Foot and hand area mu rhythms

G. Pfurtscheller*, Ch. Neuper, C. Andrew, G. Edlinger

Department of Medical Informatics, Institute for Biomedical Engineering, and Ludwig Boltzmann-Institute of Medical Informatics and Neuroinformatics, Graz University of Technology, Brockmanngasse 41, 8010 Graz, Austria

Abstract

Spontaneous EEG can display spatio–temporal patterns of desynchronized or synchronized alpha band activity. Event-related desynchronization (ERD) of rhythms within alpha and lower beta bands is characteristic of activated cortical areas ready to process information or to prepare a movement, while event-related synchronization (ERS) in the same frequency bands can be seen as an electrophysiological correlate of resting or idling cortical areas. EEG was investigated over primary sensorimotor and premotor areas during discrete hand and foot movements. ERD was found over the primary hand area during finger movement and over the primary foot area during toe movement. The former was observed in every subject, the latter was more difficult to find. From these results it can be speculated that each primary sensorimotor area has its own intrinsic rhythm, which becomes desynchronized when the corresponding area is activated. ERS, in the form of an enhanced mu rhythm on electrodes overlying the primary hand area, was observed not only during visual processing but also during foot movement. In both cases, the hand area is not needed to perform a task and, therefore, can be considered to be in an idling state. The supplementary motor area (SMA) also plays an important role in preparation and planning of movement. It is demonstrated that this area also displays rhythmic activity within the alpha band, that is both linearly and non-linearly phase coupled to the intrinsic (mu) rhythm of the primary hand area. With planning and preparation of movement, this SMA rhythm is desynchronized and also the degree of coupling between the two areas decreases.   © 1997 Elsevier Science B.V.

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1. Introduction

The brain is able to generate oscillations at different frequencies, of which one type is rhythms within the alpha band. These rhythms can be recorded over different brain areas, with the largest amplitudes found during relaxed wakefulness. Adrian and Matthews (1934) considered the alpha band activity as resting rhythms of the brain, with different areas having their own characteristic resting or 'idling' rhythms. The sensorimotor system is in an idling state when no so-

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* Corresponding author. Tel.: +43 316 8735311; fax: +43 316 812964.

matosensory input is processed and no motor output is generated, and the visual system is in such a state when no visual information processing is performed. Therefore, the occipital alpha rhythm can be considered as an idling rhythm of visual areas and the central mu rhythm as an idling rhythm of sensorimotor areas (Kuhlman, 1978).

There is, however, not only one occipital alpha rhythm but a great variety of rhythms within the same frequency band. In this context it is important to refer to the following statement of Grey Walter in Mulholland (1969):

> ''We've managed to check the alpha band rhythm with intracerebral electrodes in the occipital–parietal cortex; in regions which are practically adjacent and almost congruent one finds a variety of alpha rhythms, some of which are blocked by opening and closing the eyes, some are not, some are driven by flicker, some are not, some respond in some way to mental activity, some do not. What one sees on the scalp is a spatial average of a large number of components, and whether you see an alpha rhythm of a particular type or not depends upon which component happens to be the most highly synchronized process over the largest superficial area; there are complex rhythms in everybody''.

In addition to visual and sensorimotor rhythms, rhythmic activities of auditory cortical areas appear to exist. Niedermeyer (1990) described a 'third rhythm' within the alpha band arising from the neocortical portion of the mid-temporal region and Papakostopoulos et al. (1980) reported on a temporal 11-Hz rhythm that reacts differently to fist clenching than do the sensorimotor rhythms. A magnetoencephalic 10-Hz rhythm from the supertemporal human auditory cortex was reported by Tiihonen et al. (1991).

A well-known phenomenon is the blocking or desynchronization of rhythms within the alpha band reported by Berger (1930), Jasper and Penfield (1949), Chatrian et al. (1959) and others. The event-related desynchronization (ERD) is a specific form of EEG desynchronization. The ERD, first quantified by Pfurtscheller and Aranibar (1977), is phasic, circumscribed and very often focused over specific cortical areas. In contrast to this desynchronization, alpha band activity can also be enhanced, i.e. the EEG activity within the alpha frequency range may become more synchronized close to an event. This phenomenon is also phasic and localized and was named event-related synchronization (ERS, Pfurtscheller, 1992). Both phenomena, ERS and ERD, can be displayed in the form of time courses (Pfurtscheller and Aranibar, 1979; Van Winsum et al., 1984; Dujardin et al., 1993), maps (Pfurtscheller and Berghold, 1989; Pfurtscheller, 1991) or chronospectrograms (Defebvre et al., 1993; Derambure et al., 1993).

Alpha desynchronization is characteristic of an activated brain state and can be seen as an electrophysiological correlate of activated or excited cortical neurons (Steriade and Llinas, 1988). The cortical modules or neuronal assemblies tend to work independently and the EEG displays low amplitudes.

A synchronized activity within the alpha band can be interpreted as a neurophysiological correlate of decreased cortical excitability or even of inhibition of neuronal populations. In this case, cortical modules display synchronized behavior, i.e. they do not work independently. Accordingly, large alpha waves can be measured on the scalp due to the cooperative behavior of cortical neurons. Taking the spatial averaging effect into consideration, it is estimated that the area of cooperative activity has to be in the order of some cm^2 (Cooper et al., 1965; Lopes da Silva, 1991).

Alpha spindles are a different phenomenon and are characteristic of barbiturate anesthesia (Andersen and Andersson, 1968) and of light sleep. During the occurrence of alpha spindles, the information transmission from the thalamus to the cortex is cut off (Steriade and Llinas, 1988).

2. Data collection and processing

Similar to the computation of ERPs, the quantification of ERD is based on the averaging technique (Fig. 1). Generally, an event-related paradigm with a trial length of some seconds is

used. In our experiments the subjects performed a simple finger or foot movement in response to visual stimulation. For recording of the EEG, electrodes were placed over central and pre-central areas, with an interelectrode distance of 2.5 cm. The EEG signals were recorded with a common nose reference. To overcome the reference problem and to enhance localized pheno-mena in the EEG, the local average reference was also computed (Pfurtscheller et al., 1994). From the continuously recorded and transformed EEG data (sampling frequency 128 Hz) stimulus or movement-synchronous epochs were extracted, bandpass filtered, squared and averaged over trials. This procedure results in an average band power time course with the percentage band
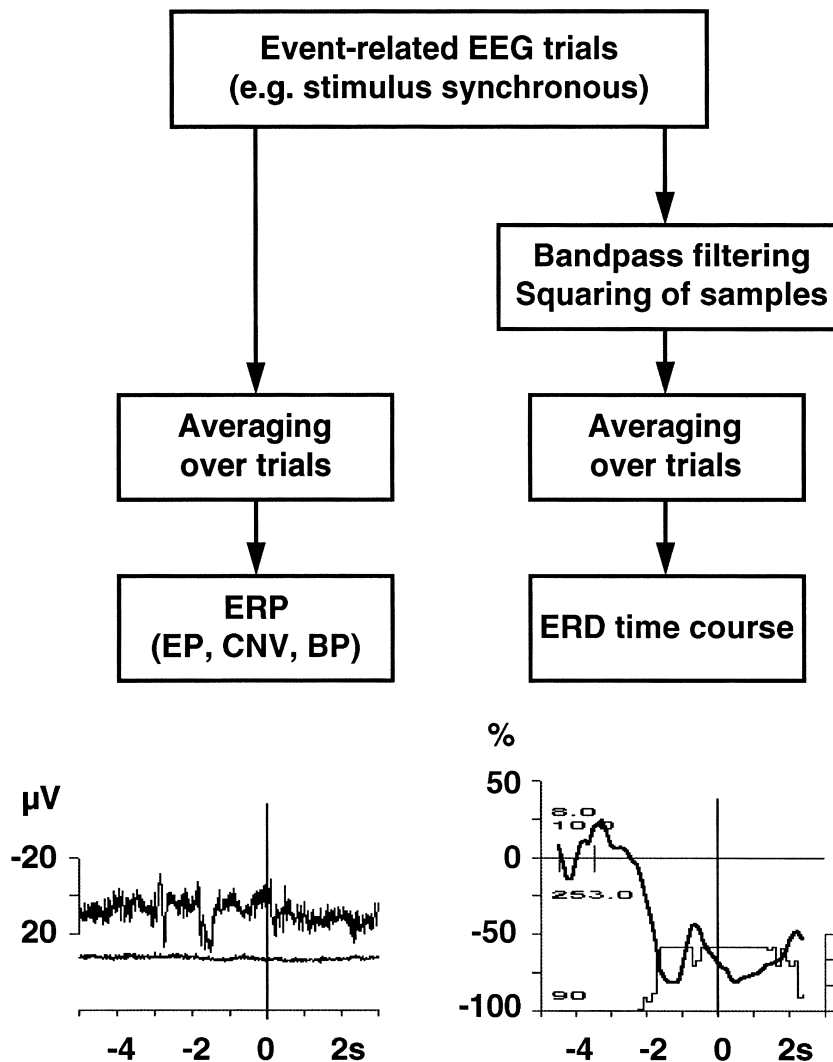

Fig. 1. Schema of ERP and ERD processing based on event-related EEG segments.

power increase (ERS) or decrease (ERD) determined in relation to a defined reference period. Further details about data processing are reported elsewhere (Pfurtscheller and Berghold, 1989; Pfurtscheller, 1991; Pfurtscheller et al., 1994).

In addition to band power time courses, coherence time courses between different electrode combinations were also calculated. Auto- (P_{xx}, P_{yy}) and cross-spectra (P_{xy}) were estimated by averaging the auto- and cross-periodograms of a 1-s windowed (Hanning) data segment across the N trials: $X_n(f)$ and $Y_n(f)$ denote the complex DFTs of the windowed data, with $*$ indicating the complex conjugate.

$$P_{xx}(f) = \frac{1}{N} \sum_{n=1}^{N} |X_n(f)|^2$$

$$P_{yy}(f) = \frac{1}{N} \sum_{n=1}^{N} |Y_n(f)|^2$$

$$P_{xy}(f) = \frac{1}{N} \sum_{n=1}^{N} X_n(f) Y_n^*(f)$$

A band-averaged squared-coherence value was then calculated as the normalization of the band-averaged cross-spectral power by the band-averaged auto-spectral power:

$$\text{Coherence:} \quad \text{COH}^2(\bar{f}) = \frac{|P_{xy}(\bar{f})|^2}{P_{xx}(\bar{f}) \; P_{yy}(\bar{f})}$$

$$0 \le \text{COH}^2(f) \le 1$$

To obtain a time course of coherence, the 1-s window was shifted in steps of 125 ms, from the start to the end of each trial. For each position of the windowed data segment, a band-averaged coherence value was calculated by the method described above. In this way, a time sequence of band-averaged coherence values, termed event-related coherence (ERCoh), could be obtained. The time index for each particular ERCoh value was taken as the mid-point of the window segment from which the coherence value was calculated (Andrew and Pfurtscheller, 1996).

Coherence measures the linear correlation between two signals at frequency f (for details see Jenkins and Watts, 1968). Higher order spectral analysis allows the detection of non-linear interrelations between frequency components. Quadratic phase coupling is detected by bispectral analysis for one signal; for quadratic relations between two signals cross-bispectral analysis is used (Kim and Powers, 1979; Ning and Bronzino, 1993).

Thus, in addition to coherence, bicoherence and cross-bicoherence were also calculated for 1-s Hanning windowed segments with averaging across the N trials:

Bicoherence

$$\text{BCOH}^2(f_1, f_2) =$$

$$\frac{|\sum_{1}^{N} X_n(f_1) \; X_n(f_2) \; X_n^* \times (f_1 + f_2)|^2}{\sum_{1}^{N} |X_n(f_1) \; X_n(f_2)|^2 \sum_{1}^{N} |X_n(f_1 + f_2)|^2},$$

$$0 \le \text{BCOH}^2(f_1, f_2) \le 1$$

Cross-bicoherence

$$\text{CBCOH}^2(f_1, f_2) =$$

$$\frac{|\sum_{1}^{N} X_n(f_1) \; Y_n(f_2) \times X_n^*(f_1 + f_2)|^2}{\sum_{1}^{N} |X_n(f_1) \; Y_n(f_2)|^2 \sum_{1}^{N} |X_n(f_1 + f_2)|^2},$$

$$0 \le \text{CBCOH}^2(f_1, f_2) \le 1$$

3. Finger movement

In the past it was generally believed that the central mu rhythm was present only in a relatively small population of normal subjects (Chatrian
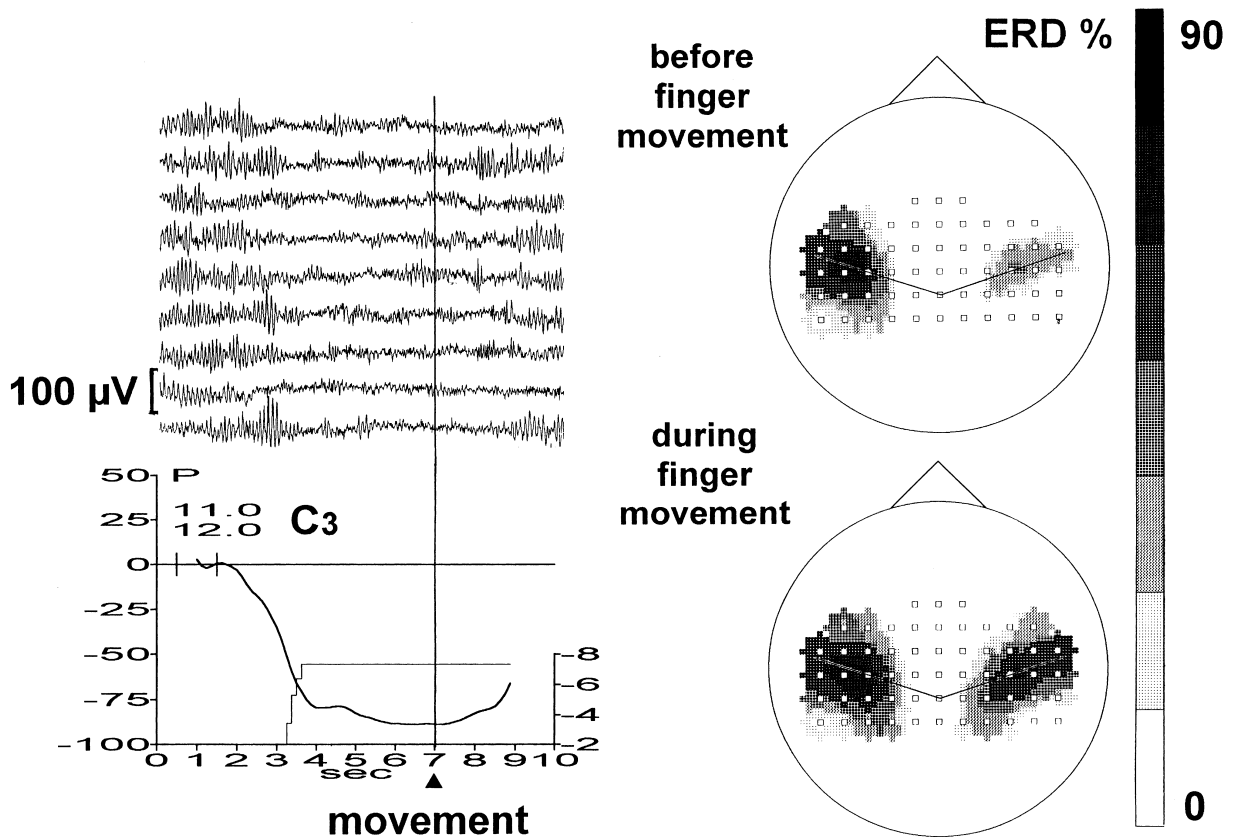
Fig. 2. *Left side*: Selected movement synchronous raw EEG trials of one subject and time course of 11–12 Hz percentage power changes during right finger movement (the reference interval from 0.5 to 1.5 s and trigger time point at 7 s are indicated). All data were obtained from electrode C3 overlying the left hand area. The ordinate displays relative band power changes (%). A positive number indicates a power increase, a negative number a power decrease. The step function in the diagram represents the statistical significance of the band power changes in steps of 10^{-2}. *Right side*: Corresponding ERD-maps computed for the 11–12 Hz band for time intervals of 125 ms starting 750 ms before and exactly with movement onset. Black indicates power decrease (max. 90%).

and Lairy, 1976). When computerized methods were used, a desynchronization of mu rhythms during hand movement was found in nearly every subject (Pfurtscheller and Aranibar, 1979; Pfurtscheller and Berghold, 1989; Derambure et al., 1993; Toro et al., 1994). Examples of single EEG trials, ERD maps computed before and during right finger movement, and band power as a function of time are displayed in Fig. 2. A series of ERD maps from left and right finger movement is shown in Fig. 3.

Sometimes, after the initial ERD, a rebound in the form of an ERS can be found after finger movement (Pfurtscheller, 1992) as similarly observed during visual processing (Pfurtscheller and Klimesch, 1992). The magnitudes of ERD and ERS depend on the amplitude of rhythmic activity during rest. If there are no alpha waves during rest, no ERD can be found. The interaction of ERD and ERS during finger movement can be seen in Fig. 4.

An interesting observation was made by Derambure et al. (1993) when comparing the ERD of young and elderly subjects during self-paced wrist movement. They found a smaller and more laterally localized ERD in young subjects compared
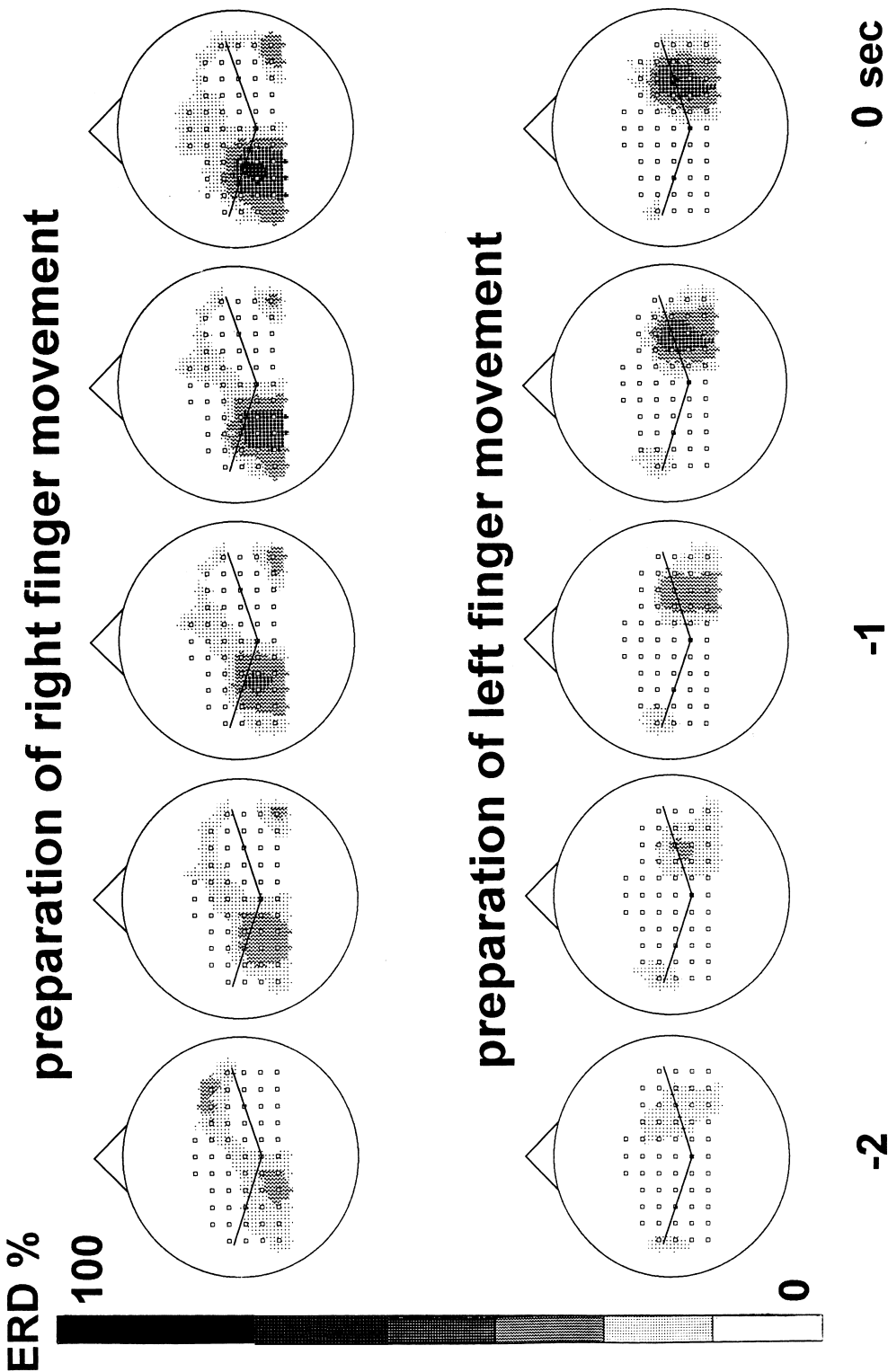
Fig. 3. Serial ERD-maps computed for the 10–12 Hz band preceding right finger (upper row) and left finger movement (lower row). The maps are calculated in time intervals of 0.5 s starting 2 s before movement onset. Scale of ERD in percentage, data of one subject.

with a more bilateral and widespread ERD, which also included premotor areas, in elderly subjects. This may be interpreted as indicating that in young subjects, the extent of the cortical area desynchronized during preparation for movement is more limited; the preparatory process would be more efficient with only a small neuronal population involved. With increasing age, the preparatory process would involve more neurons and the circuitry engaged in this process would spread to both hemispheres. This interpretation is consistent with results showing a larger ERD with increasing task-complexity where also more pro-

cessing is necessary (Van Winsum et al., 1984; Dujardin et al., 1993).

4. Foot movement

In contrast to hand or finger movement, a foot movement-related desynchronization can occasionally be found close to electrode Cz overlying the primary foot representation area. Such an example from one subject is shown in Fig. 5 along with some selected single EEG trials, the average power as a function of time and two ERD maps. As can be seen, the ERD is focused to the foot area and found not only within the alpha, but also the lower beta band around 20 Hz.

When the same subject performed brisk finger flexions and extensions, the ERD prior to movement was focused over the contralateral side (see Fig. 2). These results give evidence of the existence of not only a 'hand area mu rhythm' but also a 'foot area mu rhythm'. In addition, also a 'face area rhythm' can be expected, which is blocked by face movement, but not by finger or foot movement. This was already shown by Jasper and Penfield (1949) and recalled by Arroyo et al. (1993) in patients with an array of subdural electrodes over sensorimotor areas. Hence, we can speculate that a variety of central mu rhythms exist. Each primary sensorimotor area may have its own intrinsic rhythm, which is blocked or desynchronized when the corresponding area becomes activated.

5. Enhancement of hand area mu rhythms

It was shown that different types of visual input can enhance central mu rhythms. Brechet and Lecasble (1965) reported an enhanced mu rhythm during flicker stimulation, Koshino and Niedermeyer (1975) reported on enhanced (synchronized) Rolandic rhythms during pattern vision in 33 out of 61 subjects. Recently it wasdemonstrated that foot or tongue movement can
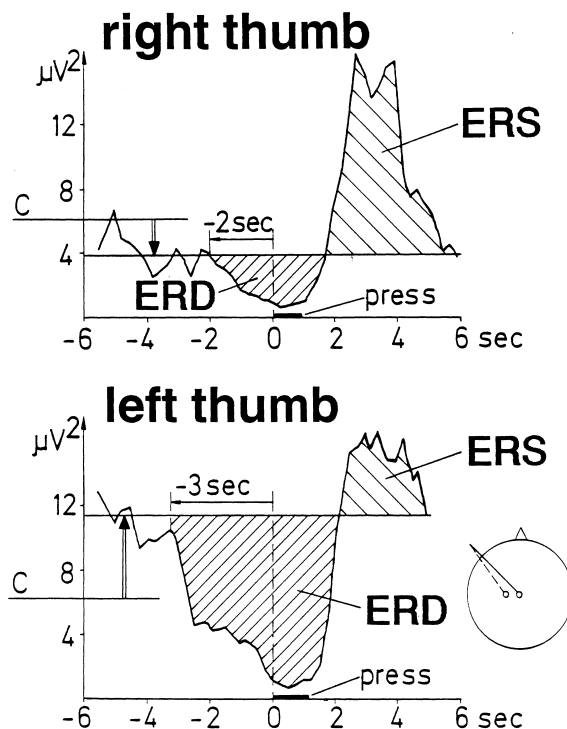

Fig. 4. Examples of alpha power time courses calculated from a bipolar EEG record over the left central region during voluntary movement (pressing a microswitch with the right (*above*) and left thumb (*below*)). The average alpha power calculated during rest is indicated by a short horizontal line marked with C. It can be seen in the figure that the magnitude of reference power (indicated by a horizontal line over the 12-s epoch) was different during right and left thumb movements. As a result of this the ERD is shorter lasting and smaller but the ERS longer lasting and larger during right than left thumb movement (modified from Pfurtscheller, 1992).
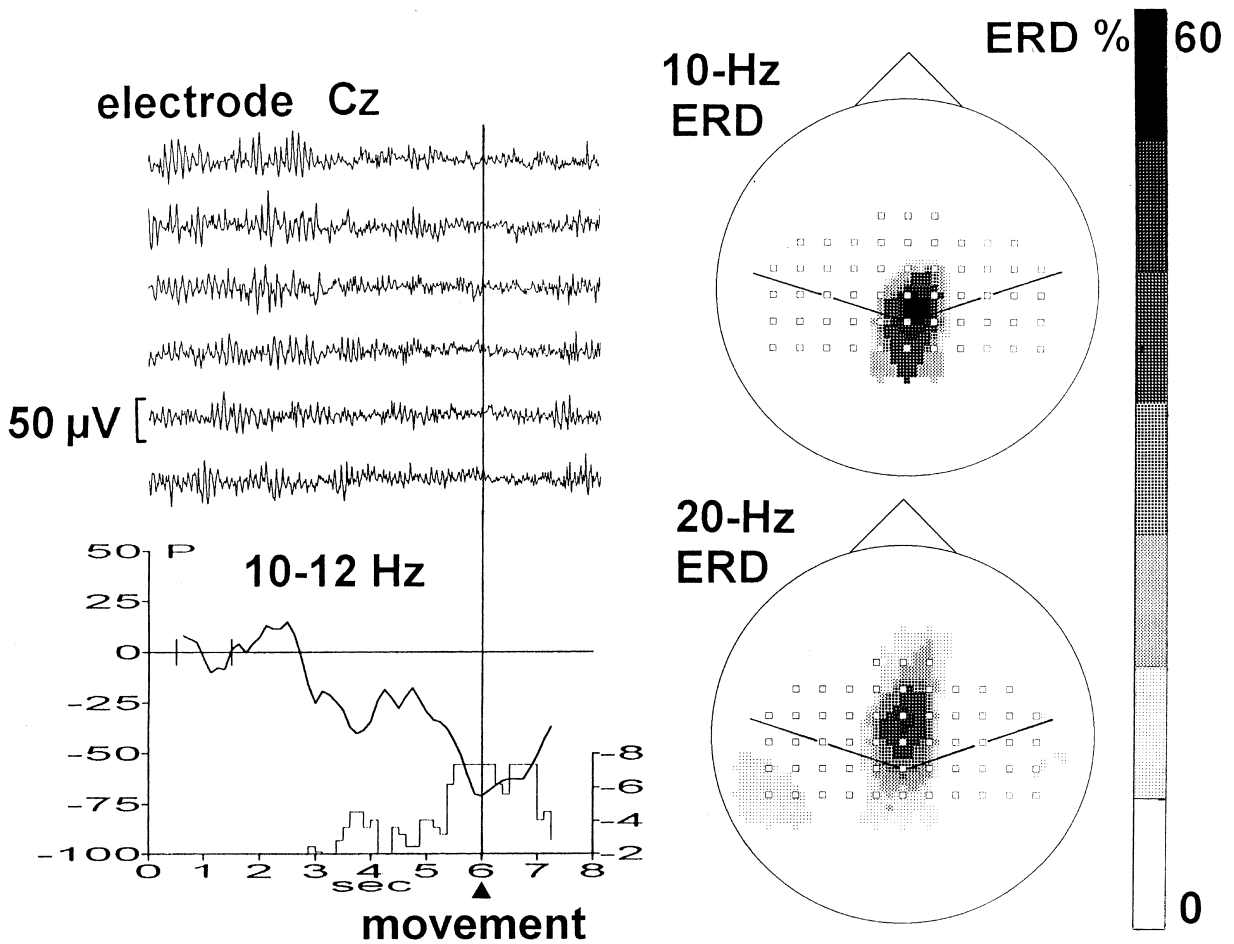
Fig. 5. *Left side*: Selected movement synchronous raw EEG trials of one subject and time course of 10–12 Hz percentage power changes during foot movement (the reference interval from 0.5 to 1.5 s and trigger time point at 6 s are indicated). All data were obtained from electrode Cz (vertex). *Right side*: Corresponding ERD-maps calculated for the 10–12 Hz and 20–24 Hz bands for a time interval of 125 ms before movement onset. Black indicates power decrease (max. 60%).

also enhance the hand area mu rhythm (Pfurtscheller and Neuper, 1994). Common to all these observations is that in the case of visual processing or foot (tongue) movement, the hand area is not involved, and therefore may be in an idling state. In this context it is of interest to refer to Gastaut (1952) who speculated that the mu rhythm is an expression of an inhibition of sensorimotor areas. Data on such enhanced or synchronized mu rhythms are displayed in Fig. 6. It can be seen from the maps that the enhancement

is localized over right and left primary sensorimotor hand areas.

The behavior of hand area mu rhythms during finger, foot and tongue movement was investigated in three subjects (Pfurtscheller and Neuper, 1994). Superimposed band power time courses from three subjects measured at electrode C3 (Fig. 7) show that synchronization and desynchronization can be found at the same electrode, depending on which type of movement is performed. There is strong evidence that this syn-
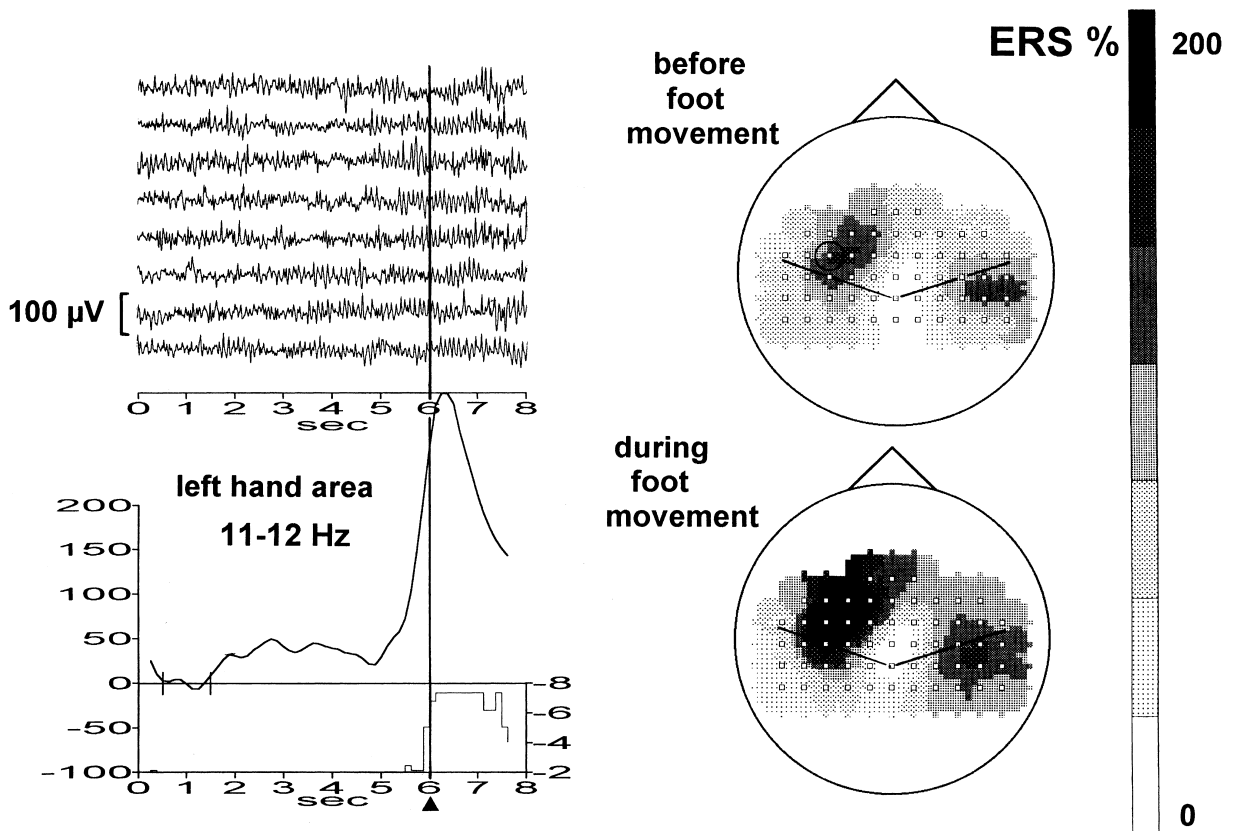
Fig. 6. *Left side*: Selected movement synchronous raw EEG trials of one subject and time course of 11–12 Hz percentage power changes during foot movement (the reference interval from 0.5 to 1.5 s and trigger time point at 6 s are indicated). All data were obtained from one electrode overlying the left hand area (2.5 cm anterior to C3) as indicated on one map on the right. *Right side*: Corresponding topographical display of 11–12 Hz power changes for time intervals of 125 ms starting 750 ms before and exactly with movement onset. Black indicates power increase (max. 200%; modified from Pfurtscheller and Neuper, 1994).

chronization is dominant in the upper alpha band and in frequency ranges around 14 Hz. This synchronization is short-lasting (phasic) and very often appears to be spindle-like.

The data of one subject were used to calculate a compressed spectral array to demonstrate that mu rhythms can be desynchronized or synchronized on the same scalp location depending on the type of movement (Florian and Pfurtscheller, 1995). Overlapped 1-s segments were fitted by autoregressive models of order 11 and the resulting spectra are plotted in a three-dimensional array. A comparison of spectra calculated for

electrode C3 during hand movement (Fig. 8 lower panel) and foot movement (Fig. 8 upper panel) shows a dominant spectral peak in the latter case.

6. Coupling between primary hand area and SMA

Along with the primary sensorimotor (MI/SI) and premotor areas, the supplementary motor area (SMA) also plays an important role in preparation or planning of movement (Roland, 1984; Goldberg, 1985). In addition to a localized ERD over the contralateral primary sensorimotor area, a localised ERD of EEG signals recorded close to

the SMA has also been found prior to voluntary self-paced finger movement (Pfurtscheller and Berghold, 1989), and suggests the possibility that the SMA also has its own intrinsic rhythm within the alpha band. Therefore, a first attempt was made to analyze phase-coupling between alpha band rhythms in the primary hand area and the SMA. In addition, coherence was calculated between left and right primary hand areas (C3 and C4), as previous work by Storm van Leeuwen et al. (1978) and Schoppenhorst et al. (1980) showed a lack of phase coupling between the mu rhythms of left and right sensorimotor areas, demonstrating that the mu rhythm generators in each hemisphere are independent.

The time course of alpha band coherence between left and right sensorimotor areas (Fig. 9, upper panel) shows low values throughout, as expected from the findings of Storm van Leuwen et al. and Schoppenhorst et al. In contrast to this, however, a squared coherence of about 0.6 is found between electrodes overlying SMA and primary hand areas during rest (first 2 s of each trial; Fig. 9, lower panel). The latter can be interpreted as a linear phase coupling between hand area mu rhythms and SMA rhythms, or in other words, the existence of coherent alpha band activity in primary sensorimotor and supplementary motor areas. Hand movement results in a desynchronization of these rhythms and a decrease of coherence.

To investigate the possibility that the high coherence found between the MI/SI area and the SMA was due simply to a volume conduction effect (i.e. that both electrodes picked up activity from the same brain area), coherence was calculated between an electrode overlying the MI/SI area (electrode 37), and all electrodes up to the SMA (i.e. between electrodes 37 and 27 (3.5 cm), 37 and 17 (7.0 cm) and between 37 and 8 (10.5 cm)). Results obtained for the same subject from three different recording sessions show that the
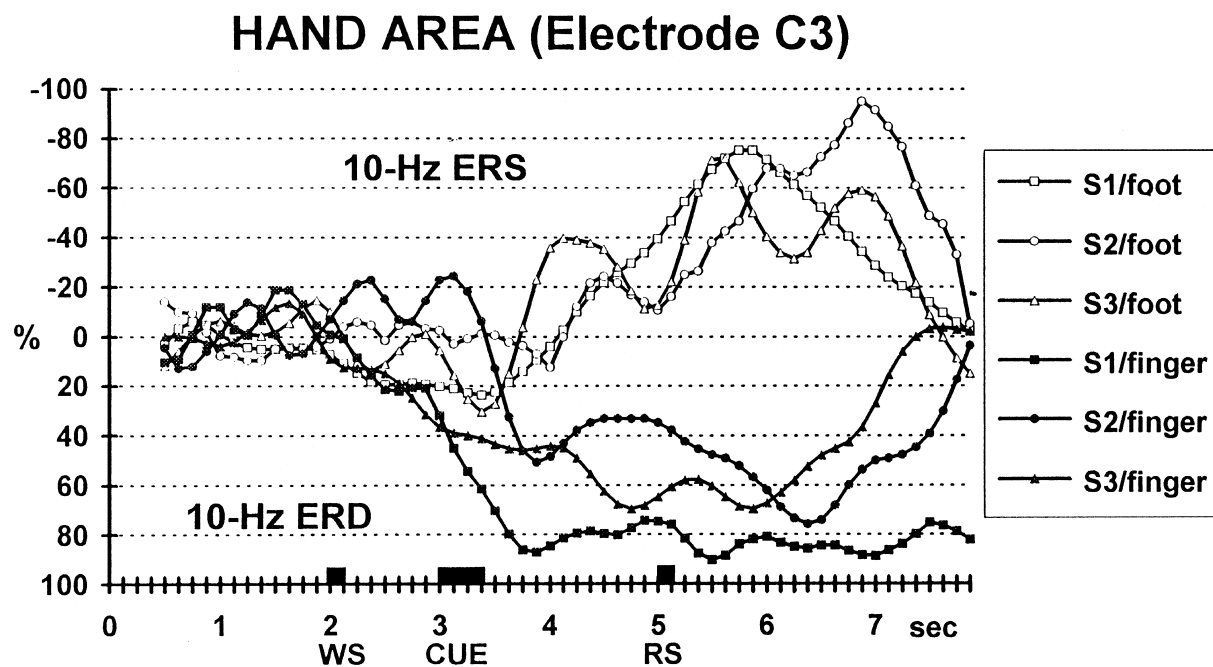

Fig. 7. Superposition of band power time courses of three subjects, recorded from electrode C3 during foot and finger movement, respectively. The CUE informed the subject which movement had to be made and the reaction stimulus (RS) indicated the start of movement (modified from Pfurtscheller and Neuper, 1994).
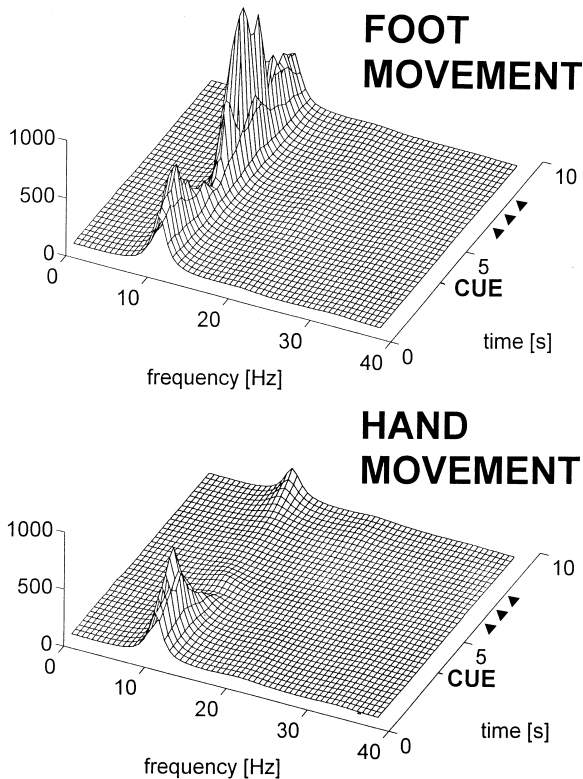
Fig. 8. Compressed power spectra calculated with an autoregressive model of order 11 during hand (*lower panel*) and foot movement (*upper panel*) for electrode C3. Timing of presentation of the CUE and execution of movement is indicated (for explanation see Fig. 7).

coherence first decreases with distance, and then increases again (Fig. 10). This result therefore rules out a volume conduction effect, and it is hypothesized that the coherence between the SMA and MI/SI is due to cortico–cortical connections and/or mutual influence from an underlying structure such as the thalamus. Preparation and execution of finger movement disrupts these cortico–cortical connections and/or the common pacing influence, and results in a decrease of the functional coupling between these areas.

An interesting question is whether the systems generating the hand area mu rhythm or the SMA rhythm have non-linear properties that may be revealed as harmonically related frequency com-

ponents. In this way a non-linear coupling between alpha and beta band components should exist. To investigate this, we used bicoherence measurements and found that central beta and mu rhythms demonstrate a quadratic phase coupling (Fig. 11). This is in agreement with the work of Dumermuth et al. (1971) on central mu rhythms and may help to interpret the arcadic shape of the mu rhythm.

For the investigation of quadratic phase coupling between SMA and primary hand area, the cross bicoherence (Ning and Bronzino, 1993) was calculated. It was found that the alpha band rhythms over the SMA are quadratically phase coupled with central beta rhythms (Fig. 12). This finding indicates that the SMA has an influence on beta rhythms in the primary hand area.

7. Conclusion

Topographical analysis of scalp EEG data with closely spaced electrodes during discrete finger and foot movements leads us to formulate the following conclusions:

1. Primary hand and foot areas have their own intrinsic rhythmic activity (mu rhythms, central beta rhythms) which desynchronize when the corresponding area becomes activated. Hand movement results in a desynchronization of mu and central beta rhythms close to the hand area in nearly every subject. A circumscribed desynchronization of mu and/or beta rhythms localized close to the vertex during foot movement is found only in some subjects.
2. Foot movement may not only result in a desynchronization close to the foot area but can produce an enhancement of hand area mu rhythms. This means that ERD (over the foot area) and ERS (over the hand area) can be found in parallel. The enhancement of hand area mu rhythms is not only found during foot movement but also during visual processing (Koshino and Niedermeyer, 1975;
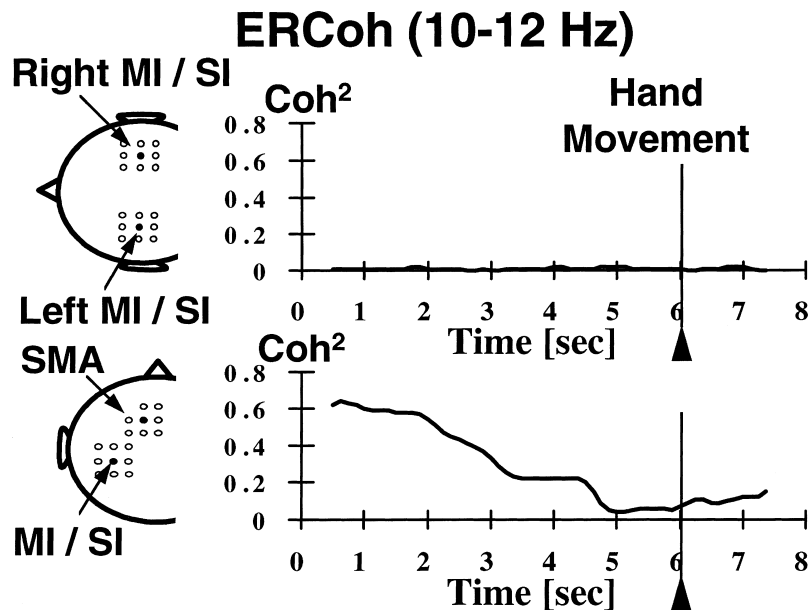
ERCoh (10-12 Hz)

Fig. 9. Event-related coherence plots during preparation and execution of right finger movement. Coherence was calculated between both primary hand areas (electrodes C3 and C4 *upper panel*) and between SMA and left hand area (*lower panel*). The electrodes used for calculation of the local average reference and the electrodes used for coherence calculation (black dots) are indicated on the left side.

SPATIAL COHERENCE (10-12 Hz)

June 1993
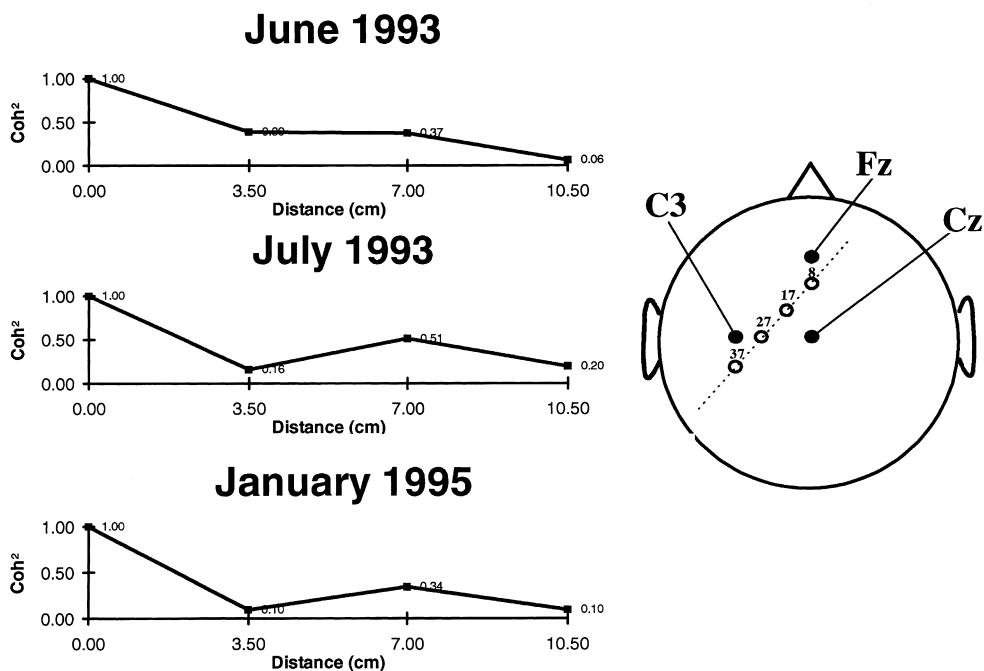
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Fig. 10. Coherence (10–12 Hz) calculated between electrodes located on a line connecting the electrode 2.5 cm behind C3 and the electrode 2.5 cm behind Fz (see insert on the right side). These measurements were made during rest on one subject on three different days. It can be seen that the coherence is not decreasing continuously with increasing distance.
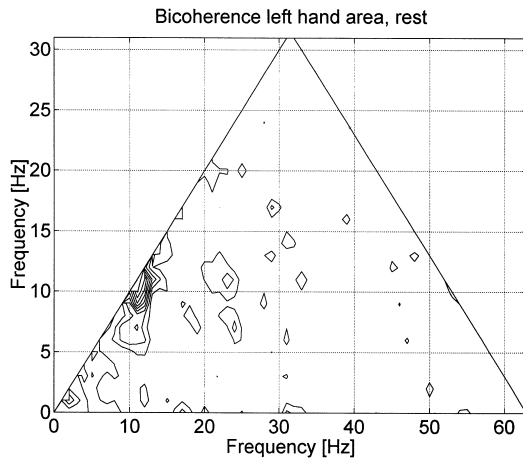
Bicoherence left hand area, rest

Fig. 11. Two-dimensional isocontour plot of the bicoherence with a step size of 0.05; x-axis and y-axis show the frequency in Hertz. The value at the crosspoint ($0 \leq$ value ≤ 1) of a frequency pair indicates the amount of quadratic phase coupling (QPC). The squared bicoherence value of 0.45 at the frequency pair 11 and 11 Hz, indicates that the frequencies of 11 and $11 + 11 = 22$ Hz are indeed phase coupled. The region within the straight lines is the sufficient region for evaluating the bicoherence.

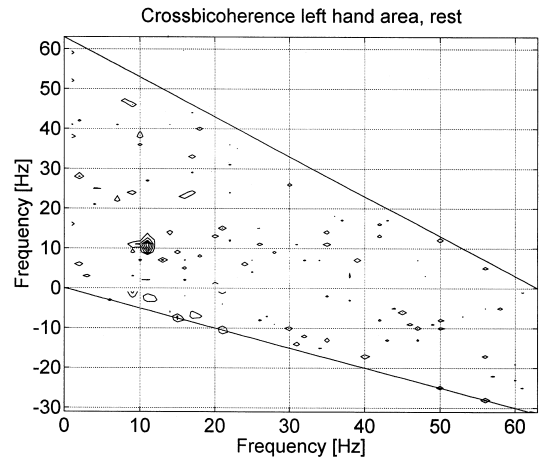Crossbicoherence left hand area, rest

Fig. 12. Two-dimensional isocontour plot of the cross-bicoherence with a step size of 0.05; x-axis and y-axis show the frequency in Hertz. Again, the value at the crosspoint ($0 \leq$ value ≤ 1) of a frequency pair indicates the amount of QPC. The squared cross-bicoherence value of 0.3 at the frequency pair 11 and 11 Hz, indicates that the frequency of 11 Hz of the SMA signal and the frequency of $11 + 11 = 22$ Hz of the M1/S1 signal are quadratically phase coupled.

Pfurtscheller, 1992) and may be explained as an electrophysiological correlate of a temporary resting or idling hand area.

3. A mu-like rhythm was found in the EEG recorded from electrodes overlying the SMA. This rhythm was coherent (high coherence) with the hand area mu rhythm during rest and desynchronized during hand movement. This gives support to the assumption that the SMA also has its own intrinsic rhythmic activity.

Acknowledgements

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