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The suppression of the μ rhythm during the creation of imagery representation of movement

Piotr Francuz, Dariusz Zapała*

Department of Experimental Psychology, John Paul II Catholic University of Lublin, Al. Racławickie 14, Lublin, Poland

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ABSTRACT

The aim of this study was to answer the following question: are there differences between the attenuation of μ rhythms, recorded with EEG in the parietal area during observation of movement and the creation of its imaginative representation? In addition, we checked the extent to which the μ rhythm suppression depends on whether the observed and the imagined movement is performed by a human or is artificial. As a result of the experiment a significant difference in μ rhythm suppression between the conditions "Observation," "Imagery," and "White noise" was recorded. It did not matter whether the motion was carried out by a human being or performed by a machine. The results are discussed in the light of findings which relate to the mirror neuron system.

The μ rhythm (also known as the central, Rolandic, sensorimotor, wicket, or arceau rhythm), was first reported in the 1950s [6,20]. In the following years this phenomenon did not attract much attention of researchers as it was thought to be relatively rare and occurring in a small percentage of the population. Only the use of more advanced methods such as independent component analysis (ICA) at the end of the twentieth century have revealed that this phenomenon is widespread and occurs in most patients [20,21]. The frequency of the μ rhythms is included in the alpha band, but the μ and alpha rhythms manifest themselves in different areas of the brain [21].

The μ rhythms oscillate around 8–13 Hz and 15–25 Hz for short periods (from .5 to 2 s), and can be recorded from the area of the sensory-motor cortex during rest. Therefore, initially this type of rhythm was identified with a lack of activity in areas of the motor cortex ("state of inaction" or "sterility") compared to the alpha rhythm. Pfurtscheller [19] describes the growth suppression of μ rhythms in the hand motor cortex during the processing of visual stimuli or movements of the feet. In both these situations, the neurons encoding the movement of the hand remain idle.

In the 1990s, attitudes to the rhythms of μ as a neurophysiological index of mental processes changed. Researchers linked this phenomenon with higher cognitive functions, such as activation of working or episodic memory in tasks requiring increased attention [10] and during mental rotation [11,13,17]. Also it transpired that suppression of μ rhythms occurs both in the execution, observation, and simulation of movement in the mind. Therefore, some researchers link this phenomenon with the operation of mirror neurons system (MNS).

Mirror neurons are groups of perceptual-motor nerve cells that are active not only when a monkey performs a certain motor activity, but also when observing another individual performing this activity. Currently, many researchers believe that the MNS is involved in processes such as imitation of [7,8] communication [1], formation of social relationships [28], understanding the actions of others [8], and empathy [4,24]. According to some researchers, due to the ease of registering μ rhythms with EEG, it is a promising marker of human MNS [22]. So far, the suppression of μ rhythms as the human marker of MNS has been used in studies of Autistic Spectrum Disorder (ASD) [2,14], the perception of humanoid robots [15], the level of engagement in social interactions [16] and the formation of mental representations of motion [18]. It should be noted, however, that such a link between suppression and the MNS is still based largely on speculation and is a highly debated issue.

In the research conducted by Umilta and his team [27], the activity of single neurons in area F5 in the brain of a monkey was recorded during both the performance of its motor activity, as well as during observation of the same activities performed by the researcher. It transpired that the MNS was active when the monkey watched the researcher's hand reaching for an object, but this effect does not occur when the researcher performed the same movement, but with no object. It was observed, however, that an analogous reaction occurs, even if the monkey knows that the experimenter's hand is reaching for the object, but cannot see it because it is hidden behind a screen. In another condition, when

* Corresponding author. Tel.: +48 668 548 184.
E-mail address: d.zapala@gmail.com (D. Zapała).

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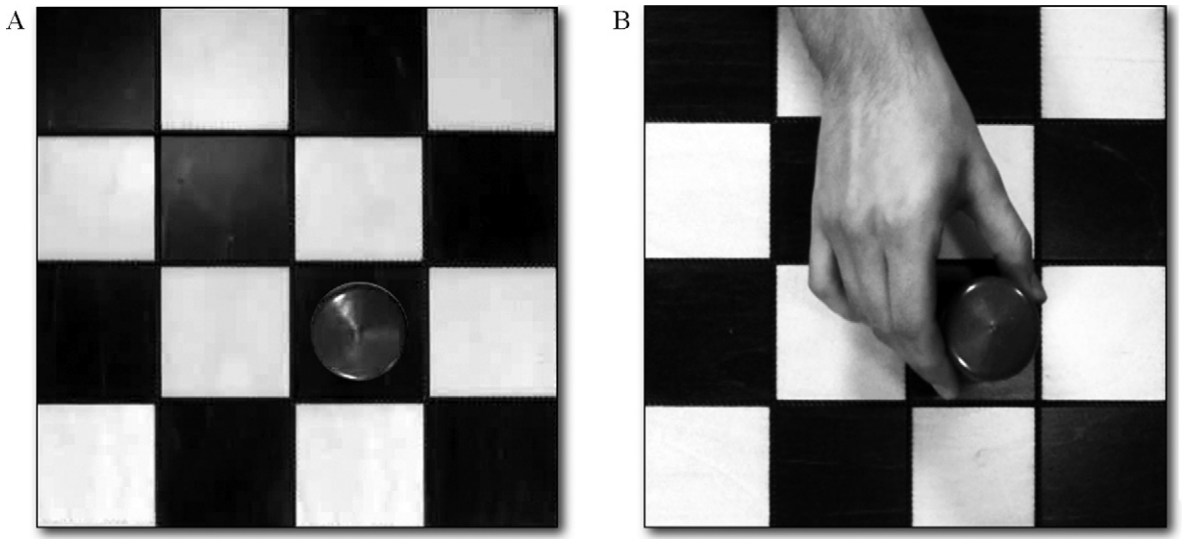

Fig. 1. Two types of pawn movement: artificial (A) and biological (B).

the monkey knows that there is no object behind the screen, then there is no response from the neurons. It may mean, therefore, that neurons from the area F5 help the animal in creating an imaginative representation of observed actions in order to anticipate their completion and understanding of a goal.

In humans, much less is known about the role of MNS in the creation of imaginative representation of an observed motion than in the case of monkeys. Difficulties in replication of experiments conducted by Italian researchers [27] in humans relate to the design of a situation in which completion of the observed motor activity is as smooth and natural as that performed by a monkey while watching an object disappearing behind a screen.

Therefore, we decided to conduct an experiment in which participants would complete in the imagery, a previously observed first phase of pawn movement while playing a board game similar to chess. Predicting opponent movements and planning one's own moves requires creating mental simulation of motor actions. As in other experiments in which the MNS activity was examined using the phenomenon of μ rhythm suppression [12,16], the imagery task in this case is to imagine activities associated with the operation on an object, performed by a limb. An additional goal was to achieve greater ecological validity than in previous studies [12,18], using an invented game. Ecological validity is crucial in the study of such phenomena as motor imagery, which is activated mostly in situations of social interaction. This was confirmed by research of mirror neurons, which used artificial objects as stimuli and then the effect of activation motor areas was not observed [3]. In another situation, when the material was real video, researchers recorded the expected response [23].

In previous studies, differences in the activity of MNS in humans have been observed depending on whether the presented motion was carried out by a human being or whether it was artificial [9,25]. To control this effect, we introduced two types of presented motion: carried by a human hand (biological motion) and computer-animated (artificial motion). If the μ rhythm suppression is indeed a good indicator of activity of the human equivalent of the MNS, it is expected to produce a different response to biological and artificial motion.

According to earlier reports [12,27] the level of attenuation of μ rhythms should be highest during the perception of motion (the condition "Observation"), but should also occur – although with less strength – while completing observed movements in the mind (the condition, "Imagery"). At the same time suppression of μ rhythms should reach the lowest level when the subject observes chaotic motion [15,16], not associated with motor activity (the control condition, "White Noise"). According to the latest hypothesis, verified in this study, the suppression of μ rhythms should be higher in the case of movement performed by humans ("Biological Motion") than in motion controlled in an automatic way ("Artificial Motion") (see [25]).

In order to verify the hypotheses an experiment was conducted. Ten students from John Paul II Catholic University of Lublin, 6 women and 4 men were tested. Participants ranged in age from 19 to 35 ($M = 23$, SD = 4.57) and showed 90% right-sided laterality. None of the subjects reported neurological disorders.

A 128-channel EEG GES 300 (EGI Inc., Eugene, OR) set was used in the experiment. During the test, the resistance of each of the electrodes below 50 kOhm (recommended by the manufacturer) and sampling frequency of 250 Hz was maintained. For the EGI device, there were no statistically significant differences between data collected at levels of impedance below 10 kOhm and about 40 kOhm [5].

Net Station Version 4.4 (Electrical Geodesics) was used in EEG registration and E-Prime 2.0 Professional (Psychology Software Tools, Pittsburgh, PA) was used to prepare the experiment. Visual stimuli were displayed on a 15 in. LCD monitor screen with a resolution of 1280 by 1024 pixels and a refresh rate of 60 Hz. The monitor was located at a distance of 60 cm from the subject. Subjects answered with a 4-button keypad Subject Response Pad (Electrical Geodesics).

256 videos were recorded. They present the movements of four colored pawns in four different directions in a game, like checkers. The movement of any pawn started on one of the eight centrally located fields of a black and white chessboard. In 128 videos pawns move alone like mechanical toys (artificial movement), and in the remaining 128 videos pawns do not move alone but are moved by the human hand (biological movement). The artificial pawn move proceeds along a straight line, at a constant speed, always at the center of the checkerboard fields, and turns were performed at exactly 90°, whereas the biological pawn move is scurried along curved trajectories, with varying speed and different time of movement from one point to another (see Fig. 1).

The experiment consisted of two phases: training and the test. During training the subject learned a few pawn moves. The learning phase of the training consisted of watching two-second videos showing the movements of the pawns. The subject could devote

as much time as he/she needed to remember the movements of various pawns. After, the different pawns were shown in different places on the chessboard, and the subject was asked to select one of four fields where the pawn would be at the end of the movement. For each pawn there were three repetitions. If any of them were done incorrectly, the cycle was repeated until an error-free criterion was reached in all trials.

After the training, there was a test phase which consisted of two parts: B (with biological movement videos only) and A (with artificial movement videos only). Half of the subjects initially performed part "B" and then part "A", and the other half, the reverse. A single exposure began with a 2-s white noise. Next the video was shown, but after moving the pawn one square on the chessboard, the video was stopped. Videos with the artificial movement lasted for 2 s, and videos with biological movement lasted from 1.8 s to 2.2 s. After a 3-s delay, the subject heard a quiet ring tone which was the sign to start the imagery task. To minimize possible effects of ringing, the same sound signal was present in every experimental condition. At that moment the subject had to imagine the completion of the movement of the pawn which he/she had just watched on the screen. The subject signaled the end of this task by pressing a button. The next exposure began after a 3-s break. Every 16th exposure was followed by a brief pause (see Fig. 2).

The EEG data was filtered in the band below .01 Hz and above 40 Hz to remove records which would not represent brain activity. Then they were segmented into equal parts, lasting from 200 ms before the appearance of each stimulus to 1500 ms after the exposure (with the amendment of 5 ms to the actual moment of exposure). Thus, 256 segments were obtained for each experimental condition: "Observation", "Imagery" and "White Noise". Segments that contained artifacts from eye movements, blinks and changes in muscle tension were removed through visual inspection as well as through NetStation's (Electrical Geodesic) automated artifact detection algorithm. Following the parameters of the automated algorithm, channels were identified as bad if the fast average amplitude exceeded 200 lVs, if the differential average amplitude exceeded 100 lVs, or if the channel had zero variance. Channels were marked bad for all trials if marked bad in 20% of all trials and trials were discarded if they contained more than 10 bad channels. The mean trial rejection rate was 41.44% across both groups. There were no differences between groups in the rate of trial rejection (biological motion $M = 41.68\%$; artificial motion $M = 41.20\%$). Other segments were subjected to wavelet transformation (Morlet) in order to extract waves with a frequency of 8–11 Hz, corresponding to the μ rhythms. In order to obtain mean values of the wave amplitude, the amplitudes from 16 electrodes were placed in positions around the field C3(36) and C4(104) and were averaged [20] (left side: 30,31,36,37,41,42,53,54; right side: 79,80,86,87,93,103,104,105).

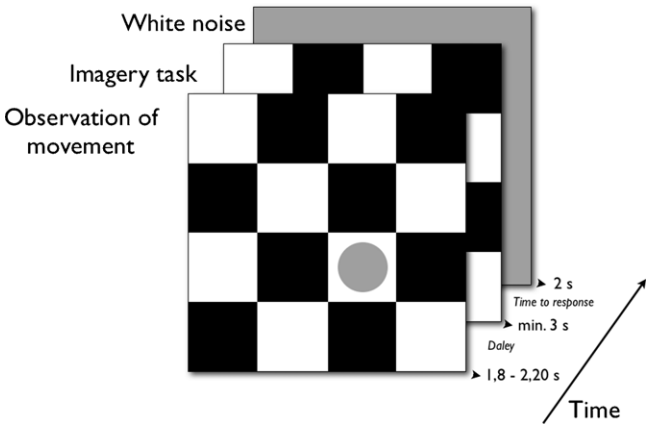

Fig. 2. Experimental paradigm.

The data collected in the experiment was submitted to an analysis of variance ANOVA ($2 \times 3 \times 2$) with the within-subject factors of MOVEMENT ("Biological Motion", "Artificial Motion"), CONDITIONS ("Observation", "Imagery", "White Noise") and LOCATION (C3, C4). It was found that the variable CONDITIONS significantly affected the suppression of μ rhythms ($F(2,18) = 16.298$, $p < .001$, $\eta^2 = .64$). The differences between the three levels of this variable are consistent with expectations (Tukey's HSD test: "Observation" vs. "Imagery", $p < .041$; "Imagery" vs. "White Noise", $p < .018$; "Observation" vs. "White Noise", $p < .001$; see Fig. 3).

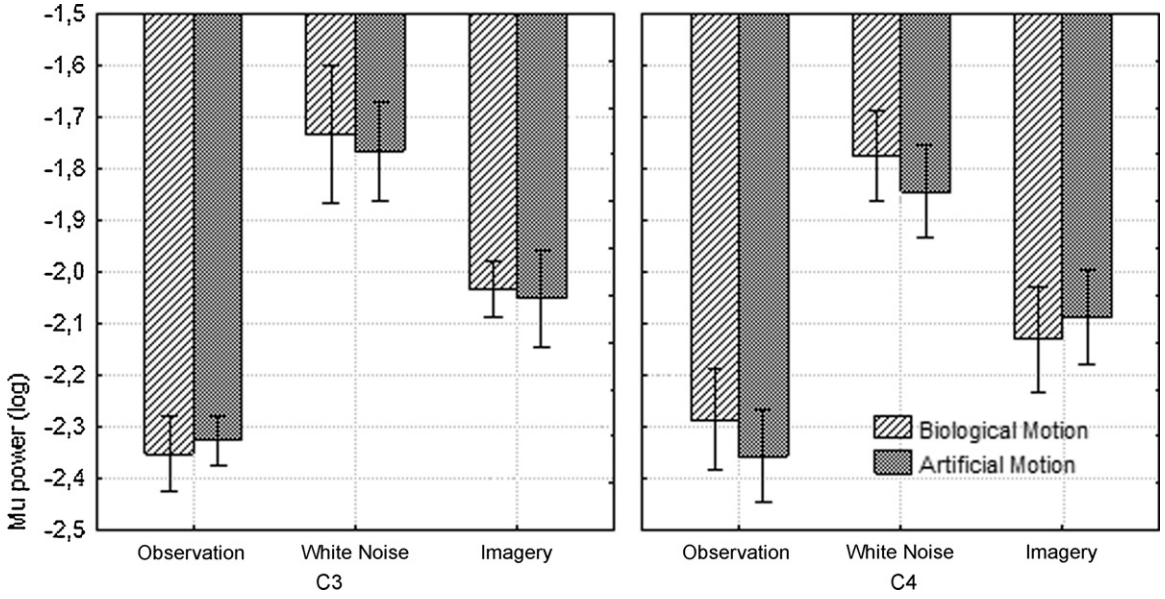

Fig. 3. Suppression during the observation and imagery of movements for scalp locations C3 and C4. Bars represent the mean log ratio of power in the μ frequency (8–13 Hz) during the Observation, Imagery and White Noise conditions. Gray stripe means "Biological Motion" and black dots mean "Artificial Motion". Error bars represent the standard error of the mean. For all values, a mean log ratio less than baseline indicates μ suppression.

The effect of the variable MOVEMENT ("Biological Motion", "Artificial Motion") on the suppression of μ rhythms within the test group was not statistically significant ($F(1,9) = .130$, $p < .73$). On the one hand, we have no reason to reject the hypothesis that the two types of motion are different because the power of the test for the null hypothesis was low ($1 - \beta < .1$). On the other hand, F-test value is very low (close to 0) and an increase in sample size would rather not be expected to significantly affect the growth of the F-test value. So, the more likely is a null hypothesis, whereby there is only one neural mechanism related to the biological and artificial movements.

It transpired that the suppression of μ rhythms recorded with the electrodes located on the right and left side of the scalp (C3(36) vs. C4(104)) was similar ($F(1,9) = 1.249$, $p < .29$). Although the power of the test for the null hypothesis was also low ($1 - \beta = .18$) we shall return later to this effect.

The distribution of differences for all experimental conditions is illustrated in Fig. 3.

These results confirm the existence of differences in the level of suppression of μ rhythms, depending on whether the movement was imagined or observed. The difference and its direction are consistent with the cited studies [12,18] and our expectations. The results for the control condition ("White Noise") and its relation to other experimental conditions also corresponds to the results of previous studies [15,16]. In our experiment, we recorded attenuation μ rhythms while a subject imagines movement, which was targeted for a specific purpose. In this case, the aim was to predict the field where the pawn would be at the end of the movement. Subjects had to perform a task which required them to perform a much more complex imagery process than just to recall the previously observed movement, as was the case in the Pfurtscheller [18] study. Perhaps the greater involvement of people tested in the task led to such a high level of statistical significance and the experimental effect caused by the variable CONDITIONS. This effect can also refer to the results of the experiment of Umilta and colleagues [27]. They found that when the monkey no longer saw the experimenter's hand movement this did not cause the expiry of the activity of MNS, provided that the animal anticipated the aim of the movement.

The results of our study indicate that there is no difference between the suppression of μ rhythms during the observation of biological and artificial movement.

Oberman et al. [15] also found no significant differences in the suppression of μ rhythms in the group observing the movement of the hand of a human and the group observing the movement of a robotic arm. The effect of observing biological and artificial motion on the suppression of μ rhythms was obtained by Stanley et al. [25] and Ulloa and Pineda [26]. In these studies, the movement was represented by moving points (the effect of point-light), which reflect the movement of the whole body, not a single limb, as in the studies of Oberman et al. [15] and ours. In other words, the suppression of μ rhythms during the observation of a biological or an artificial motion is greater when moving the entire body (figure, character), than its individual parts. This is how the stimuli were designed for the experiments of Oberman et al. [16], and Ulloa and Pineda [26].

The level of the suppression of μ rhythms in the present study was similar to the electrodes on the right and the left side of the head. This is contrary to trends observed in other studies, which used the measurement of two or three electrodes [15,16]. We therefore checked whether the number of electrodes which were taken for analysis had an effect on inter-hemispheric differences.

Thus we carried out an additional analysis taking into account the record of only two electrodes, corresponding to the location of C3(36) and C4(104) (according to the system 10–20), as well as in those previous studies [16]. It turned out that the factor LOCATION significantly affects the level of suppression of μ rhythms ($F(1,9) = 6.677$, $p < .05$, $\eta^2 = .42$). As in other experiments [20] the suppression of μ rhythm on the right side of the scalp was significantly stronger ($M = -2.15$, SD = .07) than the left ($M = -1.98$, SD = .04). The results show an interesting methodological problem associated with verifying hypotheses about differences in the suppression of μ rhythms in both hemispheres. It appears that the probability of finding differences between hemispheres is a function of the number of electrodes from which data is gathered for analysis. A larger number of electrodes means more variance within the group and greater probability of rejecting the alternative hypothesis. It is worth noting that the results of the analysis confirmed all other effects related to the factors MOVEMENT and CONDITIONS, similar to the assembly using the concentrations of 16 electrodes.

The differences in the suppression of μ rhythms between perception and imagery have been dealt with in other studies. However, in contrast to previous experiments, the task in our experiment consisted of completing previously observed actions in the imagination, rather than the simple mapping of them [12]. In order to accomplish this task, it was necessary to involve both memory processes as well as cognitive functions that allow anticipation of initiated, goal-oriented motor activity. The ability to identify the aim of a motor act is one of the main elements of the theory of mirror neurons [24]. Thus, the experimental procedure used in our study is also closer to the classical scheme of research on mirror neurons in monkeys [27] than those used in the previously mentioned experiments [12,18].

Both in the study of Umilta et al. [27] and our study, participants watched only the beginning of the motion, knew its trajectory and its purpose, and learned to perform this motion before the test. However, the experiment of Umilta et al. [27] also differed from our study in terms of the subjects (monkey vs. man), the technique of measuring the activity of the brain (the potentials of individual mirror neurons in area F5 vs. suppression of the rhythm μ), the type of movement (biological only vs. biological and artificial), and the complexity of observed movement (reaching for an object vs. several types of pawn movements).

Umilta et al. [27] found a specific pattern of neuronal activity when the monkey was convinced that the motor activity was done outside its field of view. Despite the few mentioned differences between our studies, we can assume that we have obtained the level of suppression of μ rhythms in humans which reflects the same goal-oriented process of motor activity simulation which occurred in the area F5 in monkey brains.

Disclosure

None of the authors has any financial interest or conflicts of interest in the work presented in this manuscript.

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