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# EEG Spectral Characteristics during Voluntary Motor Activity

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EEG spectral characteristics were studied in 11 essentially healthy volunteers during performance of unfamiliar finger movements with both hands with a voluntary rhythm. As compared with the resting state, preparation and performance of voluntary movements occurred on the background of decreased activation levels in almost all areas of the cortex except the right frontal area, where the EEG showed a clear increase in the power of fast (especially γ) frequencies regardless of which hand was used to perform the movements. This may be evidence for the direct involvement of this area in the processes underlying the planning, initialization, and control of voluntary movement activity.

**Keywords:** voluntary motor activity, EEG, spectral analysis, interhemisphere asymmetry, multifactorial analysis of variance.

Increasing attention in recent years has been paid to studies of the electrographic correlates of psychomotor activity. The stress is not on movements actually performed, but on their mental (ideomotor) equivalents. These are to a significant extent related to attempts to create a new channel of communication with the outside world, i.e., so-called brain-computer interfaces (BCI) [Kiroi, 2011; Hoffer et al., 1996; Kubota et al., 2000; Dornhege et al., 2007]. However, the effectiveness of BCI systems is currently low [Wolpaw et al., 2002; Birbaumer, 2006]. This technology was originally targeted at paralyzed people who had lost the ability to communicate with the external world via natural communication channels, but had retained their intellect [Pfurtscheller et al., 2000; Dobkin, 2007; Tan and Nijholt, 2010]. It is now clear that the creation of effective systems using this technology has also allowed other problems to be addressed, thus potentially providing humans with a fundamentally new channel for communication and control of various types of technical apparatus [Kiroi, 2011; Tan and Nijholt, 2010].

Performance of limb movements is known to be linked with the formation at the EEG level of a phenomenon known as "event-related desynchronization" or evoked response desynchronization (ERD) [Gao et al., 2013; Pfurtscheller and Lopez da Silva, 1999]. This phenomenon is most marked in the hemisphere contralateral to the limb (particularly the hand) performing the movement [Pfurtscheller and Neuper, 2003]. The task of identifying patterns of activity associated with the performance of movements with the fingers is significantly more difficult. Analysis of the EEG has not yielded any significant markers allowing movements of individual fingers to be classified. However, complex analysis of electro- and magnetoencephalograms has demonstrated the existence of specific potentials preceding movements performed with the fingers, particularly in the γ frequency range [Quandt et al., 2011]. The effectiveness with which patterns corresponding to finger movements could be identified using classifiers run on artificial neural networks (ANN) was more than 70% [Mohamed et al., 2011]. As this study was performed using a stimulus-response paradigm and was oriented to BCI technology, questions relating to the mechanisms and correlates of voluntary initialization and control of the performance effectiveness of motor activity were beyond its remit. Thus, studies of electrographic correlates and the neurophysiological mechanisms of voluntary motor activity in humans remain relevant in both theoretical and applied aspects.

As we and other authors have demonstrated [Kiroi et al., 2010; Rodriguez et al., 2008; Miller et al., 2010], EEG

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patterns recorded during real and mental performances of elementary hand movements are quite similar and are associated with, inter alia, the $\gamma$ frequency range, which is regarded as an electrographic correlate of specific information processes occurring in local neuronal ensembles [Dumenko, 2006; Kiroi and Belova, 2000; Pfurtscheller et al., 1997; Tallon-Baudry et al., 1998]. We did not find any clear differences between the EEG patterns recorded during performance of different movements of the same hand. This may be because we (like other authors) studied elementary, to a significant extent automated, movements, whose execution may not require the active involvement of extensive areas of the cortex.

The aim of the present work was to study temporospatial EEG patterns formed on execution of unfamiliar movements of the fingers of both hands.

**Methods**

A total of 11 essentially healthy volunteers (six male, five female; students at the Southern Federal University, right-handed, mean age 20 years) took part in the study after providing written consent. During the study, the participants were placed in a light- and sound-proofed chamber, in a comfortable posture in a chair, with a low level of illumination. Without taking the hands or the fingers not involved in the movement off the surface of the table, each subject had to perform six movements with the fingers of the right or left hand: raising and lowering the ring finger; raising the index finger and moving it right to left twice; raising and lowering the index and ring fingers together; raising the middle finger and using it to trace out the letter *я*; moving the ring and little fingers together to one side and returning to the original position; bending and straightening the little finger. These movement acts are rarely used in daily life, so their performance is not automated, such that they must require a high level of control from cortical structures, which may be reflected in the dynamics of their activity.

Performance of movements of each of these types was preceded by delivery of instructions. These were displayed on a computer screen positioned at a distance of 1 m at the subject's eye level for 20 sec and then replaced by a gaze fixation point (a white cross of size 1 × 1 cm at the center of a black screen), this serving as a signal to commence work. The subject had to perform the specific movement for 1 min at a voluntary rhythm with short intervals, without lifting the hand from the support.

EEG recordings were made continuously throughout the study, using a monopolar method in the 10/20 system from 14 symmetrical leads: *F3*, *F4*, *F7*, *F8*, *C3*, *C4*, *T3*, *T4*, *T5*, *T6*, *P3*, *P4*, *O1*, and *O2*. Reference electrodes (combined reference) were positioned on the earlobes. Additionally, bipolar recordings were made of the electrooculogram (EOG) and electromyogram (EMG) from the wrists of both hands. The EOG was used to identify blink artifacts and the EMG to define the boundaries of EEG segments corresponding to the movement preparation and execution stages. EEG, EOG, and EMG recordings were used using an Entsefalan bioamplifier (Medikom, Taganrog, Russia). The signal digitization frequency was 250 Hz for each channel and the bandpass was 0.5–70 Hz. A rejection filter (50 Hz) was also used to remove mains noise.

Artifact-free segments of EEG traces of duration 1 sec recorded at rest with the eyes open (EO) immediately preceding the beginning of the myographic response (the initialization or preparation stage, P) and during movement execution (M), both of which generally last more than 1 sec, were analyzed. Each study included analysis of 550–900 1-sec EEG fragments, each of which was analyzed by fast Fourier transformation (FFT) on the Entsefalan system; spectral power (SpP) was calculated for six frequency ranges corresponding to the $\theta$ (4–7 Hz), $\alpha$ (8–13 Hz), $\beta_1$ (14–19 Hz), $\beta_2$ (20–30 Hz), $\gamma_1$ (31–48), and $\gamma_2$ (52–70 Hz) rhythms.

Significant differences between states were evaluated using SpP by multifactorial analysis of variance (ANOVA/MANOVA) run on Statistica 5. Approximations of the initial data to a normal distribution were improved by using a log transformation. The following factors were identified: STATE (S, levels: EO, P, M), HAND (H, levels: left (Lh) and right (Rh) alone and in combination with the P and M states: LP, LM, RP, RM), LEAD (L, levels: 14 leads), and RHYTHM (R, levels: six frequency ranges). The last two factors were regarded as dependent, the others as independent. Differences were regarded as significant at $p \le 0.05$ and as showing a strong trend at $0.05 < p \le 0.08$. Percentage changes in parameters were normalized relative to the first state in the pair under comparison.

The nature of interhemisphere differences for each EEG epoch and each EEG lead and frequency range was evaluated by calculating coefficients of asymmetry ($K_{as}$) as $K_{as} = (Lead_d - Lead_s)/(Lead_d + Lead_s) \times 100\%$, which were then analyzed by analysis of variance. Positive values for $K_{as}$ indicated greater power in the leads on the right side (d), while negative values indicated greater power on the left hemisphere (s).

**Results**

Three-factor MANOVA analysis of SpP showed that overall, EEG recordings made in the state of calm waking with the eyes open had spectral characteristics which were significantly different from those recorded in the P and M states (Table 1).

It should immediately be noted that the existence of significant differences in terms of the L and R factors and the L × R interaction reflected the well-known regional and frequency characteristics of the human EEG, which have been described in the literature [Kiroy et al., 1996]; these will not be analyzed further in present study.

Detailed analysis of the results obtained using two-factor analysis showed that as compared with EO, changes in both P and M were linked with reductions in EEG SpP in virtually all leads with the exception of the right frontal lead, where, conversely, there was an increase (Fig. 1). Uni-

TABLE 1. Comparative Analysis of EEG Spectral Characteristics Recorded in 11 Subjects the Rest and during Preparation and Execution of Non-Standard Movements with the Fingers

| Source of variation | EO–P | | | | EO–M | | | | P–M | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *df* | | *F* | *p* | *df* | | *F* | *p* | *df* | | *F* | *p* |
| | effect | error | | | effect | error | | | effect | error | | |
| S | 1 | 3433 | **27.9** | **0.00** | 1 | 3571 | **30.1** | **0.00** | 1 | 6376 | 0.0 | 0.98 |
| L | 13 | 44629 | **250.8** | **0.00** | 13 | 46423 | **247.7** | **0.00** | 13 | 82888 | **1687.7** | **0.00** |
| R | 5 | 17165 | **1944.1** | **0.00** | 5 | 17855 | **1911.1** | **0.00** | 5 | 31880 | **11677.2** | **0.00** |
| S × L | 13 | 44629 | **12.6** | **0.00** | 13 | 46423 | **11.0** | **0.00** | 13 | 82888 | **11.0** | **0.00** |
| S × R | 5 | 17165 | **21.3** | **0.00** | 5 | 17855 | **15.7** | **0.00** | 5 | 31880 | **29.6** | **0.00** |
| L × R | 65 | 223145 | **202.4** | **0.00** | 65 | 232115 | **213.1** | **0.00** | 65 | 414440 | **1094.5** | **0.00** |
| S × L × R | 65 | 223145 | **8.2** | **0.00** | 65 | 232115 | **13.1** | **0.00** | 65 | 414440 | **13.0** | **0.00** |

**Notes.** *df* (effect and error) – numbers of degrees of freedom; *F* – Fisher's test; *p* – significance; significant differences ($p < 0.05$) are shown in bold.

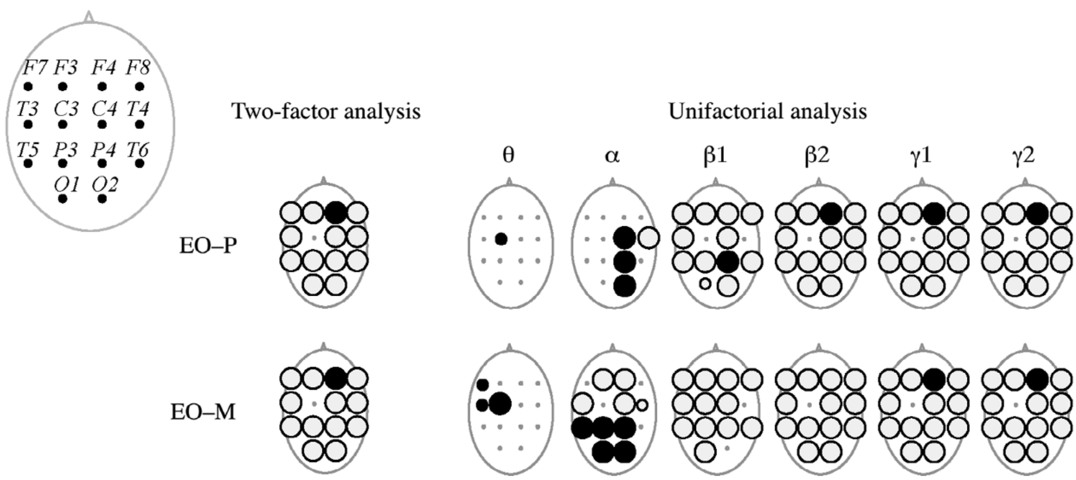


Fig. 1. Diagrams showing changes in EEG spectral power (SpP) at the preparation (P) and execution (M) stages (compared with EO). Black circles show increases in SpP; light circles show decreases; large circles show significant differences ($p \leq 0.05$); small circles show trends ($0.05 < p \leq 0.08$).

factorial analysis showed that this increase was associated with a significant increase in SpP in the rapid (β and γ) frequencies (Fig. 1). Changes at lower frequencies were considerably less marked. The EEG of the central, parietal, and occipital areas of the right hemisphere during P showed mainly an increase in the SpP of the α frequencies. During M, an increase in SpP in the α frequencies range was seen mainly on EEG traces from the posterior (parietal-occipital) leads, while the anterior leads (frontal, temporal, and central) showed decreases, with minor increases in power in the θ frequencies in the left hemisphere leads.

Separate analyses of EEG epochs recorded during the preparation and movement execution phases for the different hands showed (Fig. 2) that overall (as compared with EO), the nature of the rearrangements observed did not depend on which hand was used.

At the level of the S effect, the EEG spectral characteristics recorded in P and M were not significantly different (Table 1), though significant S × L and S × R interactions pointed to significant spatial and frequency differences between these states. Detailed analysis of the results showed that in M (as compared with P), there was an increase in the SpP of the γ frequencies (especially $\gamma_2$) on the background of a decrease in power in the α and $\beta_1$ rhythms mainly in the anterior leads (Fig. 3). Only the occipital areas showed a significant increase in SpP in all (except θ) frequency ranges.

As compared with the movement preparation stage, execution of movements with both the right and left hands led to generally similar spatial-frequency rearrangements in the EEG. The only difference was that EEG changes on performance of movements with the left hand were less marked and more asymmetrical: changes were seen predominantly in the leads on the ipsilateral (left) hemisphere at the α and $\beta_1$ frequencies.

EEG spectral characteristics recorded during execution of movements with the different hands differed more significantly ($F_{Rh\text{-}Lh}$ (1; 6376) = 19.199; $p = 0.000$). Execution of movements with the left hand led to marked re-

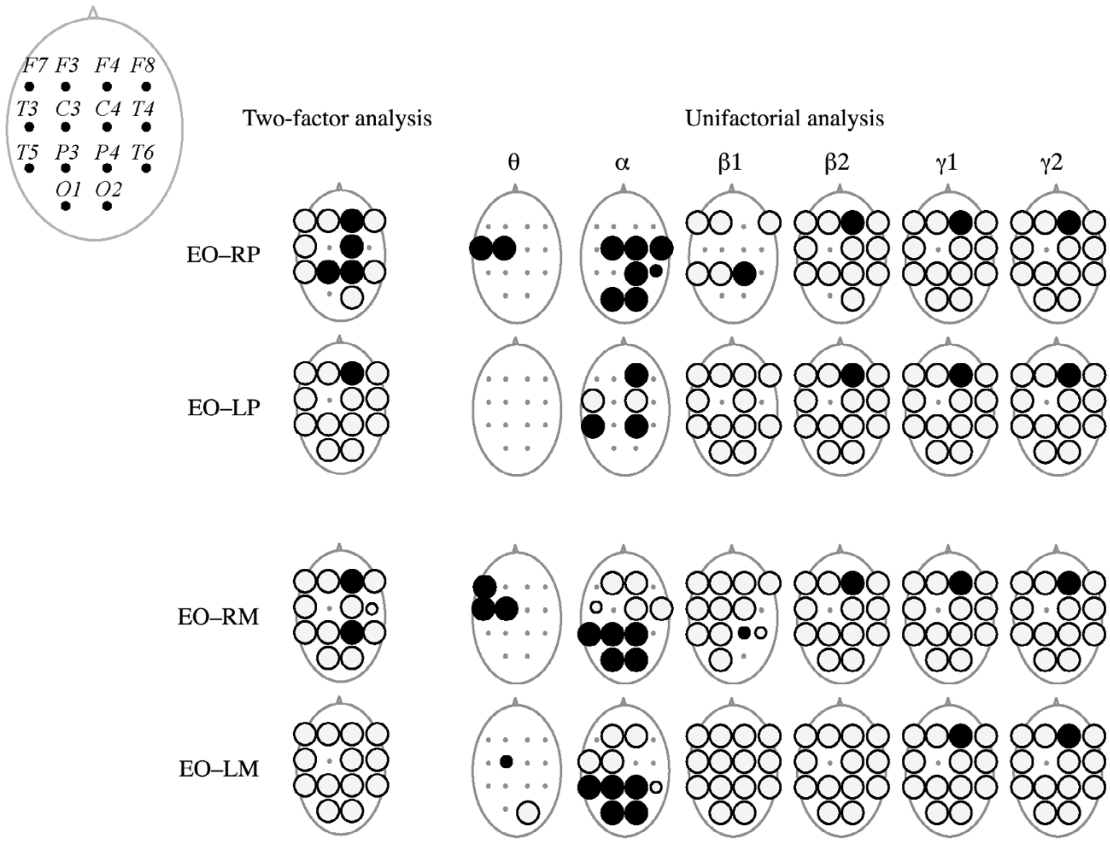


Fig. 2. Diagrams showing comparative analysis of EEG SpP recorded during preparation and execution of movements with the different hands (compared with EO). RP – preparation stage for right hand movement; RM – right hand movement; LP and LM – the same for the left hand. For further details see caption to Fig. 1.

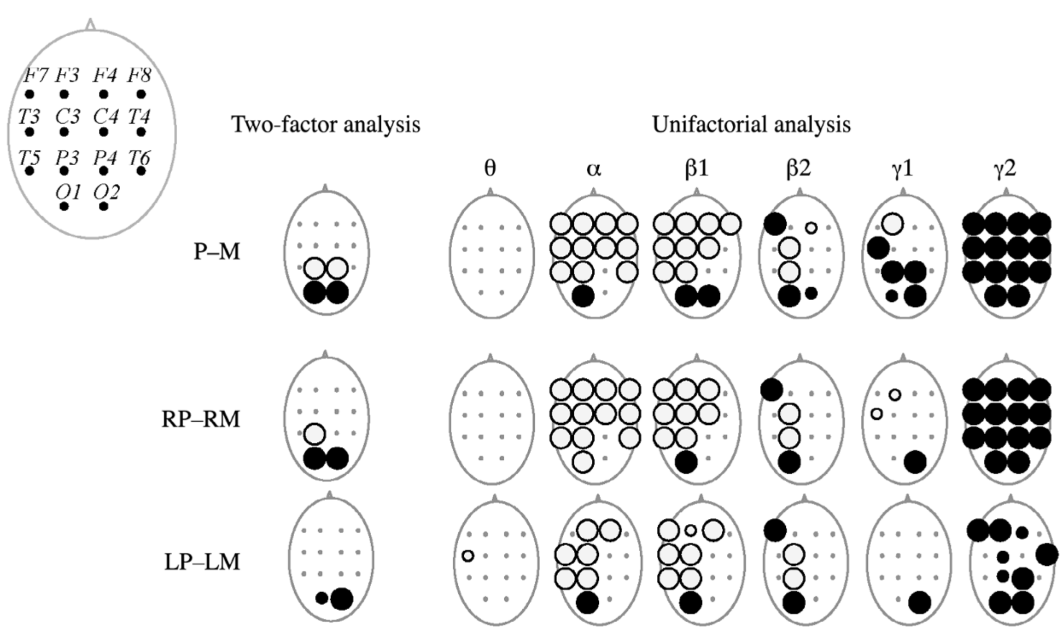


Fig. 3. Diagrams showing differences between EEG spectral characteristics recorded at the P and M stages. For further details see captions to Figs. 1 and 2.

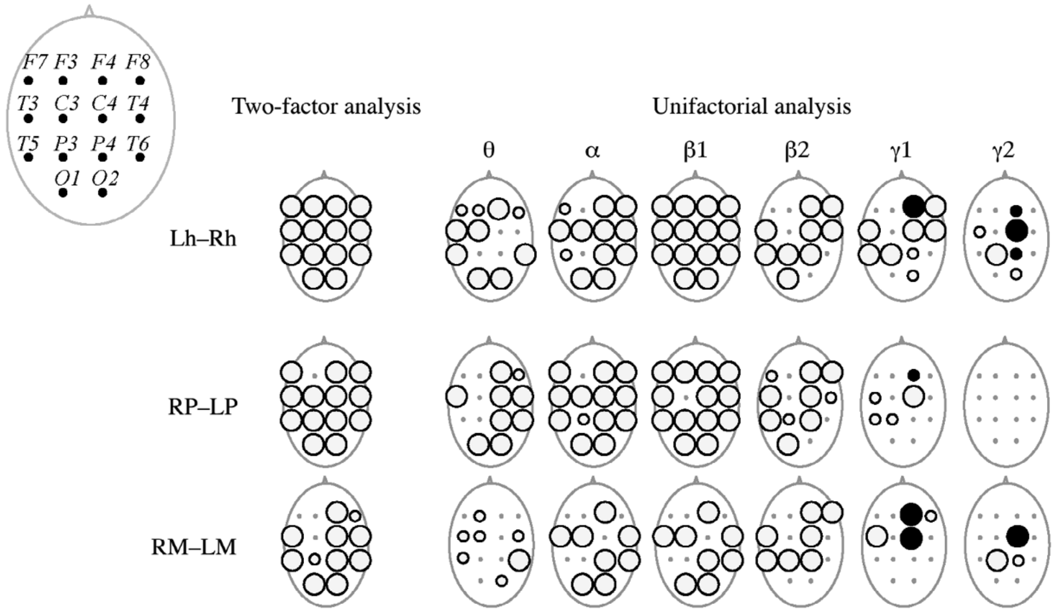


Fig. 4. Diagrams showing differences between EEG spectral characteristics recorded on preparation and execution of movements with the left (Lh) and right (Rh) hands. For further details see captions to Figs. 1 and 2.

ductions in SpP in virtually all EEG rhythms and over the whole brain (Fig. 4). The exception was the $\gamma_2$ frequency range, where SpP during execution of movements of the left hand was greater in the frontal, central, and parietal leads of the right hemisphere.

Comparative analysis showed (Fig. 4) that significant differences in the extents of the EEG frequency ranges analyzed during performance of movements with the two hands were seen at both the preparation ($F_{RP\text{-}LP}$ (1; 3118) = 12.543; $p$ = 0.001) and execution ($F_{RM\text{-}LM}$ (1; 3256) = 7.009; $p$ = = 0.008) stages. Movement preparation and execution wit left hand as compared with the right) occurred on the background of a more marked decrease in the SpP in the α and β frequencies in virtually all leads and in the θ range mainly in the right hemisphere leads and in the $\gamma_1$ range in the left. Execution of movements with the left hand occurred with less marked and more diffuse decreases in the SpP of the θ, α, $\beta_1$, and $\beta_2$ frequency ranges and was accompanied by more marked increases in the SpP of the γ1 and $\gamma_2$ frequencies in the EEG of the frontal and central areas of the right hemisphere.

Analysis of $K_{as}$ values showed that both preparation and performance of movements (as compared with EO) were linked with marked shifts in interhemisphere relationships to the right over a quite wide range of fast frequencies (from $\beta_1$ to $\gamma_2$; Fig. 5). However, this shift differed in some frequency bands and leads, such that they could lead or not lead to changes in the nature of interhemisphere relationships.

In M (as compared with P), changes in $K_{as}$ were mainly in the α frequencies: there was a decrease in the level of interhemisphere asymmetry with preservation of its profile.

Comparison of $K_{as}$ values calculated for EEG epochs recorded during performance of movements with different hands showed that on movement execution with the left hand (as compared with the right), the SpP of the θ, α, and $\beta_1$ frequencies showed predominant increases in the leads on the left hemisphere and decreases in those in the right hemisphere. The $\beta_2$ and $\gamma_1$ frequencies showed opposite changes (Fig. 6). While displacement of asymmetry to the left hemisphere occurred mainly in the anterior and central areas of the cortex, displacements to the right were seen in the posterior areas. The exception was the lower frontal leads, where the EEG showed a decrease in interhemisphere differences in all frequency ranges.

Detailed analysis of these results showed that at the stages of movement preparation and execution with the left hand, leftwards displacement of asymmetry occurred in the θ and α ranges and affected the frontal, central, temporal, and parietal areas of the cortex. At the movement execution stage, the EEG of these areas also showed a leftwards shift, though in the α and $\beta_1$ frequencies. In parallel, the $\beta_2$ and $\gamma_2$ frequencies in the central and parietal leads showed increases in differences favoring the right hemisphere.

**Discussion**

Execution of movements with the hands or fingers should evidently not lead to global changes in the functional state of the brain. Nonetheless, execution of these movements should be linked with local activation of those structures which support the necessary level of voluntary control and intrinsic control for movement execution. It might be expected that performance of less automated movements should lead to more significant changes in the EEG.

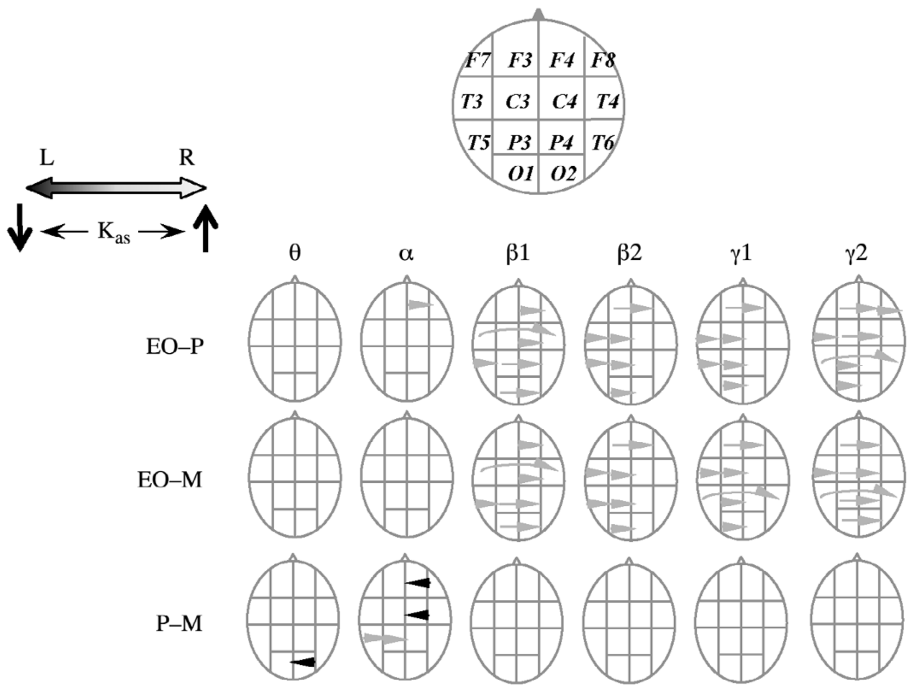


Fig. 5. Results of unifactorial ANOVA of $K_{as}$ at different stages of the study: ◀) decreases in $K_{as}$; ▶) increases in $K_{as}$; arrows show substitution of the dominant hemisphere.

According to current concepts, activation of neocortical structures in the state of waking is generally accompanied by suppression of the EEG α rhythm in combination with increases in oscillations in the β and γ ranges [Danilova, 2003; Boitsova and Dan'ko, 2010]. Opposite effects were seen at decreased levels of activation. Execution of activity (as compared with the resting state) could show effects consisting of both desynchronization and synchronization on the EEG, evidencing increases and decreases respectively in the level of activation of different areas. This is particularly linked with the fact that even rest with the eyes open is characterized by a quite high level of activation of cortical structures associated with the processes of attention, formation of free associations, and thought (Medvedev et al., 1996]. As a result, quite simple and automated activity may not only not require any significant increase in the initial level of CNS activation, but may even be linked with a decrease as a condition of its effective execution, which is typical particularly of monotonous operator activity [Kiroy and Aslanyan, 2005].

Our results provide evidence that performance of the movements used here, although unfamiliar for the subjects, did not produce any particular difficulty and did not require any global increase in the level of activation of the brain. Furthermore, the decreases in the power of the fast (β and γ) and the increases (most significantly in the posterior areas of the cortex) in slow (θ and α) frequencies in virtually all leads is evidence of some reduction in the level of activation as compared with resting. Changes in the nature of inter-hemisphere relationships in the fast frequency ranges in favor of the right hemisphere were sufficient for optimum execution of activity. The right hemisphere is known [Ivanitskii, 1993; Khomskaya, 1995; Simonov, 1998] to play the leading role in solving spatial construction tasks, perceiving the world and the self within it, and with precise representation of the space and time in which events take place. From this point of view, the activity paradigm used here is linked to the right-sided type and must elicit activation of structures on the right side, which is supported by the predominant increase in the power of the fast frequencies in the leads of the right hemisphere on movement preparation and execution.

A background of decreases in the power of the fast frequencies over almost the whole surface of the cortex increased the contrast of the increase in power in the γ frequencies on the EEG of the right frontal lead, this being more marked during preparation for than execution of movements. The anterior areas of the cortex are traditionally regarded as the coordinating and control center of the brain, supporting the formation of directed behavior and voluntary control of its performance [Luriya, 2004; Pribram, 1998]. In addition, there are data showing that these areas are directly involved in working memory processes, which supports retention of the relevant image [De Fockert et al., 2001]. As the increase in power in the γ frequencies on the EEG of the right frontal lead occurred both during the preparation stage and during the execution of all types of movements with both hands, this can be regarded as an elec-

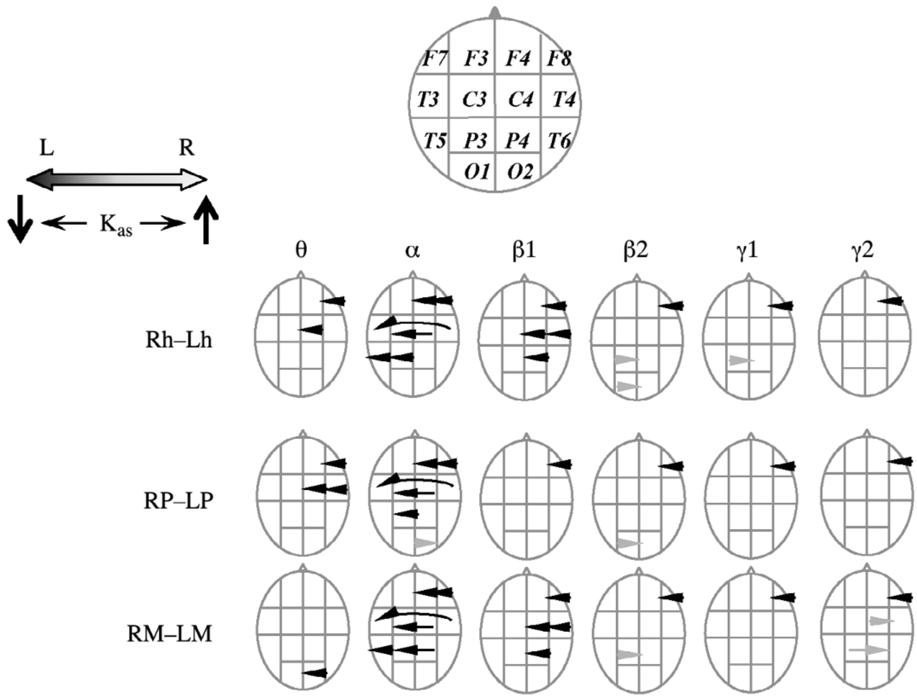


Fig. 6. Results of unifactorial ANOVA of $K_{as}$ on performance of movements with the left hand as compared with the right. For further details see caption to Fig. 5.

trographic correlate of voluntary initiation and control, as noted in particular by Raizada and Poldrack (2007), of the execution of complex motor acts. This suggestion is supported by existing data showing that the sensory and motor areas in right-handed subjects have greater representation in the left hemisphere, while associative areas have greater representation in the right hemisphere [Barrick et al., 2005].

The nature of changes in the temporospatial organization of brain bioelectrical activity at the initialization and execution stages of non-standard finger movements with both hands had a number of common features. As compared with P, the M period showed an increase in the power of the γ frequencies and a predominant decrease in power in the α and $\beta_1$ frequencies, pointing to an increase in the level of activation of cortical structures [Pfurtscheller and Neuper, 2006]. The decreases in power in the α and $\beta_1$ frequencies on performance of movements with the left hand (as compared with the preparation stage) were more lateralized, mainly affecting leads in the right hemisphere, while the increase in power in the $\gamma_2$ range was less marked than on performance of movements with the right hand. It can be suggested that preparation to execute movements with the left hand requires a higher level of cortical activation in right-handers.

Despite the fact that spectral analysis did not identify any specific interhemisphere differences on performance of finger movements with the different hands, it showed that both initialization and execution of movements with the left hand (as compared with the right) require higher levels of activation of neocortical structures, as there was, in particular, a more marked increase in power in the γ frequencies in the anterior and central leads of the right (contralateral) hemisphere. This directly indicates that for the right-handers studied here, performance of movements with the left hand was a more difficult task and required more extensive control by the premotor and motor areas of the cortex.

Analysis of interhemisphere relationships showed that on performance of movements with the left hand (as compared with the right), the lower (θ, α) and $\beta_1$ frequencies showed a general leftward shift. This may be evidence for a relative drop in the level of activation of the areas of the left (ipsilateral) hemisphere. There was also a more marked increase in power in the $\gamma_2$ frequencies in the activity of the central and parietal areas of the right hemisphere, which is evidence that these areas are activated. The decrease in the right-hemisphere dominance in virtually all frequency ranges between the symmetrical inferior frontal leads (projections of Brodmann field 47) may reflect increases in voluntary control (before enunciation of commands) by these areas of the left hemisphere on execution of movements with the left hand [Luriya, 2004].

It should be noted that on execution of all movements, the EEG of the occipital leads showed increases in power in both the slow and the fast frequencies. There are grounds for suggesting that the former may be linked with the slight reduction in the overall level of activation because of operation in conditions of decreased illumination, while the increase in the γ frequencies is a reflection of activation of the dorsal pathway for the transmission of visual information, which supports evaluation of spatial positions, movements, and interrelationships between objects in the field of vision [Mikhailova, 2005].

**Conclusions**

1. Preparation and execution of voluntary finger movements with both hands by right-handers occurs on the background of a decrease (as a global tendency) in the level of brain activation typical of the state of resting with the eyes open and redistribution of interhemisphere relationships in favor of the right hemisphere in the fast ($\beta$ and $\gamma$) frequencies.

2. Voluntary initiation and execution of non-standard finger movements with both hands was linked with a significant increase in power in the $\gamma_2$ frequencies in the activity of the right frontal lead, which is evidence for its direct involvement in the processes underlying the planning, initialization, and control of voluntary motor activity.

3. As compared with the planning (preparation) stage, execution of movement activity is associated with an increase in the level of activation of brain structures, evidenced by an increase in the EEG power of $\gamma_2$ frequencies and decreases mainly in the $\alpha$ and $\beta_1$ frequencies.

4. In right-handers, working with the left hand requires a higher level of cortical activation as early as the movement preparation stage, leading to less marked but more lateralized changes in the EEG spectral characteristics during subsequent execution (as compared with working with the right hand).

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**Abbreviations:** EMG – electromyogram; EO – state of calm waking with the eyes open; EOG – electrooculogram FFT – Fast Fourier transformation; $K_{as}$ – coefficient of asymmetry; Lh – left hand; LM – left hand movement; LP – preparation to execute a left hand movement; M – movement execution; P – preparation (initialization) for movement execution; SpP – power spectrum; Rh – right hand; RM – right hand movement; RP – preparation for right hand movement.

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