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Mu rhythm and corticospinal excitability capture two different frames of motor resonance: a TMS/EEG co-registration study

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Abstract. Humans are equipped with an extraordinary ability to understand and imitate actions by mapping the observed movement onto their own cortical motor system. Long-established lines of research have identified two correlates of this motor resonance following action observation: the mu rhythm event-related desynchronization (mu-ERD) recorded through electroencephalography (EEG) and the facilitation of motor evoked potentials (MEPs) induced by transcranial magnetic stimulation (TMS) of the primary motor cortex (M1). Yet, whether mu-ERD and MEP facilitation reflect unique or distinct mechanisms is not conclusive, as prior work did not combine simultaneous TMS-EEG recording with a trial-by-trial analysis of the two markers. To address this issue, here, we used TMS/EEG co-registration while participants observed and executed finger movements. EEG was continuously recorded while single-pulse TMS was administered over the left M1 and MEPs were recorded from the right hand. We found stronger motor cortex recruitment during action execution and observation as shown by mu-ERD. MEPs instead were larger overall during action execution and showed a facilitation specific to the muscles involved in the observed movements. Interestingly, when analyzing these two parameters using a trial-by-trial statistical approach, we did not find any relationship between mu-ERD and MEPs within the action observation condition. Our findings support the notion that EEG and TMS indices of motor resonance reflect distinct neural mechanisms.

Keywords: action observation, motor resonance, mu-ERD, MEPs, motor cortex

1. Introduction

Understanding and imitating observed actions are key abilities supported by complex neural networks which include sensorimotor brain areas involved in action performance (Caspers et al. 2010; Rizzolatti & Sinigaglia 2010, 2016; Hardwick et al. 2018). Electroencephalography (EEG) and transcranial magnetic stimulation (TMS) are two valuable, complementary non-invasive techniques that have provided important information about motor resonance. Motor resonance refers to the activation of the sensorimotor network for making actions while simply observing actions (for reviews see Fadiga et al. 2005; Pineda, 2005, 2008; Avenanti et al. 2013a; Naish et al. 2014). It is thought to reflect the activity of the mirror neuron system (di Pellegrino et al. 1992; Gallese et al. 1996; Mukamel et al. 2010) and contribute to action understanding and imitation (Pobric & Hamilton 2006; Avenanti et al. 2013b, 2018; Tidoni et al. 2013; Urgesi et al. 2014; Jacquet & Avenanti 2015; Paracampo et al. 2018).

Activation of sensorimotor brain areas during action observation and execution, is captured by the attenuation of the EEG mu rhythm (Cochin et al. 1999; Muthukumaraswamy & Johnson 2004a, 2004b; Lepage & Theoret 2006; Neuper et al. 2009; Arnstein et al. 2011). The mu rhythm is a spontaneous EEG oscillation in the alpha range (8-13 Hz) which is maximal over central sites overlying the sensorimotor cortex (McFarland et al. 2000; Pfurtscheller et al. 2000; Llanos et al. 2013). Following specific events, it can be temporarily altered, thus producing the so-called *event-related (de)synchronizations* (ERD/ERS) which have been interpreted as proof of motor cortex activation/inactivation, respectively (McFarland et al. 2000; Pfurtscheller & Neuper 1994; Pfurtscheller et al. 2000, 2006; Pineda, 2005; Llanos et al. 2013).

Another classical way to assess motor resonance is through TMS targeting the primary motor cortex (M1). TMS over M1 can induce motor-evoked potentials (MEPs) from contralateral hand muscles (Barker et al. 1985; Pascual-Leone et al. 1994; Stinear et al. 2001; Schambra et al. 2003), and the amplitude of these MEPs is thought to reflect corticospinal excitability (Rossini & Rossi 1998; Pascual-Leone et al. 1998). TMS studies have shown that observing others' actions increases the amplitude of MEPs, indicating a facilitation of corticospinal motor excitability (Fadiga et al. 1995, 2005; Catmur et al. 2007; Avenanti et al. 2007, 2013a; Borgomaneri et al. 2012).

EEG and TMS indices of motor resonance have been detected during the observation of both transitive and intransitive movements (Fadiga et al. 2005; Romani et al. 2005; Borgomaneri et al. 2012). A distinct feature of MEP indices is muscle specificity; indeed, during action observation, MEP facilitation occurs specifically in those muscles involved in the observed action (Fadiga et al. 2005; Urgesi et al. 2006; Alaerts et al. 2009) according to their dynamic recruitment during actual execution (Gangitano et al. 2001, 2004; Alaerts et al. 2010a, 2010b; Tidoni et al. 2013).

Despite the large body of research using EEG and TMS techniques to investigate motor resonance in humans, only four studies have tested whether mu-ERD and MEPs could reflect the same or distinct neural

process (Lepage et al. 2008; Lapenta et al. 2018; Prinsen & Alaerts 2020; Bekkali et al. 2021). To pursue this aim, Lepage et al. (2008) recorded MEPs induced by M1 stimulation with simultaneous EEG recording during action observation and execution. In 12 participants, they reported mu-ERD in the contralateral sensorimotor cortex as well as larger MEP amplitudes for both action execution and observation relative to a resting condition. However, they found no significant correlation between the magnitude of these two parameters in this small group of participants. Both Lapenta et al. (2018) and Prinsen & Alaerts (2020), instead, tested EEG activity and TMS-induced MEPs in two separate experimental sessions where participants were asked to observe specific movements (precision grip vs. power grip in the first study, and intransitive actions in the second one). Again, the authors found no significant correlation between mu rhythm and MEPs, thus concluding that these indices reflect distinct processes taking place in the action observation/execution matching system. Lastly, in a recent study, Bekkali et al. (2021) used simultaneous EEG and MEP recording during action observation but found no sign of mu-ERD and no relationship between EEG rhythms and MEP facilitation.

It should be noted that, in all these studies, MEPs were recorded from one muscle only and during the observation of a single action only, preventing the assessment of whether MEP facilitation truly reflects muscle-specific motor resonance or other non-specific processes such as increased arousal due to motion (Lepage et al. 2010; Naish et al. 2014). Indeed, to distinguish these possibilities, it is critical to contrast different actions that recruit distinct muscle representations (e.g., Romani et al. 2005; Catmur et al. 2007). Even more importantly, prior TMS-EEG studies analyzed the relation between EEG and TMS indices of motor resonance by averaging values of mu rhythm and MEPs in each participant and correlating these indices across participants (mean-based inter-individual correlation) – thus discarding potentially relevant information associated with trial-by-trial fluctuations of the two indices.

Considering these fluctuations is relevant, as MEPs show not only inter-subject variability (Goldsworthy et al. 2014; Iscan et al. 2016) but also consistent intra-subject variability (Goldsworthy et al. 2016; Guerra et al. 2020) that in principle could be taken into account by focusing on linear mixed models (LMM) (Madsen et al. 2019). Also, several studies have shown inter- and intra-individual differences in sensitivity in mu-ERD (Cheng et al. 2008; Weiss et al. 2020), particularly in the alpha frequency band (8-13 Hz) (Wriessnegger et al. et al. 2020). Therefore, to conclude that suppression of mu rhythm is not associated with facilitation of corticospinal excitability, a statistical model which accounts for intra- and inter-individual variability is needed.

In light of this scenario, a more precise and in-depth investigation into the possible relation between mu-ERD and MEP facilitation during action observation and execution is necessary. Here, we sought to address this issue by recording TMS-induced MEPs during simultaneous EEG acquisition, i.e., TMS/EEG co-registration, during different types of tasks designed to tap into motor resonance. Specifically, participants were asked to observe and perform finger movements with the index and little fingers, as well as to remain at rest or watch a static hand. Single-pulse TMS was delivered over the left M1 while EEG activity was recorded from the

scalp and MEPs were simultaneously recorded from the two corresponding muscles of the contralateral hand. In this way, we were able to assess trial-by-trial fluctuations in mu-ERD and MEPs and the association between them for the first time. Notably, by adopting a LMM statistical approach – which offers the opportunity to control for inter- and intra-individual variability – we provided powerful conditions to explore the association between mu-ERD and MEPs during action observation. Indeed, our approach offers the opportunity to test whether mu-ERD and MEP facilitations during action observation reflect a unique process or two distinct processes. If the two indices of motor resonance reflect the same process, we expected to find that larger MEP facilitations during action observation are predicted by larger mu-ERD. If, on the other hand, mu-ERD and MEPs reflect two distinct mechanisms, we expected to find no relationship between them. We therefore combined multiple statistical approaches, including Bayesian analyses, to evaluate the relative strength of evidence for the null vs. alternative hypotheses of a correlation between mu-ERD and MEP indices.

2. Methods

Participants

Twenty volunteers took part in the study (10 females; age $M \pm SD = 23.25 \pm 2.38$ years, range 20-31 years). This sample size fits well with prior mu-ERD and MEP studies on action observation (Pineda, 2005; Naish et al. 2014; Zhang et al. 2018). A post-hoc power analysis performed with the package ‘*simr*’ (Green & MacLeod 2016) running in R software (RStudio, Inc) revealed that, given a sample of $N = 20$ participants, the power ($1 - \beta$) of our linear mixed model (see Statistical Analysis section for further details) was 0.98, which we consider highly adequate.

All participants were right-handed according to the Oldfield Handedness Inventory (Oldfield, 1971) ($M \pm SD = 73.53\% \pm 19.19\%$ scores). None of them reported neurological or psychiatric problems or any contraindication to TMS or EEG (Rossi et al. 2009). All participants had normal or corrected-to-normal visual acuity. The experiment was approved by the Bioethical Committee at the University of Bologna and carried out in accordance with the Declaration of Helsinki. Written informed consent was obtained from each participant. The experiment was carried out at the Centre for studies and research in Cognitive Neuroscience (CsrNC) in Cesena, Department of Psychology, University of Bologna. All participants completed the experiment, and no adverse effects were reported or noticed.

Procedure

The experiment was carried out in a quiet and dark room. Participants sat at a distance of 65 cm in front of a 15” PC monitor where visual stimuli were displayed. We followed the general procedure of a prior TMS-EEG study (Zanon et al. 2018), except that that study tested other brain regions during rest and action execution only. The task used in the current study was made up of four experimental conditions: (i) Rest; (ii) Action Execution, during which participants were instructed to execute abduction-adduction movements either with

the index or the little finger; (iii) Action Observation, during which participants observed abduction-adduction movements of a right index or little finger while remaining at rest; (iv) Static Hand Observation, during which participants remained at rest while observing the same hand in a static position. Each condition was performed in different mini-blocks made up of 6 trials each. Every mini-block started with a 2-sec screen displaying the subsequent instruction – Rest (i), Action (ii), Watch (iii, iv) – followed by a black screen which lasted 1-1.5 sec. Then, for the Rest, Static Hand and Action Observation conditions, a fixation cross appeared at the center of the screen for 2 sec, while the specific finger to move (i.e., index or little finger) was displayed for the same time interval in the Action Execution condition. Subsequently, a scrambled image (obtained by scrambling the visual hand stimuli) was presented for 4 sec in the Rest and Action Execution trials. In the former, participants were instructed to relax their right hand while keeping their gaze fixated on the screen. In the latter, this image functioned as a Go signal for participants to start the required self-paced movement as soon as possible, always keeping their gaze fixated at the center of the monitor. The image of a static or dynamic hand lasting 4 sec was shown in the Static and Action Observation conditions, respectively (Figure 1A-B-C-D). The static and dynamic hand images depicted the hands of 3 male and 3 female actors.

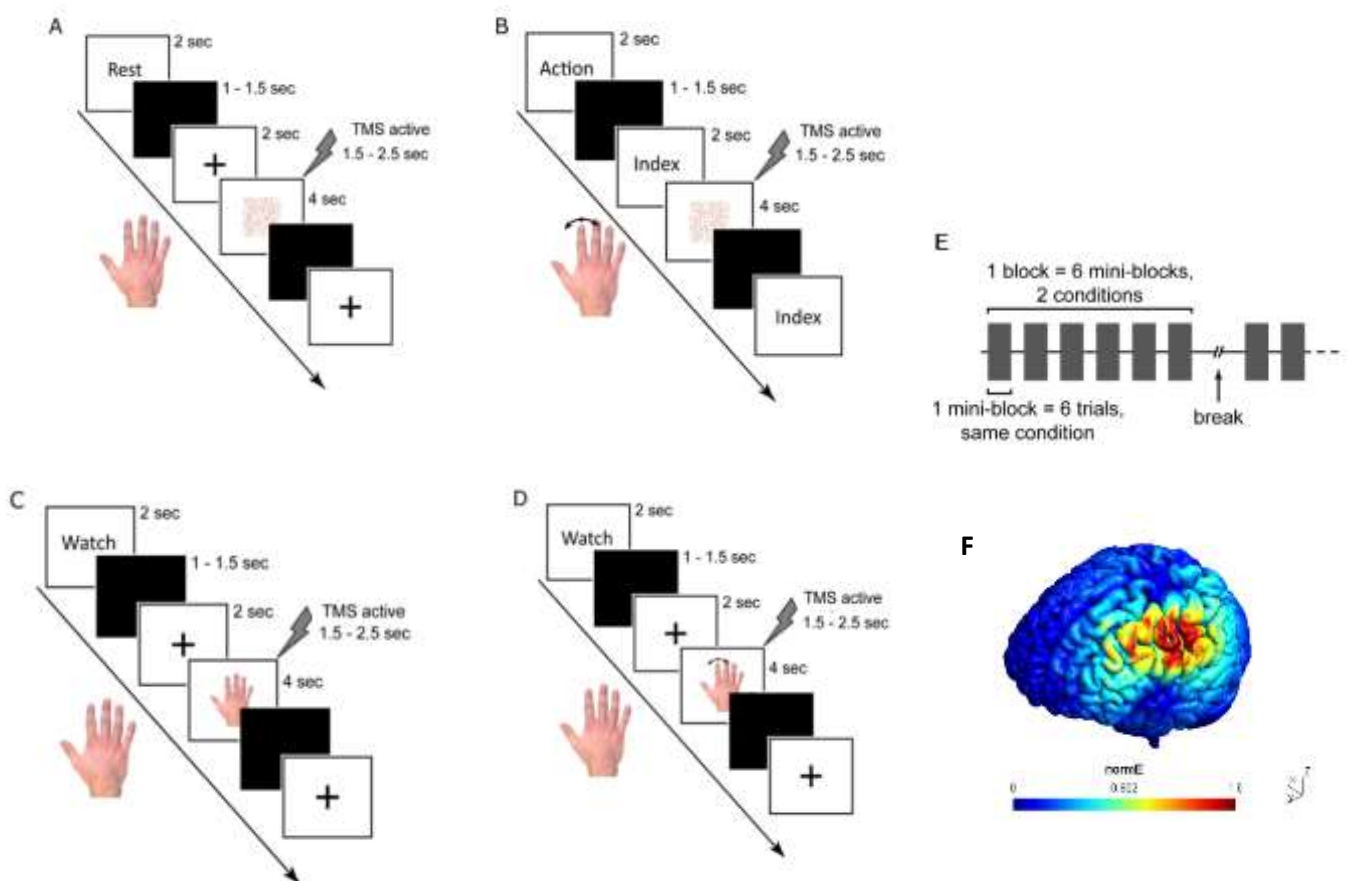


Figure 1. Schematic representation of the experimental design. A-D. Beginning sequences (1 complete trial) of the different conditions: (A) Rest, (B) Action Execution, (C) Static Hand, (D) Action Observation. **E.** Schematic representation of trial organization in blocks and mini-blocks. **F.** Simulation of normalized electric field (NormE) distribution over the targeted left M1 site (mean Talairach coordinates \pm standard deviation: $x = -35.21 \pm 7.02$; $y = -11.88 \pm 9.4$; $z = 55.51 \pm 4.91$) using SimNIBS 3.1.1. NormE intensity is color-coded from 0 to 1.6 mV/mm.

After 1.5/2.5 sec from the onset of the relevant visual stimulus (scrambled image/static hand/moving hand), a single pulse of active or sham TMS was applied over the left M1 (Figure 1F). Active and sham TMS were delivered in different mini-blocks within the same experiment, but in the present article we focus on the active mode only and, therefore, the following descriptions do not cover the sham mode (see TMS section for further details). Sham data will be presented in a separate article focusing on TMS-evoked potentials and addressing a different research question.

The experiment was divided into 18 mini-blocks of each condition in order to lighten the cognitive load – and therefore increase overall accuracy – due to the substantial number of experimental conditions and specific instructions to follow (Figure 1E). A short break was allowed between mini-blocks. The overall task was made up of 432 trials divided into 108 trials for each condition, with 90 repetitions of true trials and 18 of catch trials. In the small percentage of catch trials (around 17%), participants were asked to report the presence of a dot that could appear at the end of the image. This allowed us to check for an adequate level of vigilance throughout the entire task (for a similar procedure, see Zanon et al. 2018). The experiment was programmed in MATLAB (MathWorks Inc.), using the Psychophysics Toolbox extension (Brainard & Vision 1997; Pelli & Vision 1997; Kleiner et al. 2007) to control visual stimulus presentation and to trigger EMG, TMS and EEG.

TMS

Single monophasic magnetic pulses were administered using a 70-mm figure-of-eight coil connected to a Bistim2 TMS stimulator (MagStim Company, Ltd, UK). We placed the coil over the left M1 with the intersection of the coil aligned tangentially to the scalp and the handle pointing backward and laterally at a 45° angle away from the midline. To target the left M1, we first identified the motor hotspot of the right first dorsal interosseous (FDI) and made small adjustments to place the intersection of the coil flat against the scalp and not directly over the electrodes. The corresponding location was marked on the EEG cap to ensure proper placement of the coil throughout the experiment. To set stimulation intensity, we then determined the resting motor threshold (rMT), defined as the minimal intensity of stimulator output that produces MEPs with amplitudes of at least 50 μ V with 50% probability in the FDI muscle. Because the FDI and the ADM share very similar functional topographic maps (Melgari et al. 2008), we used the FDI hotspot and rMT for both muscles.

The experimental TMS-pulse intensity was set to 105% of each individual participant's rMT. This stimulation intensity was chosen to prevent large TMS artefacts in the EEG signal (Zanon et al. 2018), and because lower TMS intensities are capable of eliciting signs of motor resonance (Loporto et al. 2013). During sham TMS, the coil was placed tangentially to the scalp, but a Plexiglas cube was attached to the coil so that it was separated from the scalp by 5 cm. Both in active and sham TMS, a thin layer of foam (50 mm) was placed between the coil and the EEG cap to mitigate the bone conduction of sound and the occurrence of trigeminal nerve stimulation (Zanon et al. 2013, 2018). Participants wore earphones throughout the experiment to attenuate the TMS click discharge sound (Ter Braack et al. 2015). Because our aim was to investigate the relationship

between mu-ERD and MEP expressions of motor resonance, we analyzed active TMS trials only for this article, as no MEPs are elicited by sham TMS.

Neuronavigation

The SofTactic NeuroNavigation System (EMS, Italy) was used in order to identify Talairach coordinates corresponding to the hand representation in the left M1 (i.e., the FDI motor hotspot). Before starting the experiment, a reconstruction of the participant's brain was computed in Talairach space based on an MRI template, 4 craniometric landmarks (nasion,inion and preauricular points) and 80 scalp points digitized with the Polaris Vicra Optical Tracking System (NDI, Canada). This procedure has been established to ensure a global localization accuracy of approximately 5 mm (Carducci & Brusco 2012). The left M1 site stimulated during the experiment was localized at mean Talairach coordinates \pm SD: $x = -35.2 \pm 7.0$; $y = -11.9 \pm 9.4$; $z = 55.5 \pm 4.9$.

EMG recording and data preprocessing

Electromyography (EMG) was recorded using Biopac MP-35 (Biopac, USA) from the FDI and the abductor digiti minimi (ADM) muscles of the right hand, contralateral to the site of brain stimulation. The FDI and ADM muscles are responsible for controlling abduction movements of the index and little finger, respectively. EMG signal was band-pass filtered (30-500 Hz) and sampled at 5000 Hz. The absence of any voluntary contraction before the TMS pulse was visually controlled by the experimenter throughout the experiment. EMG signals were stored in a computer for offline analysis of background EMG activity (i.e., before the TMS pulse) and MEP amplitudes. EMG activity before the stimulation was root mean square (RMS) transformed and averaged in the period -100 to -1 ms prior to TMS. Because the focus of this study is on the relationship between EEG and MEPs, we focused on active TMS trials only in all analyses, as no MEP can be recorded in sham TMS trials. In each condition, trials with an EMG amplitude greater than 2 standard deviations from the mean were discarded from successive analyses (total rejection rate ~3%). For each trial involving active TMS, MEPs were induced in the two target muscles and peak-to-peak MEP amplitude (in mV) was computed in the 10-70 ms period following TMS. For each participant and condition, MEPs were normalized through logarithmic transformation (in line with Lepage et al. 2008).

EEG recording

EEG was acquired through a TMS-compatible EEG amplifier (BrainAmp DC, BrainProducts GmbH, Germany) along with 60 TMS-compatible sintered electrodes (EasyCap GmbH, Germany) mounted onto an elastic cap according to the 10/5 coordinate system. Additionally, two electrodes were placed on the outer canthi of the eyes to monitor saccades (hEOGI and hEORr) while another one was placed beneath the left eye to detect eye-blinks (vEOGI). Reference and ground electrodes were placed on the AFz electrode site and the

right mastoid, respectively. Impedance was kept under 5Ω for each electrode. The sampling rate was set to 5000 Hz and the recorded signal was low-pass filtered at 1000 Hz (DC recording).

EEG preprocessing and data analysis

EEG recordings were analyzed using MATLAB R2019b (The MathWorks) and the Fieldtrip MATLAB toolbox (<http://www.fieldtriptoolbox.org>) (Oostenveld et al. 2011), in line with the pipeline reported by Herring et al. (2015) (<http://www.fieldtriptoolbox.org/tutorial/tms-eeeg/>). First, the signal was divided into epochs of 7 seconds — from -3.5 to +3.5 seconds around the TMS pulse. Then, the TMS artefact was identified in the time interval between -2 ms and +15 ms around TMS pulse onset, and data in that interval were cut and interpolated using a cubic function (Rogasch et al. 2014; Zanon et al. 2018). The signal was downsampled to 500 Hz and noisy trials were rejected by adopting the criterion of 10^4 variance thresholds (total rejection rate: 4.4%). Independent Component Analysis (FastICA) was performed and ICA components reflecting TMS-related and other cranial muscle artefacts (Korhonen et al. 2011), as well as eye-blinks and saccades (Jung et al. 2000), were discarded through visual inspection by adopting a conservative approach to avoid dispersing relevant information (total rejection rate: < 5%).

The signal was re-referenced to the channel average and high/low pass filters were applied (cutoff frequency = 100/1 Hz). TMS-locked oscillations were analyzed based on time-frequency representations (TFRs) by means of a Fast Fourier Transform (FTT). A Hanning sliding tapered time window of 50 ms was applied to the four experimental conditions by selecting 1-50 Hz frequencies in the time interval from -3 to +2 seconds around TMS onset. Linear trends and mean of the power were subtracted from every time window concomitantly to the time-frequency analysis (Luck, 2005). An absolute baseline correction was performed for each TFR by subtracting the power of the pre-TMS interval (from -3 to -2.5 seconds) from the whole selected time window. In the final pre-processing step, the grand average was computed for each experimental condition, excluding the vigilance trials. Lastly, by visually inspecting TF graphs as well as scalp maps of different time windows and frequency bands, we decided to focus our successive analyses on mu rhythm (8-13 Hz) in the -1.5 to -0.5-second temporal window before the onset of the impulse. We thus extrapolated the power values which were averaged from C3 and CP3 electrodes over the left sensorimotor cortex.

Statistical analysis

We conducted a series of preliminary analyses to check participants' behavioral performance by assessing their accuracy in the vigilance task and EMG activity during the EEG recording. We focused on EMG activity prior to TMS pulses to ensure that participants activated their muscles in the Action Execution conditions and were at rest in the remaining conditions (e.g., during action observation). To this aim, a repeated measures analysis of variance (RM ANOVA) with the variables Condition (Rest, Action Execution, Static, Action Observation) and Muscle (FDI, ADM) as within-subjects factors was conducted. In a further test, to ensure that muscle activation corresponded to the executed movements, we analyzed EMG activity from the FDI and

ADM muscles in the Action Execution condition using a RM ANOVA with Muscle (FDI, ADM) and Movement (Congruent, Incongruent) as within-subjects factors to take correspondence with the executed movement into consideration. As a further control, we performed the same analysis on the Action Observation condition to ensure that no subtle EMG pre-activation was detected before TMS administration.

Concerning MEPs, we first carried out an exploratory 2-way RM ANOVA with Condition (Rest, Action Execution, Static, Action Observation) and Muscle (FDI, ADM) as within-subjects factors on log-transformed MEP amplitudes. Then, we tested motor resonance by assessing TMS-induced MEPs and mu-ERD. Because a main feature of motor resonance in TMS-induced MEP research is muscle congruency (e.g., Naish et al. 2014), we focused on Action Observation trials and analyzed mean MEPs using a 2-way RM ANOVA with the factors Muscle (FDI, ADM) and Movement (Congruent, Incongruent) as within-subjects factors to detect motor resonance.

For EEG data, a 1-way RM ANOVA was conducted to confirm mu-ERD in the contralateral motor cortex when performing and watching actions. Baseline-subtracted mu power was entered into the ANOVA as the dependent variable, and Condition (Rest, Action Execution, Static, Action Observation) was entered as the within-subjects factor. Post-hoc analyses were carried out using Duncan's test. Moreover, to detect activation, one sample t-tests against zero were carried out for each experimental condition. A further 2-way RM ANOVA was performed by adding the factor Hemisphere (Left, Right) to assess mu-ERD over the right hemisphere, as well (see Supplementary Material). We also carried out a 1-way RM ANOVA with the factor Condition on beta-ERD values to explore whether action observation and execution affected this frequency band (see Supplementary Material).

To answer our central experimental question, we computed correlation analyses between MEP indices of motor resonance (i.e., the difference in MEP amplitude between the congruent and the incongruent movement for each muscle¹) and mu-ERD during Action Observation across subjects using averaged values; moreover, we computed correlations using all single-trial data points pooled together at the group (see below) and single-subject levels (see Supplementary Material). To match trials from EEG and EMG measurements, we discarded all trials where at least one of the two values was not present. A total rejection rate of 7.89% was achieved. We also performed Bayesian correlations in order to directly evaluate the relative strengths of evidence for the null and alternative hypotheses, thus providing quantification of the degree to which the data support either hypothesis (Dienes, 2014; Rouder et al. 2017).

Additionally, to further check for any relation between the two indices, we carried out a LMM on the single-trial data. MEP indices of motor resonance (i.e., congruent minus incongruent movements) were entered into

¹ For example, for the FDI muscle, MEP indices were computed as the difference between the index finger and little finger movements, whereas for ADM MEPs, we computed the difference between the little finger and index finger movements. Then, in subsequent analyses for index finger movements, we considered FDI MEPs (index minus little finger movements), whereas for little finger movements we considered ADM MEPs (little minus index finger movements).

the model as the dependent variable, with Muscle (FDI, ADM) as a fixed within-subjects factor, mu-ERD as a covariate, and subject variability as a random effect.

To ensure that the results were not affected by outliers, we repeated the main analyses (average correlations, trial-by-trial correlations, LMM) after discarding possible outlier values (see Supplementary Material). Moreover, to check not only for linear relationships, but also non-linear relationships, the LMM and the correlations were repeated with the addition of non-linear exponentials of mu-ERD values (see Supplementary Material). Finally, the main analyses (average correlations, trial-by-trial correlations, LMM) were repeated again using MEP values obtained by subtracting the average values of (i) Static and (ii) Rest conditions from congruent trials for each participant (see Supplementary Material). Significance was set at $p < 0.05$ Holm (LMM) post-hoc tests were used to follow up any significant interactions.

ANOVAs were performed using Statistica v. 12. Bayesian analyses were implemented using default priors in JASP v. 0.15.1 (Jasp Team 2021). Correlation analyses and LMMs were performed using both the ‘nlme’ package (<https://cran.r-project.org/web/packages/nlme/nlme.pdf>) in R 1.2.5019 (RStudio, Inc) and Jamovi 1.0.7.0 (<https://www.jamovi.org>) software.

3. Results

Preliminary analyses. First, the accuracy of participants in reporting the presence of a dot in vigilance trials was analyzed. Overall, an average accuracy of 99.05% ($\pm 0.1\%$ standard deviation) was reached at the group level. Errors included 68 missing responses (82.93% of total errors) and 14 false alarms (17.07%). No participant had an accuracy lower than 90%. Therefore, all participants were included in the subsequent analyses.

EMG pre-activity. Analysis of EMG activity before TMS ensured that participants were correctly activating their muscle during the experiment. The Muscle x Condition ANOVA on the EMG signal revealed a main effect of Condition ($F_{3,57} = 38.93$; $p < 0.001$, $\eta_p^2 = 0.67$) accounted for by the higher signal in the Action Execution condition (mean \pm SD: 0.20 mV \pm 0.11) compared to Rest (0.02 mV \pm 0.01, $p < 0.001$), Static (0.03 mV \pm 0.01, $p < 0.001$) and Action Observation (0.02 mV \pm 0.03, $p < 0.001$) conditions, which did not differ from one another (all $p > 0.60$). The main effect of Muscle and the Muscle x Condition interaction were not significant (all $F \leq 2.48$, all $p \geq 0.084$), indicating comparable muscle activations in the FDI and ADM muscles.

As expected, the two muscles were differentially activated as a function of the type of executed movement. The Muscle x Movement ANOVA showed a significant main effect of Movement ($F_{1,19} = 34.47$; $p < 0.001$, $\eta_p^2 = 0.64$) with larger signals for Congruent (0.31 mV \pm 0.19) than for Incongruent (0.09 mV \pm 0.04) movements (Figure 2A). This effect was qualified by a Muscle x Movement interaction ($F_{1,19} = 8.42$; $p = 0.009$,

$\eta_p^2 = 0.31$). Post-hoc tests confirmed larger EMG activation for congruent than for incongruent movements in both muscles (in both cases $p = 0.001$), but also showed that, in the congruent condition, the FDI ($0.34 \text{ mV} \pm 0.23$) showed higher activity than the ADM muscle ($0.28 \text{ mV} \pm 0.17$, $p = 0.005$), whereas in the incongruent condition, the FDI ($0.08 \text{ mV} \pm 0.04$) and ADM ($0.10 \text{ mV} \pm 0.04$) showed comparable activity ($p = 0.36$). The Muscle x Movement ANOVA on EMG signals during Action Observation showed no main effects or interactions (all $F \leq 1.36$, all $p \geq 0.26$), confirming that participants did not show pre-TMS modulation of muscle activity during action observation.

TMS-induced MEPs. The Muscle x Condition ANOVA conducted on MEP amplitudes showed a main effect of Muscle ($F_{1,19} = 5.30$; $p = 0.033$, $\eta_p^2 = 0.22$), with larger amplitudes in the FDI ($0.93 \text{ mV} \pm 0.63$) than the ADM muscle ($0.69 \text{ mV} \pm 0.54$). There was also a main effect of Condition ($F_{3,57} = 37.81$; $p < 0.001$, $\eta_p^2 = 0.67$), with larger MEPs in the Action Execution condition ($1.69 \text{ mV} \pm 1.19$) relative to all the other conditions (range: $0.47\text{-}0.51 \text{ mV}$; all $p < 0.001$), which in turn did not differ from one another (all $p \geq 0.27$). These main effects were qualified by a Muscle x Condition interaction ($F_{3,57} = 10.42$; $p < 0.001$, $\eta_p^2 = 0.35$). Post-hoc analyses confirmed that, in both muscles, MEPs were larger in the Action Execution condition than in the other conditions (all $p < 0.001$). Moreover, relative to Rest, we observed marginally larger MEPs in the Action Observation and Static Hand conditions ($p \leq 0.06$), which in turn did not differ from one another (all $p \geq 0.40$). Finally, MEPs in the FDI and ADM were comparable during Action Execution ($p = 0.67$), whereas they were larger in the FDI than in the ADM muscle in the remaining conditions (all $p < 0.001$).

Notably, in the previous analysis, MEPs during Action Observation were only marginally larger than MEPs during Rest and did not consistently differ from the Static Hand condition, which may suggest little or no motor facilitation and therefore no signs of motor resonance. However, a main feature of motor resonance is muscle specificity: motor facilitation should be detected only in those muscles involved in performing the observed action and not in incongruent muscles. Therefore, to address the issue of muscle congruency, in a further analysis, we focused on Action Observation trials only and distinguished between index and little finger movements. These observed movements were classified as congruent or incongruent relative to the recording muscle: for MEPs from the FDI muscle, we considered index finger abductions as congruent movements and little finger abductions as incongruent movements. Conversely, for MEPs recorded from the ADM muscle, we considered little finger abductions as congruent movements.

The Muscle x Movement ANOVA conducted on MEP amplitudes during Action Observation showed a main effect of Muscle ($F_{1,19} = 6.79$; $p = 0.017$, $\eta_p^2 = 0.26$), with larger amplitudes detected in the FDI ($0.54 \text{ mV} \pm 0.36$) than the ADM muscle ($0.42 \text{ mV} \pm 0.37$). Importantly, there was a main effect of Movement ($F_{1,19} = 5.05$; $p = 0.037$, $\eta_p^2 = 0.21$), showing greater amplitudes when observing congruent movements relative to the recorded muscle ($0.49 \text{ mV} \pm 0.36$) than incongruent movements ($0.47 \text{ mV} \pm 0.38$). That is, motor excitability was higher in the muscle corresponding to the observed movement (Figure 2B). No interaction was found, indicating comparable motor resonance effects in the two recorded muscles ($F_{1,19} = 0.63$, $p = 0.44$, $\eta_p^2 = 0.03$).

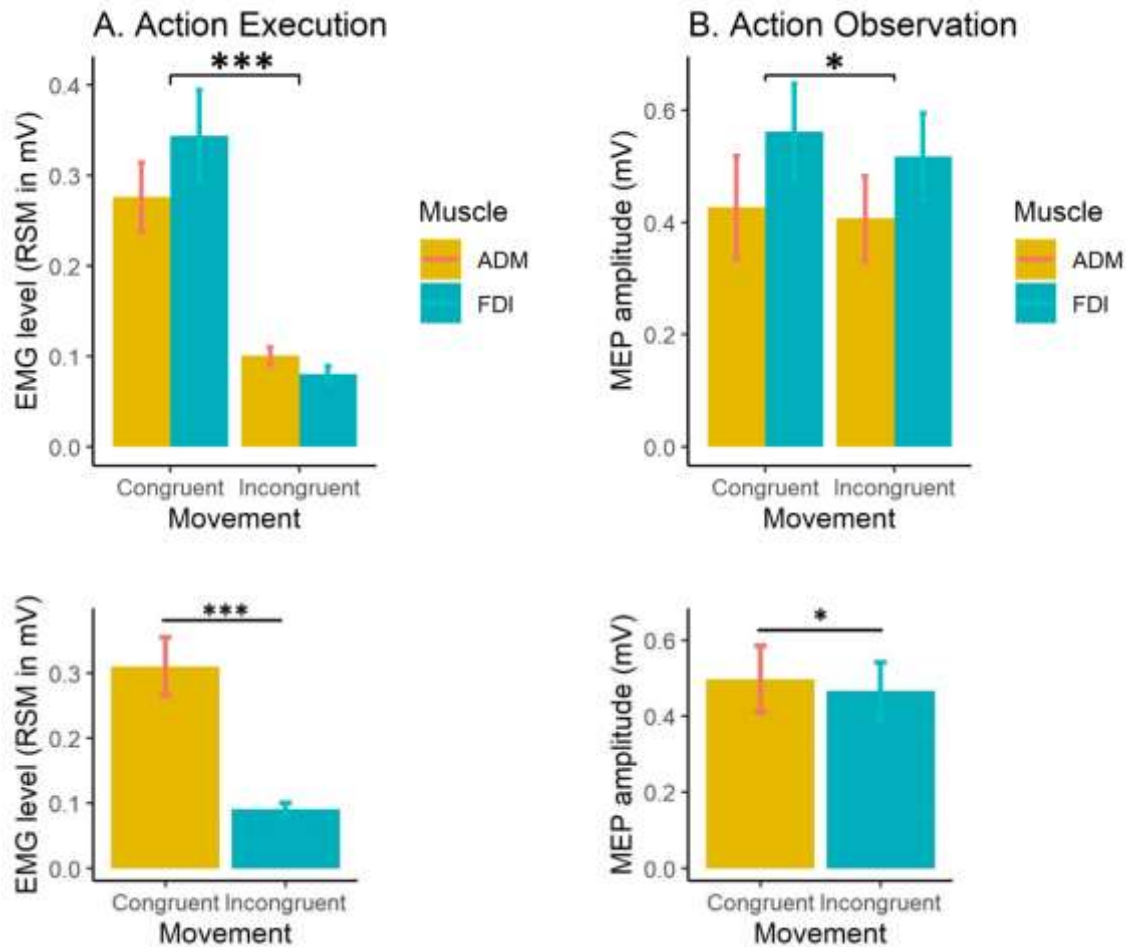


Figure 2. (A). EMG level during action execution. (B) MEP amplitudes during action observation. Top panels show the EMG response separately for the two muscles. Bottom panels show the main effect of Movement, indicating larger EMG activity when performing abduction/adduction movements congruent with the recorded muscle. Amplitudes are represented in raw values (in mV) instead of log-transformed values as used in the statistics. Error bars denote standard error of the mean.

Mu rhythm. The RM ANOVA showed a main effect of Condition ($F_{3,57} = 4.61$, $p = 0.006$, $\eta_p^2 = 0.2$; Figure 3). Post-hoc tests showed that Action Observation ($-0.56 \mu\text{V} \pm 0.96$) entailed a stronger mu-ERD than Static Observation ($-0.15 \mu\text{V} \pm 0.20$; $p = 0.01$) and Rest ($-0.10 \mu\text{V} \pm 0.33$; $p = 0.004$), which did not differ from one another ($p = 0.71$). Similarly, Action Execution ($-0.45 \mu\text{V} \pm 0.50$) showed stronger mu-ERD than Static Observation ($p = 0.054$) and Rest ($p = 0.03$). Mu-ERD was comparable during Action Execution and Action Observation ($p = 0.44$). One sample t-tests confirmed that the mu rhythm was strongly desynchronized during Action Execution ($t_{19} = -3.95$, $p < 0.001$) and Action Observation ($t_{19} = -2.60$, $p = 0.018$); we also observed a small but consistent mu-ERD during Static Observation ($t_{1679} = -3.37$, $p = 0.003$) but not during Rest ($t_{19} = -1.35$, $p = 0.19$). These findings support the notion that observing actions performed by others engages the sensorimotor cortex similarly to when we perform the same actions. Mu-ERD during action observation and execution was not limited to central electrodes over the left hemisphere; rather, it extended over the right

hemisphere (Figure S1). On the other hand, further analyses showed that the beta rhythm was suppressed only during execution and not during action observation (Figure S2).

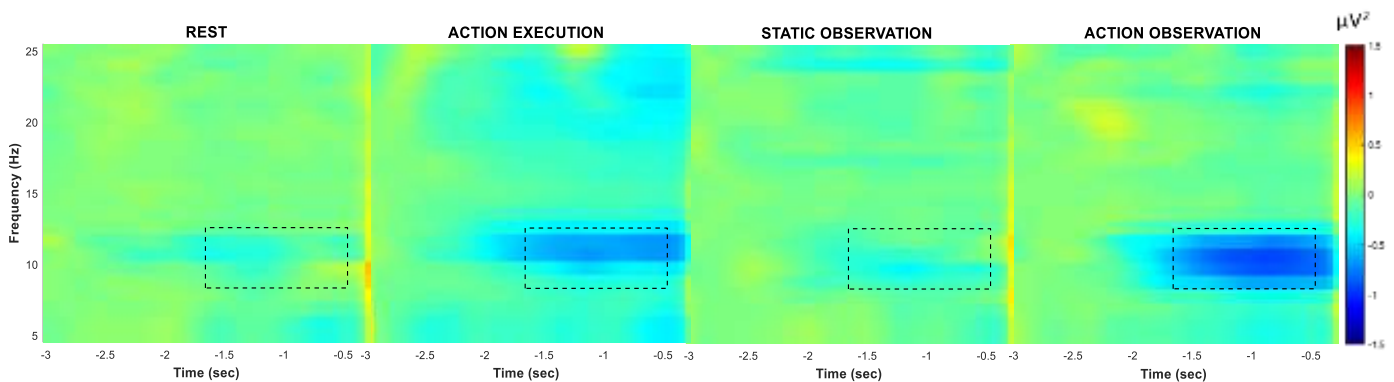


Figure 3. Mu rhythm oscillations in the four experimental conditions (Rest, Action Execution, Static Observation and Action Observation). Time-frequency (TF) plots representing EEG activity before the TMS pulse averaged from electrodes C3 and CP3. The x-axis and the y-axis depict Time (seconds) and Frequency (Hz), respectively. The color bar on the right side ranges from -1.5 to $+1.5 \mu V^2$ of EEG power, with blue indicating desynchronization and red indicating synchronization. The dashed rectangles outline both the frequencies (8-13 Hz) and the time-window (-1.5 to -0.5 sec) selected for statistical analysis. Mu-ERD is clearly visible during Action Execution and Action Observation but not during Rest and Static Observation.

Relation between mu rhythm and MEPs during Action Observation. The correlation analyses computed across participants on averaged individual values of mu-ERD and MEP facilitation during Action Observation showed no significant association ($r = -0.095$; $p = 0.69$; see Figure 4A for separate plotting of MEPs from the two muscles). Similarly, no significant correlation was observed when pooling trial-by-trial data of all participants ($r = 0.011$, $p = 0.68$). Bayesian correlations computed over these indices showed positive/strong evidence in favor of the null hypothesis (average values correlation: $BF_{01} = 3.352$; single-trial correlation: $r = 0.011$, $BF_{01} = 28.812$). These null results were also confirmed at a single-subject level (Figure S3), where correlation analyses performed individually on single-trial basis did not show any significant relationship across participants.

To further test our data, we performed a LMM that showed no relation between mu rhythm and MEP facilitations during Action Observation ($p = 0.49$) (Figure 4B) and only revealed a main effect of Muscle ($F_{1,1531} = 17.58$, $p < 0.001$), indicating larger amplitudes of FDI MEPs than ADM MEPs. Additional control analyses consistently confirmed a lack of both linear and non-linear relations between mu-ERD and MEP facilitation (see Supplementary Results).

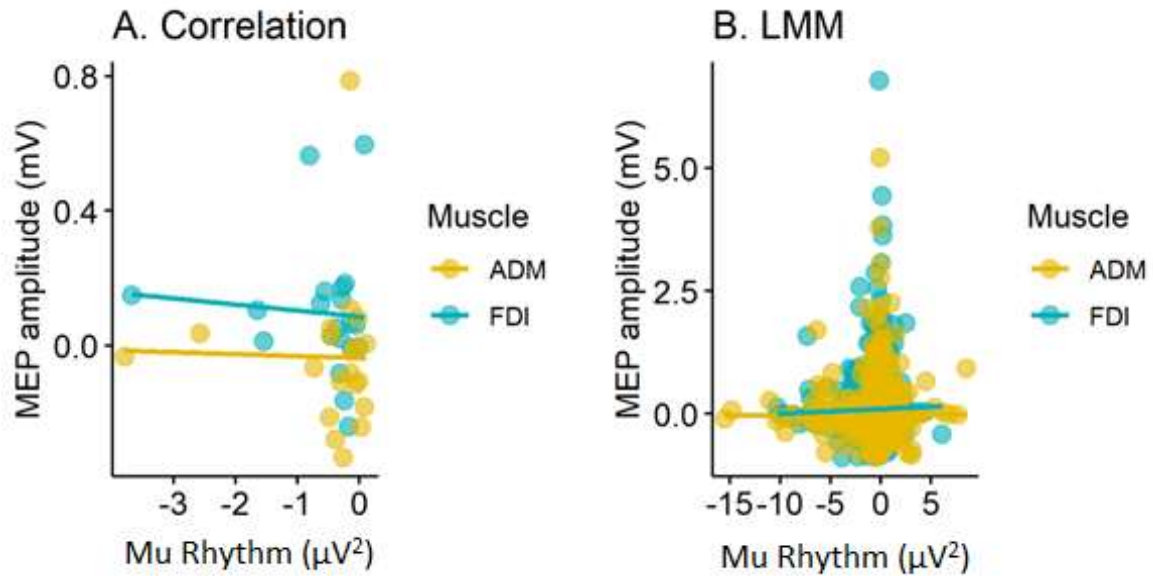


Figure 4. Relationship between mu rhythm and MEP indices of motor resonance in the Action Observation condition **A)** from averaged data (correlation) **B)** and on a trial-by-trial basis (LMM). In all graphs, the x-axis represents mu (mV^2), while MEP amplitudes (in mV) during congruent relative to incongruent movements are depicted in the y-axis. In graph A, each dot represents a single participant, while in graph B each dot represents a trial. In all graphs, dot color characterizes the specific muscle (yellow-ADM, light blue-FDI) and regression lines are shown for both muscles.

4. Discussion

Despite extensive knowledge about the involvement of the sensorimotor cortex during action observation and execution (Fadiga et al. 2005; Pineda, 2005; Caspers et al. 2010; Avenanti et al. 2013; Hardwick et al. 2018), it remains unclear whether two key markers of motor resonance – EEG-based mu-ERD and TMS-based MEP modulations – could reflect similar or distinct neural processes (Lepage et al. 2008; Lapenta et al. 2018; Prinsen & Alaerts 2020), as prior work did not combine TMS-EEG co-registration with a trial-by-trial analysis of the two markers to provide sensitive conditions to evaluate their association.

To answer this question, we carried out a TMS-EEG co-registration study where participants were invited to watch another person performing specific finger movements, as well as to make those movements themselves. While executing the task, single-pulse TMS was delivered over the left M1 while EEG and EMG activity were simultaneously recorded. Our results confirm that both mu-ERD and MEPs reflect motor system activation, as shown by i) the greater mu-ERD over central/centro-parietal electrodes in the action execution and action observation conditions compared to control conditions; ii) the larger MEPs recorded when executing the action with respect to all the remaining conditions, together with a muscle specificity effect revealed by MEPs in the action observation condition. However, when directly comparing mu-ERD and MEPs, we were unable to find any significant relationship between the two measures.

Concerning the first point, that is, the greater mu-ERD over the left sensorimotor cortex while executing and observing a movement, our results confirm the well-established suppression of mu frequency bands during both voluntary movement performance and action observation, especially in the contralateral sensorimotor cortex (McFarland et al. 2000; Pfurtscheller et al. 2000, 2006; Pineda, 2005; Braadbaart et al. 2013; Frenkel-Toledo et al. 2014), thus providing EEG evidence of motor resonance.

The MEP data also appear to be in line with the existing literature. Indeed, it is common knowledge that there is a strong facilitation of corticospinal excitability during action execution (Lepage et al. 2008; Prinsen & Alaerts 2020) and a similar (although weaker) facilitation is observed during action observation (Fadiga et al. 1995; Naish et al. 2014). Interestingly, in the present study, we tested a critical feature of motor resonance, i.e., muscle specificity. While prior TMS-EEG studies assessed motor resonance by testing MEPs from a single muscle during the observation of a single type of action (Lepage et al. 2008; Lapenta et al. 2018; Prinsen & Alaerts 2020; Bekkali et al. 2021), here, we optimized the design by testing two distinct muscles during observation of two types of actions differentially recruiting the target muscles. Our findings indicate that motor resonance occurred according to fine-grained somatotopic rules: for both muscles, we found greater corticospinal excitability during the observation of congruent than incongruent movements; that is, when participants observed index abductions/adductions, we recorded larger MEPs in the FDI muscle, while observation of little finger movements increased MEPs in the ADM muscle. These findings confirm that the MEP facilitations truly reflected motor resonance rather other non-specific processes (Lepage et al. 2010; Naish et al. 2014).

Notably, to test the relation between mu-ERD and MEPs, we combined both frequentist and Bayesian correlational analyses and investigated trial-by-trial variability using a linear mixed model. Using multiple statistical approaches, we provided compelling evidence in favor of the independence of these two indices of motor resonance: there was no relation between mu-ERD recorded by EEG and the MEPs elicited by TMS over the left primary motor cortex when watching others' actions.

Although Lepage et al. (2008), Lapenta et al. (2018) and Prinsen & Alaerts (2020) have already found an absence of any significant correlation between these two parameters when watching others' actions, our study provided strong evidence in support of this result by adopting an extended statistical approach. Indeed, it should be noted that mu-ERD and MEPs greatly vary between participants as well as within the same participant and experimental condition (Pfurtscheller et al. 2006; Goldsworthy et al. 2016; Madsen et al. 2019). These features strongly necessitate a trial-by-trial approach when dealing with these kinds of data (for a review on LMM statistical power, see Dean & Nielsen 2007). In accordance with this, we adopted statistical analyses (i.e., linear mixed model and single-subject correlation analysis) that allowed us control for intra-subject and trial-by-trial variability. These analyses showed no significant relation between mu-ERD and MEP facilitation during action observation. Moreover, by adopting a Bayesian approach, we also provided positive evidence supporting the null hypothesis of no relation between the two neurophysiological indices.

Therefore, we provide the first evidence of the independence of mu-ERD and MEP indices of motor resonance when directly comparing these two measures at both single-trial and single-subject levels. The independence of EEG and TMS parameters may appear puzzling, as both mu-ERD and MEPs are often interpreted as signs of motor cortex activation. Several scholars have proposed that the mu rhythm should be interpreted as more “somatosensory” than “motor” (Hari et al. 1997; Cheyne et al. 2003; Simões et al. 2004). Indeed, mu-ERD is also typically observed when sensing tactile or painful stimuli on the body (Cheyne et al. 2003; Gaetz & Cheyne 2006; van Ede et al. 2010, 2011; Spaccasassi et al. 2021), which are conditions that engage the somatosensory cortex. In a similar vein, it is possible that, during action observation, suppression of mu rhythm would reflect activation of the somatosensory cortex. This would be in keeping with studies showing that the somatosensory cortex is consistently activated when watching others’ actions (Rossi et al. 2002; Avikainen et al. 2002; Gazzola et al. 2006, 2007; Caspers et al. 2010; for a review, see Keysers et al. 2010), that it exchanges information with the rest of the action observation network (Avenanti et al. 2007; Valchev et al. 2016) and that it contributes to action recognition (Jacquet & Avenanti 2015; Valchev et al. 2017; Paracampo et al. 2017), possibly by providing information about the somatosensory features of observed actions (e.g., Avenanti et al. 2007; Keysers et al. 2010). Notably, co-registration of EEG and fMRI shows a relationship between mu-ERD over central electrodes and BOLD activity over somatosensory areas during movement observation and execution (Arnstein et al. 2011). This would be in line with the notion that the somatosensory cortex is a key source of oscillations in the 8-13 Hz frequency band (Salmelin & Hari 1994; Ritter et al. 2009) and could have a role in the mu-ERD during action observation. Interestingly, Arnstein and colleagues found no consistent relation between mu-ERD and BOLD activity in a classical motor node of the mirror neuron system, i.e., the inferior frontal cortex (IFC), at the border between the ventral premotor cortex and the posterior inferior frontal gyrus (Arnstein et al. 2011). Conversely, Avenanti and colleagues showed that downregulation of the IFC with low-frequency repetitive TMS disrupted MEP facilitation during observation of finger movements, whereas downregulation of the somatosensory cortex did not affect the magnitude of this MEP index of motor resonance (Avenanti et al. 2007, 2013a). Taken together these prior studies support the idea of dissociable neural networks driving mu-ERD and MEP facilitations during action observation, and thus converge with the present findings suggesting distinct neural mechanisms underlying these physiological responses to observed actions. Assuming that mu-ERD would reflect processing of somatosensory aspects of observed actions, one possible avenue for future research could be to try to independently manipulate the quantity of motor and somatosensory features of observed actions and test the effect on MEPs and mu-ERD (e.g., Avenanti et al. 2007; Quandt et al. 2013).

Recently, both Thies et al. (2018) and Madsen et al. (2019) tracked the relation between mu rhythm and MEPs by simultaneously collecting EEG and TMS-EMG data while participants were at rest. Thies et al. (2018) found a weak and overall positive relation between cortical oscillatory power within the alpha band (8-13 Hz) and cortical excitability as measured with TMS and MEPs. However, using a powerful statistical approach, Madsen et al. (2019) showed no evidence of a relationship between mu rhythm and MEPs at rest. Further evidence of dissociations between these EEG and MEP measures comes from studies investigating the neural

correlates of empathy for pain (for a review, see Riečanský & Lamm 2019). Indeed, while both EEG (mu-ERD) and TMS (MEP facilitation) indices of motor resonance converge toward increased cortical excitability during action observation, the same indices tend to diverge when seeing painful stimuli on the bodies of other people. Seeing pain in others induces a reduction in MEP amplitudes specific to the muscle that participants observe being painfully stimulated (Avenanti et al. 2005, 2009; Minio-Paluello et al. 2006, 2009), whereas EEG shows an attenuation of sensorimotor rhythms when watching others' pain that reflects cortical activation (Cheng et al. 2008; Riečanský et al. 2015; Riečanský & Lamm 2019).

Our findings further support the conclusion that mu rhythm and MEPs reflect largely independent mechanisms – at least during observation of actions. This conclusion is also supported by a recent study in which transcranial alternating current stimulation administered at 10 Hz over M1 (i.e., at the frequency of mu oscillations) did not affect the magnitude of MEP facilitation during action observation (Wang et al. 2021), whereas other transcranial stimulation protocols known to modulate M1 excitability influenced MEP facilitation (Qi et al. 2019a, 2019b; but see Avenanti et al. 2007). Thus, while M1 excitability appears relevant to the MEP index of motor resonance, oscillatory activity at a mu frequency does not.

Interestingly, Hetu et al. (2016) recently provided evidence suggesting there is no correlation between MEP facilitation due to action observation and behavioral markers of motor resonance (i.e., motor priming and interference effects during action observation). Taken together, this study and TMS-EEG experiments, including the present experiment, hint at the presence of multiple independent mechanisms underlying apparently correlated phenomena during action observation.

The independence of mu-ERD and MEP facilitation could be related to the different spatial and temporal characteristics of the two techniques. Indeed, while EEG mu-ERD would reflect slow oscillatory activity from an area wider than M1 (e.g., possibly involving somatosensory areas), TMS is able to instantaneously capture fluctuations in corticospinal excitability by stimulating discrete populations of neurons in M1. Moreover, MEP amplitudes could be affected by a spinal contribution (Baldissera et al. 2002) which is not considerably captured by EEG recordings. Additionally, watching others' actions (i.e., right hand movements) usually yields a desynchronization of sensorimotor cortices in both hemispheres, not just the contralateral one (Heida et al. 2014), as we also reported here (Figure S1). Further, while mu-ERD is located over central areas during action execution, it involves more extensive fronto-parietal areas during action observation (Fox et al. 2016). In contrast, TMS' modulations of MEPs are specific to the muscles involved in the observed actions, suggesting they reflect activity restricted to specific groups of neurons in M1.

A possible limitation of the present study is that we selected the mu rhythm band at a group level (8-13 Hz) rather than extrapolating individual mu ranges at a single-subject level (e.g., each participant could have exhibited stronger mu rhythm at a different frequency range within the 8-13 Hz band). This approach could have led to higher type II error, despite our results being in line with the previous literature (Lepage et al. 2008; Lapenta et al. 2018; Prinsen & Alaerts 2020; Bekkali et al. 2021). Moreover, our analyses focused on mu rhythm rather than on faster activity, e.g., in the beta range (Hari et al. 1998; Wang et al. 2021). Yet, in our

study, beta-ERD only occurred during action execution; we observed little or no modulation of beta rhythms during action observation (Figure S3). It is well established that action execution robustly reduces beta activity, which cannot be merely considered as a harmonic resulting from the non-sinusoidal waveform of mu activity (McFarland et al. 2000). Moreover, despite prior research mostly focusing on mu-ERD, there is also evidence of changes in beta activity during action observation – although more consistent effects are commonly observed with goal-oriented actions (e.g., grasping or manipulating objects) rather than repetitive finger movements (e.g., Muthukumaraswamy & Johnson 2004; Avanzini et al. 2012). While we do not rule out that action observation could alter beta oscillations, it is possible that the type of finger movements we used in this study may have prevented us from detecting a consistent beta-ERD. Thus, one aim of future TMS-EEG research would be to further test possible relationships between neurophysiological markers of motor resonance using goal-directed actions and a trial-by-trial analysis – although, so far, TMS-EEG studies showing beta-ERD during observation of goal-directed actions reported no relationship with MEPs using averaged values (Lapenta et al. 2018; Bekkali et al. 2021).

Conclusion

When watching people making actions, we map the observed movements onto the corresponding areas of our own motor cortex that would have been activated if we were the agent of that action. This ‘*motor resonance mechanism*’ is well captured by desynchronization of mu rhythm oscillations recorded through EEG as well as by facilitation of motor-evoked potentials elicited by TMS of the observer’s M1. In the present work, through a TMS/EEG co-registration study, we tried to understand whether these two parameters reflect the same or distinct neural processes during action observation. Despite applying a powerful trial-by-trial statistical approach, we observed no relation between the two markers, even though both were sensitive to action observation. Our results suggest that mu-ERD and MEPs reflect two distinct processes occurring within the action observation network. We therefore confirmed William James intuition when he stated that “*every mental representation of a movement awakens to some degree the actual movement which is its object*” (James, 1890), but failed to find the red thread that binds EEG and TMS motor resonance signatures.

Competing interest Authors have nothing to declare.

Author’s contributions CS: analyzed the data and wrote the manuscript. MZ: designed the experiment, collected the data and revised the manuscript. SB: collected the data and revised the manuscript. AV: conceptualized the experiment, analyzed the data and wrote the manuscript.

Open practices The study in this article earned Open Data and Open Materials badges for transparent practices. Materials and data for the study are available at <http://doi.org/10.17605/OSF.IO/9A8WB>.

Declaration of competing interest Authors have nothing to declare.

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References

- Arnstein, D., Cui, F., Keysers, C., Maurits, N.M., & Gazzola, V. (2011). μ -suppression during action observation and execution correlates with BOLD in dorsal premotor, inferior parietal, and SI cortices. *Journal of Neuroscience* 31, 14243-14249.
- Avanzini, P., Fabbri-Destro, M., Dalla Volta, R., Daprati, E., Rizzolatti, G., & Cantalupo, G. (2012). The dynamics of sensorimotor cortical oscillations during the observation of hand movements: an EEG study. *PLoS One*, 7(5), e37534.
- Avenanti, A., Annella, L., Candidi, M., Urgesi, C., & Aglioti, S.M. (2013a). Compensatory plasticity in the action observation network: virtual lesions of STS enhance anticipatory simulation of seen actions. *Cerebral Cortex* 23, 570-580.
- Avenanti, A., Buetti, D., Galati, G., & Aglioti, S. M. (2005). Transcranial magnetic stimulation highlights the sensorimotor side of empathy for pain. *Nature neuroscience*, 8(7), 955-960.
- Avenanti, A., Bolognini, N., Maravita, A., & Aglioti, S.M. (2007). Somatic and motor components of action simulation. *Current Biology* 17, 2129-2135.
- Avenanti, A., Candidi, M., & Urgesi, C. (2013b). Vicarious motor activation during action perception: beyond correlational evidence. *Frontiers in Human Neuroscience* 7, 185.
- Avenanti, A., Minio-Paluello, I., Sforza, A., & Aglioti, S. M. (2009). Freezing or escaping? Opposite modulations of empathic reactivity to the pain of others. *cortex*, 45(9), 1072-1077.
- Avenanti, A., Paracampo, R., Annella, L., Tidoni, E., & Aglioti, S.M. (2018). Boosting and decreasing action prediction abilities through excitatory and inhibitory tDCS of inferior frontal cortex. *Cerebral Cortex* 28, 1282-1296.
- Avikainen, S., Forss, N., & Hari, R. (2002). Modulated activation of the human SI and SII cortices during observation of hand actions. *Neuroimage* 15, 640-646.
- Baldissera, F., Borroni, P., Cavallari, P., & Cerri, G. (2002). Excitability changes in human corticospinal projections to forearm muscles during voluntary movement of ipsilateral foot. *Journal of Physiology* 539, 903-911.
- Barker, A.T., Jalinous, R., & Freeston, I. L. (1985). Non-invasive magnetic stimulation of human motor cortex. *Lancet* 325, 1106-1107.
- Bartur, G., Pratt, H., & Soroker, N. (2019). Changes in mu and beta amplitude of the EEG during upper limb movement correlate with motor impairment and structural damage in subacute stroke. *Clinical Neurophysiology* 130, 1644-1651.
- Bekkali, S., Youssef, G. J., Donaldson, P. H., Hyde, C., Do, M., He, J. L., ... & Enticott, P. G. (2021). Is there a relationship between EEG and sTMS neurophysiological markers of the putative human mirror neuron system?. *Journal of neuroscience research*.

- Borgomaneri, S., Gazzola, V., & Avenanti, A. (2012). Motor mapping of implied actions during perception of emotional body language. *Brain Stimulation* 5, 70-76.
- Braadbaart, L., Williams, J.H., & Waiter, G.D. (2013). Do mirror neuron areas mediate mu rhythm suppression during imitation and action observation? *International Journal of Psychophysiology* 89, 99-105.
- Brainard, D.H., & Vision, S. (1997). The psychophysics toolbox. *Spatial Vision* 10, 433-436.
- Carducci, F., & Brusco, R. (2012). Accuracy of an individualized MR-based head model for navigated brain stimulation. *Psychiatry Research: Neuroimaging* 203, 105-108.
- Caspers, S., Zilles, K., Laird, A.R., & Eickhoff, S.B. (2010). ALE meta-analysis of action observation and imitation in the human brain. *Neuroimage* 50, 1148-1167.
- Catmur, C., Walsh, V., & Heyes, C. (2007). Sensorimotor learning configures the human mirror system. *Current Biology* 17, 1527-1531.
- Cheng, Y., Yang, C.Y., Lin, C.P., Lee, P.L., & Decety, J. (2008). The perception of pain in others suppresses somatosensory oscillations: a magnetoencephalography study. *Neuroimage* 40, 1833-1840.
- Cheng, Y., Lee, P.L., Yang, C.Y., Lin, C. P., Hung, D., & Decety, J. (2008). Gender differences in the mu rhythm of the human mirror-neuron system. *PLoS One* 3, e2113.
- Cheyne, D., Gaetz, W., Garnero, L., Lachaux, J.P., Ducorps, A., Schwartz, D., & Varela, F.J. (2003). Neuromagnetic imaging of cortical oscillations accompanying tactile stimulation. *Cognitive Brain Research* 17, 599-611.
- Classen, J., Steinfelder, B., Liepert, J., Stefan, K., Celnik, P., Cohen, L.G. et al. (2000). Cutaneomotor integration in humans is somatotopically organized at various levels of the nervous system and is task dependent. *Experimental Brain Research* 130, 48-59.
- Cochin, S., Barthelemy, C., Roux, S., & Martineau, J. (1999). Observation and execution of movement: similarities demonstrated by quantified electroencephalography. *European Journal of Neuroscience* 11, 1839-1842.
- Costantini, M., Galati, G., Ferretti, A., Caulo, M., Tartaro, A., Romani, G. L., & Aglioti, S.M. (2005). Neural systems underlying observation of humanly impossible movements: an fMRI study. *Cerebral Cortex* 15, 1761-1767.
- Dean, C.B., & Nielsen, J.D. (2007). Generalized linear mixed models: a review and some extensions. *Lifetime Data Analysis* 13, 497-512.
- di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (1992). Understanding motor events: a neurophysiological study. *Experimental Brain Research* 91, 176-180.
- Dienes, Z. (2014). Using Bayes to get the most out of non-significant results. *Frontiers in Psychology* 5, 781.
- Fadiga, L., Craighero, L., & Olivier, E. (2005). Human motor cortex excitability during the perception of others' action. *Current Opinion in Neurobiology* 15, 213-218.
- Fadiga, L., Fogassi, L., Pavesi, G., & Rizzolatti, G. (1995). Motor facilitation during action observation: a magnetic stimulation study. *Journal of Neurophysiology* 73, 2608-2611.
- Fogassi, L., Gallese, V., Fadiga, L., Luppino, G., Matelli, M., & Rizzolatti, G. (1996). Coding of peripersonal space in inferior premotor cortex (area F4). *Journal of Neurophysiology* 76, 141-157.
- Fox, N.A., Bakermans-Kranenburg, M.J., Yoo, K.H., Bowman, L.C., Cannon, E.N., Vanderwert, R.E., et al. (2016). Assessing human mirror activity with EEG mu rhythm: A meta-analysis. *Psychological Bulletin* 142, 291.
- Frenkel-Toledo, S., Bentin, S., Perry, A., Liebermann, D. G., & Soroker, N. (2014). Mirror-neuron system recruitment by action observation: effects of focal brain damage on mu suppression. *NeuroImage* 87, 127-137.
- Gaetz, W., & Cheyne, D. (2006). Localization of sensorimotor cortical rhythms induced by tactile stimulation using spatially filtered MEG. *Neuroimage* 30, 899-908.
- Gallese, V. (2011). Embodied simulation theory: imagination and narrative. *Neuropsychoanalysis* 13, 196-200.

- Gazzola, V., Rizzolatti, G., Wicker, B., & Keysers, C. (2007). The anthropomorphic brain: the mirror neuron system responds to human and robotic actions. *Neuroimage* 35, 1674-1684.
- Goldsworthy, M.R., Hordacre, B., & Ridding, M.C. (2016). Minimum number of trials required for within-and between-session reliability of TMS measures of corticospinal excitability. *Neuroscience* 320, 205-209.
- Goldsworthy, M.R., Müller-Dahlhaus, F., Ridding, M.C., & Ziemann, U. (2014). Inter-subject variability of LTD-like plasticity in human motor cortex: a matter of preceding motor activation. *Brain Stimulation* 7, 864-870.
- Green, P., & MacLeod, C. J. (2016). SIMR: an R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution*, 7(4), 493-498.
- Guerra, A., López-Alonso, V., Cheeran, B., & Suppa, A. (2020). Variability in non-invasive brain stimulation studies: reasons and results. *Neuroscience Letters* 719, 133330.
- Hardwick, R.M., Caspers, S., Eickhoff, S.B., & Swinnen, S.P. (2018). Neural correlates of action: Comparing meta-analyses of imagery, observation, and execution. *Neuroscience & Biobehavioral Reviews* 94, 31-44.
- Hari, R., Salmelin, R., Mäkelä, J.P., Salenius, S., & Helle, M. (1997). Magnetoencephalographic cortical rhythms. *International Journal of Psychophysiology* 26, 51-62.
- Hari, R., Forss, N., Avikainen, S., Kirveskari, E., Salenius, S., & Rizzolatti, G. (1998). Activation of human primary motor cortex during action observation: A neuromagnetic study. *Proceedings of the National Academy of Sciences of the United States of America* 95, 15061-15065.
- Heida, T., Poppe, N.R., de Vos, C.C., van Putten, M. J.A.M., & van Vugt, J.P.P. (2014). Event-related mu-rhythm desynchronization during movement observation is impaired in Parkinson's disease. *Clinical Neurophysiology* 125, 1819-1825.
- Héту, S., Taschereau-Dumouchel, V., Meziane, H.B., Jackson, P.L., & Mercier, C. (2016). Behavioral and TMS markers of action observation might reflect distinct neuronal processes. *Frontiers in Human Neuroscience* 10, 458.
- Hooks, B.M. (2017). Sensorimotor convergence in circuitry of the motor cortex. *Neuroscientist* 23, 251-263.
- Iscan, Z., Nazarova, M., Fedele, T., Blagovechtchenski, E., & Nikulin, V.V. (2016). Pre-stimulus alpha oscillations and inter-subject variability of motor evoked potentials in single-and paired-pulse TMS paradigms. *Frontiers in Human Neuroscience* 10, 504.
- Jacquet, P.O., & Avenanti, A. (2015). Perturbing the action observation network during perception and categorization of actions' goals and grips: state-dependency and virtual lesion TMS effects. *Cerebral Cortex* 25, 598-608.
- James, W. (1890). *The principles of psychology*, Vol II.
- Jung, T.P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., & Sejnowski, T.J. (2000). Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. *Clinical Neurophysiology* 111, 1745-1758.
- Keysers, C., Kaas, J.H., & Gazzola, V. (2010). Somatosensation in social perception. *Nature Reviews Neuroscience* 11, 417-428.
- Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., & Broussard, C. (2007). What's new in psychtoolbox-3. *Perception* 36, 1-16.
- Korhonen, R.J., Hernandez-Pavon, J.C., Metsomaa, J., Mäki, H., Ilmoniemi, R.J., & Sarvas, J. (2011). Removal of large muscle artifacts from transcranial magnetic stimulation-evoked EEG by independent component analysis. *Medical & Biological Engineering & Computing* 49, 397-407.
- Lapenta, O.M., Ferrari, E., Boggio, P.S., Fadiga, L., & D'Ausilio, A. (2018). Motor system recruitment during action observation: No correlation between mu-rhythm desynchronization and corticospinal excitability. *PLoS One* 13, e0207476.
- Lepage, J.F., Saint-Amour, D., & Théoret, H. (2008). EEG and neuronavigated single-pulse TMS in the study of the observation/execution matching system: are both techniques measuring the same process? *Journal of Neuroscience Methods* 175, 17-24.

- Lepage, J.F., Tremblay, S., Théoret, H. (2010). Early non-specific modulation of corticospinal excitability during action observation. *European Journal of Neuroscience* 31, 931-937.
- Lepage, J.F., & Théoret, H. (2006). EEG evidence for the presence of an action observation–execution matching system in children. *European Journal of Neuroscience* 23, 2505-2510.
- Loporto, M., Holmes, P.S., Wright, D.J., & McAllister, C.J. (2013). Reflecting on mirror mechanisms: motor resonance effects during action observation only present with low-intensity transcranial magnetic stimulation. *PLoS One* 8, e64911.
- Llanos, C., Rodriguez, M., Rodriguez-Sabate, C., Morales, I., & Sabate, M. (2013). Mu-rhythm changes during the planning of motor and motor imagery actions. *Neuropsychologia* 51, 1019-1026.
- Luck, S.J. (2005). Ten simple rules for designing ERP experiments. *Event-related potentials: A methods handbook*, 17-32. Publisher: The MIT press. Editors: Handy, Todd C.
- Madsen, K.H., Karabanov, A.N., Krohne, L.G., Safeldt, M.G., Tomasevic, L., & Siebner, H.R. (2019). No trace of phase: Corticomotor excitability is not tuned by phase of pericentral mu-rhythm. *Brain Stimulation* 12, 1261-1270.
- McFarland, D.J., Miner, L.A., Vaughan, T.M., & Wolpaw, J.R. (2000). Mu and beta rhythm topographies during motor imagery and actual movements. *Brain Topography* 12, 177-186.
- Minio-Paluello, I., Avenanti, A., & Aglioti, S. M. (2006). Left hemisphere dominance in reading the sensory qualities of others' pain?. *Social Neuroscience*, 1(3-4), 320-333.
- Minio-Paluello, I., Baron-Cohen, S., Avenanti, A., Walsh, V., & Aglioti, S. M. (2009). Absence of embodied empathy during pain observation in Asperger syndrome. *Biological psychiatry*, 65(1), 55-62.
- Muthukumaraswamy, S.D., & Johnson, B.W. (2004a). Changes in rolandic mu rhythm during observation of a precision grip. *Psychophysiology* 41, 152-156.
- Muthukumaraswamy, S.D., & Johnson, B.W. (2004b). Primary motor cortex activation during action observation revealed by wavelet analysis of the EEG. *Clinical Neurophysiology* 115, 1760-1766.
- Naish, K.R., Houston-Price, C., Bremner, A.J., & Holmes, N.P. (2014). Effects of action observation on corticospinal excitability: Muscle specificity, direction, and timing of the mirror response. *Neuropsychologia* 64, 331-348.
- Neuper, C., Scherer, R., Wriessnegger, S., & Pfurtscheller, G. (2009). Motor imagery and action observation: modulation of sensorimotor brain rhythms during mental control of a brain–computer interface. *Clinical Neurophysiology* 120, 239-247.
- Oldfield, R.C. (1971). The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9, 97-113.
- Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.M. (2011). FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience* 2011, 156869.
- Paracampo, R., Montemurro, M., de Vega, M., & Avenanti, A. (2018). Primary motor cortex crucial for action prediction: a tDCS study. *Cortex* 109, 287-302.
- Paracampo, R., Tidoni, E., Borgomaneri, S., di Pellegrino, G., & Avenanti, A. (2017). Sensorimotor network crucial for inferring amusement from smiles. *Cerebral Cortex* 27, 5116-5129.
- Pascual-Leone, A., Tormos, J.M., Keenan, J., Tarazona, F., Cañete, C., & Catalá, M.D. (1998). Study and modulation of human cortical excitability with transcranial magnetic stimulation. *Journal of Clinical Neurophysiology* 15, 333-343.
- Pascual-Leone, A., Valls-Solé, J., Wassermann, E.M., & Hallett, M. (1994). Responses to rapid-rate transcranial magnetic stimulation of the human motor cortex. *Brain* 117, 847-858.
- Pelli, D.G., & Vision, S. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision* 10, 437-442.
- Pfurtscheller, G. (2000). Spatiotemporal ERD/ERS patterns during voluntary movement and motor imagery. In *Supplements to Clinical Neurophysiology* 53, 196-198.

- Pfurtscheller, G., Brunner, C., Schlögl, A., & Da Silva, F.L. (2006). Mu rhythm (de) synchronization and EEG single-trial classification of different motor imagery tasks. *NeuroImage* 31, 153-159.
- Pfurtscheller, G., & Neuper, C. (1994). Event-related synchronization of mu rhythm in the EEG over the cortical hand area in man. *Neuroscience Letters* 174, 93-96.
- Pfurtscheller, G., Neuper, C., & Krausz, G. (2000). Functional dissociation of lower and upper frequency mu rhythms in relation to voluntary limb movement. *Clinical neurophysiology* 111, 1873-1879.
- Pineda, J.A. (2005). The functional significance of mu rhythms: translating “seeing” and “hearing” into “doing”. *Brain Research Reviews* 50, 57-68.
- Pineda, J.A. (2008) Sensorimotor cortex as a critical component of an 'extended' mirror neuron system: Does it solve the development, correspondence, and control problems in mirroring? *Behavioral and Brain Functions* 4, 47.
- Qi, F., Nitsche, M.A., & Zschorlich, V.R. (2019a). Interaction between transcranial random noise stimulation and observation-execution matching activity promotes motor cortex excitability. *Frontiers in Neuroscience* 13, 69.
- Qi, F., Nitsche, M.A., & Zschorlich, V.R. (2019b). Modulating observation-execution-related motor cortex activity by cathodal transcranial direct current stimulation. *Brain Sciences* 9, 121.
- Quandt, L. C., Marshall, P. J., Bouquet, C. A., & Shipley, T. F. (2013). Somatosensory experiences with action modulate alpha and beta power during subsequent action observation. *Brain research*, 1534, 55-65.
- Riečanský, I., Paul, N., Kölbl, S., Stieger, S., & Lamm, C. (2015). Beta oscillations reveal ethnicity ingroup bias in sensorimotor resonance to pain of others. *Social cognitive and affective neuroscience*, 10(7), 893-901.
- Riečanský, I., & Lamm, C. (2019). The role of sensorimotor processes in pain empathy. *Brain topography*, 32(6), 965-976.
- Ritter, P., Moosmann, M., & Villringer, A. (2009). Rolandic alpha and beta EEG rhythms' strengths are inversely related to fMRI-BOLD signal in primary somatosensory and motor cortex. *Human brain mapping*, 30(4), 1168-1187.
- Rizzolatti, G., & Sinigaglia, C. (2010). The functional role of the parieto-frontal mirror circuit: interpretations and misinterpretations. *Nature Reviews Neuroscience* 11, 264-274.
- Rizzolatti, G., & Sinigaglia, C. (2016). The mirror mechanism: a basic principle of brain function. *Nature Reviews Neuroscience* 17, 757-765.
- Rogasch, N.C., Thomson, R.H., Farzan, F., Fitzgibbon, B.M., Bailey, N.W., Hernandez-Pavon, J.C., et al. (2014). Removing artefacts from TMS-EEG recordings using independent component analysis: importance for assessing prefrontal and motor cortex network properties. *Neuroimage* 101, 425-439.
- Romani, M., Cesari, P., Urgesi, C., Facchini, S., & Aglioti, S.M. (2005). Motor facilitation of the human cortico-spinal system during observation of bio-mechanically impossible movements. *Neuroimage* 26, 755-763.
- Rossi, S., Hallett, M., Rossini, P. M., Pascual-Leone, A., & Safety of TMS Consensus Group. (2009). Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. *Clinical Neurophysiology* 120, 2008-2039.
- Rossi, S., Tecchio, F., Pasqualetti, P., Olivelli, M., Pizzella, V., Romani, G.L., et al. (2002). Somatosensory processing during movement observation in humans. *Clinical Neurophysiology* 113, 16-24.
- Rossini, P.M., & Rossi, S. (1998). Clinical applications of motor evoked potentials. *Electroencephalography and Clinical Neurophysiology* 106, 180-194.
- Rouder, J.N., Morey, R.D., Verhagen, J., Swagman, A.R., & Wagenmakers, E.J. (2017). Bayesian analysis of factorial designs. *Psychological Methods* 22, 304.
- Salmelin, R., & Hari, R. (1994). Spatiotemporal characteristics of sensorimotor neuromagnetic rhythms related to thumb movement. *Neuroscience*, 60(2), 537-550.
- Schambra, H.M., Sawaki, L., & Cohen, L.G. (2003). Modulation of excitability of human motor cortex (M1) by 1 Hz transcranial magnetic stimulation of the contralateral M1. *Clinical Neurophysiology* 114, 130-133.

- Simões, C., Salenius, S., & Curio, G. (2004). Short-term (≈ 600 ms) prediction of perturbation dynamics for 10- and 20-Hz MEG rhythms in human primary sensorimotor hand cortices. *Neuroimage* 22, 387-393.
- Spaccasassi, C., Dijkerman, C.H., Maravita, A., Ferrante, O., & de Jong, M.C. (2021). Body-space interactions: same spatial encoding but different influence of valence for reaching and defensive purposes. *Journal of Cognitive Neuroscience* 33, 2149-2166.
- Stinear, C.M., Walker, K.S., & Byblow, W.D. (2001). Symmetric facilitation between motor cortices during contraction of ipsilateral hand muscles. *Experimental Brain Research* 139, 101-105.
- Ter Braack, E.M., de Vos, C.C., & van Putten, M.J. (2015). Masking the auditory evoked potential in TMS-EEG: a comparison of various methods. *Brain Topography* 28, 520-528.
- Thies, M., Zrenner, C., Ziemann, U., & Bergmann, T.O. (2018). Sensorimotor mu-alpha power is positively related to corticospinal excitability. *Brain Stimulation* 11, 1119-1122.
- Tidoni, E., Borgomaneri, S., di Pellegrino, G., & Avenanti, A. (2013). Action simulation plays a critical role in deceptive action recognition. *Journal of Neuroscience* 33, 611-623.
- Urgesi, C., Candidi, M., & Avenanti, A. (2014). Neuroanatomical substrates of action perception and understanding: an anatomic likelihood estimation meta-analysis of lesion-symptom mapping studies in brain injured patients. *Frontiers in Human Neuroscience* 8, 344.
- Urgesi, C., Candidi, M., Fabbro, F., Romani, M., & Aglioti, S.M. (2006). Motor facilitation during action observation: topographic mapping of the target muscle and influence of the onlooker's posture. *European Journal of Neuroscience* 23, 2522-2530.
- Valchev, N., Gazzola, V., Avenanti, A., & Keysers, C. (2016). Primary somatosensory contribution to action observation brain activity—combining fMRI and cTBS. *Social Cognitive and Affective Neuroscience* 11, 1205-1217.
- Valchev, N., Tidoni, E., Hamilton, A.F.D.C., Gazzola, V., & Avenanti, A. (2017). Primary somatosensory cortex necessary for the perception of weight from other people's action: A continuous theta-burst TMS experiment. *Neuroimage* 152, 195-206.
- van Ede, F., de Lange, F., Jensen, O., & Maris, E. (2011). Orienting attention to an upcoming tactile event involves a spatially and temporally specific modulation of sensorimotor alpha- and beta-band oscillations. *Journal of Neuroscience* 31, 2016-2024.
- van Ede, F., Jensen, O., & Maris, E. (2010). Tactile expectation modulates pre-stimulus β -band oscillations in human sensorimotor cortex. *Neuroimage* 51, 867-876.
- Wang, L., Nitsche, M.A., Zschorlich, V.R., Liu, H., Kong, Z., & Qi, F. (2021). 20 Hz Transcranial Alternating Current Stimulation Inhibits Observation-Execution-Related Motor Cortex Excitability. *Journal of Personalized Medicine* 11, 979.
- Weise, K., Numssen, O., Thielscher, A., Hartwigsen, G., & Knösche, T.R. (2020). A novel approach to localize cortical TMS effects. *Neuroimage* 209, 116486.
- Weiss, S.M., Laconi, R.N., & Marshall, P.J. (2020). Individual differences in anticipatory mu rhythm modulation are associated with executive function and processing speed. *Cognitive, Affective, & Behavioral Neuroscience* 20, 901-916.
- Zanon, M., Battaglini, P.P., Jarmolowska, J., Pizzolato, G., & Busan, P. (2013). Long-range neural activity evoked by premotor cortex stimulation: a TMS/EEG co-registration study. *Frontiers in Human Neuroscience* 7, 803.
- Zanon, M., Borgomaneri, S., & Avenanti, A. (2018). Action-related dynamic changes in inferior frontal cortex effective connectivity: A TMS/EEG coregistration study. *Cortex* 108, 193-209.
- Zhang, J. J., Fong, K. N., Welage, N., & Liu, K. P. (2018). The activation of the mirror neuron system during action observation and action execution with mirror visual feedback in stroke: a systematic review. *Neural Plasticity* 2018, 2321045.