Assessment of Mental Fatigue in Healthy Participants During Extended BCI-HMD Sessions

Nina Evetović [1*], Roman Rosipal [1,2], Arina Polyanskaya[1], Zuzana Rošťáková[1], Leonardo Jose Trejo[2]

[1] Institute of Measurement Science, Slovak Academy of Sciences, Slovakia

[2] Pacific Development and Technology, LLC, CA, USA

*nina.evetovic@savba.sk

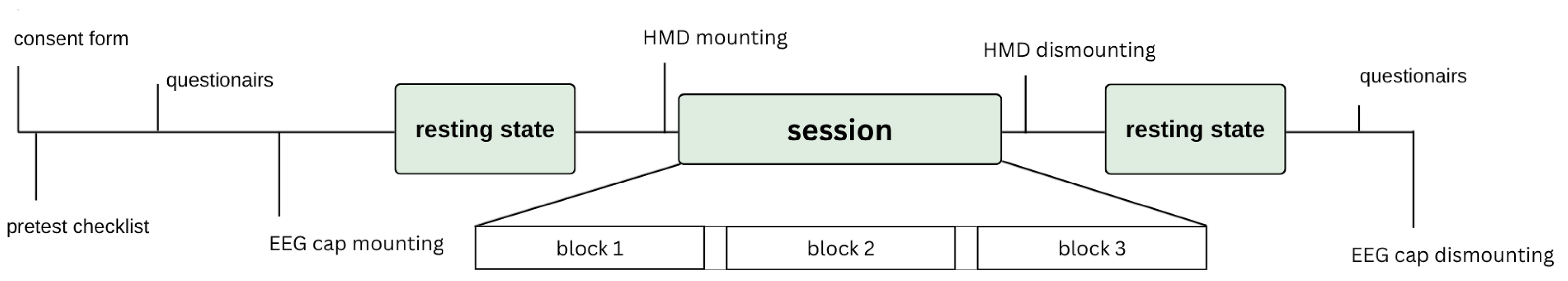
Introduction

Brain–computer interfaces (BCIs) with virtual reality (VR) via head-mounted displays (HMDs) show strong potential for post-stroke rehabilitation. However, prolonged BCI-HMD use can induce **mental fatigue**, reducing motor imagery (MI) performance and engagement.

This study investigates neural markers of fatigue during extended BCI-HMD VR sessions in healthy participants. Using **N-way Partial Least Squares (N-PLS)**, we extracted latent EEG patterns associated with fatigue induced by sustained MI.

Experimental Setup and Procedure

We implemented a three-session protocol to investigate mental fatigue during prolonged use of a BCI-HMD system. Each VR session comprised three blocks of motor imagery trials, with continuous EEG monitoring and pre/post resting-state recordings to capture fatigue dynamics.



Participants completed three experimental conditions:

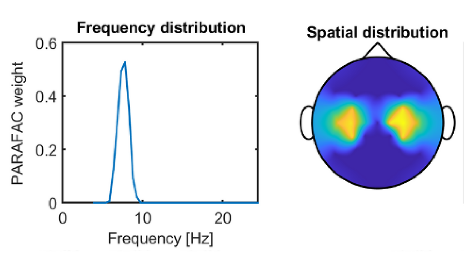
- Mirror Box session - to extract individual sensorimotor activity models
- Motor Imagery (MI) session - participants performed motor imagery in VR
- Control session -participants passively observed the VR environment

relax	pause 1	VR	pause 2
15s	5s	max 20s	2-7s

single trial structure

During the Mirror Box session we extracted the μ rhythm for VR motor imagery training for neuro-motor rehabilitation.

1. Train with mirror-box
2. Extract PARAFAC model
3. Train in VR



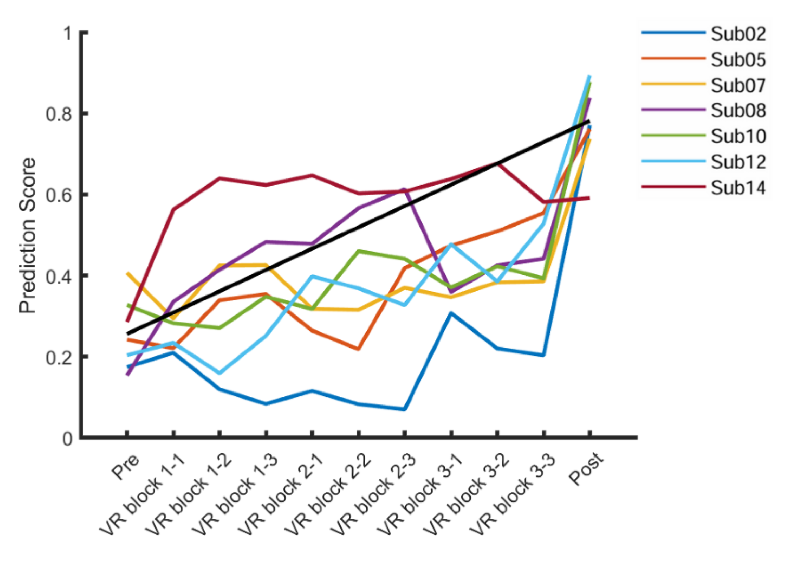
Results

Initial N-PLS analyses revealed that temporal tracking confirmed progressive accumulation of mental fatigue across sessions, even with real-world EEG containing artifacts.

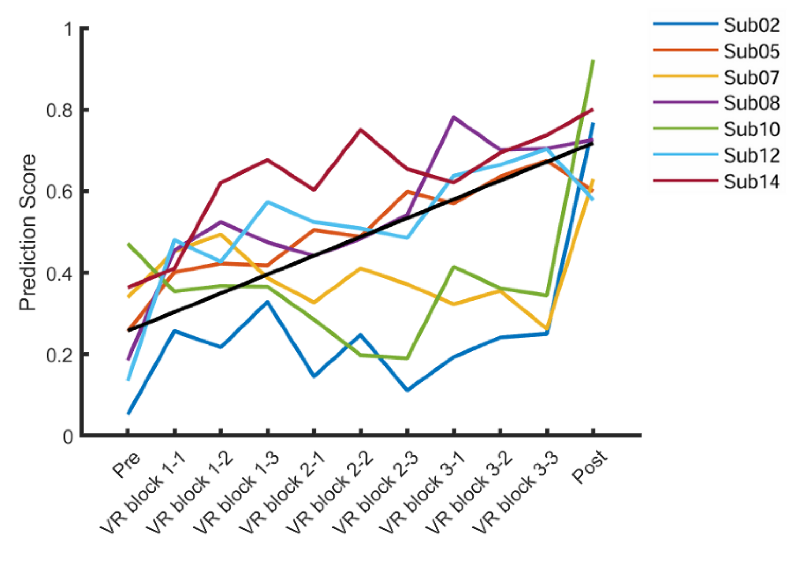
However, a key question remained:

⟶ How can we better **isolate fatigue-specific EEG signatures** from concurrent task-related, sensorimotor, activity?

We deflated the 10-channel μ components used to detect motor imagery from the original N-PLS model to isolate fatigue-related effects independent of training.



MI session

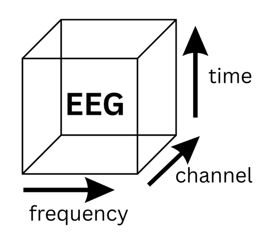


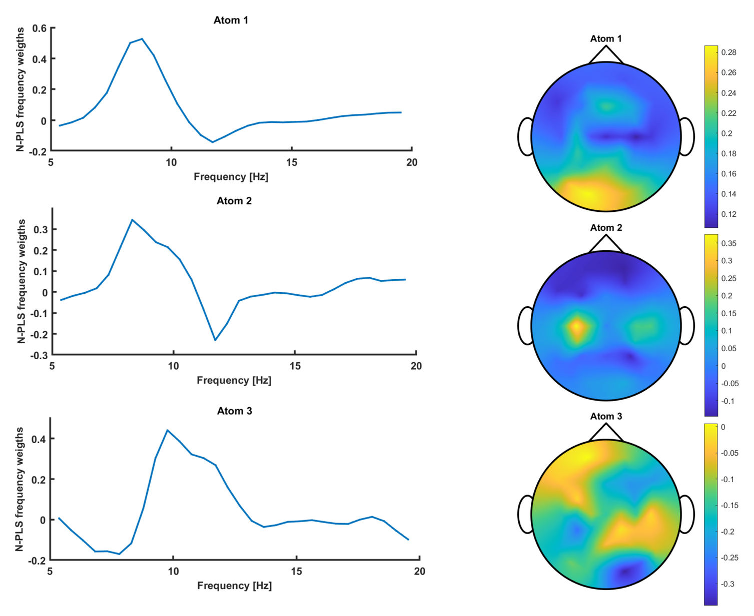
Control session

Even after deflating the μ rhythms, the progression of predictions from one class to the next remains clearly visible.

Case Example: Subject 05

- Applied N-PLS to extract latent components from the EEG tensor (trials × channels × frequencies)
- N-PLS components can be interpreted via spectral features in resting-state data





Iterations:

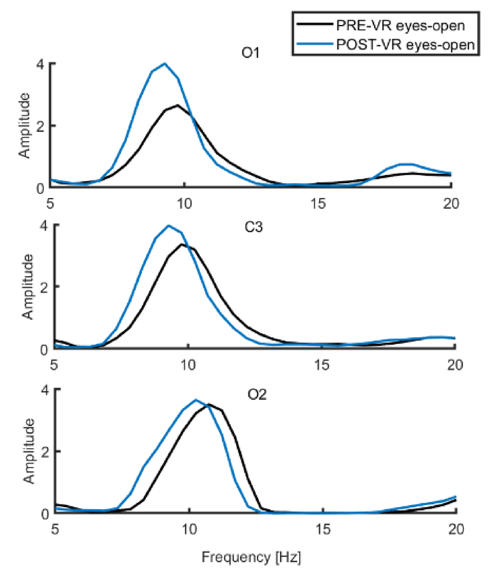
- Find weights/loadings to maximize covariance with $\mathbf{Y}$
  $\mathbf{t}$: scores, $\mathbf{w}^{(2,3)}$: loadings, $\mathbf{q}$: response loadings
- Compute rank-1 tensor: $\hat{\mathcal{X}}_f = \mathbf{t}_f \circ \mathbf{w}_f^{(2)} \circ \mathbf{w}_f^{(3)}$
- Deflate: $\mathcal{X} \leftarrow \mathcal{X} - \hat{\mathcal{X}}_f$, $\mathbf{Y} \leftarrow \mathbf{Y} - \mathbf{t}_f \mathbf{q}_f^{\top}$
- Repeat for all components $f = 1, \ldots, F$

Scores $\mathbf{t}_f$ used as predictors

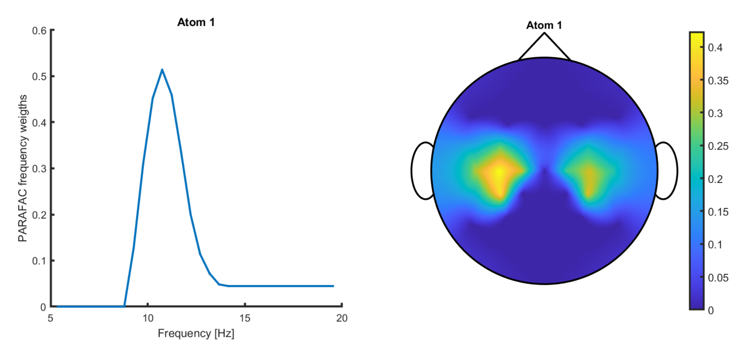
We deflated the trained μ-rhythm to ensure predictions reflect neural modulations beyond motor imagery changes:

$$\mathcal{X}_{\text{deflated}} = \mathcal{X} - \mathbf{t}_r \circ \mathbf{w}_r^{(2)} \circ \mathbf{w}_r^{(3)}$$

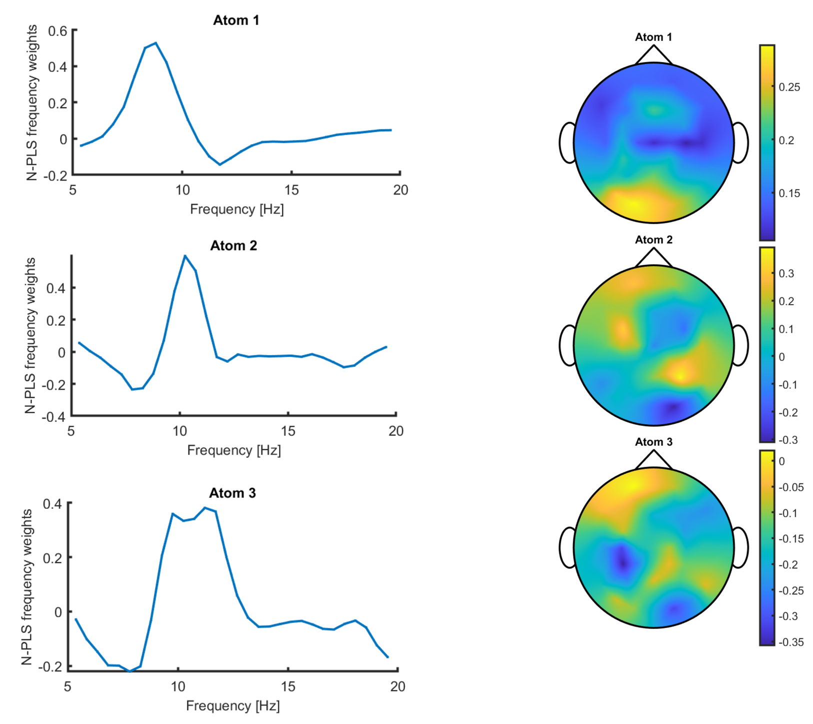
where $\mathbf{t}_r$ is the mode-1 score vector, $\mathbf{w}_r^{(2)}$ and $\mathbf{w}_r^{(3)}$ are the mode loadings, and $\circ$ denotes the outer product. The residual tensor $\mathcal{X}_{\text{deflated}}$ is then used for prediction.



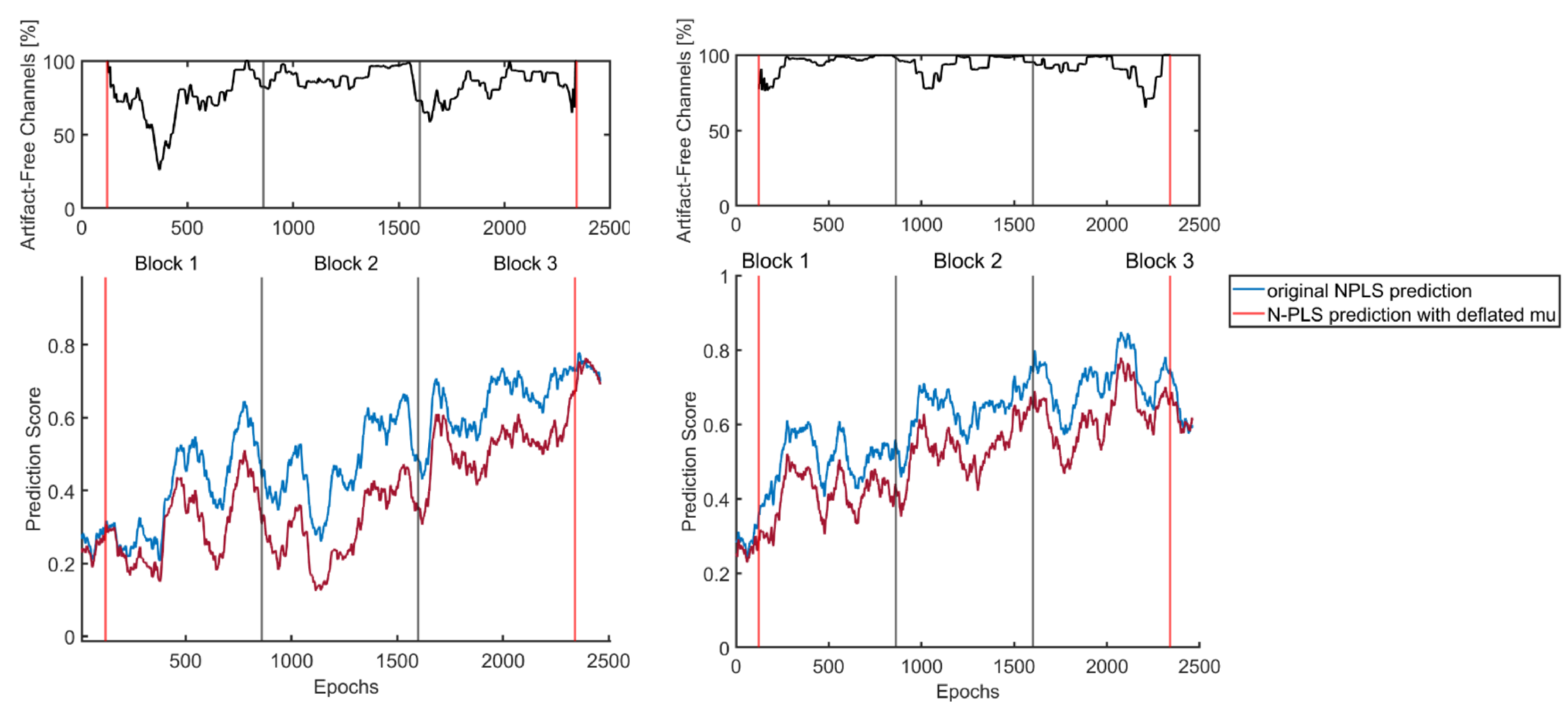
Harmonic Spectra



μ-rhythm pattern



The μ-component does not influence the fatigue slope; overall the model remains robust and resistant to training-induced effects.



N-PLS prediction for subject 05 - MI session (left) and control session (right)

Acknowledgement

This project has received funding from the European Union's research and innovation programme under the *Marie Skłodowska-Curie* grant agreement No 101118964 and the *NextGenerationEU* through the Recovery and Resilience Plan for Slovakia under project No. 09I03-03-V04-00205, No. 09I03-03-V04-00443 and APVV-21-0105, TInVR, programs.

Funded by the European Union