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# Mu rhythm separation from the mix with alpha rhythm: Principal component analyses and factor topography

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## ABSTRACT

**Background:** EEG mu rhythm suppression is assessed in experiments on the execution, observation and imagination of movements. It is utilised for studying of actions, language, empathy in healthy individuals and preservation of sensorimotor system functions in patients with schizophrenia and autism spectrum disorders. While EEG alpha and mu rhythms are recorded in the same frequency range (8–13 Hz), their specification becomes a serious issue.

**The new method:** is based on the spatial and functional characteristics of the mu wave, which are: (1) the mu rhythm is located over the sensorimotor cortex; (2) it desynchronises during movement processing and does not respond on the eyes opening. In EEG recordings, we analysed the mu rhythm under conditions with eyes opened and eyes closed (baseline), and during a motor imagery task with eyes closed. EEG recordings were processed by principal component analysis (PCA).

**Results:** The analysis of EEG data with the proposed approach revealed the maximum spectral power of mu rhythm localised in the sensorimotor areas. During motor imagery, mu rhythm was suppressed more in frontal and central sites than in occipital sites, whereas alpha rhythm was suppressed more in parietal and occipital sites. Mu rhythm desynchronization in sensorimotor sites during motor imagery was greater than alpha rhythm desynchronization.

The proposed method enabled EEG mu rhythm separation from its mix with alpha rhythm.

**Conclusions:** EEG mu rhythm separation with the proposed method satisfies its classical definition.

## 1. Introduction

Mu rhythm is defined as an EEG rhythm with a frequency of 8–13 Hz emerging over sensorimotor regions of the brain. It was first described by Henri Gastaut and was called rolandic, since it was observed in the rolandic areas of the brain (Gastaut, 1952). This new rhythm was described as ‘rhythm en arceau’, ‘arch-shaped rhythm’, or a rhythm with a pointed shape. Being identified first in adults, it was then found in children (Covello et al., 1975), and in animals, in cats and in monkeys (Bouyer et al., 1987).

Gastaut showed that the subject’s own movements lead to a decrease in power (suppression) of the mu wave, and in further experiments mu suppression was found to occur not only during movement, but also during motor imagery (Chatrjian et al., 1959). Another difference between mu and alpha rhythms lies in their reactivity: the alpha

rhythm spectral power is attenuated on eyes opening, whereas opening or closing the eyes does not change the reactivity of the mu rhythm (Kuhlman, 1978).

Over the past decade, the number of studies on the mu rhythm has markedly increased. Its suppression was proposed as a characteristic feature of the activity of the human mirror neuron system (MNS), as mu rhythm reacts when the individual performs an action or observes it (Muthukumaraswamy et al., 2004; Oberman et al., 2007a). However, not all researchers agree that the suppression of mu rhythm is a reliable indicator of the activity of the MNS (Aleksandrov and Tugin, 2010; Hobson and Bishop, 2016). In particular, Hobson and Bishop (2016) assume that mu suppression may still indicate MNS activity, but this effect is weak and unreliable since it is easily mixed with alpha rhythm. Indeed, it is often problematic to distinguish mu and alpha rhythms since they share the same frequency range of 8–13 Hz.

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When studying mu rhythm, the choice of the experimental paradigm is of great importance as it may define whether the mu rhythm is eventually suppressed or not. Currently, the tasks used to isolate mu rhythm are very different from each other: from action execution and action observation (Aleksandrov and Tugin, 2010; Muthukumaraswamy et al., 2004; Perry and Bentin, 2010), perception of emotional faces (Moore et al., 2012) to the perception of the sentences containing movements (Moreno et al., 2013), or musical notes (Behmer and Jantzen, 2011).

Other differences between the existing approaches concern the choice of the baseline condition, relative to which mu rhythm suppression is calculated, as well as the location and number of EEG channels where the electrical activity is studied. Many studies of mu rhythm suppression have reported results exclusively in central sites, but in order to be sure that mu rhythm suppression indicates activity changes in motor areas, it is important to exclude these changes elsewhere. Perry and Bentin (2010) noted that when studying mu rhythm suppression, it is necessary to take into account not only the central sites, but also the occipital regions to fully understand the phenomenon. In the study of mu rhythm in patients with autism, it was shown that apart from C3, C4 and Cz, no other sites showed a consistent suppression of mu rhythm (Bernier et al., 2007). Though, in motor imagery, in addition to central areas, frontal and parietal cortical zones are shown to be activated (for review see Hanakawa, 2016).

Often in studies, the long periods of time that are not associated with any stimulus are chosen as a baseline. Mu rhythm reactivity is measured by evaluating the decrease or increase in time of the signal amplitude, reflecting desynchronisation or synchronisation, respectively (Pfurtscheller and Lopes da Silva, 1999). The induced synchronisation/desynchronisation is measured as a percentage of the power relative to the baseline; therefore, it depends on the values of rhythmic activity within this interval. For instance, Oberman et al. (2005, 2007b) refer to the baseline as an interval without any stimulation or use a video with white noise as a baseline condition; the experimental conditions include various actions that the subject observes. In the resting state when the subject does not receive any stimulation, alpha rhythm values may be higher than under experimental conditions. Then, when the experiment conditions are subtracted from the baseline, there is an increased likelihood of a significant decrease in the values in the range of 8–13 Hz, which is interpreted as mu rhythm suppression (Pfurtscheller and Lopes da Silva, 1999). In order to exclude the vigilance changes that are associated with the beginning and the end of stimulus presentation from the analysis, Oberman et al. (2007b) removed the first and the last 10 s in each stimulus block from the analysis. A similar (Oberman et al., 2007b) procedure was followed by Moreno et al. (2013), whereby the first and last 7.5 s of each block of stimuli were removed from the analysis to control expectancy.

A resting state is not considered as a baseline in all cases. For this purpose, Perry and Bentin (2010) once utilised rolling tennis balls. This baseline condition was compared to other experimental conditions consisting of hand movements accompanied by various instructions. In the study of Moreno et al. (2013), the presentation of abstract sentences served as the baseline, which were then compared to sentences indicating actions (for example, 'I cut the bread') and to a presentation of actions (movements on a video). Muthukumaraswamy et al. (2004) suggested yet another baseline – the subject was asked to observe the examiner stretching his hand palm down. This condition was subtracted from another condition, where the subject performed the movement itself. The application of these conditions allowed the authors to equate the relative values of the alpha rhythm in two conditions, and therefore more precisely isolate the mu rhythm. In addition to the cluster of eight sites located around C3 and C4, the spectral power in occipital sites was analysed to evaluate the alpha rhythm and more accurately isolate the mu rhythm.

Since mu and alpha rhythms share similar frequency characteristics, sensorimotor activity, assessed on a sensory level, is likely to be

contaminated by visual alpha activity due to volumetric conductivity. In order to disentangle the two rhythms, the methods of independent components (Cuellar, Del Toro, 2017) and decomposition into independent components using the second-order blind identification (SOBI) have recently been applied (Moore et al., 2012; Yin et al., 2016). These approaches are based on individual topographic maps for identifying the mu rhythm. They combine the components into clusters based on localisation corresponding to the mu rhythm. Independent components that exhibit topographic and spectral characteristics that do not correspond to the mu rhythm are excluded from the clusters.

To date, the issue of identification of mu rhythm remains open. Our method is a special case of Blind Source Separation (BSS) method that uses, along with the physical (topography and spectrum) characteristics, also physiological characteristics of mu rhythm (reactivity). The methodological feature of the method is the use for Principal Component Analysis with the difference of covariance matrices of two states – resting with eyes open and motor imagery with eyes closed in order to identify the individual factors corresponding to the mu rhythm. Our approach of extracting mu rhythm from a mix with alpha rhythm is based on the spatial and functional characteristics of the mu wave: location over the sensorimotor cortex, desynchronization while processing of movement, lack of desynchronization on the eyes opening.

The proposed method of the analysis capitalises on the reactivity of the mu wave on motion visualisation, and in this particular case, motion imagery. We expect that the motion imagery task with eyes closed elicits greater mu wave suppression than the eyes open condition.

## 2. Methods

### 2.1. Participants

A total of 108 (51 females; mean age 26.5, SD 7.9 years) healthy right-handed adults participated in the study. Exclusion criteria were: any reported history of neurological or psychiatric disorder. Before the study, all of the participants gave their informed consent to participate in the study. The study was approved by the local ethical committee of the Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences.

### 2.2. Experimental tasks

The subjects underwent an EEG procedure while sitting on a chair in a darkened room. EEG in all subjects was recorded at rest (with eyes closed, EC) (1) and with eyes open, EO (2); during a motion imagery task (eyes closed) (3); and during a mental arithmetic task (with eyes closed) (4). In the instructions for the task (3), the subjects were asked to imagine the process of walking along a well-known road (2 min). After the task, all of the subjects provided a self-report. In the self-report, each subject provided the description of the destination they reached and the images of the surroundings. Quantitative analysis of the task was not performed. As for the mental arithmetic task, we used standard Kraepelina counting (4) with the instruction to count down from 200 in steps of 7 within a time limit of 100 s. All of the subjects had to provide their feedback at the end of the task on the result of the counting.

### 2.3. EEG acquisition and data pre-processing

Biopotentials were recorded from 19 electrodes: Fp1, Fp2, F3, F4, F7, F8, C3, C4, T3, T4, T5, T6, P3, P4, O1, O2 and midline sites (Fz, Cz, Pz) according to the International 10–20 System (Jasper, 1958). Electrode locations are shown on Fig. 1. Reference electrodes were placed on the linked earlobes. Low pass filters were set at 70 Hz, and a time constant of 0.3 s was used. EEG traces of 100 s were recorded and quantified at 200 Hz by an EEG mapper from the company MBN, Russia. All of the electrode impedances were maintained at or below 10

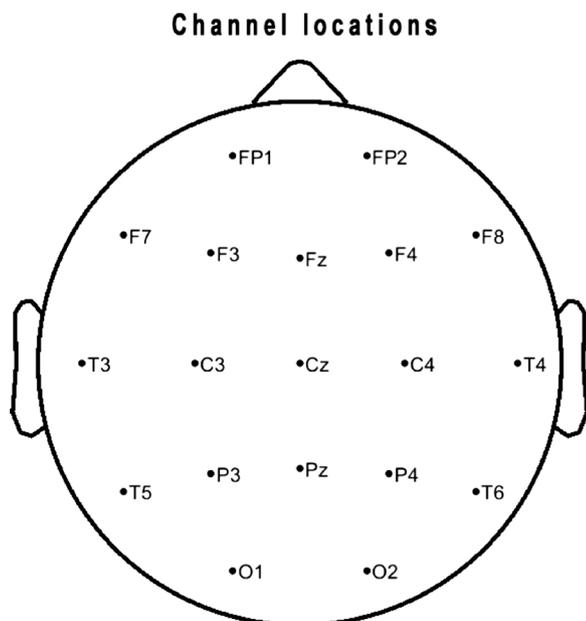


Fig. 1. EEG channel locations.

kOhm, with most EEG sites near 5 kOhm. EEG editing included a custom designed multiple-source eye correction method (Novototskii-Vlasov et al., 2007) with subsequent rejection of the EEG segments that contained eye movement contaminations and muscle artefacts. From the 100 s EEG-record, 10–15 five-second artefact-free intervals were chosen by an expert. These EEG segments underwent fast Fourier transform (FFT) with subsequent averaging and obtaining of the individual averaged power spectra for each frequency band.

#### 2.4. Algorithm for the EEG mu rhythm separation from the mix with alpha rhythm

1. Input EEG files (EC, EO, motion imagery) were filtered in the extended alpha band frequency 6–14 Hz.

2. Both EO and motion imagery files were used together for the PCA analysis. For this reason, the covariance matrices between the sites were calculated for both files, and then the difference between these matrices was normalised by the corresponding record lengths in order to provide independence of the analysis results from these lengths.

$$\mathbf{E} = \mathbf{A} * \mathbf{A}^T / t_1 - \mathbf{B} * \mathbf{B}^T / t_2,$$

where  $\mathbf{E}$  – difference matrix (EO - movement),  $\mathbf{A}$  – filtered EEG matrix during the EO condition,  $t_1$  – EO record duration,  $\mathbf{B}$  – filtered EEG matrix during motion imagery,  $t_2$  – corresponding record duration. Matrix  $\mathbf{E}$  underwent PCA, i.e., pairs of eigenvectors  $\mathbf{x}_i$  and eigenvalues  $\lambda_i$  being the solution of the equation

$$\mathbf{E} \mathbf{x}_i = \lambda_i \mathbf{x}_i$$

were sought.

As a result of this step, we obtained individual topographic maps for the distribution of the factors  $\mathbf{x}_i$  across the scalp.

3. On the basis of the obtained maps, EEG signals corresponding to each of the factors were calculated. For this purpose, filtered EEG files (6–14 Hz) were multiplied (as matrices) by the maps obtained in the previous step.

$$\mathbf{y}_i = \mathbf{x}_i^T \mathbf{A}, \quad \mathbf{z}_i = \mathbf{x}_i^T \mathbf{B}.$$

4. By the standard procedure (using the Fourier transform), power

spectra for each of the factors in the EO and motion imagery condition were obtained

$$\mathbf{y}_i(f) = \sum \exp(i2\pi ft) \mathbf{y}_i(t), \quad P_{iy} = \mathbf{y}_i \mathbf{y}_i^*,$$

$$\mathbf{z}_i(f) = \sum \exp(i2\pi ft) \mathbf{z}_i(t), \quad P_{iz} = \mathbf{z}_i \mathbf{z}_i^*,$$

where  $P_{iy}$  and  $P_{iz}$  are the spectral powers of the  $i$ th factor during EO and motion imagery task, correspondingly.

5. Factor spectra obtained for two conditions were compared and those that showed  $P_z < P_y$  were selected (i.e. those that are more inhibited during the movement than during EO). Factor topography (predominance in F, C, P sites)  $\mathbf{x}_i$  served as an additional selection criterion.

6. Filtered with 6 Hz high-pass filter original EEG files were multiplied (as matrices) by the maps corresponding to selected factors. The obtained results were summed taking into account the topographies of selected factors. Thus, from the whole EEG recording, only the mu rhythm was left in each derivation.

$$\mathbf{y}_{i\mu} = \sum \mathbf{x}_i \mathbf{y}_i, \quad \mathbf{z}_{i\mu} = \sum \mathbf{x}_i \mathbf{z}_i.$$

#### 2.5. Data analysis

Spectral power for the alpha and mu rhythms was calculated separately for each of the four experimental conditions. The mean power ( $\mu\text{V}^2 / \text{Hz}$ ) was computed across epochs. Prior to the statistical analysis, the spectral powers were logarithmically transformed ( $\ln$ ) to normal distribution. The mu rhythm spectral power was analysed in the frequency range of 8–13 Hz after the pre-processing (sections 2.3, 2.4). The spectral power of the alpha rhythm (the sum of the activity) was analysed in the frequency range of 8–13 Hz without additional pre-processing.

To identify the differences between the alpha and mu rhythms, we analysed: the topographic distribution of the spectral power in the resting state; suppression of the alpha and mu rhythms on eyes open, in the motion imagery task, and the mental arithmetic task. We analysed the spectral power values of the alpha and mu rhythms in the projections of the sensorimotor cortex - in areas C3, C4, in frontal sites F3, F4 and in parietal sites P3, P4. The index of suppression of the mu rhythm was calculated as the difference in spectral power under eyes open, the motion imagery, the mental arithmetic conditions, and at rest in the corresponding cortical areas. To ensure that any observed effect is mu rhythm specific and does not mix with the occipital alpha rhythm (Hobson and Bishop, 2016), these calculations were also performed for occipital sites (O1, O2).

#### 2.6. Statistical analysis

Statistical analysis was performed using STATISTICA 10.0 and MatLab R2016b software. The changes in the spectral power of alpha and mu on eyes open condition, in the mental arithmetic task and under motion imagery conditions were compared with closed eyes. We conducted a repeated measures ANOVA including three within-subject factors (condition - 4 levels; electrode - 4 levels; hemisphere: left, right). Also, using a repeated measures ANOVA, we analysed the suppression index in three experimental conditions (eyes open, mental arithmetic, motion imagery) separately for the alpha and mu rhythms; at the last stage, the index of suppression of the alpha and mu rhythms was compared for the motion imagery condition (one between-group factor mu or alpha). Greenhouse-Geisser corrections were applied to correct for violations of sphericity and homogeneity. The main significant effects were followed by post-hoc comparisons, which were adjusted using a Bonferroni post hoc test.

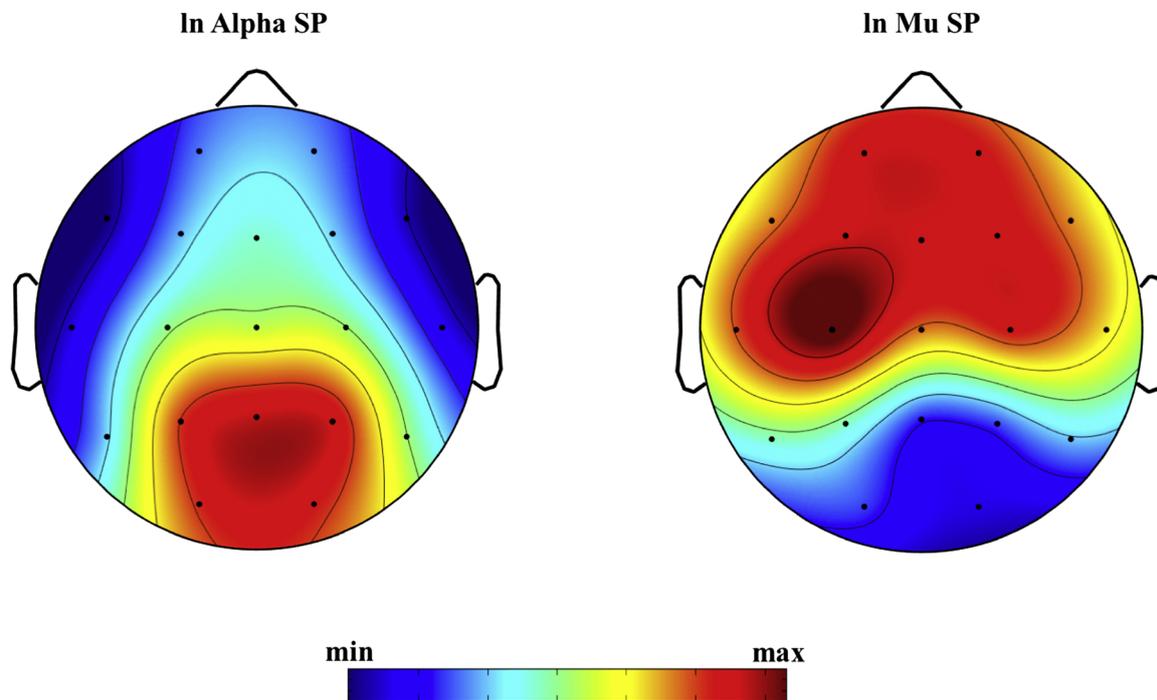


Fig. 2. Topography distribution of mu and alpha rhythms in the resting state (eyes closed).

### 3. Results

#### 3.1. Comparison of topographic and spectral characteristics of alpha and mu EEG rhythms at rest (eyes closed)

Prior to EEG processing by the method of spatial-spectral selection, the alpha rhythm had a maximum in the parieto-occipital sites. An analysis of the spectral power of activity in the frequency band of 8–13 Hz at rest (eyes closed) showed that after the separation of the mu rhythm, its maximum, unlike the alpha rhythm, was located in the central cortical sites (Fig. 2).

#### 3.2. Changes in spectral power of alpha and mu EEG rhythms during cognitive tasks compared to rest (eyes closed)

The results of the repeated measures ANOVA are summarised in Table 1.

Compared to the baseline, suppression of the alpha rhythm was significant in eyes open condition and in all cognitive tests in all leads ( $p < 0.0001$ ). Compared to the resting state, suppression of the mu rhythm was significant when performing the mental arithmetic task in P4 ( $p < 0.05$ ) and during the motion imagery task - in F3, F4, C3, C4 and P3 sites ( $p < 0.0001$ ).

#### 3.3. Comparison of the index of suppression of alpha and mu rhythms under different conditions (Fig. 3)

The results of the repeated measures ANOVA are summarised in Table 2 (Fig. 3).

Suppression of the alpha rhythm in the eyes open condition was significantly higher than in the mental arithmetic task and the motion imagery task in all sites ( $p < 0.0001$ ). Suppression of the alpha rhythm in the mental arithmetic task was greater than in the motion imagery task in all sites, except for F4: C3, P3, P4 ( $p < 0.0001$ ), O1, O2 ( $p < 0.001$ ), C4 ( $p < 0.01$ ), F3 ( $p < 0.05$ ). Suppression of the mu rhythm in the motion imagery task was greater than in the eyes open condition in F3, F4, C3 ( $p < 0.0001$ ) and C4 ( $p < 0.001$ ), and more than in the mental arithmetic task in sites F4 ( $p < 0.0001$ ), C3 ( $p < 0.001$ ), F3, C4 ( $p < 0.05$ ). Suppression of the mu rhythm in eyes open condition and in the mental arithmetic task did not differ.

#### 3.4. Comparison of suppression of alpha and mu rhythms in the central and frontal sites in the motion imagery task

The main effect of RHYTHM factor was found to be significant ( $F(1, 107) = 15.36, p < 0.001$ ) as well as RHYTHM X ELECTRODE factor - ( $F(3, 321) = 12.27, p < 0.0001$ ). Suppression of the mu rhythm in the motion imagery task was greater than suppression of the alpha rhythm in the frontal and the central sites: F4, C3, C4 ( $p < 0.0001$ ), F3 ( $p < 0.001$ ).

### 4. Discussion

The methodological feature of the method is the use of the difference of covariance matrices of two states – a resting state with eyes open and motor imagery task with eyes closed – for PCA. We consider as the mu-rhythm those components of the general range of mu-alpha, whose reaction to imaginary movement is greater than to eyes opening

Table 1

Repeated measures ANOVA of the spectral power of the mu and alpha rhythms under four conditions: resting state (baseline, eyes closed), resting state (eyes open), mental arithmetic (eyes closed), motion imagery (eyes closed).

	Mu	Alpha
CONDITION	$F(3, 321) = 28.74, p < 0.0001$	$F(3, 321) = 198.90, p < 0.0001$
CONDITION X ELECTRODE	$F(9, 963) = 5.606, p < 0.0001$	$F(9, 963) = 58.18, p < 0.0001$
CONDITION X ELECTRODE X HEMISPHERE	$F(9, 963) = 0.855, p = 0.497$	$F(9, 963) = 0.79, p = 0.506$

**Table 2**

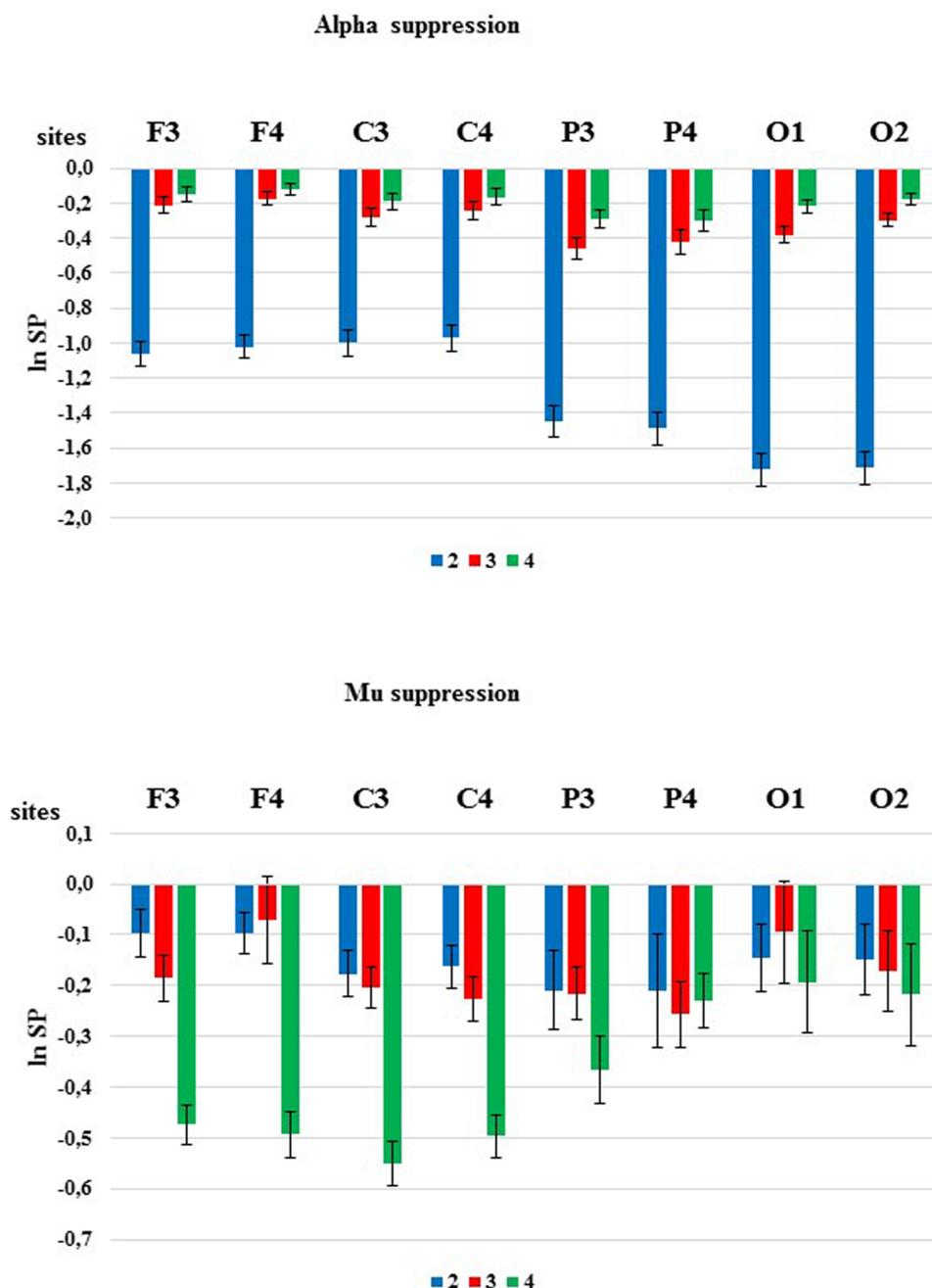
Repeated measures ANOVA of mu and alpha suppression in three active conditions in comparison to the resting state (eyes closed).

	Mu	Alpha
CONDITION	F(2, 214) = 17.04, p < 0.0001	F(2, 214) = 179.49, p < 0.0001
CONDITION X ELECTRODE	F(6, 642) = 6.402, p < 0.001	F(6, 642) = 70.38, p < 0.0001
CONDITION X ELECTRODE X HEMISPHERE	F(6, 642) = 0.97, p = 0.417	F(6, 642) = 1.853, p = 0.121

(taking into account the topography of factors). As a result, we obtain for each subject an individual set of factors corresponding to the EEG mu rhythm. After that, the matrix of an individual set of selected factors can be used to determine mu rhythm in any EEG record with different tasks for a given subject. In our study, we distinguished mu-rhythm, respectively in each of the four experimental conditions (two baselines,

two cognitive tasks) separately for each subject. As the baseline, we used the condition “eyes closed”, since cognitive tasks were performed with eyes closed.

Mu suppression is widely applied in cognitive neurobiology in the study of motor acts, to determine the role of the mirror neuron system in social processes in healthy subjects and in mental disorders. One of



**Fig. 3.** Suppression of mu and alpha rhythms in eyes open condition, mental arithmetic task and motion imagery task in sites F3, F4, C3, C4, P3, P4, O1, O2. Condition 2 – suppression in eyes open condition, condition 3 - suppression in the mental arithmetic task, condition 4 - suppression in the motion imagery task.

the currently unresolved issues is that, for example, the differences in attention between states can lead to widespread changes in the power signal of the alpha rhythm, which can mimic the mu rhythm suppression (Hobson and Bishop, 2017). Thus, the issue with the distinction between mu and alpha rhythm can be largely solved by the proposed method. In order to isolate the mu rhythm from the mix with the alpha rhythm, we selected a motion imagery task, which was performed with eyes closed. This task was chosen for several reasons. First, the difference between the mu and alpha rhythms is likely to be observed during eyes opening: the alpha rhythm is suppressed on eyes opening, while the mu rhythm does not change either on eyes opening or when the eyes are closed at rest (Kuhlman, 1978). Instead, the mu rhythm responds to any representation of movement. Consequently, in order to ensure the adequacy of the factors related to the mu rhythm, we chose the factors that would have demonstrated the greater suppression of the spectral power during the motion imagery task with closed eyes and not under the eyes open condition. Indeed, in our study, no statistically significant suppression of the mu rhythm was found in the eyes open compared to the closed eyes conditions. One of the characteristics of the EEG mu rhythm is the arch-shaped waveform (Gastaut, 1952; Kuhlman, 1978), which is due to the coexistence of two components distributed in the alpha and beta bands (Tiihonen et al., 1989; Hari, 2006; Avanzini et al., 2012). After processing the EEG files using the proposed methodological approach, a mu rhythm with a characteristic waveform and maximum amplitude in central leads (Supplement 1) was identified. The obtained arch-shape of the mu waveform in our study is ascribed to the fact that the topographic factors identified for the alpha rhythm range from EEG records with open eyes and motor imagery task were multiplied by the original EEG containing the high-frequency part of the spectrum, including the beta rhythm.

Second, studies of motor imagery have revealed many similarities between imaginary and performed actions on behavioural, physiological and neural levels, which confirms their “functional equivalence” (Jeannerod, 1994; Kilteni et al., 2018). Neuroimaging studies have shown that during motion imagery, the frontal motor areas, the parietal areas, and the cerebellum regions are activated, which partially overlap with the brain network activated during movement (Héту et al., 2013). It is also known that motor images of various effectors activate the corresponding sites of the somatotopically organised motor cortex (Ehrsson et al., 2003).

Until now, methods of separating the EEG mu rhythm from a mix with the alpha rhythm are sparse. The advantage of the method proposed in this paper is that the selection of factors using PCA occurs on the basis of two EEG recordings (eyes open and the situation of motion representation with eyes closed), which allows to take into account classical ideas about the mu rhythm: it is not suppressed when opening the eyes, but it is suppressed in situations involving motor acts. The selected factors are further applied both to the state taken as the baseline and to any experimental situation. In our study, we compared the suppression of alpha and mu rhythms in the same experimental situations, which confirmed the adequacy of the application of the proposed method to isolate the mu rhythm from a mix with the alpha rhythm and assess the specificity of the mu rhythm in response to action representation.

Comparison of the mu and alpha rhythms, selected by the proposed method, showed various localizations of the spectral power maximums for these rhythms. The maximum mu rhythm spectral power was located in the central regions, but the alpha rhythm was detected mainly in parietal-occipital regions. Indeed, they are considered to differ in topography and sensitivity, as alpha rhythm is more pronounced in the occipital regions and responds to changes in visual stimulation and vigilance, while mu rhythm is detected in the sensorimotor areas and responds to subjects’ own movements (Hobson and Bishop, 2016, 2017). Nevertheless, due to the overlap of alpha and mu rhythm ranges, it is necessary to strictly control the factor of vigilance involvement. However, Fox et al. (2016) suggest that the close relationship of alpha

and mu rhythms can be a reflection of close coordination of movement and vigilance, so the change in alpha activity may be an integral part of the processes associated with motor activity.

One of the classic markers for alpha rhythm is a phenomenon called “alpha blockade”. It is well known that eyes opening and mental activity suppress alpha rhythm (Klimesch, 1999). In our study, the alpha rhythm, unlike the mu rhythm, had the greatest degree of suppression on eyes opening. The EEG alpha rhythm was also significantly suppressed when solving an arithmetic task, but not as a response to motor imagination.

Our results suggest a decrease in the power of the mu rhythm relative to the baseline (eyes closed) that is more pronounced in motion imagery, and a decrease in the power of the alpha rhythm relative to the background (eyes closed) that is greater when the eyes are open compared with other experimental conditions. Under the conditions of motion imagery, the suppression of the mu rhythm was greater than when performing another cognitive task (mental arithmetic). Some studies show that mu rhythm, just like alpha rhythm, is linked to vigilance and cognitive processes. Chatrian et al. (1959) found that mu rhythm is also suppressed during the solving of arithmetic tasks. In our study, the suppression of mu rhythm in the right parietal area was identified when solving the mental arithmetic task. Indeed, it was previously shown that finger discrimination and the mental arithmetic induced a similar pattern of activity within the parietal areas (Andres et al., 2012). Schoppenhorst et al. (1980) reported the instability of the mu rhythm: it may be suppressed during increased as well as decreased vigilance. Though, the authors’ conclusions resulted from a poor differentiation between mu and alpha rhythms.

Motor imagery tasks activate various cortical and subcortical areas, which essentially coincide with areas for performing movements, including the frontal, central and parietal ones (review by Hanakawa, 2016). Our study revealed predominant suppression of the EEG mu rhythm in the central, frontal areas, and in the left parietal region. Recently, it was shown that the left inferior parietal lobe is critical to the manipulation and control of motor images (Kraeutner et al., 2019).

One of the limitations of our study is the difficulty to track and strictly control the result of task performance. A quantitative analysis of the details of the images was not applicable and we obtained only the qualitative self-reports of the subjects. Therefore, we cannot identify the ratio of kinaesthetic and visual components when performing tasks on motor imagination. Indirectly, from the results obtained, it can be assumed that, on average, in the group, there was a predominantly kinaesthetic representation of one’s own movement, since the suppression of mu rhythm was detected in the frontal cortical areas. It has been shown that in untrained subjects with a kinaesthetic type of motor imagery, the frontal cortex activity is suppressed during motor imagination, while in subjects with a visual type of motor imagery, the frontal cortex is always active (Chholak et al., 2019). In order to overcome this limitation, it is potentially possible to select other motor tasks for the mu rhythm identification, but the task must be performed with eyes closed. We assume that this may be visual imagery of simple movement, for example: clenching a fist or fists of two hands. It is also possible to use a task with a simple movement execution, but the subject must be with eyes closed.

Another limitation of the method is that it’s not applicable to the beta component of the mu rhythm. The mu rhythm includes at least two components in the frequency bands alpha (8–13 Hz) and beta (15–25 Hz), which have different source locations and reactivity when performing various motor tasks, which suggests their different functional roles (Angelini et al., 2018). The high degree of independence of mu and beta rhythms is also evidenced by the fact that mu waves are not detected in some subjects, but there is reactivity in the beta range during sensorimotor activities (Pfurtscheller, 1981). Our methodological approach that is based on the suppression of alpha when opening the eyes, is not suitable for the beta range because it has other features when opening the eyes. Our methodological approach that is based on

the suppression of alpha rhythm when opening the eyes, is not suitable for the beta range because it has other features when opening the eyes: beta activity shows a decrease from a closed-eyed to an open-eyed state, predominantly in the posterior and right hemisphere regions, and is accompanied by an increase in activity in the frontal regions. The alpha band differs from the other bands by a vast decrease in activity from closed eyes to open eyes, without any topographic change, whereas topographic changes are evident in the beta range when the eyes are opened (Barry et al., 2007). For details see Supplement 2.

There are a number of studies devoted to the influence of different types of baselines on the degree of mu rhythm desynchronization. Tangwiriyasakul et al. (2013) took dynamic (for example, jumping balls) and static stimuli (for example, pictures) as baselines and discovered that dynamic stimuli increased the number of desynchronizations in some of the subjects. However, no optimal baseline for the entire group was found, and the authors concluded that experiments with motor pictures may require calibration in order to determine which baseline was most suitable for each subject. In another study, Puzzo et al. (2011) examined mu rhythm desynchronization during movement observation. They found that the magnitude of desynchronization varies according to the reference interval used (calm wakefulness or non-biological movement). Using the proposed technique resolves issues with the search for the optimal baseline since any condition taken as a baseline (eyes open or eyes closed) will allow selecting the mu rhythm in the frequency 8–13 Hz. We assume that the factors identified by the two EEG records (eyes open, movement imagination with eyes closed) can be applied to other tasks to isolate the EEG mu rhythm, including the recordings of evoked potentials (ERP). In the future, in order to determine the factors corresponding to the EEG mu-rhythm more accurately, it is necessary to use frontal-central and central-parietal electrodes when registering EEG. As a reference point, one should apply the resting state with eyes open and movement execution (with eyes closed) to determine factors related to mu rhythm, since the suppression of the mu rhythm when making an actual movement is supposedly greater than when imagining a movement. The spectral power and the reactivity of the selected mu rhythm in this case should be greater. This assumption requires experimental verification.

## 5. Conclusions

The proposed method of detecting and isolating mu rhythm from EEG records of subjects with eyes closed, eyes open and motion imagery with eyes closed, based on the principal component method allowed us to: 1) identify the mu rhythm based on its typical response to opening the eyes and motion task; 2) to determine the mu rhythm topography; 3) to perform spatial-frequency filtering of the EEG record in order to isolate the purified mu rhythm.

The use for PCA of the difference of covariance matrices of two states – resting state with eyes open and motor imagery task with eyes closed allowed us to identify the mu rhythm. The mu rhythm isolated from a mix with the alpha rhythm has all the characteristics of a sensorimotor rhythm previously described in the literature: localization of the maximum spectral power in the central cortical sites, the absence of a significant reduction when opening eyes and cognitive load not related to movement, and when performing motor tasks compared to the baseline - the suppression of its power mostly in the central regions. The novelty of the approach compared to recently published methods (Cuellar, Del Toro 2017; Moore et al., 2012, and Yin et al., 2016) is the inclusion of functional characteristics (reactivity) in addition to the spatial and spectral characteristics.

## Authors contribution

ZG designed the study and wrote the original protocol together with YZ. ZG recruited the participants, and performed the EEG assessment. BNV developed the method, analysed the data. EL has done the

literature search and drafted parts of the manuscript. ZG and YZ wrote the first draft of the manuscript and contributed to the data interpretation. All of the authors discussed the results and contributed to the final version of the paper and have approved it.

## Declaration of Competing Interest

The authors have declared no competing interests.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.jneumeth.2020.108892>.

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