of the precentral gyrus plays also a more general role in sensorimotor control.

From the present and former results we summarize that there is evidence for an inhibition of neuronal networks in the hand representation area during imagination of foot movement. This inhibition results in a divergent behavior of mu and
beta activities, i.e., in an enhanced synchronization of the hand area mu rhythm, but not, as expected, in enlarged stimulus-induced beta oscillations.

Acknowledgments

This study is part of the ongoing PhD thesis of one of the authors (M.W.) and has been supported by the “Fonds zur Förderung der wissenschaftlichen Forschung”, project P14831.

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