CORTICAL CORRELATES OF THE LINK BETWEEN ERROR PROCESSING AND VIRTUAL EMBODIMENT: A COMBINED TMS-EEG-IMMERSIVE VIRTUAL REALITY STUDY

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INTRODUCTION

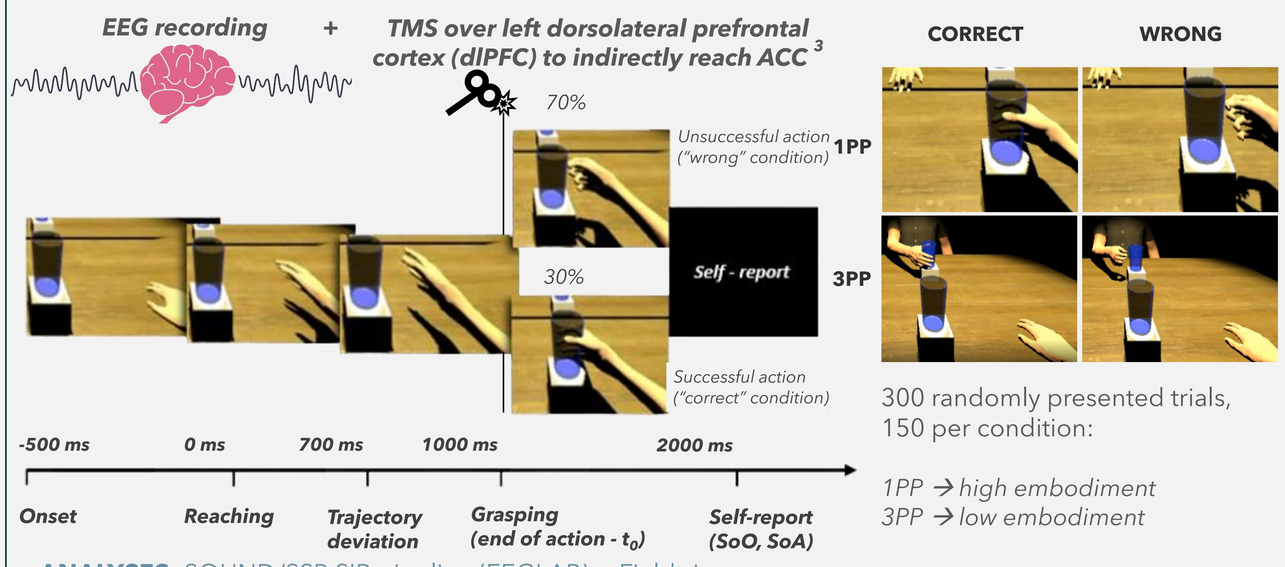
The mere observation of errors committed by a **virtual avatar** from a **first-person perspective (1PP)** elicits electrocortical signatures such as ***Error-related Negativity* (ERN), *Error Positivity* (Pe), *Delta*** and ***mid-frontal Theta* (MFT) synchronization** [1], each indexing specific functional aspects of error processing in different time windows. Correct outcomes also lead to a modulation of electrocortical activity, expressed by a small negative deflection defined as ***Correct-related negativity* (CRN).**

Interestingly, electrocortical signatures of performance monitoring, mainly generated from the **Anterior Cingulate Cortex (ACC),** occur when individuals experience a **sense of embodiment with the virtual avatar (i.e., when the avatar is seen from 1PP).** Moreover, **observing errors reduces embodiment** over the virtual avatar, as indexed by lower **Sense of Ownership (SoO)** and **Sense of Agency (SoA)** [2] **ratings.**

This suggests a **potential dynamic interaction between self-related body representations and the performance monitoring system.**

METHODS

TMS-EEG-IVR task in which 34 healthy participants (2 groups, 17 sham) observe from a first- (1PP) or third (3PP) person perspective an avatar performing successful or erroneous reach-to-grasp actions.



300 randomly presented trials, 150 per condition:

1PP → high embodiment
3PP → low embodiment

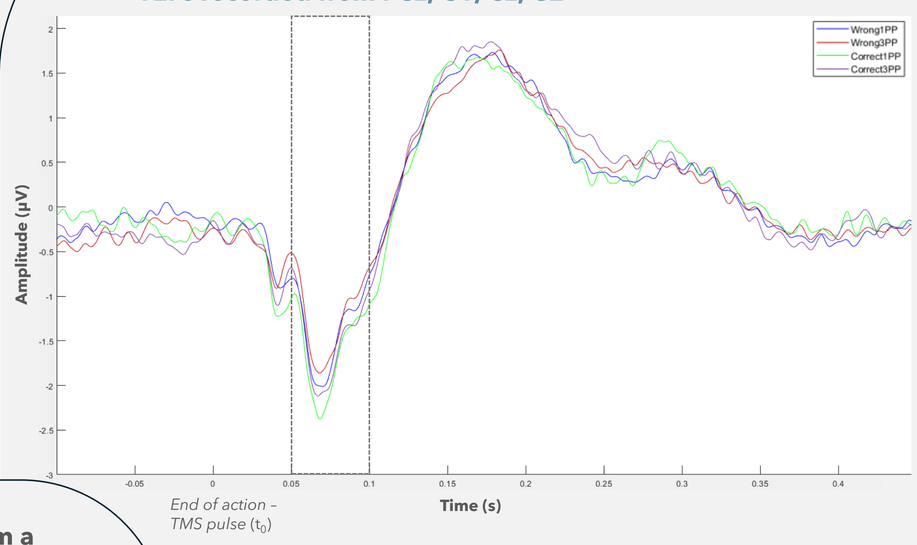
ANALYSES: SOUND/SSP-SIR pipeline (EEGLAB) + Fieldtrip

- **time domain → TMS-evoked potentials (TEPs)**
- **time frequency domain (TFR), main focus on Delta (0.5 -3.5 Hz) and Theta band (4-8 Hz)**
- **cluster-based permutation t-tests** → 1000 repetitions, Monte-Carlo correction, 20-500 ms time window
  - **ANOVA for mean embodiment ratings (SoA, SoO)**

TIME DOMAIN RESULTS

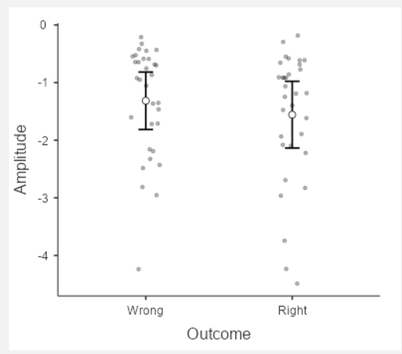
Current sample: 16 (4 excluded due to poor EEG signal; 10 F, age 25.5 ± 2.5, mean ± SD); experimental group

TEPs recorded from FCz, C1, Cz, C2

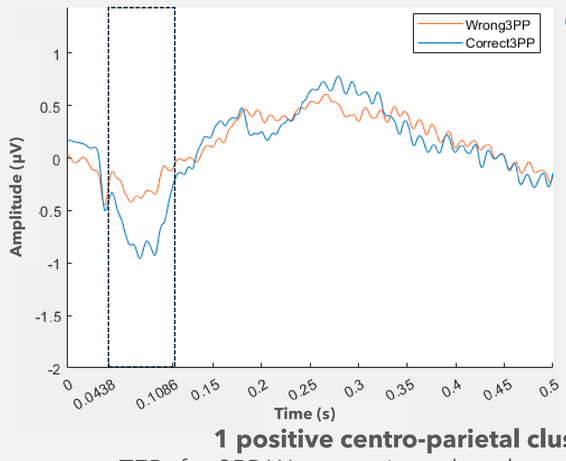


End of action – TMS pulse (t_0)

rmANOVA on mean amplitude in the ERN/CRN time window (50-100 ms)

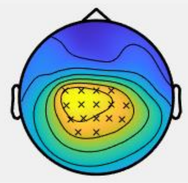


TEPs/ERN in 1PP and 3PP for wrong actions show a smaller deflection in amplitude compared to the **CRN associated to correct actions** (Outcome main effect, $F_{(15,1)} = 5.20$; $p = 0.037$).



CLUSTER-BASED PERMUTATION TESTS
Wrong 3PP vs Correct 3PP

44-108 ms



C3, C1, Cz, C2, CP3, CP1, CPz
CP2, CP4, P1, Pz, P2, P4, PO3, POz

1 positive centro-parietal cluster (p = 0.001, range 44-108 ms)
TEPs for 3PP Wrong actions show less negative amplitude compared to TEPs associated to Correct actions in 3PP.

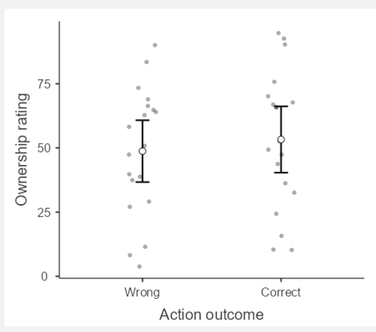
BEHAVIORAL RESULTS

Current sample: 20 (12 F; age = 26 ±4.6 mean ± SD), experimental group

Wrong 1PP vs Wrong 3PP

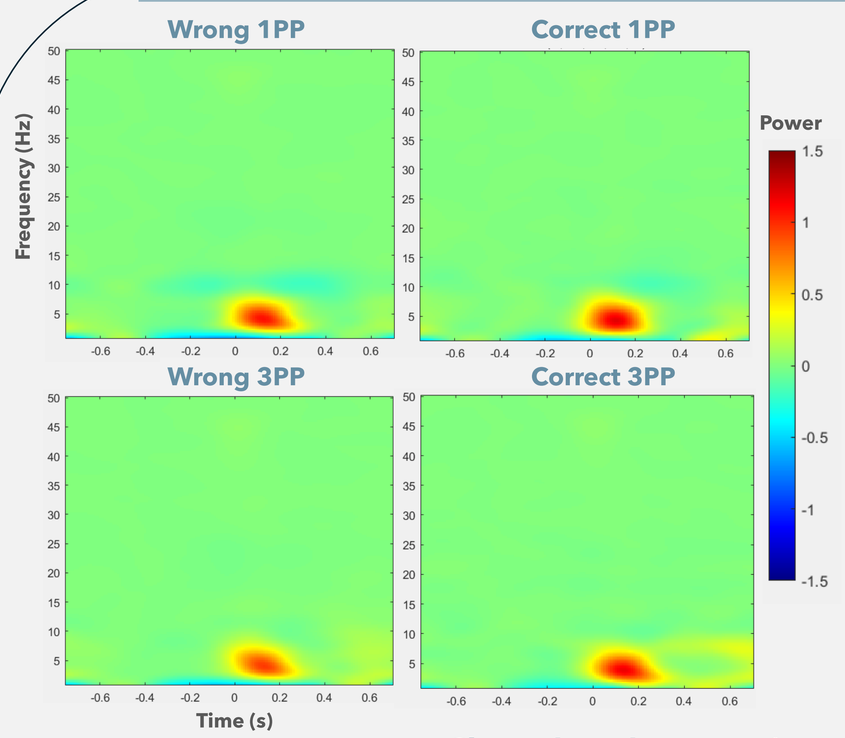
Participants referred **higher embodiment ratings for wrong actions** when the virtual body was seen from **1PP** compared to 3PP ($F_{(19,1)}$ SoO = 52.5, SoA = 28, both $p < 0.001$), indicating that **different perspectives effectively modulate sense of embodiment in IVR.**

Wrong 1PP vs Correct 1PP



Participants referred **lower Ownership ratings in 1PP** when the virtual body committed **wrong actions** compared to correct actions ($F_{(19,1)} = 5.95$ $p = 0.025$), suggesting a transient feeling of disembodiment and thus an **interaction between self-related body representations and error processing.**

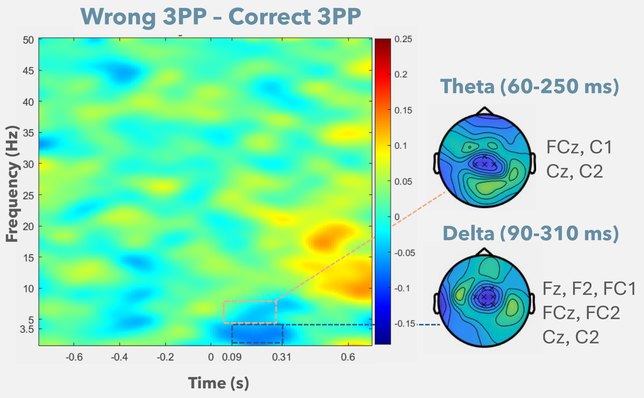
TIME-FREQUENCY RESULTS



The following plots show an increase in power in **Delta (0.5-3.5 Hz)** and **Theta (4-8 Hz)** frequency bands in all conditions following the action outcome - TMS pulse (t_0 = 0 s) in Fz, FC1, FCz, FC2, Cz electrodes.

Cluster-based permutation tests

Wrong 3PP – Correct 3PP



Theta (60-250 ms)

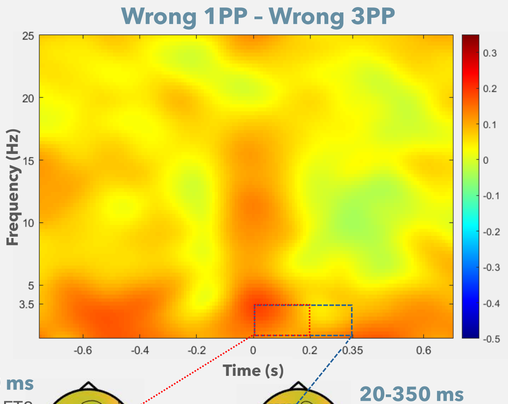
FCz, C1
Cz, C2

Delta (90-310 ms)

Fz, F2, FC1
FCz, FC2
Cz, C2

2 negative fronto-central clusters:
Delta p = 0.027; Theta p = 0.06
Wrong actions in 3PP elicit lower Delta and Theta power compared to Correct 3PP actions.

Wrong 1PP – Wrong 3PP



20-200 ms
F8, F10, FT8
C6, T8, CP6
TP8, P4, P6
PO4, O2

20-350 ms
Fp1, AF7, F5
F3, FC5, FC3
FC1, C3

2 positive clusters in the Delta band:
Right lateral p= 0.035; Left frontal p = 0.014
Wrong actions in 1PP elicit higher Delta power compared to Wrong 3PP actions.

CONCLUSIONS

Preliminary results indicate a **transient TMS-induced impairment of error processing** at the electrophisiological level in **fronto-central (i.e., error-related) ROIs,** both in time (**TEPs**) and frequency domains (**Delta and Theta band**), where **reduced activity** has been observed **for wrong actions** compared to correct actions **in both perspectives** (**1PP, 3PP**). Additional source analyses will help disentangle whether this is due to interference in ACC activity caused by carry-over neuromodulation effects or by premature activation of the dlPFC during the error-processing timeline.

Increased Delta power and higher ownership ratings for wrong actions in 1PP compared to 3PP suggest **greater involvement of the performance monitoring network** in conditions **where embodiment plays a crucial role**. Future connectivity analyses will shed light on the existence of an interaction between the networks responsible for error processing and self-related body representations.

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2. Pezzetta, Rachele, Nicolardi, V., Tidoni, E., & Aglioti, S. M. (2018). Error, rather than its probability, elicits specific electrocortical signatures: A combined EEG-immersive virtual reality study of action observation. *Journal of Neurophysiology, 120*(3), 1107–1118.
3. Wang, J. B., Hassan, U., Bruss, J. E., Oya, H., Uitermarkt, B. D., Trapp, N. T., Gander, P. E., Howard, M. A., Keller, C. J., & Boes, A. D. (2024). Effects of transcranial magnetic stimulation on the human brain recorded with intracranial electrocorticography. *Molecular Psychiatry, 29*(5), 1228–1240.