Brain Computer Interface (BCI) Neurorehabilitation Training in Virtual Reality (VR):

Neurorehabilitation Training Design

To mediate the motor rehabilitation of patients after stroke, we developed a proprietary virtual human hand simulator using VR technologies. We used the web-based visualization framework A-Frame (https://aframe.io). Three VR scenarios - a cube, a cup, and a lock with a key were created (**Figure 1**). Oculus Quest 2 head-mounted display (HMD) was used to display 3-D VR scenarios.

Figure 1: An example of the virtual environment (a cup) with an object grip animation created using the A-Frame web framework.

The experiment consists of a series of trials in which the subject is instructed to imagine a movement of his avatar hand in VR mentally. In the first step, a subject sees his avatar hand on the table spatially placed in the position to mimic and perceive the subject's own hand maximally. During this stage, the subject is instructed to relax and not perform motor imagery, cognitive or other mental tasks. After a predefined time, a virtual item (a cube, a cup, and a lock with a key) is displayed on the table, and the subject is audio-instructed to "move". Items are displayed in a random order. During this motor imagery period, EEG is evaluated. If the level of EEG changes reaches a predefined threshold detecting the subject's mental motor imagery process (a successful trial), a trigger sent to the VR environment starts the pre-programmed movement of the avatar hand. At the end of the VR visualization, "well-done" audio notice is played. A new trial follows with an audio command "relax". If the mental motor imagery process is not detected during a predefined time, an audio command "pause" is played, followed by an audio "relax", starting a new trial (**Figure 2**).

In successful trials, **functional electrical stimulation** (**FES**) on the paretic arm extensor muscle group was applied during the pre-programmed VR movement **(Figure 3**).

Each training session/day consists of 30 trials distributed equally into three blocks. At the beginning and end of each BCI-VR training session, a 2-minute eyes-closed (EC) and eyes-open (EO) relaxed state EEG is recorded (**Figure 2**).

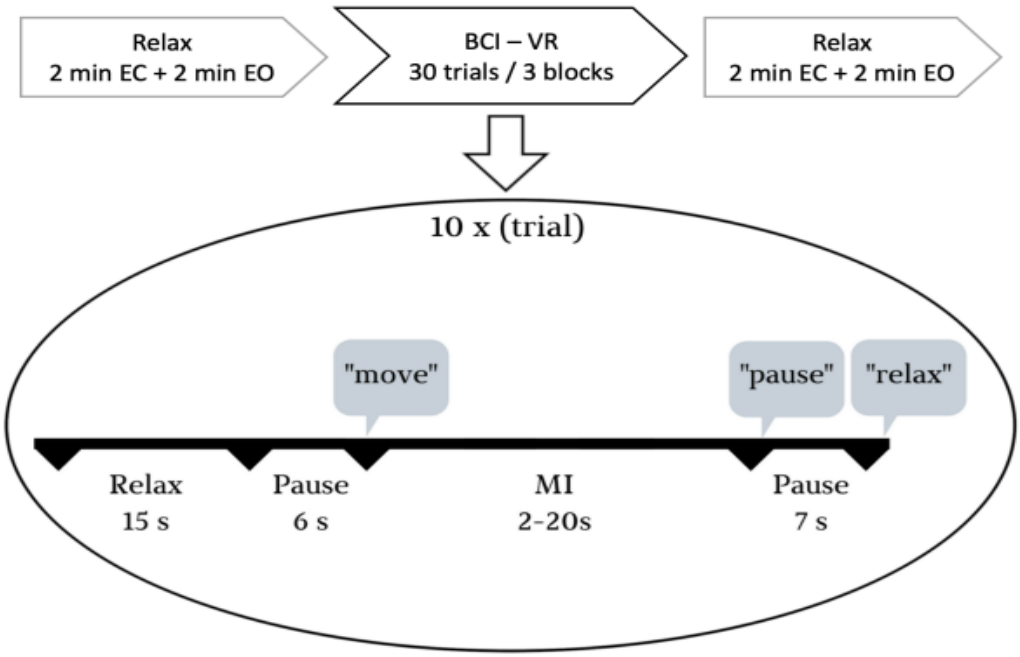

Figure 2: A scheme of a BCI-VR training session/day. At the beginning and end of each training session, a 2-minute eyes-closed (EC) and eyes-open (EO) resting state EEG is recorded. MI – motor imagery.

Figure 3: A picture of a subject with Oculus Quest 2 head-mounted display, g.tec g.Nautilus Pro wearable EEG headset, and functional electrical stimulation (FES) electrodes applied to the subject's forearm group of muscles.

Cybersickness and Mental State Questionnaire: A questionnaire focused on cybersickness, and mental state was applied during the experiment. The questionnaire was completed before the first BCI-VR block and after each BCI-VR block of trials. This was applied during BCI-VR training of subject 207.

Subjects:

Subject 201:
A 66-year-old man with residual right-sided hemiparesis after a stroke. The patient participated in the BCI-VR training in 16 training days spanning time from October 13, 2022, until December 16, 2022.

Subject 207:
An 84-year-old man with residual left-sided hemiparesis after a stroke. The patient participated in the BCI-VR training in 13 training days spanning time from May 11, 2023, until June 22, 2023.

EEG:

During all resting and BCI-VR training blocks, a trained technician recorded EEG continuously using active Ag/AgCl electrodes embedded in an elastic fabric cap. g.Tec Nautilus PRO wearable wireless EEG headset was used. The technician placed the electrode cap on the participant's head according to the manufacturer's instructions, attaching six active EEG left-side scalp electrodes (FC3, C1, C3, C5, CP3, and O1), six active right-side electrodes (FC4, C2, C4, C6, CP4, and A2). A **linked-ears reference** and one ground electrode AFz were used. A **sampling frequency of 250 Hz** was used.

MATLAB and EDF file names description:

- BCI-VR data:
    - A filename has a structure: *subject number_day_VR training block*
    - Three training blocks VR1, VR3, and VR3 are available.
    - For example, the file name *207_day4_VR02.edf* represents EEG data in the EDF format of subject 207, recorded on the 4th day of training, during the second block of 10 trials.
- Rest-ECEO files
    - A filename has a structure: *subject number_day_condition*
    - Four training conditions ECS (eyes-closed start), EOS (eyes-open start), ECE (eyes-closed end), and EOE (eyes-open end) are available. Start means recording before the BCI-VR training, and end means after the BCI-VR training

MATLAB EEG files structure description:

A MATLAB structure *data* is used to store EEG data, channel labels and sampling frequency information.

```
>> data

data =

  struct with fields:

       series: [30208×11 double]
    sampleFreq: 250
    chanLabels: {'FC3'  'C1'  'C3'  'C5'  'CP3'  'O1'  'FC4'  'C2'  'C4'  'C6'  'CP4'}
```

EEG data are stored in a matrix form *data.series*, and the order of the columns aligns with electrode labels stored in the *data.chanLabels*.

MATLAB files of the BCI-VR training periods have additional experimental information stored in the *dataOrgVR* variable consisting of four cell arrays organized in columns. The first column represents experimental time in 2-sec epochs with a sliding window of 0.5 seconds. The second column represents time scores of the PARAFAC model used to determine motor imagery efforts and are computed for each 2-second-long epoch. The third column indicates the time position of the "relax", "1st_pause", "move", and "2nd_pause" audio events. Note, "2nd_pause" ends a successful or unsuccessful trial and an audio notice "well-done" (successful trial) or "pause" (unsuccessful trial) is played. No audio notice is played at "1st_pause". In the case of a successful trial, VR visualization starts at the time denoted as "robot[….".

MATLAB BCI-VR training files also contain the structure *paramVR*, where internal parameters of the experimental setting and PARAFAC model are stored.