Event-Related Desynchronization Analysis During Action Observation and Motor Imagery of Transitive Movements

Stefania Coelli[1][a], Alessandra Calcagno[1][b], Federico Temporiti[1,2][c], Roberto Gatti[2,3][d], Manuela Galli[1][e] and Anna M. Bianchi[1][f]

[1]Department of Electronic, Information and Bioengineering, Politecnico di Milano, Milan, Italy
[2]Physiotherapy Unit, Humanitas Clinical and Research Center - IRCCS, Rozzano, Milan, Italy
[3]Department of Biomedical Sciences, Humanitas University, Pieve Emanuele, Milan, Italy

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Abstract: Rehabilitation and motor skill learning approaches based on Action Observation (AO) and Motor Imagery (MI) rely on the assumption that the sensorimotor system is stimulated by AO and MI tasks similarly to the actual execution of a movement. An advantage of AO over MI is that it is less dependent on subject's imagination ability, and a direct comparison of their effect on cortical activations during complex upper limb movements has been rarely examined. Therefore, in this study we compare sensorimotor event related desynchronization (ERD) patterns, as a measure of cortical activation, collected from 46 healthy volunteers performing AO and MI protocols. In both mu and beta sensorimotor rhythms a stronger ERD was elicited by AO, characterized by an evident lateralization in the contralateral side of the brain with respect to the limb involved in the observed movement.

1 INTRODUCTION

The mirror mechanism is related to the response of the brain that transforms the visual perception of actions, performed by others, into a motor representation in the brain of the observer (Rizzolatti and Sinigaglia, 2010). It has been shown that, during action observation (AO), the cortical areas that are normally activated during motor execution (ME), are similarly activated, supporting the existence of the so-called motor-resonance phenomenon, even if several factors influence the patterns and the strength of such response (Kemmerer, 2021). These factors may be grouped in four categories according to Kemmerer: i) relation between agent and observer, ii) factors involving the action, iii) factors involving the actors and iv) factors related to the observer. Also the action's context may play a role (Kemmerer, 2021). Researches in recent years have demonstrated, for example, that the observation of a movement from a first person perspective produces a stronger modulation of the Rolandic sensorimotor rhythms (Angelini et al., 2018; Drew et al., 2015). Moreover, watching a transitive motor task (i.e., object directed) is more engaging than observing an intransitive action (Coll et al., 2017). The possibility of using the mirror mechanism to stimulate the sensorimotor system has been exploited as an innovative rehabilitation approach called Action Observation Therapy (Calcagno et al., 2022; Rizzolatti et al., 2021; Temporiti et al., 2020). This motor learning approach could be adopted to facilitate another promising framework for the acquisition and recovery of motor skills, that is the internal simulation of motor action, i.e. Motor Imagery (MI) (Daeglau et al., 2021; Gonzalez-Rosa et al., 2015). Like AO, MI has been

[a] https://orcid.org/0000-0003-4104-4790
[b] https://orcid.org/0000-0003-3989-1712
[c] https://orcid.org/0000-0003-1771-2365
[d] https://orcid.org/0000-0002-4669-1287
[e] https://orcid.org/0000-0003-2772-4837
[f] https://orcid.org/0000-0002-8290-7460

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shown to activate the similar brain network also supporting ME in studies employing Electroencephalography (EEG) to monitor brain response (Gonzalez-Rosa et al., 2015; Neuper et al., 2005). Nevertheless, in term of rehabilitation practice, the efficacy of MI paradigms is limited by the ability of the subjects in performing a correct imagination task, even of simple movements, while the observation of complete and transitive movements is believed to strongly activate the sensorimotor cortex.

The dynamical activation of the brain during motor- and sensorial- related stimulation is typically measured by the event-related desynchronization (ERD) of the sensorimotor cortical rhythms in the mu (8-12 Hz) and beta (14-24 Hz) EEG frequency bands over central motor areas of the brain (Neuper et al., 2005; Tacchino et al., 2017). Few studies presented a direct comparison of the ERD patterns characterizing AO and MI of complex movement (Gonzalez-Rosa et al., 2015), in order to understand to which extent they overlap. To address this topic, in the current study, we compare sensorimotor ERD patterns extracted from EEG signals acquired on a group of healthy young volunteers performing AO and MI protocols. Specifically, three complex transitive manual dexterity tasks were employed and the effect of the different complexity of the movement was further studied.

2 MATERIALS AND METHODS

2.1 Data Acquisition

During the experiment, EEG signals were collected from 46 right-handed healthy participants (Age: 20-30, 22 female) using a 61-channel cap and the SD LTM 64 express polygraph recording system (Micromed, Mogliano Veneto, Italy). Signals were sampled at 1024 Hz and the impedances were kept under 20KOhm using a conductive hydrogel.

The action observation (AO) and motor imagery (MI) protocol was approved by the Internal Ethical Committee of the Istituto Clinico Humanitas (Rozzano, Italy). All the subjects signed an informed consent before the recordings. The stimulation sequence consisted in the presentation of a 6.5-s-long video-clip containing an upper limb movement performed from the visual perspective of the subject (1st person) and executed by a gender-matched actor. Only the upper limb of the actor was visible. The video-clip was preceded by a 3-s period of rest (fixation of a cross) and 2 seconds of preparation (red dot) displayed on a screen positioned in front of the participant. The stimulation sequence was repeated for 20 trials. The same sequence was repeated for the motor imagery task but, in this case, only the first frame of the video was shown for the same amount of time (6.5 seconds). During the motor imagery task, participants were asked to image performing the movement themselves. Again, 20 trials were recorded. AO and MI sequences together formed a single stimulation block. Three stimulation blocks (W1, W2 and W3) were delivered to participants separated by resting periods during which volunteers were free to move. In each block a different transitive movement was shown in the video-clip (Figure 1).

The three movements were characterized by a different level of interaction with objects. W1 consisted in picking-up five small coins, W2 presented the use of a hammer to hit a nail, and W3 displayed the interaction with tweezers to move a small object into a plastic glass. The presentation order of the videos was randomized.

2.2 Data Pre-Processing and Analysis

EEG signals were pre-processed using EEGLAB toolbox and custom scripts optimized for the study aim (Cassani et al., 2022). First, data were band-pass filtered between 1 and 45 Hz with a FIR, zero-phase filter, down sampled to 256 Hz and bad channels were visually selected and removed. Signals were cut into epochs from -5 to +6.5 seconds with respect to the main stimulus presentation (start of the video/frame presentation). The extended Infomax independent component analysis was applied to the concatenated epochs and with the support of the IClabel plugin (Pion-Tonachini et al., 2019), the source of artifacts were identified and removed. The previously rejected bad channels were interpolated, and signals were re-referenced to the common average reference. Finally, epochs with residual artefacts were visually checked and rejected.

Cleaned trials of each participant, separately for AO and MI were used to compute the time-frequency representation. The time-frequency analysis was performed through EEGLAB toolbox using Morlet wavelets starting from 3 cycle and expanding linearly with the frequency for continuous transform as suggested in the literature (Angelini et al., 2018; Avanzini et al., 2012; Tacchino et al., 2017). EEG power values were calculated for 145 linearly spaced frequencies (from 4 Hz to 30 Hz) and along 200 time bins resulting in a time resolution of ~0.05 seconds. To select both the individual baseline period and the mu frequency range, the two-second period from -4

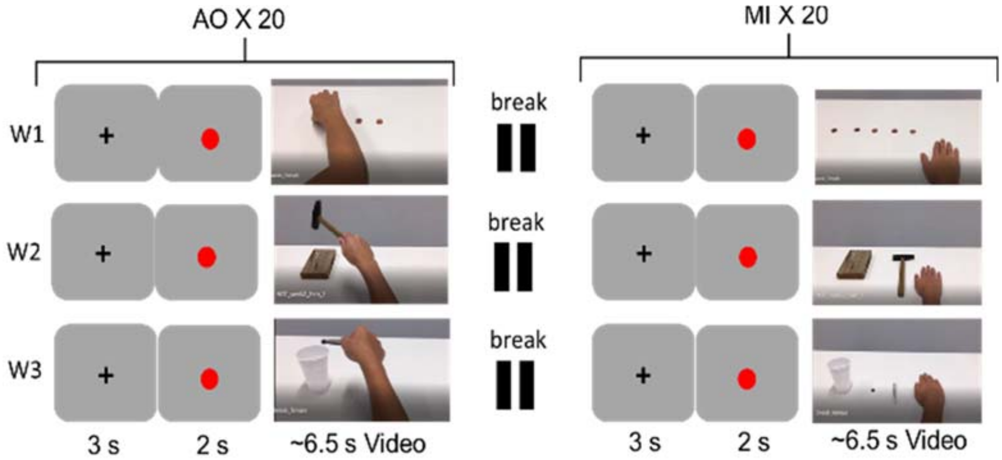

Figure 1: Stimulation sequence for action observation (AO) and motor imagery (MI) tasks.

to -2 sec with respect the main stimulus presentation, corresponding to the cross fixation, was analyzed at C3 channel position.

We identified the best baseline interval as the 1-s-long segment (50% overlapping moving window) showing the highest power value associated to the averaged alpha power between 8 and 12 Hz. Once the baseline had been selected, the individual mu frequency (IMF) was identified as the power peak between 8 and 12 Hz in the baseline. This procedure was repeated for the six conditions (AO/MI; three videos W1, W2 and W3). While the specific baseline was selected in each condition, the final IMF was obtained as the median of the six values extracted. We then defined the mu band as the frequency range between IMF-1 Hz and IMF+1 Hz, while the standard low beta frequency range was used [14 - 20] Hz (Angelini et al., 2018). In the two frequency ranges the %ERD was finally computed along each time bin *t* as in (1)

$$\%ERD(t)=(P(t)-B)/B*100 \quad (1)$$

where P(t) is the mean power in the analyzed frequency range at each time-point, and B the power of the same frequency range averaged in the selected baseline period. The ERD time course was divided into consecutive and not overlapping 1-s-long time windows from -1 to +4 seconds and the mean %ERD value for each window was computed. The ERD time course was further analyzed restricted to six brain regions of interest (B-ROI) averaging the ERD at the channel position associated to each B-ROI: Frontal left (FRL: F3, FC1, FC3), Frontal right (FRR: F4, FC2,FC4), Central Left (CL: C1, C3, C5), Central right (CR: C2, C4, C6), Centro-Parietal left (CPL: CP3, CP1, P3) and Centro-Parietal right (CPR: CP4, CP6 , P4). The asymmetry of the Centro-parietal area is due to the removal of some EEG channels (e.g., CP5 and CP2) operated by the acquisition system in order to simultaneously acquire EMG bipolar signals.

Two repeated measure ANOVAs were applied to the data, one for each frequency range, with 4 within factors: 3 video Types (W) x 6 B-ROIs x five Time windows (f0 = pre stimulus ERD, from f1 to f4 post stimulus segments) x 2 Tasks (AO and MI). Data were first tested for normality and log-transformed when necessary. Outliers were also detected (> 3*SD of the ERD percentage value) and if the participants were identified as outlier in at least two windows and more than two brain areas, their data were discarded. This choice was made to easily and automatically recognize subjects with an abnormal behaviour (6 subject were removed). When the sphericity of the variances was not respected, the Greenhouse-Geisser correction was applied.

3 RESULTS

3.1 Individual Mu-Rhythm Modulations

Figure 2 displays for each time window and video type, the mean and standard error values for both action observation and motor imagery tasks computed on the final set of 40 participants.

The ANOVA test identified a significant main effect for the factor Task ($F(1,40)=20.39$; $p= 5.46e-05$), B-ROIs ($F(3.4,136.2)=22.83$; $p = 4.73e-13$) and Time ($F(1.5,61.2)=37.4$; $p= 7.27e-10$), but not for video Type ($F(2,80)=0.69$; $p= 0.5$)). A significant Task*B-ROI*Time interaction was detected ($F(8.5, 341.2)=2.04$; $p=0.037$), and the following two-factors interactions: Task*B-ROI ($F(3.65, 145.9)=6.73$; p=

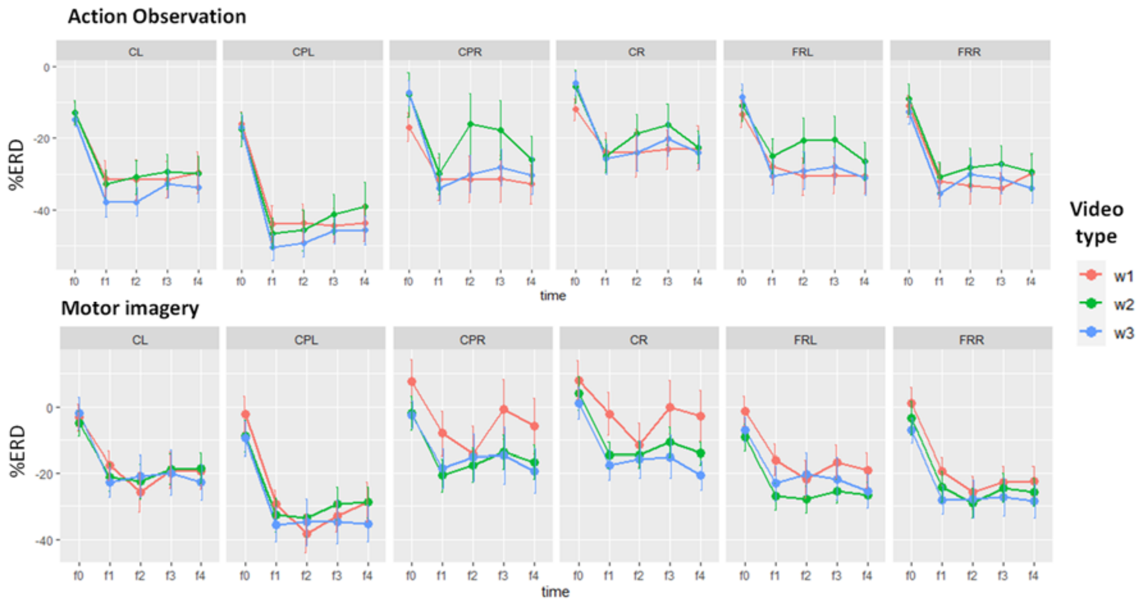

Figure 2: Mean and standard error of the mean (SEM) of mu-rhythm %ERD values for the five windows of interest (-1s to +4 s) of both AO and MI tasks in each analyzed region of the scalp. Colours represent different video types. CL: central left, CPL: centro-parietal left, CPR: centro parietal right, CR: central right, FL: frontal left and FR: frontal right.

9.45e-05), B-ROI*Time (F(5.8,232.8)=13.5; p= 7e-13), Task*Time (F(2.43,97.4)=4.2; p=0.013). Finally the interaction W*Time was also significant (F(5.7,226.6)=2.27; p= 0.042).

Splitting by brain regions, significant interaction between task and time were found in three regions, namely CL (F(3.1,377.6)=5.3; p=0.001), CPL(F(3.1,381.8)=9.4; p=3.42e-06) and CPR(F(3.2,390.4)=9.4; p= 0.005). In these regions, the task effect was significant in each window (p<0.005) indicating a stronger ERD for the AO task (Table 1).

Splitting the ANOVA by tasks, we found for the AO a significant interaction B-ROI*Time (F(6.99, 286.51)=0.349, p= 2.64e-11).

Table 1: P-values of the significant differences between task type (AO vs MI) in each B-ROIs and window of the mu ERD. CL: central left, CPL: centro-parietal left, CPR: centro parietal right, CR: central right, FL: frontal left and FR: frontal right.

ROI	f0	f1	f2	f3	f4
CL	0.001	9.6e-10	0.0001	8.8e-06	3.1e-06
CPL	0.005	4.5e-10	0.0002	0.0001	9.2e-07
CPR	0.003	7.3e-09	7.2e-05	4.5e-05	1.1e-06
CR	0.004	6.2e-07	0.0002	0.001	3.2e-05
FRL		0.002		0.02	0.002
FRR	0.018	3.5e-05		0.008	0.004

Splitting again by time, in every time window after the stimulus presentation a significant effect of the ROI was found, while no effect was found in f0 after Bonferroni's correction. The post-hoc analysis with Bonferroni's correction (Table 1) showed a stronger mu ERD in the left centro-parietal (CPL) ROI with respect to all the other ROIs in each time window during video observation. The left central ROI showed a significantly stronger ERD in each window with respect to CR, supporting the lateralization of the mu-rhythm modulation. The two frontal areas were never different. Investigating the time effect in each B-ROI (Table 2) we found that in each region, f0 was different from all the other time windows suggesting a strong effect of the video presentation (p <0.0001). Moreover, significant differences were observed in CL, CPL and CR between f2 and f3, due to a partial re-synchronization in f3 (p_{CL} =0.025; p_{CPL}=0.001 and p_{CR} =0.033).

Concerning the MI, we found a significant B-ROI*Time interaction (F(6.29, 251.58)=0.4, p= 4.28e-08), but also a W*time significant interaction (F(6.17, 246.6)=0.77, p =0.02). Exploring the first, in every time window a significant effect of the ROI was found. The post-hoc analysis with Bonferroni's correction showed a stronger mu ERD in the left centro-parietal (CPL) ROI with respect to all the other ROIs in each time window from f1 to f4, but also with respect to CL, CPR and CR in f0.

Table 2: Corrected p-values of the significant differences among B-ROIs in each task and window of the mu ERD. CL: central left, CPL: centro-parietal left, CPR: centro parietal right, CR: central right, FL: frontal left and FR: frontal right.

	AO					MI				
	f0	f1	f2	f3	f4	f0	f1	f2	f3	f4
CL Vs CPL		1.0e-13	1.6e-12	9.3e-14	1.0e-11	0.042	1.7e-13	3.1e-13	7.1e-10	2.2e-09
CL Vs CPR										
CL Vs CR		1.2e-08	1.9e-10	3.96e-11	4.86e-07		8.4e-05	7.0e-07	1.1e-05	0.0002
CL Vs FRL		0.045	0.01							
CL Vs FRR										
CPL Vs CPR		1.4e-07	2.2e-10	3.7e-10	1.64e-06	0.035	1.8e-08	6.1e-11	4.3e-08	5.2e-07
CPL Vs CR		4.5e-18	6.0e-21	5.18e-24	3.52e-16	3.88e-05	4.48e-17	7.9e-19	3.9e-14	8.8e-13
CPL Vs FRL		6.8e-14	2.1e-16	2.4e-13	1.1e-10		1.1e-06	1.3e-08	9.7e-06	2.7e-05
CPL Vs FRR		7.8e-14	1.6e-17	8.2e-16	3.3e-12		3.7e-07	3.2e-09	1.5e-05	2.5e-05
CPR Vs CR		1.1e-07	0.0009	1.2e-05	6.5e-06		0.007	0.033		
CPR Vs FRL										
CPR Vs FRR									0.021	
CR Vs FRL				0.001	0.007	0.0007	1.3e-07	4.3e-06	6.9e-07	1.4e-07
CR Vs FRR		0.0004	0.0009	8.78e-08	0.0002	0.019	7.8e-10	6.2e-10	1.2e-09	1.8e-08
FRL Vs FRR										

In all the time windows, CR was found significantly different from both the frontal regions and the left central and centro-parietal ones. Specifically, CR showed a weaker ERD (Table 2). Similarly, to the AO case, exploring the effect of the time in each B-ROI, f0 was different from all the other time windows suggesting an effect of the video presentation ($p< 0.0001$). Moreover, in CL and CPL a partial resynchronization was observed in f3 and f4 with respect to f2 ($p<0.05$).

For the MI case, we further explored the effect of the video type focusing on each window from f1 to f4 in which the video was presented. In f1, W1 showed the less strong ERD ($p < 0.001$), in f2 no differences were significant, in f3 W1 showed an overall re-synchronization, while W3 induced a more persistent ERD ($p<0.001$).

3.2 Beta Band Modulations

Figure 3 shows for each time window and video type, the mean and standard error values of both action observation and motor imagery ERD.

The ANOVA test identified a significant main effect for the factor Task ($F(1,41)= 14.7$, $p=0.0004$), B-ROIs ($F(3.44,141)=25.22$, $p= 2.5e-14$) and Time ($F(2.02,82.9)= 58.3$, $p= 1.24e-16$).

A significant Task*B-ROI*Time interaction was detected ($F(9.8, 402.34)= 2.21$, $p=0.017$), and the following two-factors interactions: Task*B-ROI ($F(3.44,141.2)=3.23$, $p=0.019$), B-ROI*Time ($F(6.78,278)=11.1$, $p=4.33e-12$), Task*Time ($F(3.1,125.4)=3.6$, $p=0.015$). Nor the main effect neither the interactions including the video Type factor were found significant.

Splitting by brain regions, significant interaction between task and time were found in three regions, namely CL ($F(3.7,460.7)=6.24$, $p=0.0001$), CPL($F(3.4,421.8)=8.1$, $p=1.17e-05$) and CPR($F(3.3,411.9)=2.8$, $p=0.036$), as for the mu band.

In these regions, the task effect was significant in each window indicating a stronger ERD for the AO task as reported on (Table 3).

Splitting the ANOVA by tasks, we found for the AO a significant interaction B-ROI*Time ($F(6.03, 253.34)=6.3$, $p = 3.33e-06$). Splitting the again by time, in every time window a significant effect of the ROI was found (Table 4). The post-hoc analysis with Bonferroni's correction showed a stronger mu ERD in the left centro-parietal (CPL) ROI with respect to all the other ROIs in each time window during video observation and only with respect to CR and FRR in f0.

Table 3: P-values of the significant differences between task type (AO vs MI) in each B-ROIs and window of the Beta ERD.

ROI	f0	f1	f2	f3	f4
CL		4.9e-06	9.7e-05	0.004	0.026
CPL		1.5e-07	0.0002	0.006	0.043
CPR	0.008	2.97e-06	0.0001	0.0002	4.8e-05
CR	0.024	0.0001	0.003		0.04
FRL		0.002	0.024	0.037	
FRR		0.0008	0.035		

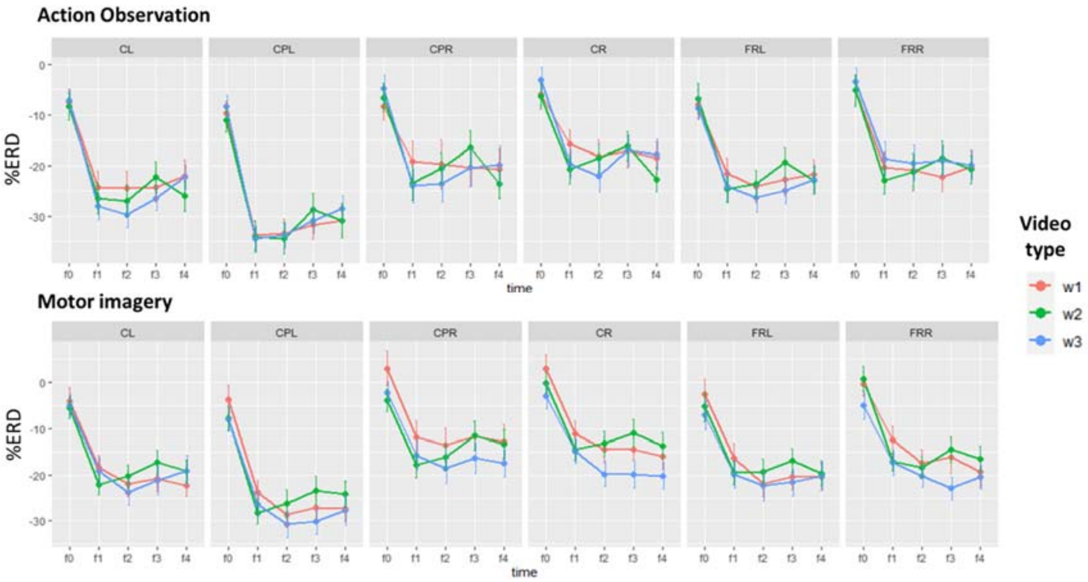

Figure 3: Mean and standard error of the mean (SEM) of beta band %ERD values for the five windows of interest (-1s to +4 s) of both AO and MI tasks in each analyzed region of the scalp. Colours represent different video types. CL: central left, CPL: centro-parietal left, CPR: centro parietal right, CR: central right, FL: frontal left and FR: frontal right.

The left central ROI showed a significantly stronger ERD in each window with respect to the CR from f1 to f4, supporting the lateralization of the mu-rhythm modulation. The two frontal areas were never different. Investigating the time effect in each B-ROI we found that in each region, f0 was different from all the other time windows suggesting a strong effect of the video presentation ($p<0.0001$). The windows f1 to f4 were not different in all the B-ROI except for CPL, where f3 and f4 showed a significant re-synchronization with respect to f1 and f2 ($p<0.05$).

Concerning the MI, we found a significant B-ROI*Time interaction ($F(9.89, 405.3)=3.3$, $p=0.0004$). In every time window a significant effect of the ROI was found. The post-hoc analysis with Bonferroni's correction showed a stronger beta ERD in the left central (CL) and left centro-parietal (CPL) ROI with respect to all the other ROIs in each time window during the MI task. CR and CPR were found significantly different from both CL and CPL also during the red-circle pre-task period (f0).

Similarly, to the AO case, exploring the effect of the time in each B-ROI, f0 was different from all the other time windows suggesting an effect of the MI task.

4 DISCUSSION AND CONCLUSIONS

The aim of this work was to compare the dynamical cortical activation patterns observed during AO and MI tasks in a group of healthy young volunteers. As a measure of sensorimotor response to the presented stimulations, we computed the ERD time course in both individual mu and standard beta frequency ranges.

To increase the stimulation effect, the video-clips used in the experiment comprised complex upper limb object-directed (transitive) movements performed from the observer's perspective (Angelini et al., 2018; Coll et al., 2017). For the MI task, the same movements were asked to be imagined and a frame of the video was shown to facilitate the imagination. In all the explored brain regions, a stronger mu ERD was elicited by the observation, rather than the imagination of the movement, in line with previous study by Gonzalez-Rosa et al., 2015. Even so, the activation patterns were similar, with an evident lateralization over the contralateral brain areas and, in particular, a stronger engagement of the CPL region, which can be associated to the somatosensory cortex.

This latter results is in line with the hypothesis that both AO and MI brain response may be more correctly related to the sensory integration rather than to the actual motor execution functions (Coll et al., 2017). Since sensorimotor mu and beta oscillations are not completely independent (Tacchino et al., 2020), the modulation of the beta power followed the same trend of significance detected in the mu band. In this direction, further investigation at the source level would provide a more precise distinction between the two Rolandic oscillations.

Table 4: Corrected p-values of the significant differences among B-ROIs in each task and windows of the beta ERD. CL: central left, CPL: centro-parietal left, CPR: centro parietal right, CR: central right, FL: frontal left and FR: frontal right.

	AO					MI				
	f0	f1	f2	f3	f4	f0	f1	f2	f3	f4
CL Vs CPL		3.1e-12	5.6e-09	5.1e-07	2.3e-08		1.8e-07	2.3e-07	5.6e-09	1e-06
CL Vs CPR				0.03		0.026	0.023	0.002	3.7e-05	0.001
CL Vs CR		5.3e-09	4.0e-08	1.5e-08	0.002	0.0009	6.1e-07	7.5e-06	0.0006	0.031
CL Vs FRL										
CL Vs FRR		0.006	0.002	0.028			0.047			
CPL Vs CPR		1.8e-10	5.7e-08	1.6e-08	4.4e-05	0.0008	1.0e-09	4.5e-11	7.6e-14	1.7e-10
CPL Vs CR	0.002	2.3e-23	9.8e-18	6.3e-17	1.5e-11	9.1e-05	5.0e-15	1.8e-13	1.0e-14	1.0e-10
CPL Vs FRL		4.8e-12	7.1e-10	2.1e-06	2.7e-06		1.9e-06	8.4e-06	6.2e-07	7.6e-05
CPL Vs FRR	0.002	1.2e-15	4.9e-14	2.7e-11	1.2e-10	0.014	7.5e-10	1.16e-10	3.8e-07	1.5e-06
CPR Vs CR										
CPR Vs FRL								0.003	9.0e-06	0.001
CPR Vs FRR										
CR Vs FRL		0.002	0.0004	0.001			0.0007	0.002	0.006	
CR Vs FRR										
FRL Vs FRR										

Overall, the increasing complexity of the movement was not a significant factor, even if some actions seem to be more difficult to imagine than others. Interestingly, the small influence of the video type, present for the mu rhythm modulation, was absent for the beta band, where the ERD pattern was more consistent across video type and cortical regions.

In conclusion, current results support the potentiality of an action observation approach for stimulating the sensorimotor system with a less reliance on the subject's imaginative abilities, essential for achieving good results in motor imagery protocols. Nevertheless, further studies are needed to test the efficacy of an AO intervention alone on motor skills learning and its effect on brain rhythm modulation patterns.

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