Modular organization of reaching and grasping movements investigated using EEG microstates

Minguillon J., Pirondini E., Coscia M., Leeb R., *IEEE Member*, Millán J.d.R., *IEEE Senior Member,* Van De Ville D., *IEEE Senior Member,* Micera S., *IEEE Senior Member.*

***Abstract* — How movements are generated and controlled by the central nervous system (CNS) is still not well understood.**

In this work, we tested the hypothesis of a modular organization of the brain activity during the execution of voluntary movements. In particular, we extracted meta-stable topographies as a measure for global brain state, so-called microstates, from electroencephalography (EEG) data during pure planar reaching movements as well as reaching and grasping of different objects, and we compared them with those extracted during resting-state. The results showed the emergence of specific EEG microstates related to movement execution.

Our results provide evidence about the benefits of EEG microstate analysis for motor control studies and their importance to better understand brain reorganization in neurological pathologies.

I. Introduction

Modularity is a model able to explain movement execution and generation. It has been suggested that arm movements are composed of discretely generated sub-movements [1] and that the muscle activity during movements results from the synergistic co-activation of motor modules of neural origin [2].

A modular organization seems also to be present in the brain networks. During resting-state, the brain activity appears organized in meta-stable states characterized by a period of coherent synchronized activation of neural networks that can be detected from the recording of scalp EEG activity as polarity-independent topographic maps with duration of 80-150 ms [3-5]. These meta-stable states have been called functional EEG microstates [3-5] and suggested to be basic building blocks of information processing; e.g., they correlate with well-known fMRI resting-state networks that have been attributed to phonological processing, visual imagery, attention reorientation, and subjective interoceptive-autonomic processing [6].

A recent study [7] investigated EEG microstates during the execution of a reaching task that requires online movement corrections. In this preliminary study, the authors showed that the onset/offset of each sub-movement correlates in timing with the occurrence of a sequence of three particular microstates whose localized sources were in the fronto-parietal areas usually involved in the control of motor corrections.

The analysis of EEG microstates could lead to a simplified perspective of brain activity during movement execution allowing the detection of the different neural populations active in the brain at each time instant.

However, EEG microstates during the execution of voluntary movements have not yet been investigated.

The aim of this study is to characterize for the first time the EEG microstates during the execution of movements. For this purpose, we investigated the EEG microstates during pure planar reaching movements and reaching and grasping with four different grasp types and we compared them with EEG microstates obtained during resting-state.

According to the hypothesis of a modular organization of the brain activity, we expect to find common and specific EEG microstates across the different motor tasks.

II. Methods

A. Participants and protocol

Five right-handed healthy young subjects (5 males, average age 26.7±2.7) were enrolled in the study. The experiment was approved by the BMI Ethics Committee for Human Behavioral Research of the EPFL. The subjects had to execute pure planar reaching movements and to reach, grasp, and hold 16 different objects accounting for 4 different grasp types: ulnar pinch, pulp pinch, five fingers pinch, and cylindrical grasp. Each grasp type accounted for 3 "abstract" objects with different dimensions (small, medium, and large) and an object of common use (a key, a coin, a small box, and a bottle, respectively for ulnar pinch, pulp pinch, five fingers pinch, and cylindrical grasp).

The subjects seated on a chair with the right arm relaxed on a table. In the starting position, the elbow was flexed of about 90°, the forearm was parallel to the trunk, and the right hand was placed on a starting button with the palm downward. The object was placed by the examiner on the table, in front of the subject, 30 cm far from the border of the

J. Minguillon, E. Pirondini, M. Coscia and S. Micera are with the Translational Neural Engineering Laboratory, Center for Neuroprosthetics and School of Engineering, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland (e-mail: jesus.minguilloncampos@epfl.ch, elvira.pirondini@epfl.ch, martina.coscia@epfl.ch; corresponding author: E. Pirondini, tel: +41-21-69-31047).

M. Coscia is also with the Instituto di Neuroscienze del Consiglio Nazionale delle Ricerche (CNR), Pisa, Italy.

R. Leeb and J.d.R. Millán are with the Chair of Non-Invasive Brain-Machine Interface, Center for Neuroprosthetics, School of Engineering, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland (e-mail: robert.leeb@epfl.ch, jose.millan@epfl.ch).

D. Van De Ville is with MIPLab, School of Engineering, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland and with the Department of Radiology and Medical Informatics, University of Geneva (e-mail: dimitri.vandeville@epfl.ch).

S. Micera is also with the Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy (e-mail: silvestro.micera@epfl.ch).

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

table closest to the subjects. The subjects voluntarily started the movement, reached, grasped, held the object for approximately 2 seconds, released it and moved back to the initial position. Between two tasks, a resting period of about 2 seconds was respected. During the pure reaching movements, the task was equivalent, but the subjects just moved to the object position without grasping any object. Each planar reaching movement and grasping was repeated 15 times. The movements were executed at comfortable speed and, in case of reaching and grasping movements, the order of the objects was randomized.

EEG data were acquired continuously using a 64 channels Active-Two system (Biosemi, Amsterdam Netherlands) with a sampling rate of 2048 Hz.

Task events, such as the beginning of the reaching, the beginning of the grasping/end of the reaching, and the end of the task were detected by using two buttons in the start and object position synchronized with the EEG data.

Before the experiment, the brain activity during resting-state with eyes closed was recorded for about 10 minutes.

B. EEG pre-processing

EEG data were preprocessed using MATLAB (MathWorks, Natick MA) and EEGLAB toolbox [8].

The data were down-sampled to 128 Hz, high-pass filtered with a zero phase IIR filter (cutoff frequency 1 Hz), low-pass filtered with a zero phase IIR filter (cutoff frequency 40 Hz), and finally re-referenced to a common average reference. Independent component analysis (ICA) was performed to remove 'eye blink' and 'eye movement'.

For the data related to movement execution, epochs were extracted (from 400 ms before the beginning of the movement to the end of reaching/grasping of the object) and a pre-stimulus baseline correction was applied. Following visual inspection for removal of epochs containing artifacts, an additional procedure for artifacts removal was applied based on ICA and dipole analysis, as described in [8]. Only IC components whose dipoles resided inside the brain volume of the head model and had less than 15% of residual variance were retained (30.4±2.4%, 34.0±4.0%, 40.0±2.4% of components were retained for resting state, pure reaching and reaching and grasping). The retained ICs were visually inspected and components representing artifactual activity were rejected (2.4±0.7, 0.8±0.5 and 2.4±0.3 components were rejected for resting-state, pure reaching and reaching and grasping). Reconstructed EEG data were visually inspected a last time and epochs still containing 'artifacts' were removed. Finally, the epochs for the pure reaching movements and for each grasp type were separately averaged.

C. Microstate extraction

EEG microstates were extracted for each subject with the CARTOOL software [9] by using the modified K-means algorithm (rejecting segments whose length was less than 32 ms) in resting-state (60 seconds), in the averaged pure reaching epochs, and in the averaged reaching and grasping epochs pulling together the averaged epochs of the four grasp types. The optimal number of microstates was determined by means of a cross-validation criterion (*i.e.,* minimum cross-correlation). The same number of microstates was retained for each subject. The microstate maps of each subject were then submitted to a second cluster analysis in order to identify the dominant maps across the subjects. A k-means clustering with the restriction that each microstate of a subject had to be classified into a different cluster was used. The reference maps were selected as those that highly spatially correlated with the other maps in the same cluster. The microstate maps of each subject were matched with the reference maps showing the higher spatial correlation. The similarity of EEG microstates across the three conditions (*i.e.,* resting-state, pure reaching movements, and reaching and grasping movements) was determined based on the spatial correlation (**R**), by using the *corr2* Matlab function. The global field power (GFP) of each subject for each condition was then segmented using the reference maps.

Finally, we studied the rules governing the syntax of EEG microstates occurrence by computing the state transition matrices considering one and two previous states [10]. We excluded the probability to remain in the same state from the computation.

D. Metrics and statistical analysis

To characterize and compare the EEG microstates in the three conditions, two metrics were calculated: the mean EEG microstate duration and the percentage of total analysis time covered [4]. For the EEG microstates shared among the three conditions and for the EEG microstates shared between pure reaching and reaching and grasping movements, a Friedman test followed by a post hoc analysis by using the Dunn's test was computed for each metric.

III. RESULTS

Four EEG microstates were extracted for each subject for the resting-state condition. The four reference microstates were very similar to the ones found in previous works [4, 5] (Figure 1, top row). Six EEG microstates have been extracted during pure reaching (Figure 1, central row): four of them (*i.e.,* microstates A, B, C, and D) were similar to

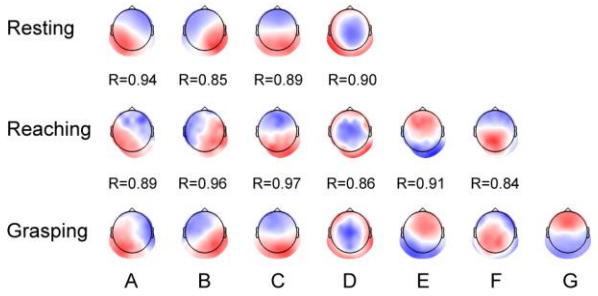

Figure 1. EEG microstates during resting-state (top row), pure reaching movements (central row), and reaching and grasping movements (bottom row). R is the correlation value: it is reported for A, B, C and D between resting-state and pure reaching movements and between resting-state and reaching and grasping movements, and for E and F between pure reaching and reaching and grasping movements.

	Mean duration (ms)							Total analysis time covered (%)						
	A	**B**	**C**	**D**	**E**	**F**	**G**	**A**	**B**	**C**	**D**	**E**	**F**	**G**
RS	81.98 (4.00)	91.07 (6.46)	139.40 (23.23)	74.19 (4.28)				18.13 (3.23)	23.85 (2.59)	45.15 (5.09)	12.88 (2.73)			
R	84.24 (10.94)	62.40 (5.69)	88.61 (10.64)	79.69 (13.57)	71.12 (6.42)	103.13 (29.51)		17.54 (4.10)	12.87 (2.92)	23.27 (6.67)	12.87 (4.05)	18.25 (4.58)	17.78 (5.56)	
	72.40 (7.98)	63.02 (6.71)	97.54 (20.68)	66.15 (6.42)	76.92 (10.74)	76.66 (3.87)	100.39 (26.88)	12.35 (2.60)	7.84 (1.27)	17.55 (6.38)	13.53 (3.51)	17.94 (4.20)	10.66 (2.33)	27.82 (11.18)
	64.24 (5.41)	95.10 (15.81)	63.06 (5.20)	71.29 (10.90)	83.72 (16.39)	61.52 (10.50)	91.72 (24.17)	9.48 (1.43)	19.90 (2.63)	20.22 (6.94)	6.00 (1.92)	22.45 (6.39)	15.44 (2.64)	24.80 (9.24)
	50.78 (8.01)	90.63 (30.12)	72.27 (13.19)	82.23 (20.36)	86.17 (19.75)	63.64 (6.11)	117.68 (12.54)	4.22 (1.52)	13.43 (6.42)	10.66 (3.01)	14.71 (4.89)	17.45 (3.43)	13.36 (4.18)	33.92 (5.03)
	55.34 (6.56)	75.52 (21.82)	84.77 (7.95)	114.26 (19.16)	106.30 (13.11)	63.28 (13.04)	126.82 (41.40)	9.97 (3.43)	12.94 (4.51)	13.92 (2.87)	16.30 (5.31)	26.47 (7.44)	6.08 (1.11)	21.57 (8.70)

Table 1. The mean duration and the total analysis time covered for the EEG microstates in resting-state (**RS**), pure reaching (**R**) and each grasp type (cylindrical grasp, five fingers pinch, pulp pinch, and ulnar pinch). Mean and standard error were calculated over the five subjects. Values in red indicate a significant difference between resting-state and reaching and grasping movements ($p < 0.05$). Values in blue indicate a significant difference between pure reaching movements and reaching and grasping movements ($p < 0.05$).

those extracted during resting-state (**R**>0.85) while two (*i.e.,* microstates E and F) were specific for pure reaching movements (**R**<0.60 with microstates A, B, C, and D of resting-state). Seven EEG microstates were extracted for reaching and grasping movements (Figure 1, bottom row): four of them (*i.e.,* microstates A, B, C, and D) corresponded to those found in the resting-state (**R**>0.85), EEG microstate E and F corresponded to the microstate E and F in pure reaching (**R**>0.80, **R**<0.60 for microstate E with microstates A, B, C, and D of resting-state and **R**<0.53 for microstate F with microstates A, B, C, and D of resting-state). The microstate G was specific for reaching and grasping movements (**R**<0.62 with microstates A, B, C, and D of the resting-state and **R**<0.78 with microstates E and F of the pure reaching movements).

During the resting-state, the four microstates had comparable features with the ones of age-matched healthy subjects reported in literature (Table 1, [4, 5]).

The mean duration of the four common EEG microstates between resting-state and pure reaching was similar; whereas the total time covered was slightly shorter in reaching movements than in resting-state (Table 1). However, no significant differences were found for the pure reaching condition with respect to the resting state. The EEG microstates E, F, and G covered about the 40% and 50% of the total time analyzed for pure reaching and reaching and grasping movements, respectively. Overall, during reaching and grasping, the four EEG microstates of the resting-state tended to become shorter and cover less time during movement execution.

We also investigated the occurrence of the EEG microstates during movement execution. In Figure 2, we reported the normalized grand averaged GFP with the timing sequence of the microstates during pure reaching movements and for each grasp type. In particular, for each grasp type, the peak of the normalized grand averaged GFP occurred after the beginning of the movement. We observed an increased frequency of occurrence of the EEG microstates in reaching and grasping movements with respect to the sequence of the EEG microstates during pure reaching movements. We could also observe that the frequency of occurrence increased from the "power grasps" (*i.e.,* five finger pinch and cylindrical grasp) to the "precision grips" (*i.e.,* pulp and ulnar pinch), where more attention is required. The EEG microstates E and G were the most prevalent

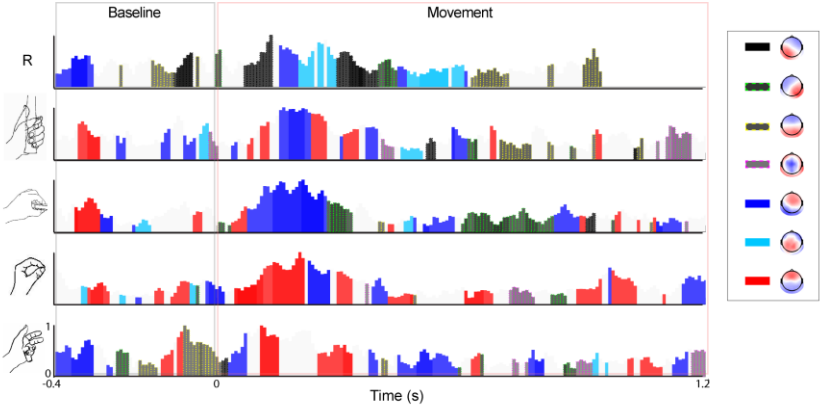

Figure 2: The EEG microstate timing sequence for pure reaching movements (top row), and for each grasp type (cylindrical grasp, five fingers pinch, pulp pinch, and ulnar pinch). The timing sequence of the microstates is reported on top of the normalized grand average GFP. The timing sequence was determined calculating for each time point the most prevalent microstate among the subjects. The transparency levels code the number of subjects presenting the prevalent microstate. Graduation of gray colors codes the four EEG microstates present in resting-state. Blue, cyan, and red colors code microstate E, F, and G, respectively. White color codes the time points where all the five subjects presented a different microstate.

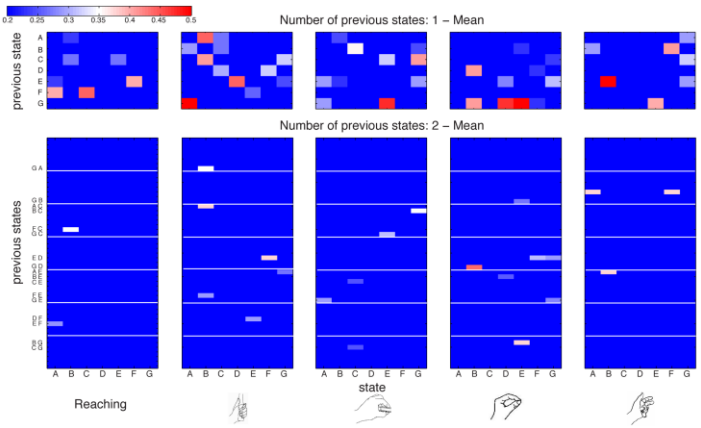

Figure 3: State transition matrices computed considering one previous state (on the top) or two previous states (on the bottom) for pure reaching movements (first column) and for each grasp type (cylindrical grasp, five fingers, pulp, and ulnar pinch). The color bar codes significant probabilities values. The values reported represented the mean values across the five subjects.

during movement execution, in particular, during reaching and grasping movements; whereas A, B, C and D were less present during movement execution, in particular, for the "precision grips". The EEG microstate E occurred in correspondence to the GFP peak for the pure reaching movements and for the "power grasps"; whereas the "precision grips" presented the EEG microstate G in correspondence of the GFP peak. The EEG microstate F was present for pure reaching movements after the GFP peak, and it was less present for grasping movements.

Finally, in order to assess the rules governing the occurrence of the EEG microstates, we computed the state transition matrices considering one and two previous states (Figure 3). Reaching and grasping movements presented more significant transitions than pure reaching movements. Pure reaching movements had significant transitions from microstate A to B, from microstate C to B, and from microstate E to A. These transitions were also present in the "power grasps", while pure reaching movements did not show common transitions with the "precision grips". Significant transitions from microstate C to G and from E to G were common in the 4 grasps; five fingers, pulp, and ulnar pinch presented also the opposite transition from microstate G to E. The "power grasps" presented also a significant transition from microstate G to A and from microstate B to C. Finally, cylindrical grasp and pulp pinch showed a significant transition from microstate D to F and from E to D. The transition matrices considering two previous states did not show common significant transitions among the different movements.

IV. Conclusions

Our preliminary results support the hypothesis that brain activity during movement execution is organized in a modular way. Indeed, we found similar EEG microstates between resting-state and the execution of voluntary movements. During movement, the occurrence of the common EEG microstates is limited by the manifestation of movement-specific EEG microstates. In particular, we found two new co-activations of brain networks for reaching movements and one specific for grasping.

As in resting-state, the occurrence of a microstate seems to facilitate the appearance of another: the syntax in the temporal occurrence of EEG microstates was more complex for reaching and grasping movements, compared to pure reaching movements.

The analysis of EEG microstates helps to describe the organization of brain networks and their temporal activation. We believe that the proposed methodology is useful to study brain activity during movement execution, and can help understanding brain plasticity and reorganization in neurological disorders.

References

[1] E. Burdet, and T. E. Milner, 'Quantization of human motions and learning of accurate movements', *Biolog. Cybern*, 78, (4), pp. 307-318, 1998.

[2] E. Bizzi, and V. C. Cheung, 'The neural origin of muscle synergies', *Front. Comput. Neurosci.*, 7, pp. (51) 1-6, 2013.

[3] D. Lehmann, W. K. Strik, B. Henggeler, T. Koenig, and M. Koukkou, 'Brain electric microstates and momentary conscious mind states as building blocks of spontaneous thinking: I. Visual imagery and abstract thoughts', *Int J. Psychophysiol*, 29, (1), pp. 1-11, 1998.

[4] T. Koenig, L. Prichep, D. Lehmann, P. V. Sosa, E. Braeker, H. Kleinlogel, R. Isenhart, and E. R. John, 'Millisecond by millisecond, year by year: normative EEG microstates and developmental stages', *Neuroimage*, 16, (1), pp. 41-48, 2002.

[5] D. Van de Ville, J. Britz, and C. M. Michel, 'EEG microstate sequences in healthy humans at rest reveal scale-free dynamics', *PNAS*, 107, (42), pp. 18179-18184, 2010.

[6] J. Britz, D. Van De Ville, and C. M. Michel, 'BOLD correlates of EEG topography reveal rapid resting-state network dynamics', *NeuroImage*, 52, (4), pp. 1162-1170, 2010.

[7] L. Dipietro, M. Plank, H. Poizner, and H. Krebs, 'EEG microstate analysis in human motor corrections', in *Proceeding of the* 4th *edition of the* IEEE/RAS-EMBS BioRob 2012, pp. 1727-1732.

[8] A. Delorme, and S. Makeig, 'EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis', *J Neurosci Meth*, 134, (1), pp. 9-21, 2004.

[9] D. Brunet, M. M. Murray, and C. M. Michel, 'Spatiotemporal analysis of multichannel EEG: CARTOOL', *Comp Intell Neurosci*,, pp. 1-15, 2011.

[10] D. Lehmann, P. L. Faber, S. Galderisi, W. M. Herrmann, T. Kinoshita, M. Koukkou, A. Mucci, R. D. Pascual-Marqui, N. Saito, and J. Wackermann, 'EEG microstate duration and syntax in acute, medication-naive, first-episode schizophrenia: a multi-center study', *Psych Res Neuroimaging*, 138, (2), pp. 141-156, 2005.