Frequency, space and time tensor decomposition of motor imagery EEG in BCI applied to post-stroke neurorehabilitation

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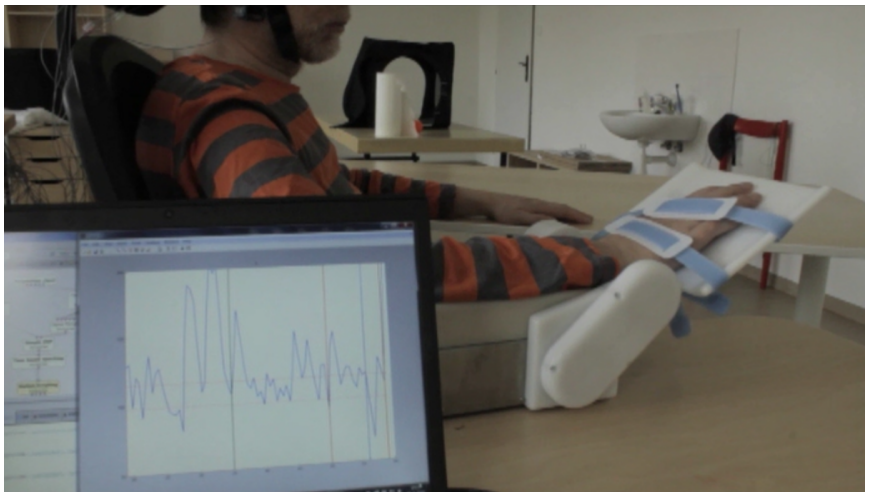
IWANN 2023, June 19, Ponta Delgada
Session A.1: Real World Applications of BCI Systems

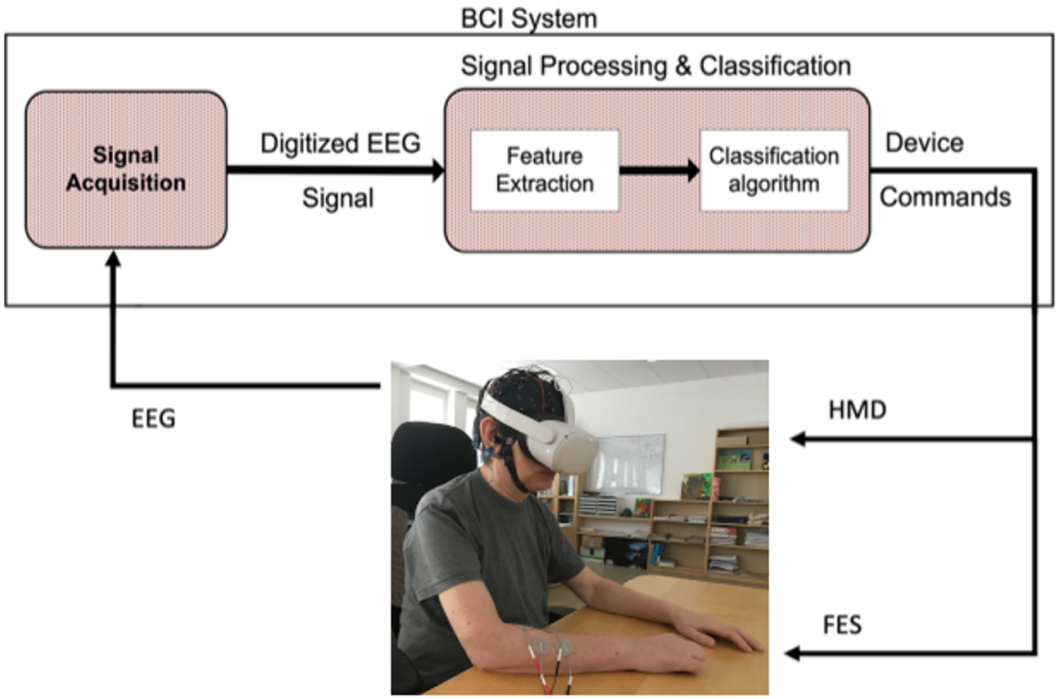
To develop a clinically efficient, mentally controlled system for motor recovery after stroke.

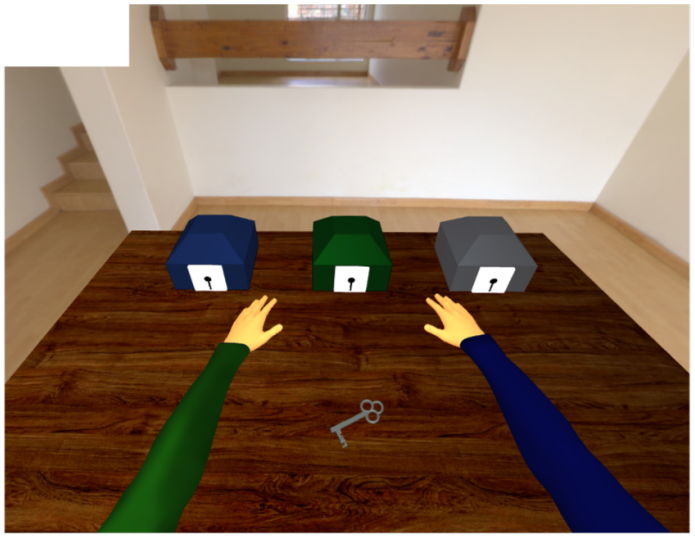
Phase 1 (2014 - 2018)



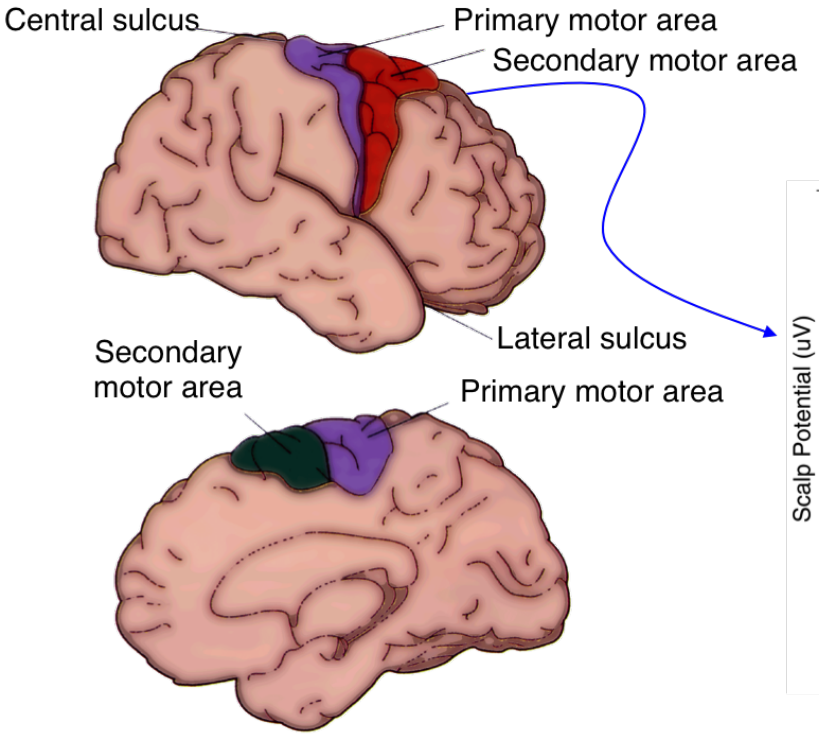
Phase 2 (2018 - 2023)

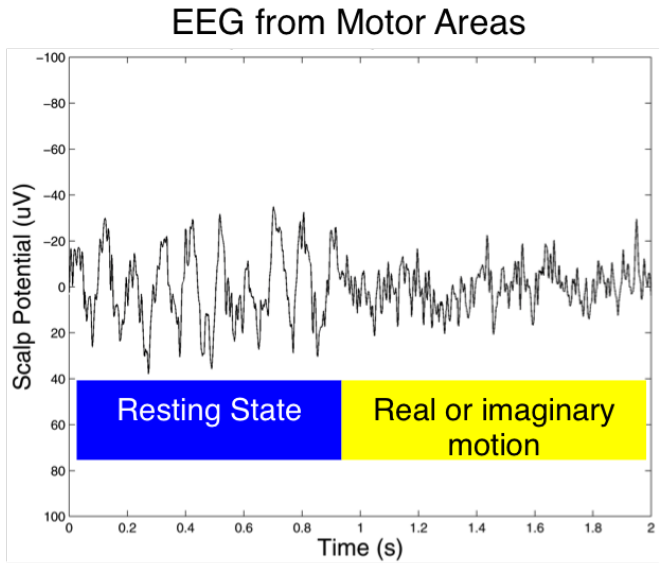
BCI with Head-Mounted Display (BCI-HMD)





Desynchronization of SMR





(Adapted from Beatty, 1995)

Narrowband Oscillatory EEG Sources
How to Get Them?

Brain Oscillations vs. Scale-free Brain Activity

Trends Cogn Sci. 2014 September ; 18(9): 480–487. doi:10.1016/j.tics.2014.04.003.

Scale-free brain activity: past, present and future

Biyu J. He

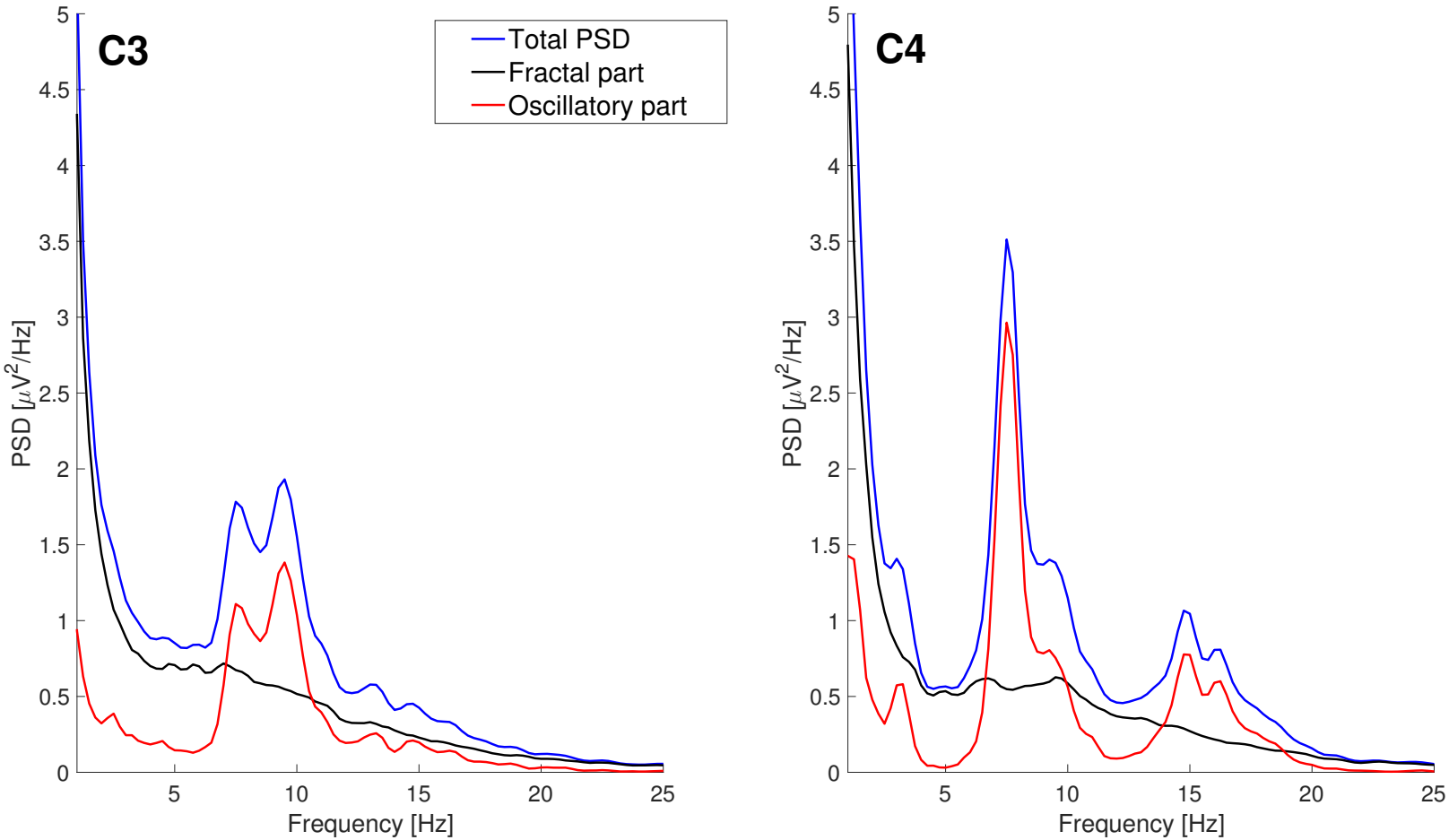
Neuron. 2010 May 13; 66(3): 353–369. doi:10.1016/j.neuron.2010.04.020.

The temporal structures and functional significance of scale-free brain activity

Biyu J. He[1,*], **John M. Zempel**[2], **Abraham Z. Snyder**[1,2], and **Marcus E. Raichle**[1,2,3,4]

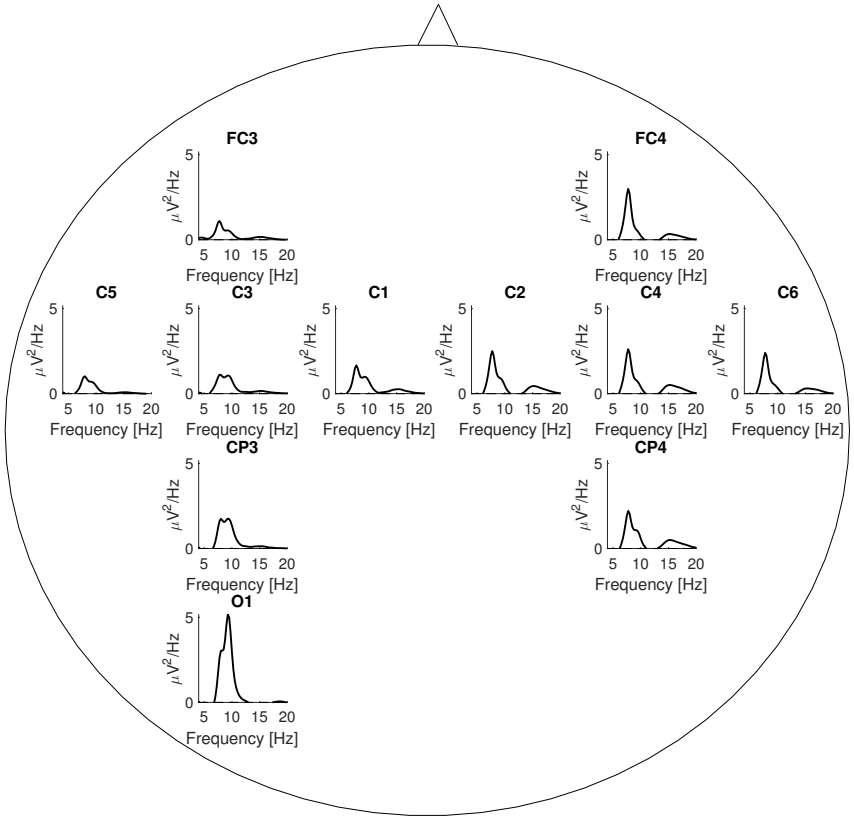
- *"..... there are two types of brain activity that coexist: the broadband, arrhythmic activity and the narrow-band, rhythmic oscillations".* [He, 2014]
- EEG recorded from the scalp originates from electrical currents generated by a mixture of a large number of quasi-random neural sources across the entire cortex (broadband background EEG) and a small number of more localized cortical sources whose power spectra are narrow-band (oscillatory).
[Nunez, 2006; He, 2014]

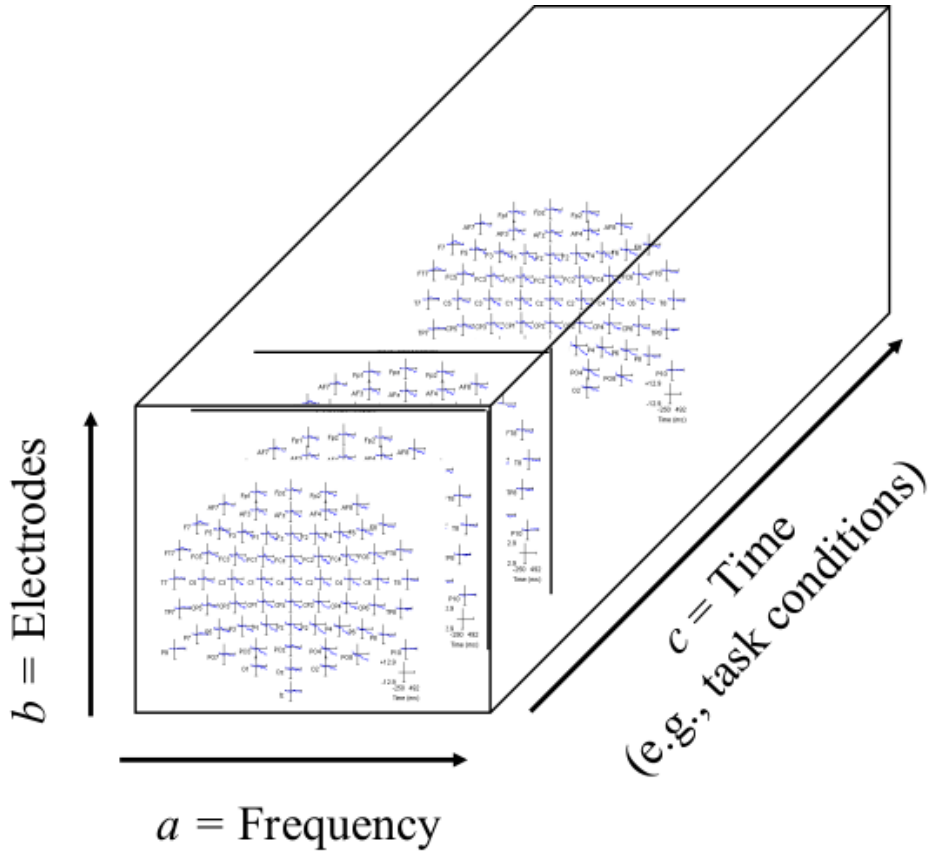
Irregular-Resampling Auto-Spectral Analysis (IRASA) [Wen & Liu, 2016]



Decomposition of the power spectrum density (PSD) into the fractal (scale-free) and oscillatory components underlying the eyes-closed awake state recorded after mirror- box training. Plots represent means of the IRASA decomposition computed separately for 4-s-long overlapping segments of approximately two minutes long resting block at two central EEG electrodes C3 and C4. Frequencies were restricted to the range 1-25 Hz for the visualization purposes..

EEG Latent Structure in Time-Space-Frequency - tensor representation





Goal: for **tensor** $\mathbb{X} \in \mathbb{R}^{I \times J \times K}$ find its decomposition, i.e. matrices

$$A = [a_1, \ldots, a_F] \in \mathbb{R}^{I \times F}, \quad \|a_f\| = 1,$$
$$B = [b_1, \ldots, b_F] \in \mathbb{R}^{J \times F}, \quad \|b_f\| = 1,$$
$$C = [c_1, \ldots, c_F] \in \mathbb{R}^{K \times F}, \quad \|c_f\| = 1$$

such that

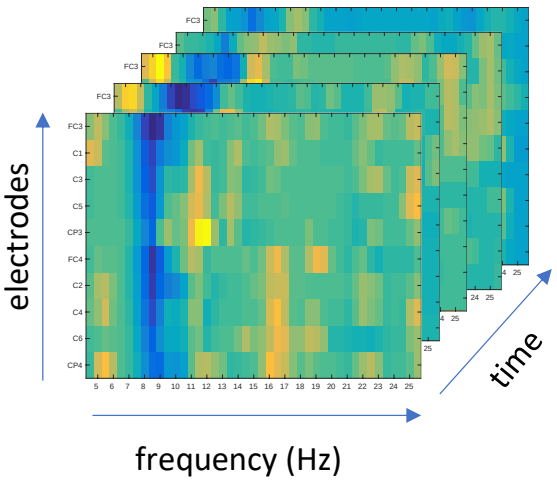
$$\mathbb{X} = \sum_{f=1}^{F} a_f \circ b_f \circ c_f + \mathbb{E} \qquad \textit{where} \circ \textit{is outer product}$$

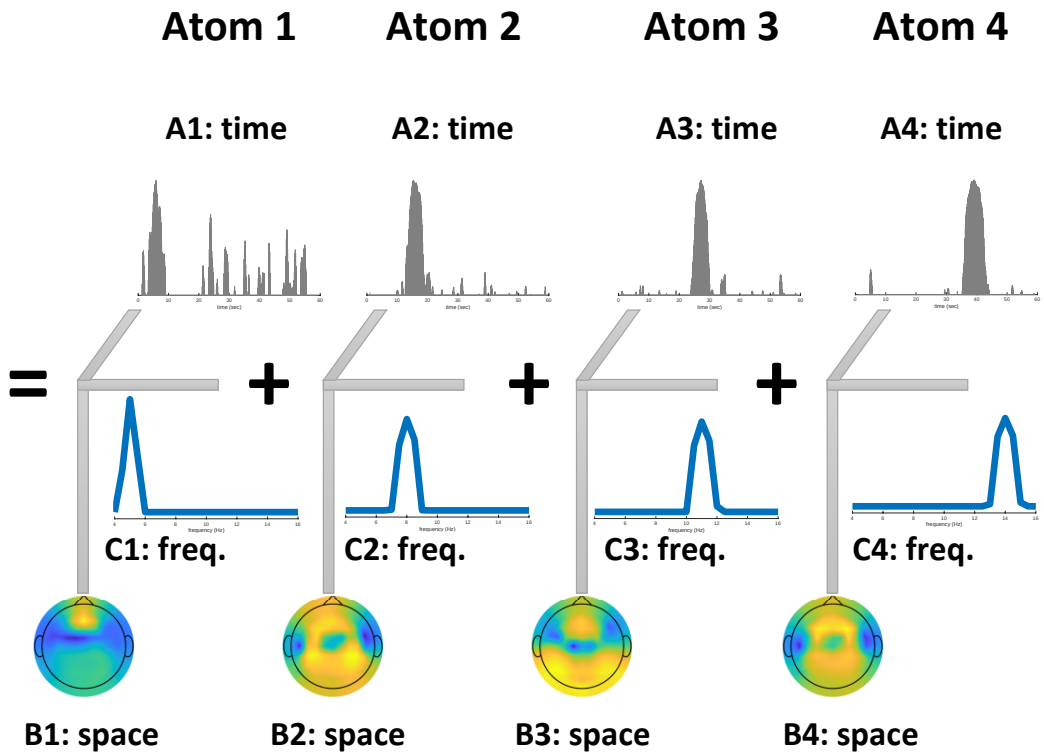
$$x_{ijk} = \sum_{f=1}^{F} a_{if} b_{jf} c_{kf} + e_{ijk}$$

The criterion:

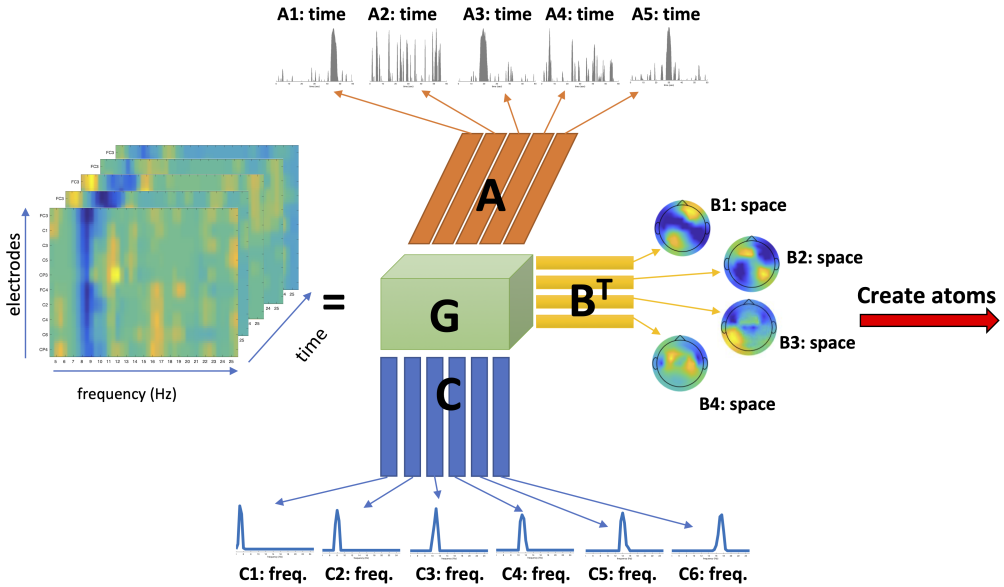
$$\min_{a_{if}, b_{jf}, c_{kf}} = \|x_{ijk} - \sum_{f=1}^{F} a_{if} b_{jf} c_{kf}\|^2$$

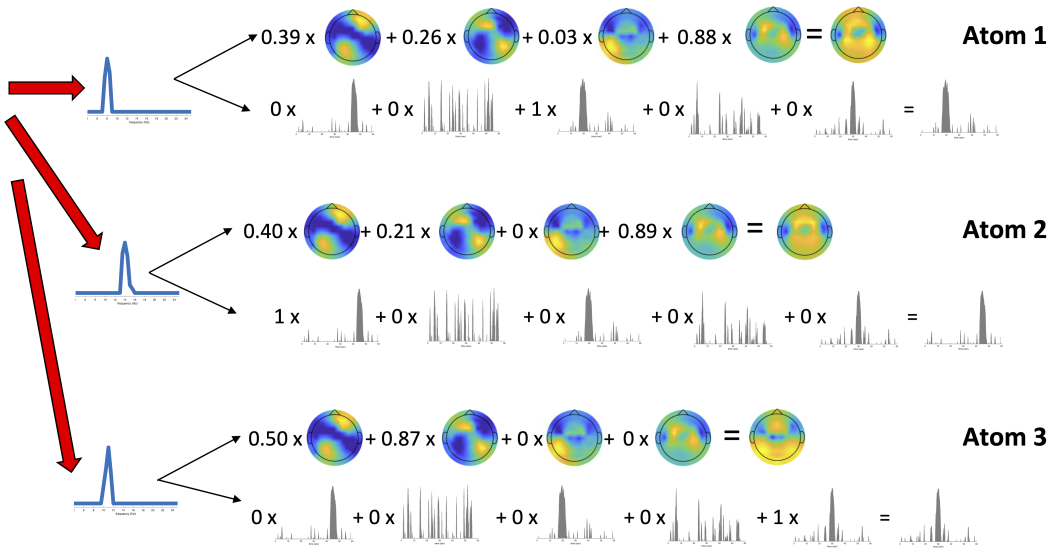
Parallel Factor Analysis (PARAFAC) – scheme



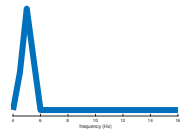


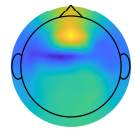
Tucker model - scheme

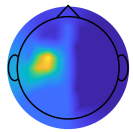




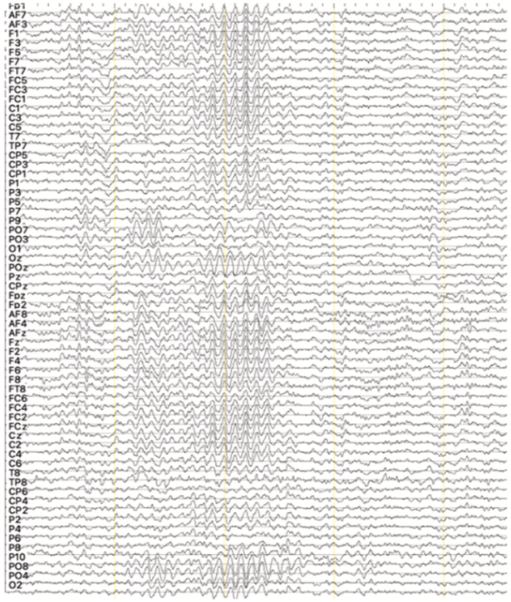
1. ortogonality
   - → simplification of calculations
   - → **BUT** in EEG has no neurophysiological interpretation
2. **non-negativity**
   - → tensor $\mathbb{X}$ is formed by the non-negative spectrum
   - → time, space and frequency scores; tensor $\mathbb{G}$
3. **unimodality**
   - → freq. score → the factor characterizes one frequency
   - → spatial score → radial EEG sources
4. **bimodality**
   - → spatial score → tangential EEG sources

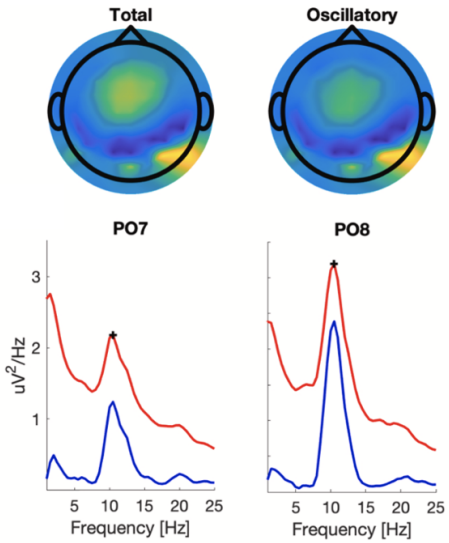


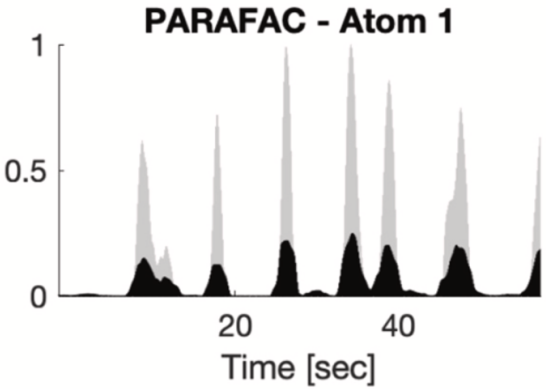


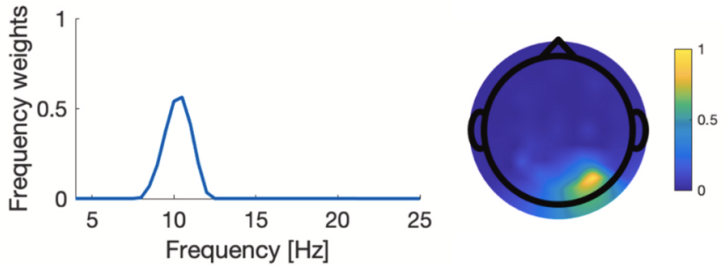


Time Scores - posterior α example









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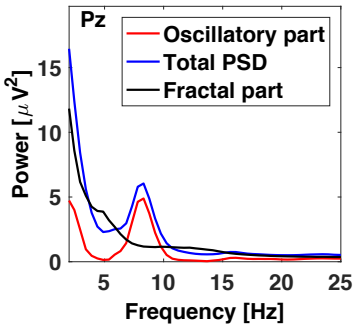
Tensor decomposition of human narrowband oscillatory brain activity in frequency, space and time

Roman Rosipal [a,b,*], Zuzana Rošťáková [a], Leonardo Jose Trejo [b]

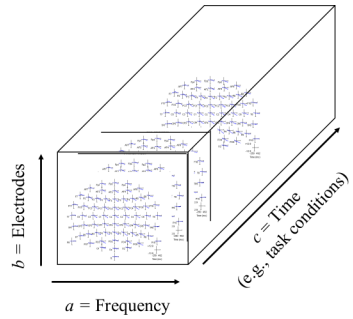
Procedural Steps - scheme

Experiment (EEG)
EEG recording & preprocessing

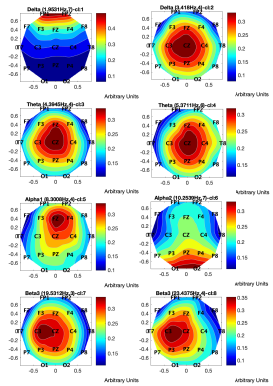
IRASA Spectrum Decomposition



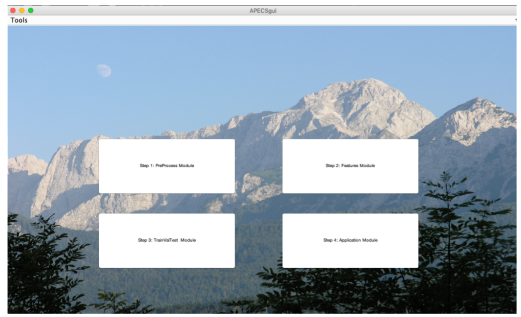
Multi-way Data Structure



PARAFAC



Clustering (e.g. DBSCAN)



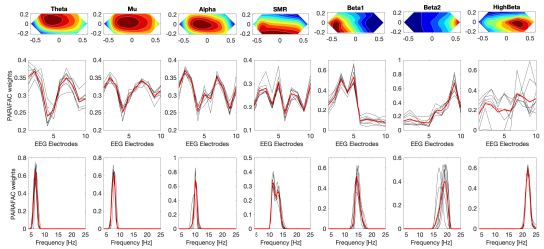
Extracted Atoms

Train Patients
Control Time-Scores

Mirror-Box & BCI-VR Neurorehabilitation Training

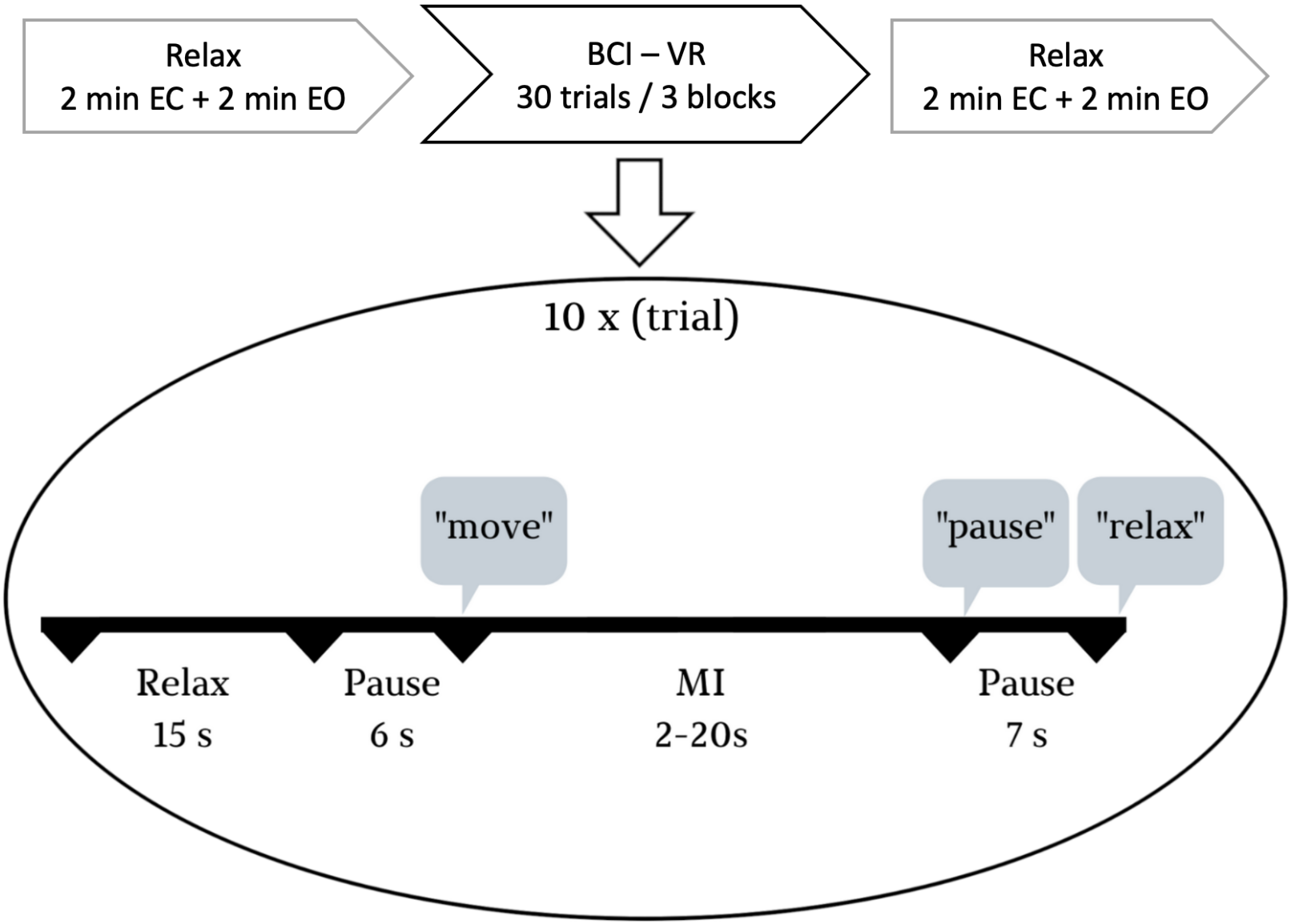
Step1:
Train with Mirror-Box

Step 2:
Extract PARAFAC Atoms

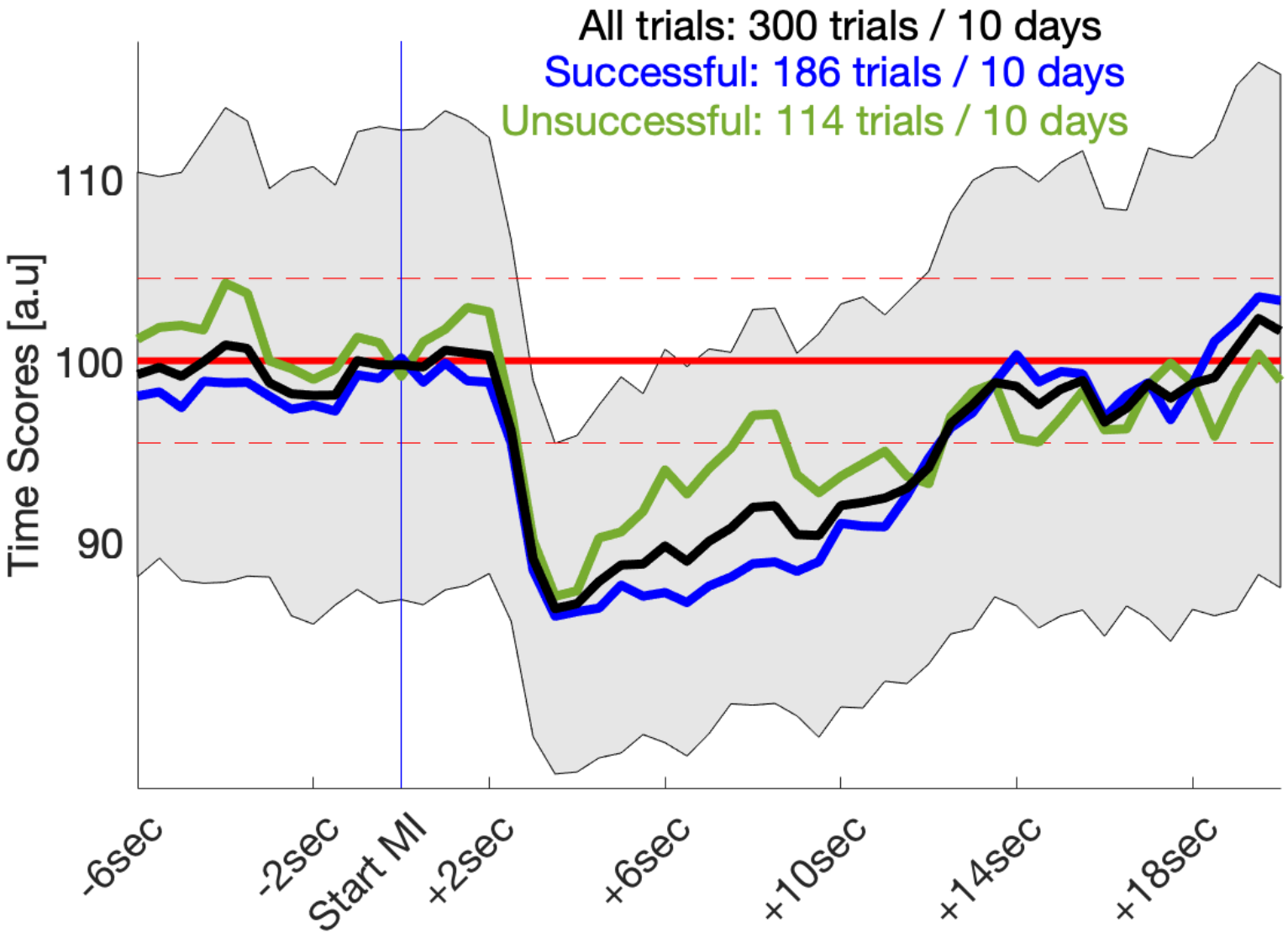


Step 3:
Train in VR

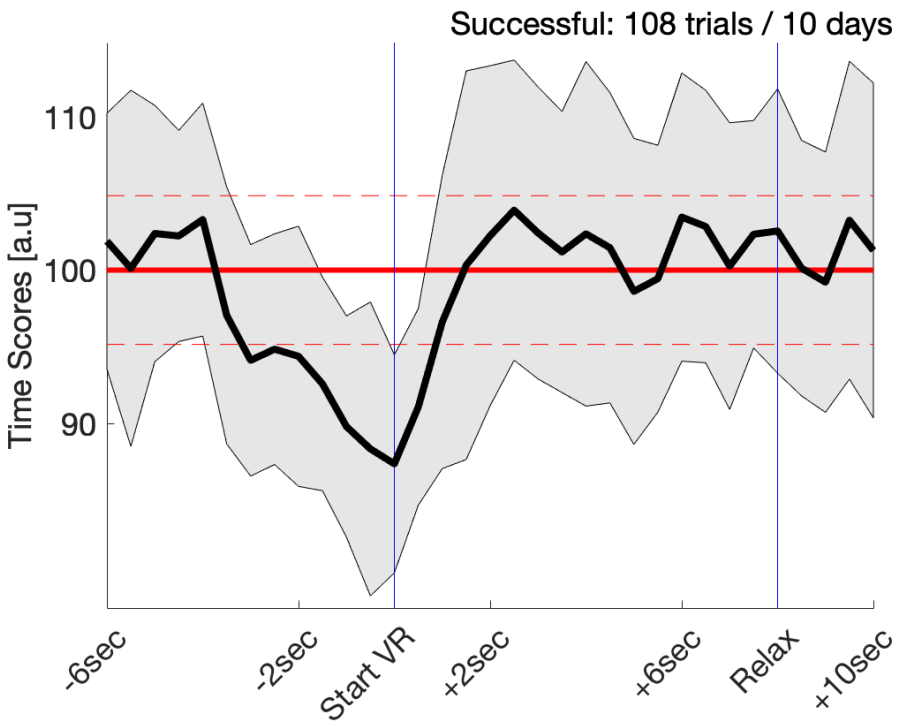
BCI-VR Time Protocol



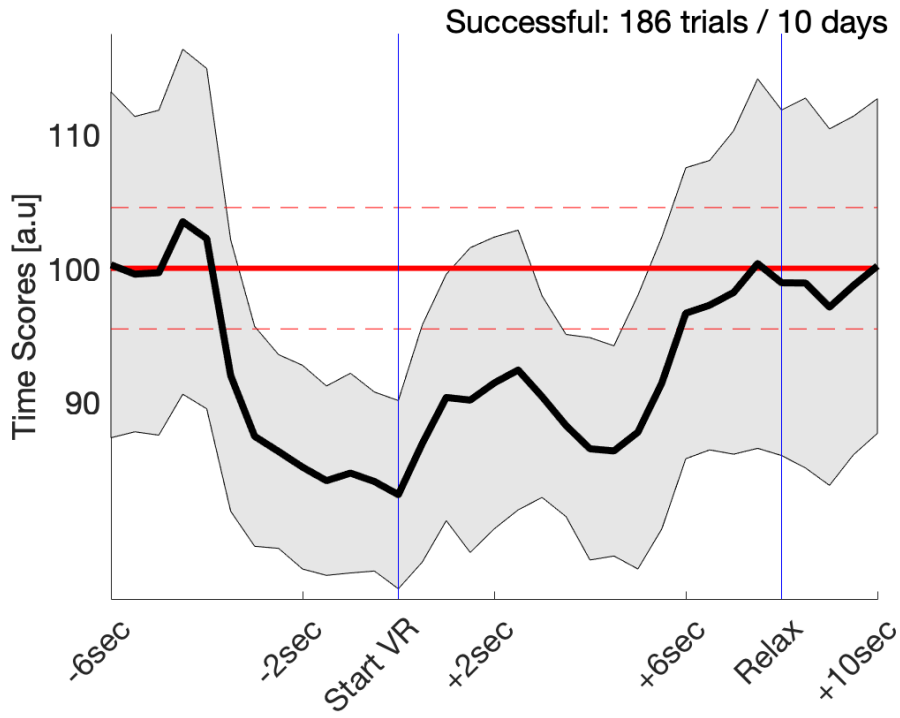
sub 207, 84 yrs. old male, left-hand hemiplegia



Sub 201, 66 yrs. old male
right-hand hemiplegia

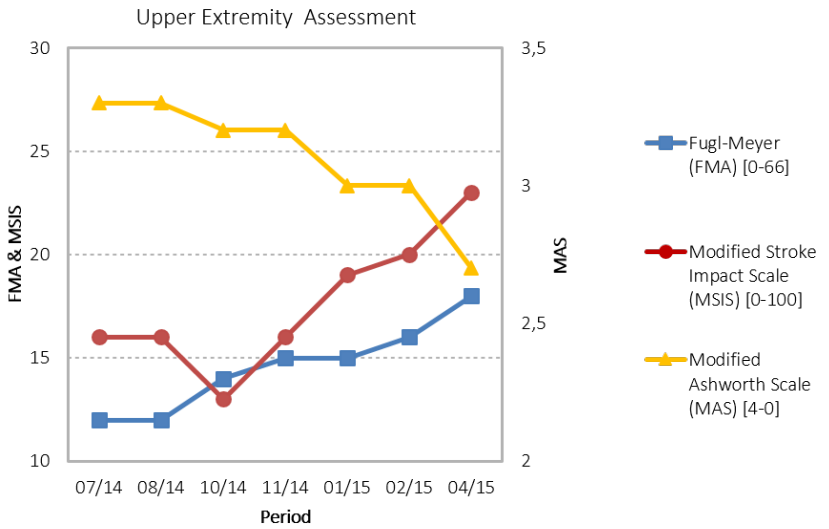


Sub 207, 84 yrs. old male
left-hand hemiplegia

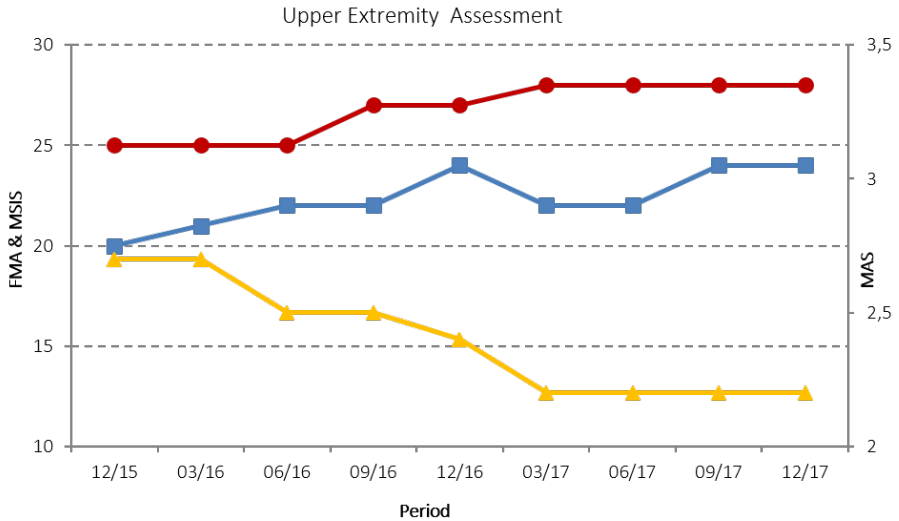


Sub 201, 66 yrs. old male, right-hand hemiplegia

Mirror Therapy



Robotic Splint



After 10 sessions of BCI-VR, there was a small motor skills improvement (the box and block test), but no other significant clinical changes were observed.

Sub 207, 84 yrs. old male, left-hand hemiplegia

The Nine-Hole Peg Test

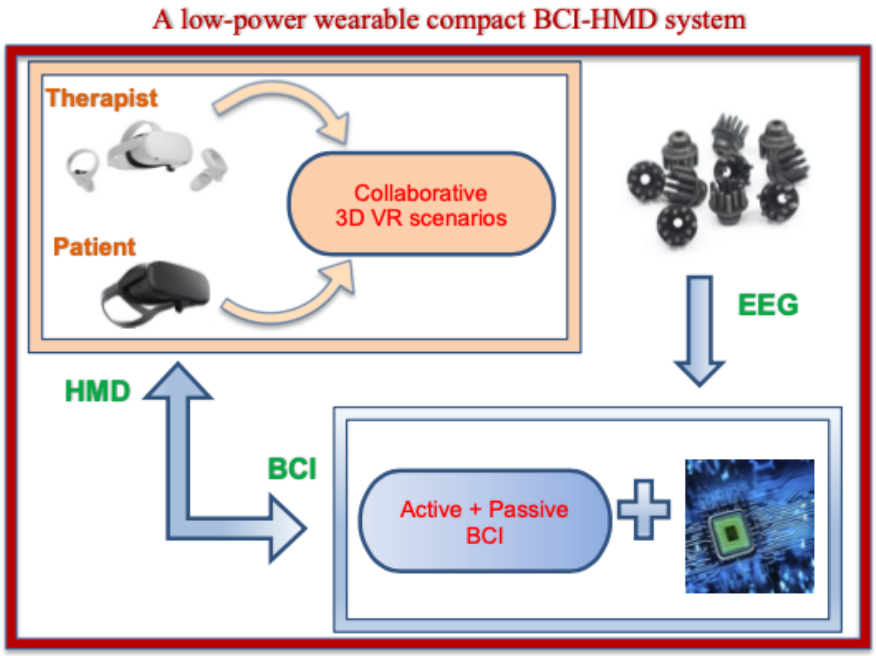
Date	Left	Right
Prior Mirror Box (18.01.2023)	78 sec	33 sec
Prior BCI-VR (15.03.2023)	66 sec	29 sec
After 11. sessions of BCI-VR (15.06.2023)	45 sec	30 sec

The Box and Block Test

Date	Left	Right
Prior Mirror Box (18.01.2023)	18 per min	32 per min
Prior BCI-VR (15.03.2023)	25 per min	37 per min
After 11. sessions of BCI-VR (15.06.2023)	26 per min	38 per min

There was an improvement of motor skills in the wrist and fingers, it was also confirmed by goniometric examination.

Collaborative BCI-VR



Thank you!