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# Motor execution reduces EEG signals complexity: Recurrence quantification analysis study

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## ABSTRACT

The development of new approaches to detect motor-related brain activity is key in many aspects of science, especially in brain–computer interface applications. Even though some well-known features of motor-related electroencephalograms have been revealed using traditionally applied methods, they still lack a robust classification of motor-related patterns. Here, we introduce new features of motor-related brain activity and uncover hidden mechanisms of the underlying neuronal dynamics by considering event-related desynchronization (ERD) of  $\mu$ -rhythm in the sensorimotor cortex, i.e., tracking the decrease of the power spectral density in the corresponding frequency band. We hypothesize that motor-related ERD is associated with the suppression of random fluctuations of  $\mu$ -band neuronal activity. This is due to the lowering of the number of active neuronal populations involved in the corresponding oscillation mode. In this case, we expect more regular dynamics and a decrease in complexity of the EEG signal recorded over the sensorimotor cortex. In order to support this, we apply measures of signal complexity by means of recurrence quantification analysis (RQA). In particular, we demonstrate that certain RQA quantifiers are very useful to detect the moment of movement onset and, therefore, are able to classify the laterality of executed movements.

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The detection of the motor-related brain activity for noninvasive electroencephalogram (EEG)-based brain–computer interfaces (BCIs) is an actively discussed topic in many areas of research. This is of special interest in the context of neurorehabilitation and non-muscular control of remote devices using BCI-based techniques. Traditionally used methods for motor-related feature extraction, such as spatial filtering and time-frequency analysis, allow one to associate motor actions with event-related desynchronization (ERD) of  $\mu$ -band oscillations (8–13 Hz) over the sensorimotor cortex. However, these features, i.e., location of brain activity sources, amplitudes of spectral components, etc., are of strong inter- and intrasubject variability. Moreover, inherent nonstationarity and a poor signal-to-noise ratio of EEG signals strongly complicate the detection and classification of motor-related patterns in single trials. To find new features of the motor-related brain activity, we explore EEG signals from

the viewpoint of signal complexity. In particular, we put forward the hypothesis that  $\mu$ -band ERD causes the reduction of random fluctuations of neuronal activity, resulting in a more regular behavior of EEG signals during motor task accomplishments. With this goal in mind, we apply recurrence quantification analysis (RQA), a nonlinear method that describes the recurrence structure of a system by several quantifiers, in order to examine its complexity and uncover hidden underlying phenomena. Our findings show that certain RQA measures, namely, determinism and recurrence time entropy, allow one to reveal new features associated with neuronal activity complexity reduction. These measures are not only sensitive to the transitions from background to motor-related brain activity but also very useful for distinguishing different types of motor actions (left/right limbs motion), which is valuable in the context of potential BCI applications.

## I. INTRODUCTION

The study of motor-related brain activity is a challenging task at the intersection of neuroscience, medicine, nonlinear physics, and engineering. This problem is closely related to the neurorehabilitation of post-stroke patients suffering motor and cognitive impairment.<sup>1</sup> Another branch of actual research demanding brain motor-related activity decryption is a mental control of robotic systems, prosthetic devices, and vehicles.<sup>2</sup> Translating the recorded signals of brain activity into control commands, brain-computer interfaces (BCIs) can provide a communication channel between the human and the external device.<sup>3–5</sup>

Recently, considerable progress has been achieved in invasive BCIs for motor control. This is due to the principles of the invasive interfaces operation, which rely on the firing properties of individual neurons or small groups of neighboring neurons modulating their activity according to the motor tasks.<sup>6</sup> In this case, motor-related neuronal activity patterns are pronounced and well reproduced, which allows one to develop precise schemes for motor control.<sup>5,7</sup> Despite the outstanding ability for an accurate detection and translation of brain motor commands, the application of invasive BCIs for daily purposes is extremely difficult since it requires complex brain surgery, which is performed in rare cases of urgent need.

On the contrary, noninvasive BCIs are easy to apply and much more convenient in terms of usability. Among the variety of neuroimaging methods, electroencephalography (EEG) appears to be one of the most suitable for routine BCI applications.<sup>8</sup> A comprehensive review on the current state and future perspectives of sensorimotor EEG-based interfaces was given by Yuan and He.<sup>9</sup> Traditionally, methods of spatial filtering,<sup>10,11</sup> machine learning,<sup>12,13</sup> and time-frequency analysis<sup>14,15</sup> are the core algorithms for feature extraction in this context.

However, the detection and classification of motor-related patterns of brain activity using noninvasive techniques are much more complicated. The fact is that EEG simultaneously records electrical activity of a large group of neuronal populations located close to the measuring sensor.<sup>16</sup> Generally, distinct neuronal ensembles do not behave in coherency. Therefore, EEG signals represent a complex mixture of local neuronal activity components. The latter determines inherent critical properties of EEG signals, such as a poor signal-to-noise ratio and nonstationarity. Besides, a number of studies reported that traditional features of motor-related brain activity, such as amplitudes of EEG signals, power spectral density, time-frequency, and spatial features, basically show inter- and intra-subject variability.<sup>15,17–19</sup> Hence, it is of high interest to find relevant features and methods that will withstand the discussed weaknesses of EEG recordings.

It is known that motor tasks block ongoing activity in the  $\mu$ -band (8–13 Hz) of a EEG record, i.e., event-related desynchronization (ERD) takes place.<sup>14</sup> Motor-related ERD implies a time-locked decrease in the number of active neurons involved in  $\mu$ -oscillations.<sup>20</sup> We hypothesize that this is equivalent to a suppression of spontaneous fluctuation of neuronal activity in the corresponding frequency band compared to the preceding background activity. Thus, we expect that motor-related neuronal dynamics should be reflected in EEG recordings by the signal's complexity reduction.

To explore this phenomena, we apply recurrence quantification analysis (RQA), which provides a rich number of relevant measures of complexity.<sup>21,22</sup> RQA is a powerful tool for the analysis of biological signals, specifically heart rate variability,<sup>23,24</sup> muscle activity,<sup>25,26</sup> sleep,<sup>27–29</sup> and pathological EEGs.<sup>30,31</sup> Early RQA studies that focused on EEG analysis demonstrated the ability of RQA measures to quantify N400 event-related potentials (ERPs) in single trials,<sup>32</sup> which emphasizes the robustness of the RQA approach in the context of the current study.

In summary, this work intends to find new features of motor-related brain activity with the focus on the motor-related reduction of EEG signal's complexity in the  $\mu$ -band. Here, we test our hypothesis on the upper limb motor execution tasks and apply RQA to quantify changes of signal complexity caused by the motor task accomplishment. We demonstrate that certain RQA quantifiers are sensitive to the transition from background to motor-related brain activity which, in turn, reveals differences between left and right upper limb movements.

The paper is organized as follows. Section II describes the details of our experimental study, the data pre-/postprocessing, and briefly the RQA method. Section III is devoted to the analysis of the time-dependent RQA measures and the inference of task vs background differences along with differences between left and right limb movements. Finally, we summarize our results and discuss them in the context of BCI development in Sec. IV.

## II. METHODS

### A. Participants

Participants were recruited among the employees and students of the Innopolis University. During the data preparation, we selected 10 subjects (7 male, 3 female) according to the following checklist: healthy, aged 18–33, right-handed, never participated in this or similar experiments before, and having no history of brain tumors, trauma, or stroke-related medical conditions. All the participants were pre-informed about the goals and design of the experiment. Experimental studies were performed in accordance with the Declaration of Helsinki and approved by the local research Ethics Committee of Innopolis University.

### B. Data acquisition

EEG signals along with electromyograms (EMGs) from both hands were recorded using a noninvasive EEG/EMG system “Encephalan-EEGR-19/26” (Medicom MTD company, Taganrog, Russian Federation). Electrocardiogram (ECG) and electrooculogram (EOG) were also recorded for further removal of cardiac and eye-movement artifacts. All recorded signals were amplified and digitized at the sampling rate of 250 Hz. In order to record motor brain activity, we used 9 EEG Ag/AgCl electrodes Fc3, Fcz, Fc4, C3, Cz, C4, Cp3, Cpz, Cp4 located over the motor cortex according to the international “10–10” system proposed by the American Electroencephalographic Society. To capture hand movements execution, we placed 4 EMG electrodes as follows: 1 reference on the wrist and 1 on the forearm muscle for each hand.

### C. Experimental setup

The session started with a 5-min recording of background brain activity, during which the participants were instructed to relax and listen to classical music. They were also instructed not to think about anything special and to make no hand movements. Then, each participant, during the active phase of the experiment, performed two types of motor actions according to the experimental protocol, i.e., movements for the left and right hands [Fig. 1(a)]. Each hand movement implied squeezing the hand into a fist after the first signal, holding it down to the second signal, and then relaxing. The time interval between the first and the second signals was chosen randomly for each motor task in the range 4–5 s and the time interval between the second signal of the current task and the first signal of the next task (resting period) was randomly chosen in the range 6–8 s [Fig. 1(b)]. The active phase of the experiment consisted of 30 repetitions of each type of motor task (60 total) and the overall duration of the experimental procedure was approximately 18 min per participant, including background activity recording.

### D. Data preprocessing

The following preprocessing steps were carried out to prepare raw EEG and EMG recordings for further analysis.

First, cardiac and eye-movement artifacts were removed using recorded ECG and EOG signals via artifact removal method based on the Gram–Schmidt process.<sup>33</sup> A Notch filter around 50 Hz was applied to EEG and EMG data to exclude power line effects.

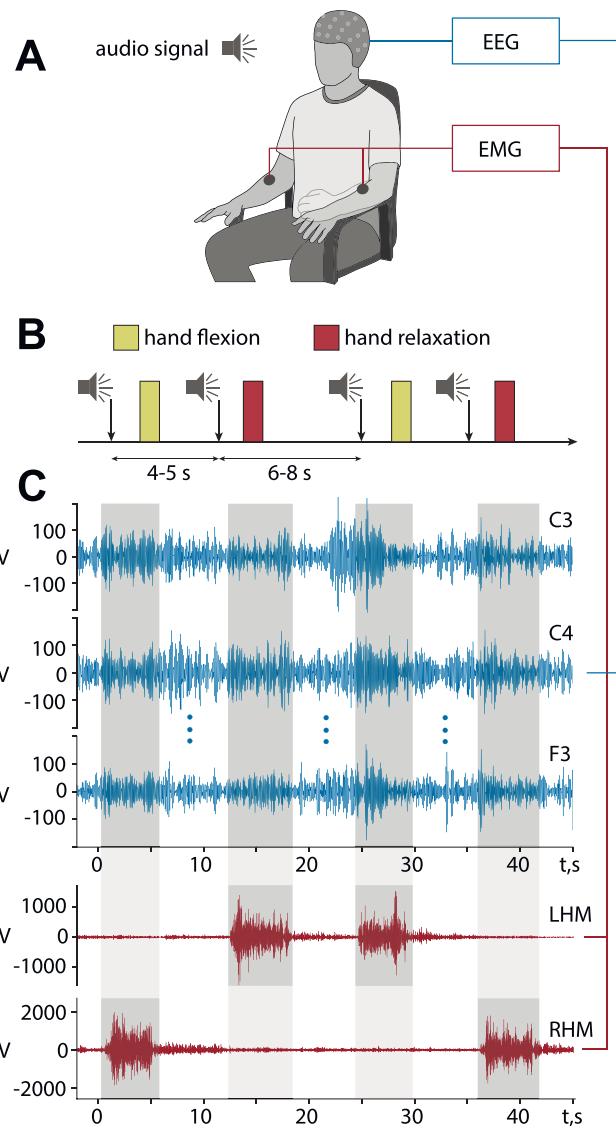
Second, we applied a fifth-order Butterworth bandpass filter in the range of 8–13 Hz to the 18 min multichannel EEG signals in order to extract  $\mu$ -band neuronal oscillations associated with motor-related brain activity. EMG recordings were also bandpass filtered (10–100 Hz) to capture pronounced high-frequency fluctuations of muscle activity caused by muscle tension during movement execution [Fig. 1(c)]. The latter allows one to determine exact times for the beginning and the end of movement executions and to study the motor-related brain activity at these specific intervals.

Finally, the bandpass filtered time series (both EEG and EMG) were split into 60 trials, each lasting 18 s (6 s before and 12 s after the command, totaling 4500 data points), i.e., 30 attempts for the left and right hands.

The considered EEG trials represent nine-dimensional multivariate sets  $\mathbf{X}(t) = (x_{Cp4}(t), x_{C4}(t), x_{Fc4}(t), x_{Cp2}(t), x_{Cz}(t), x_{Fc2}(t), x_{Cp3}(t), x_{C3}(t), x_{Fc3}(t))^T$  composed of EEG signals recorded over the sensorimotor brain area [Fig. 2(a)]. To describe brain dynamics in three areas of interest, we separated  $\mathbf{X}$  into three 3D subsets, according to their location on the scalp [Fig. 2(b)]:

1. right hemisphere (RH):  $\mathbf{X}_R(t) = (x_{Cp4}(t), x_{C4}(t), x_{Fc4}(t))^T$ ;
2. left hemisphere (LH):  $\mathbf{X}_L(t) = (x_{Cp3}(t), x_{C3}(t), x_{Fc3}(t))^T$ ; and
3. longitudinal fissure (F):  $\mathbf{X}_F(t) = (x_{Cp2}(t), x_{Cz}(t), x_{Fc2}(t))^T$ .

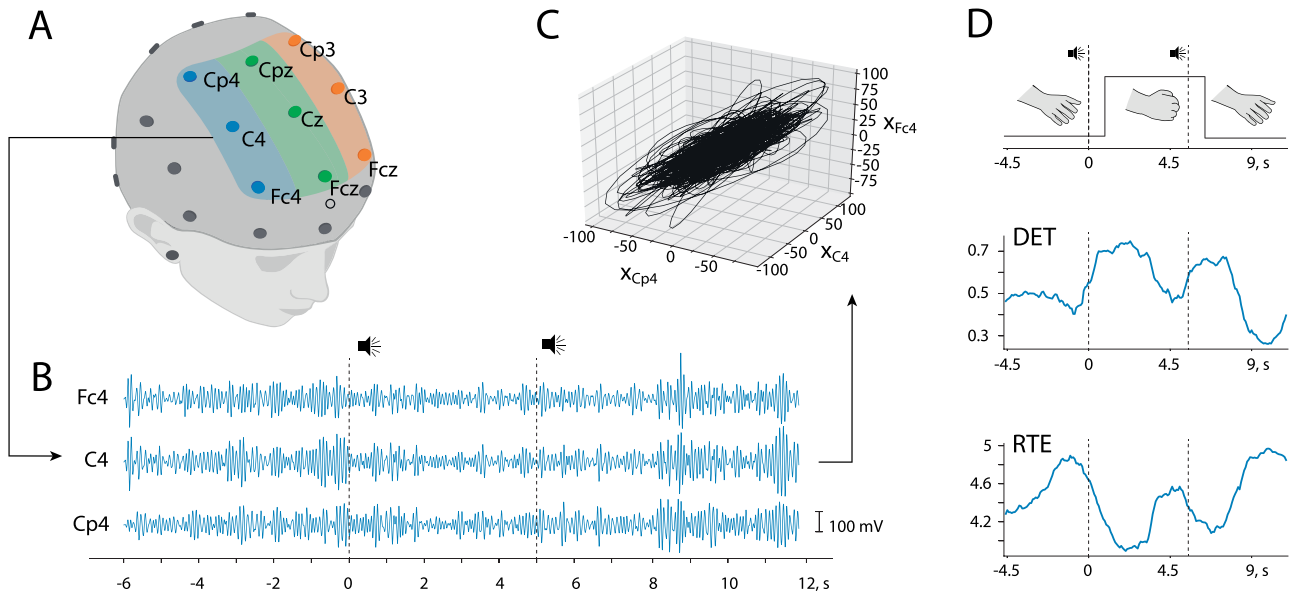
Consequently, from a physical perspective, each brain area is represented by a three dimensional trajectory, treating the constitutive time series as state variables [Fig. 2(c)]. This way of state space trajectory construction is convenient in the context of multivariate EEG analysis and circumvents the single variable embedding problem.<sup>34–37</sup>



**FIG. 1.** (a) Schematic representation of the experimental procedure. Subjects were sitting comfortably in the chair while performing motor actions of left and right hands on audio signal command. (b) Experimental sequence. Time intervals between the signals were chosen randomly in ranges 4–5 s between first and second signals for one task and 6–8 s from second signal of previous and first signals of the next task. (c) Examples of recorded  $\mu$ -bandpass filtered EEG and EMG signals (LHM, left-hand movement; RHM, right-hand movement).

Of particular note is the fact that the further analysis deals with sensor-level EEG recordings. This is done to exclude EEG pre-processing steps related to source reconstruction and capture general effects of motor-related activity from the viewpoint of an overall decrease of complexity of the underlying neuronal processes in the sensorimotor cortex. The advantages and limitations of such an approach will be discussed in Sec. III.





**FIG. 2.** Step-by-step visualization of the EEG signal analysis. (a) EEG electrodes, located at the sensorimotor area, forming a multivariate set  $\mathbf{X}(t)$ : right hemisphere [subset  $\mathbf{X}_R(t)$ , blue area], left hemisphere [subset  $\mathbf{X}_L(t)$ , orange area], and longitudinal fissure [subset  $\mathbf{X}_F(t)$ , green area]. (b) Example of a motor-related EEG trial from  $\mathbf{X}_R(t)$  (left-hand movement). Vertical dashed lines correspond to the first and second audio signal at 0 s and 5 s, respectively. (c) Representation of the current trial from  $\mathbf{X}_R(t)$  as a trajectory in 3D phase space. (d) Illustrative scheme of the movement execution accessed from a EMG signal (top panel) and corresponding time-dependent measures of DET (middle panel) and RTE (bottom panel).

### E. Recurrence quantification analysis

Being a fundamental property of most dynamical systems, recurrence implies that the system's state repeats itself in time.<sup>38</sup> It is represented as neighboring points (states) of the system's trajectory in its state space. A common way of visualizing the system's repeating states is the recurrence plot (RP), which can show structures such as diagonal and horizontal/vertical lines and areas of different recurrence densities.<sup>21</sup> Certain structures are related to the system's complexity, and recurrence quantification analysis (RQA) was introduced to analyze them numerically using various measures of complexity.<sup>22</sup>

To analyze the recurrence structures in the selected brain areas, using the multivariate set  $\mathbf{X}$  (Sec. II D), we created a binary recurrence matrix

$$R_{ij} = \begin{cases} 1 & \text{if } (\varepsilon - \|\mathbf{X}_i - \mathbf{X}_j\|) < 0, \\ 0 & \text{otherwise,} \end{cases} \quad (1)$$

where  $\mathbf{X}_{ij} = \mathbf{X}(t_{ij})$ ,  $i, j = 1, \dots, N$  with  $N = 4500$  for the number of considered states  $\mathbf{X}_i$ . The recurrence threshold  $\varepsilon$  determines the size of the neighborhood in state space in which states are being considered recurring.<sup>21</sup> When analyzing an RP, one should take into account that the obtained results can crucially depend on the choice of this threshold. To provide a robust representation of the RP and ensure comparability within the samples, i.e., data from different participants, we determined the value of the threshold  $\varepsilon$  for each sample as the 3rd percentile of the pairwise distance distribution, following Kraemer *et al.*<sup>39</sup>

To access time dependence of the estimated RQA quantifiers, we used a running window along the main diagonal line of each RP with a window size of  $w = 750$  data points (3 s) and a shift  $\delta w = 20$  data points (0.08 s).

In the current study, we want to quantify regularity and complexity of EEG signals affected by motor tasks execution. Therefore, we pick two suitable RQA quantifiers, namely, the Determinism (DET) and the recurrence time entropy (RTE). DET is defined as the ratio of recurrence points that form diagonal lines to all recurrence points found in the RP,

$$DET = \frac{\sum_{l=l_{min}}^w lP(l)}{\sum_{l=1}^w lP(l)}, \quad (2)$$

where  $P(l)$  is the histogram of diagonal lines  $l$  in the RP and  $l_{min} = 2$  is the minimal considered length of a diagonal line. The presence of diagonal lines in the RP is an important indicator of a deterministic process, since in this case, trajectories at different points in time evolve in a similar manner. More correlated and regularized processes are characterized by longer diagonal lines and less isolated points.

Along with DET, we estimate the recurrence time entropy (RTE)—a complexity measure based on the “white” (non-recurrent) vertical lines indicating recurrence times  $t_w$ ,

$$RTE = - \sum_{t_w=1}^{T_{max}} p(t_w) \ln p(t_w), \quad (3)$$

where  $p(t_w) = h(t_w) / \sum_{t_w} h(t_w)$  is the estimated probability of a recurrence time  $t_w$  and  $h(t_w)$  is the histogram of recurrence times obtained from the RP. This RQA measure is well suited for capturing the transitions between periodic and chaotic dynamics (and vice versa), because it is related to the Kolmogorov–Sinai entropy.<sup>40</sup> A regular process results in low *RTE* values, with a chaotic process increasing the number of different recurrence times, thus increasing its distribution  $h(t_w)$  and, consequently, increasing the *RTE* value.

Typical single-trial time series of *DET* and *RTE* are shown in Fig. 2(d). One can see the increase of *DET* and the decrease of *RTE* associated with two motor actions, respectively, following the corresponding audio signal. A detailed discussion of RQA results will be given based on the between-subject analysis in Sec. III. For each participant, we average the RQA time series over the trials and exclude the baseline level (3 s prior the first audio signal),

$$\begin{aligned}\Delta DET(t) &= DET(t) - DET_{bckg}, \\ \Delta RTE(t) &= RTE(t) - RTE_{bckg},\end{aligned}\quad (4)$$

where  $DET_{bckg}$  and  $RTE_{bckg}$  are mean values of *DET* and *RTE* 3 s prior the first audio signal.

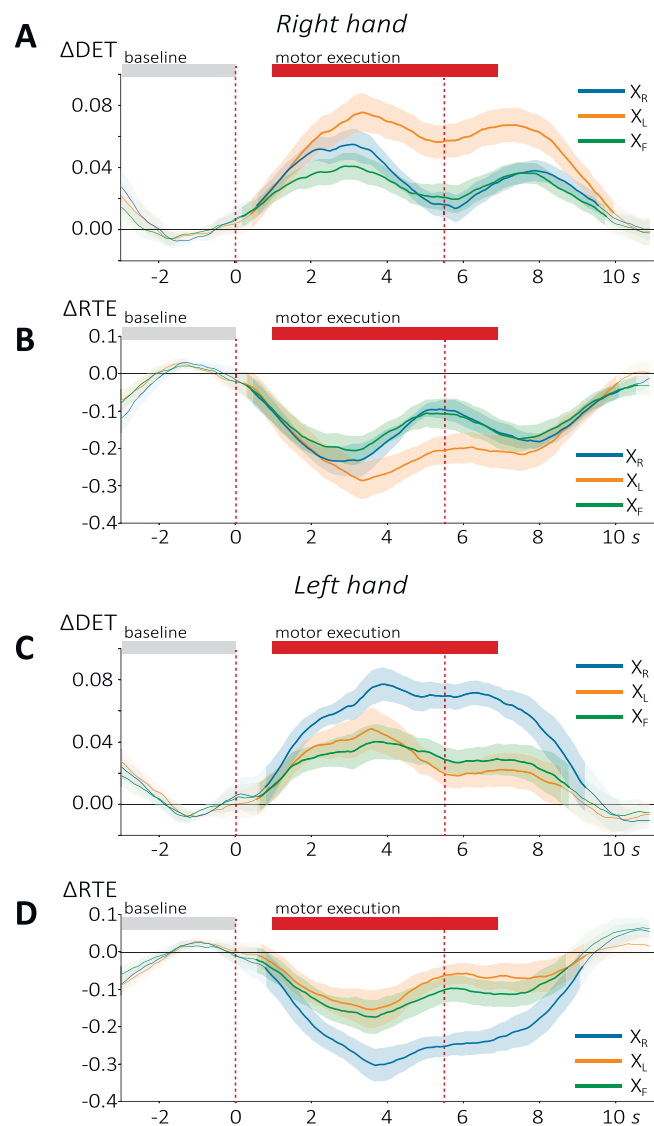
All RQA related computations were performed using the DynamicalSystems software library for Julia programming language.<sup>41</sup>

## F. Statistical test

The motor-related changes of the RQA measures calculated at the different (area, time)-pairs are treated as different aspects of the data with respect to which the experimental conditions (motor-task vs baseline and left vs right limb movement) will be compared. Each (area, time)-pair is tested via statistical t-test. Since we do not know exactly the locus of the possible differences in the (area,time)-domain, the multiple comparisons problem (MCP) takes place. To control family-wise error rate (FWER) and address the MCP, we used nonparametric statistical test based on the random partitions following Maris and Oostenveld.<sup>42</sup>

## III. RESULTS AND DISCUSSION

To address the main problem of the current study, namely, the quantification of an expected reduction in the complexity and randomness of neuronal processes in the sensorimotor cortex in the execution of motor tasks, we consider general cross-subject effects of motor-related changes in the corresponding RQA time series. First, we analyze the transition from (random) background neuronal activity to brain activity in the accomplishment of motor tasks. Figure 3 shows the results of *DET* and *RTE*, averaged over the subjects and along with the standard error, for the movements of right Figs. 3(a) and 3(b) and left Figs. 3(c) and 3(d) hands. As noted in Sec. II D, we are particularly interested in differences in results regarding the right hemisphere ( $X_R$ , blue), the left hemisphere ( $X_L$ , orange), and the longitudinal fissure ( $X_F$ , green). These results indicate that motion execution is associated with an increase in *DET* [Figs. 3(a) and 3(c)]. In addition, *DET* takes local maxima near start (approximately 2–4 s after the first audio command) and end (approximately 7–8 s after the first command) of the motion execution. The positions of the local maxima are clearly associated



**FIG. 3.** Time dependence of  $\Delta DET$  and  $\Delta RTE$  averaged over all subjects ( $\pm SE$ ) for the right hemisphere ( $X_R$ , blue), the left hemisphere ( $X_L$ , orange), and the longitudinal fissure ( $X_F$ , green) in the case of the right [(a) and (b)] and left-hand movements [(c) and (d)], respectively. Bold areas highlight the time intervals of significant divergence from the baseline level ( $p < 0.05$ , MCP corrected via a nonparametric statistical test). In each panel, the red dashed lines indicate the moments of the first (0 s) and the second (5.5 s) audio signals and the black horizontal line corresponds to zero level. Gray boxes show 3 s baseline interval before the first audio signal, and red boxes show the interval of movement execution obtained from averaged EMGs.

with the hand flex and hand relaxation that are performed after the first and second audio commands, while the *DET* values decrease when holding the hands in a compressed state. The execution of motor tasks in this experimental setup is thus clearly characterized by the pronounced local increase of *DET*. In fact, the growth of *DET*

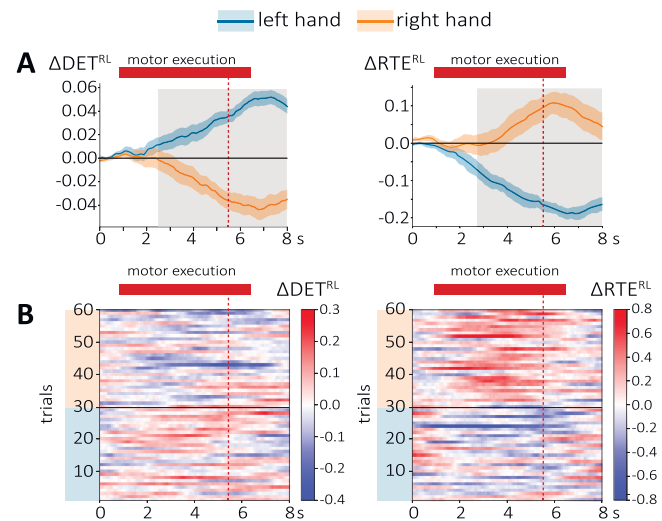
implies a predictable or regular motor neuronal activity. This finding is consistent with our hypothesis that motor action is associated with the suppression of random  $\mu$ -band fluctuations in the EEG that are inherent in the background activity. Local peaks of  $DET$  are accompanied by a decrease of  $RTE$  [Figs. 3(b) and 3(d)]. This also shows that the underlying motor neuronal activity recorded by the EEG becomes less chaotic and complex. A nonparametric statistical test in the (area,time)-domain (cf. Sec. II F) shows that the described motor changes of the RQA quantifiers compared to the background activity are significant ( $p < 0.05$ ) for all three considered areas during the duration of the motor task execution. The occurrence of significant changes about 1.5 s before and after the execution of the motor task is related to the half width of the selected window size  $w = 3$  s. It is noteworthy that the RQA measurements return to the background level after the end of the movement, which is a clear indication of the backward transition of the neuronal dynamics into the background mode.

It should be noted that the RQA time series for the right and left hands have a similar qualitative time course (two maxima/minima associated with hand flexion and relaxation) but assume involvement of the different brain areas. Particularly, the right-hand movement reduces the complexity of neural dynamics in the left hemisphere more [orange curve in Figs. 3(a) and 3(b)] and the left hand movement—in the right hemisphere [blue curve in Figs. 3(c) and 3(d)]. It coincides with the known contralaterality of the brain's motor-related activity. However, complexity reduction in the ipsilateral brain area and fissure region, even being not such pronounced, is also observed during the movement execution. This could be due to the volume conduction/field spread effect, which is critical for noninvasive measurements.<sup>43</sup> Despite these limitations, analyzing the complexity of neuronal dynamics using RQA makes it possible to distinguish between the further discussed lateral types of motor actions.

Let us take a closer look at the differences in brain dynamics during right and left-hand movements with respect to contralateral effects. For further analysis, we only use the  $X_R$  and  $X_L$  records and introduce a measure of asymmetry as the differences between RQA measures in the right and left hemisphere for both hands,

$$\begin{aligned}\Delta DET^{RL}(t) &= \Delta DET^R(t) - \Delta DET^L(t), \\ \Delta RTE^{RL}(t) &= \Delta RTE^R(t) - \Delta RTE^L(t),\end{aligned}\quad (5)$$

where superscripts  $R$  and  $L$  indicate right and left hemispheres, respectively. Figure 4(a) shows the course of  $\Delta DET^{RL}(t)$  and  $\Delta RTE^{RL}(t)$  during the motion execution, averaged over all subjects and along with the standard error. Here, the first audio signal corresponds to the time  $t = 0$ . In addition to the previous results, Fig. 4 shows that the reduction of the complexity of the neural dynamics during the execution of left- and right-hand movements takes place in a different way. A comparison of  $\Delta DET^{RL}$  and  $\Delta RTE^{RL}$  for left- and right-hand movements using a nonparametric statistical test shows that both measures reflect significant differences between the types of movement. Specifically, reducing the complexity of the underlying neuronal dynamics results in pronounced interlateral asymmetry during movement execution, which is reflected in a maximum at  $DET$  and a minimum at  $RTE$  in the case of the left-hand movement and vice versa for the right. Note that the asymmetry



**FIG. 4.** (a) Time dependence of  $\Delta DET^{RL}$  and  $\Delta RTE^{RL}$ , derived from EEG data of the right and left hemispheres [Eq. (5), see text for details]. Measures are averaged over the subjects and displayed as mean  $\pm$  SE. Shaded areas mark the areas with significant differences between the time series corresponding to left- and right-hand movements ( $p < 0.05$ , MCP corrected via nonparametric statistical test), and the red boxes indicate the movement execution interval determined from averaged EMGs. (b) Exemplary representation of motor-related EEG samples analysis on an individual test level using  $\Delta DET^{RL}$  and  $\Delta RTE^{RL}$ . EEG experiments are arranged as follows: left-hand movements (trials 1–30, highlighted in blue) and right-hand movements (trials 31–60, highlighted in orange).

measures based on both  $DET$  and  $RTE$  show significant differences of right- and left-hand motions [Fig. 4(a)]. The introduced measures discriminate the brain dynamics associated with left- and right-hand movements may be based on a statistical test (cf. Sec. II F) at an interval that approximately covers the motion execution (2.5–8 s after the first audio signal). In fact, the disclosed properties of motor-related EEG samples associated with contralateral asymmetry are suitable for a single-trial analysis and classification. Figure 4(b) shows the exemplary representation of RQA applied to individual EEG experiments collected from a randomly selected subject. It can be seen that the chosen RQA quantifiers are able to clearly distinguish between left- and right-hand movements: the former are characterized by the positive  $\Delta DET^{RL}(t)$  and simultaneously negative  $\Delta RTE^{RL}(t)$  values and vice versa for the latter.

In summary, we would like to emphasize that the discussed features of motor neuronal activity detected by EEG signals at the sensor level through RQA complexity measurements are clearly observed and well reproduced in the experimental group under consideration. What is more important is that the generality of the cross-subject analysis provided also applies to the single-trial analysis [see exemplary illustration in Fig. 2(e)]. The latter, together with the low computational cost of RQA algorithms, offers the prospect of their application in EEG-based BCIs for motion control and assessment. However, the implementation of the RQA methods for stable operation in real-time detection and classification of motor-related brain states requires additional extensive research.

#### IV. CONCLUSION

We have used RQA to study new features of motor-related neuronal processes that are measured by noninvasive EEG. In our analysis, we have focused on the consideration of time-dependent RQA quantifiers based on diagonal lines (determinism, *DET*) and non-recurrent vertical lines (recurrence time entropy, *RTE*). These measures are suitable for detecting transitions between regular (periodic) and irregular (chaotic) dynamics and for quantifying the complexity of the system under study. Both quantifiers clearly show that the direct execution of motor tasks is associated with a large increase in the regularity of the EEG signals, i.e., a reduction in the complexity of underlying motor-related neuronal processes. In other words, RQA has shown that  $\mu$ -band ERD causes a reduction in random fluctuations in neuronal activity inherent in the background brain activity, leading to more regular behavior of the EEG signal during the motor task execution. In addition to detecting an increase in motor-related regularity of brain dynamics, *DET* and *RTE* measurements are sensitive enough to indicate the difference between two lateral types of motion due to the inherent differences in neuronal response. Specifically, we observed a strong increase in regularity in the sensorimotor area contralateral to the executed movement. Despite the limitations of EEG analysis at the sensor level, such as volume conduction/field spreading effect, interhemispheric asymmetry of motor-related brain activity was identified using both *DET* and *RTE* measures. These findings statistically support significant differences between two types of performed movements.

Overall, the current results are consistent with and complement the well-known concepts of motor-related brain processes. We suppose that the discovered features of neuronal dynamics in the sensorimotor cortex and the robust RQA methods of identification and classification will contribute to the study of the noninvasive EEG-based BCI development for motor control and rehabilitation.<sup>5,44–46</sup>

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