Mirror-therapy as a way to start BCI robot-assisted rehabilitation: a single case longitudinal study of a patient with hemiparesis

Roman Rosipal[1,3], Natália Porubcová[1], Barbora Cimrová[2,3], Igor Farkaš[2]

(1) Institute of Measurement Science, Slovak Academy of Sciences, Bratislava (2) Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava, Slovakia
(3) Pacific Development and Technology, LLC, CA, USA

http://www.um.sav.sk/projects/BCI-RAS/

The Seventh International BCI Meeting, May 21 – 25, 2018, Pacific Grove, CA, USA

Summary

To improve upper-limb neuro-rehabilitation in chronic stroke patients we apply new methods and tools of clinical training and machine learning for the design and development of an intelligent system allowing the users to go through the process of self-controlled training of impaired motor pathways. We combine the brain–computer interface (BCI) technology with a robotic arm system into a compact system that can be used as a robot-assisted neuro-rehabilitation tool: **(1)** We use mirror therapy (MT) not only to improve motor functions but also to identify subject's "atoms," i.e. spectral-spatial EEG patterns associated with imagined or real-hand movements, using parallel factor analysis. **(2)** We designed and tested a BCI-based robotic system using motor imagery in a patient with an impaired right upper limb. The novelty of this approach lies in the control protocol which uses spatial and spectral weights of the estimated sensorimotor atoms during the MT sessions.

Study Design

Mirror therapy (9-months), is an innovative treatment approach where an individual rehearses a specific limb movement by reflecting the movements of the non-paretic side in the mirror as if it were the affected side [1]. A link between motor imagery and passive action observation was found and associated with the concept of mirror neurons [2].

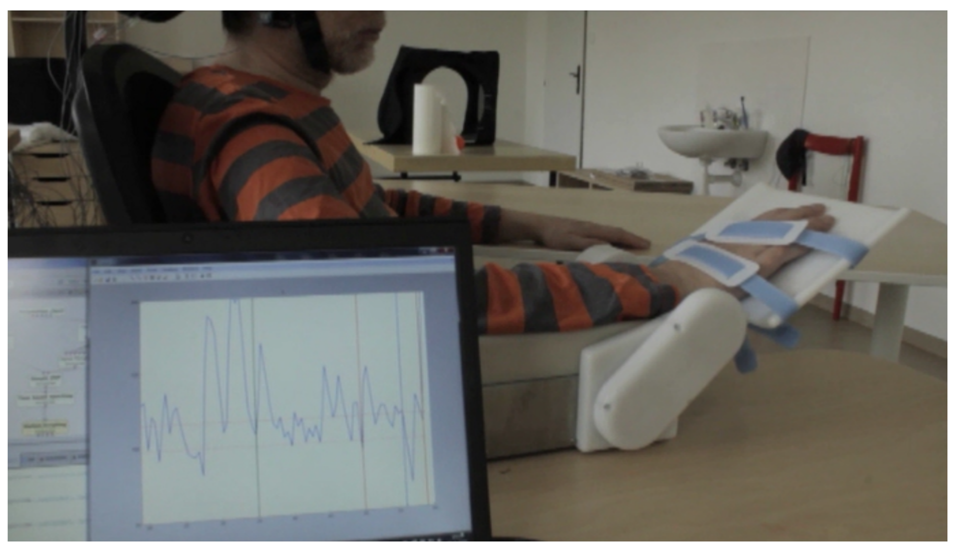
PARAFAC - EEG "Atoms", logarithmically transformed power spectra densities (PSD) of EEG segments are analyzed by three-way parallel factor analysis (PARAFAC) [3, 4]. Define a 3-dim. data matrix $\mathbf{X}$ $(I \times J \times K)$ of PSD estimates at I time segments, J electrodes and K frequencies. Then, three loading matrices, $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ with elements $a_i^{(f)}$ (time scores), $b_j^{(f)}$ (spectral wights) and $c_k^{(f)}$ (spatial weights) define the PARAFAC model which decomposes $\mathbf{X}$ as

$$x_{ijk} = \sum_{f=1}^{F} a_i^{(f)} b_j^{(f)} c_k^{(f)} + \epsilon_{ijk}$$

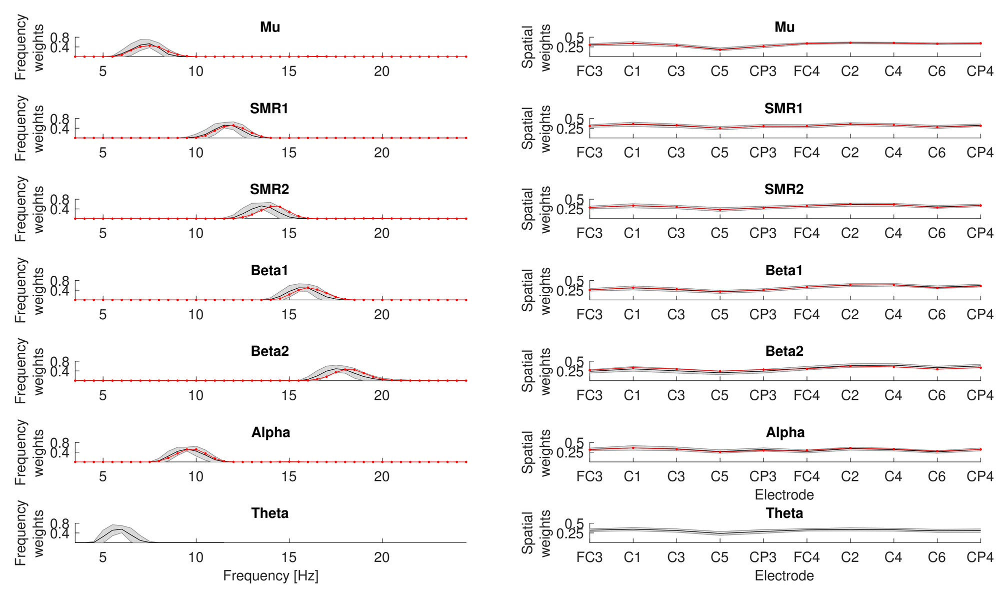
where x_{ijk} are elements of $\mathbf{X}$, ϵ_{ijk} are the residual errors and F stands for a number of components (atoms). The loading elements are found by minimizing the sum of squares of ϵ_{ijk}

$$\min_{a_i^{(f)} b_j^{(f)} c_k^{(f)}} \|x_{ijk} - \sum_{f=1}^{F} a_i^{(f)} b_j^{(f)} c_k^{(f)}\|$$

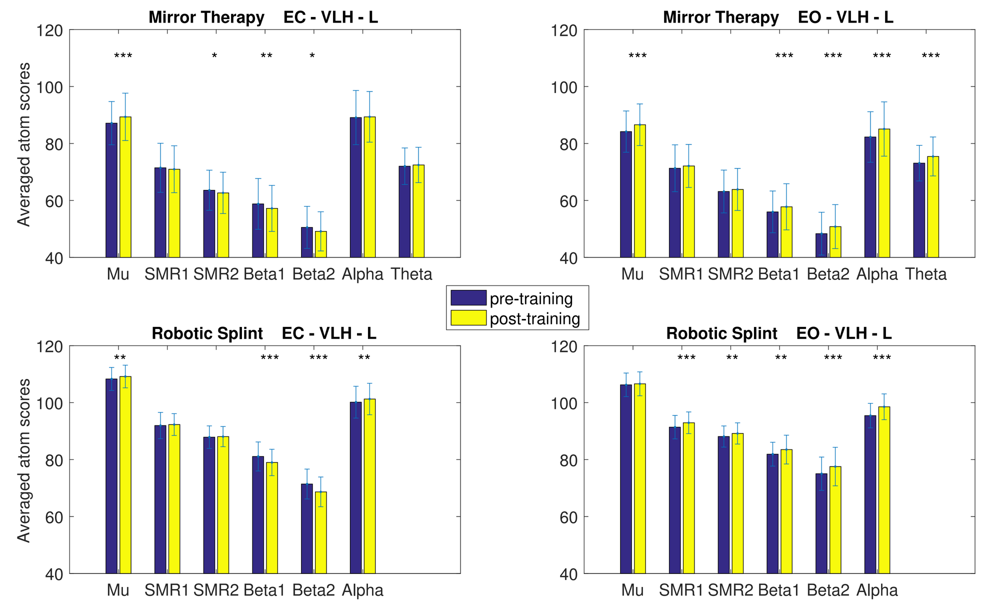
BCI-Controlled Robotic Splint (18 months), following the recommendations of a clinical expert, we designed and constructed a robotic splint (with one degree of freedom). The splint is controlled using the time scores of the selected atoms extracted from EEG recorded during the MT sessions. Flexible score thresholds can be set.



Oscillatory Rhythms

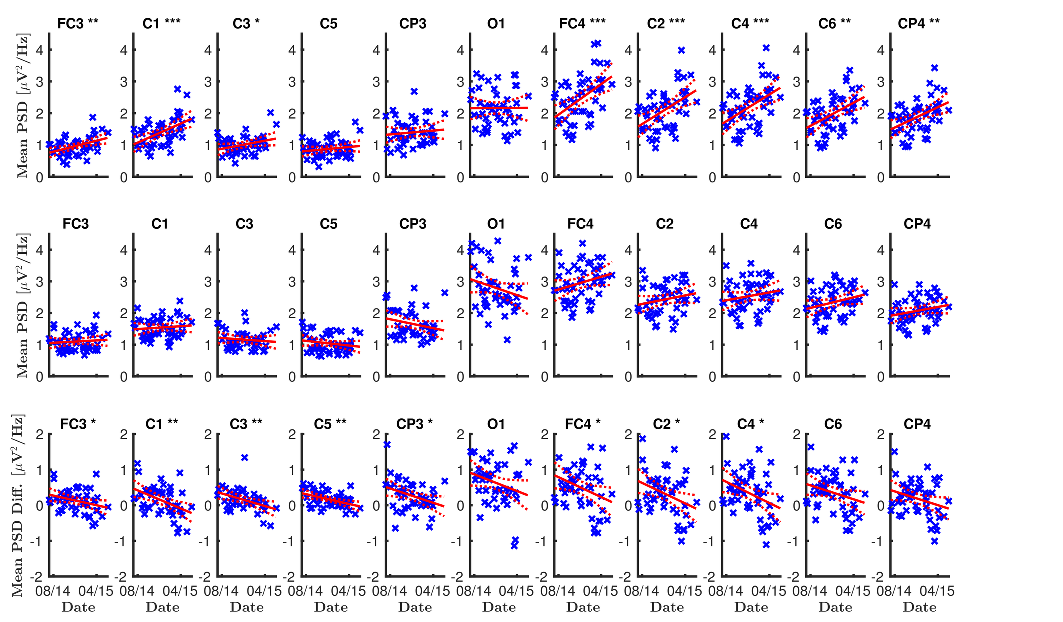


Mean values of the PARAFAC spectral (left column) and spatial (right column) weight vectors obtained during the Mirror Therapy (MT, black) and training with the Robotic Splint (red). Each row represents the means for one of the seven extracted oscillatory rhythms (atoms). Shaded area represents the standard deviation of MT averages.

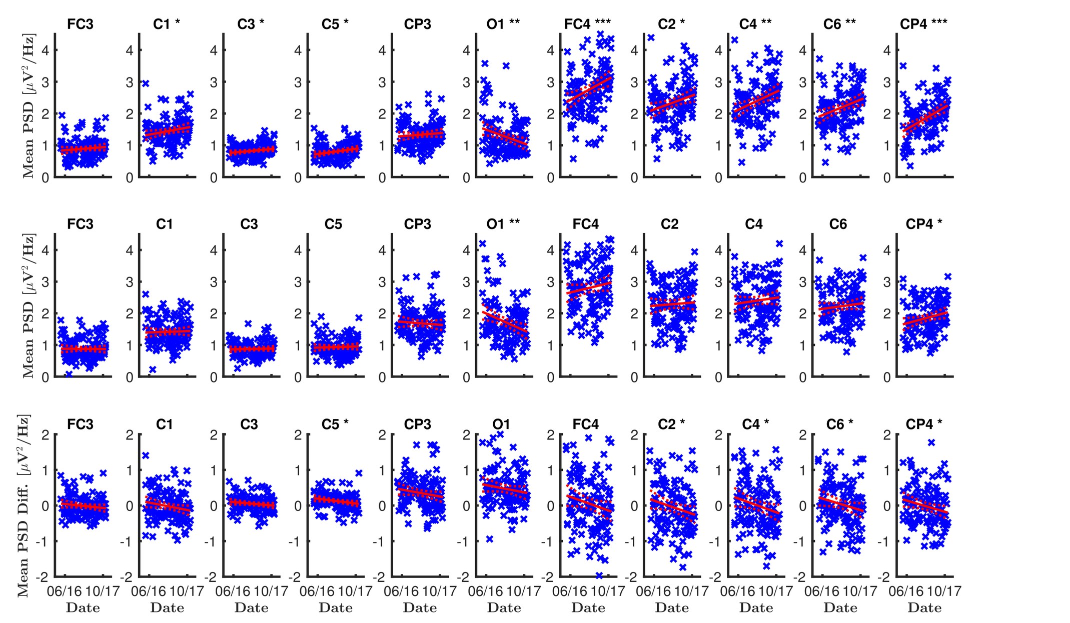


*Mean values of the PARAFAC atom scores computed during the resting period with eyes closed. The blue bars represent pre-training session, yellow bars post-training. Significant differences between the two sessions are highlighted (***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$)*

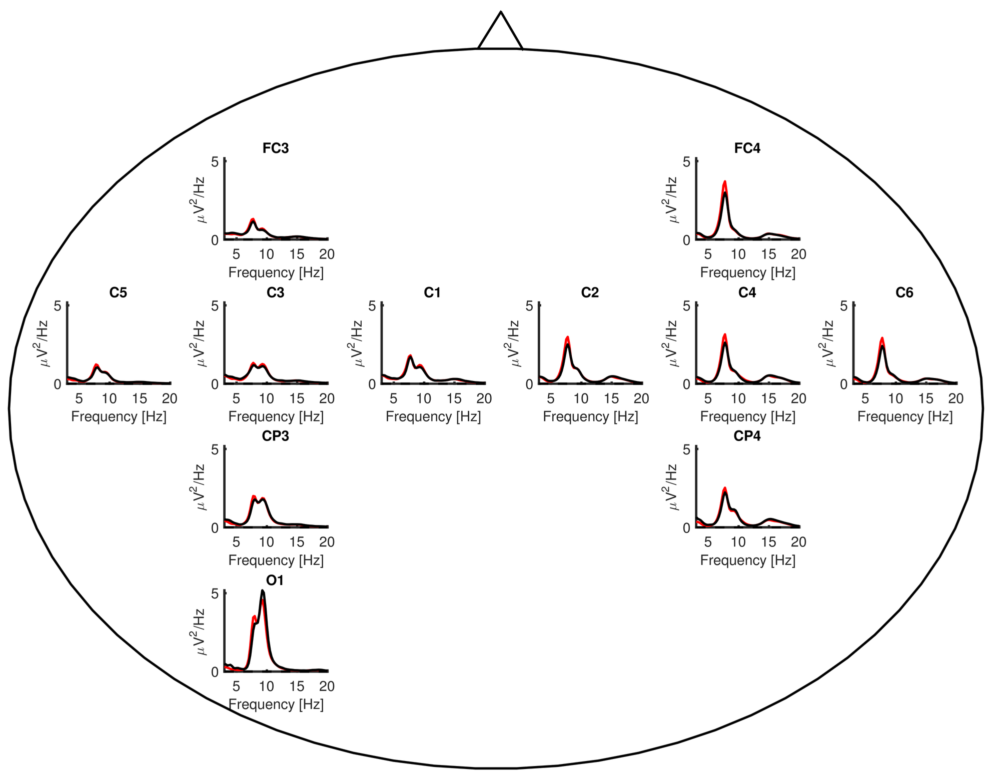
To study and test changes of oscillatory rhythms at each EEG electrode separately, the irregular-resampling auto-spectral analysis (IRASA) method was applied to separate fractal (representing background EEG) and harmonic (representing oscillatory EEG) components in the power spectrum of EEG segments [5].



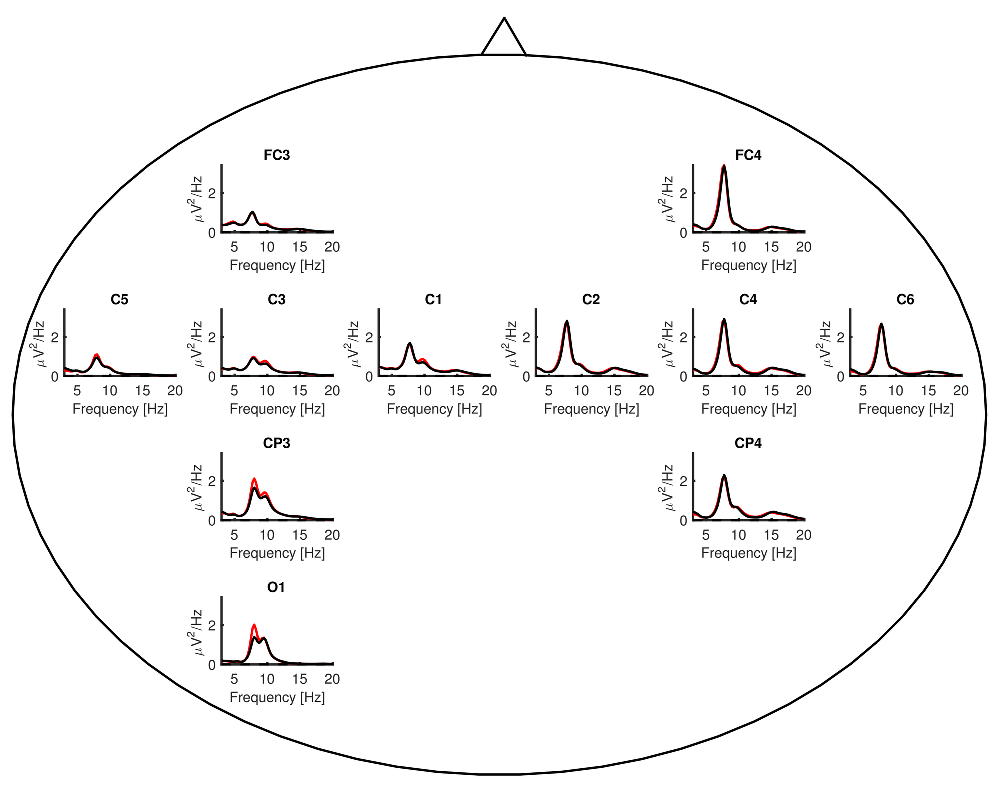
Mirror Therapy: *Averaged Mu rhythm harmonic part of the EEG power spectrum for the eyes closed condition. Each value is an average computed for a session (day). The first and second rows represent averages of pre-training and post-training periods. The third row represents the post- and pre-training difference. Solid lines represents linear fit to data, 95% confidence interval for each point is represented by dotted lines. Linear fits with significant non-zero slopes are denoted by stars (***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$).*



Robotic Splint: *Averaged Mu rhythm harmonic part of the EEG power spectrum for the eyes closed condition. Each value is an average computed for a session (day). The first and second rows represent averages of pre-training and post-training periods. The third row represents the post- and pre-training difference. Solid lines represents linear fit to data, 95% confidence interval for each point is represented by dotted lines. Linear fits with significant non-zero slopes are denoted by stars (***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$).*



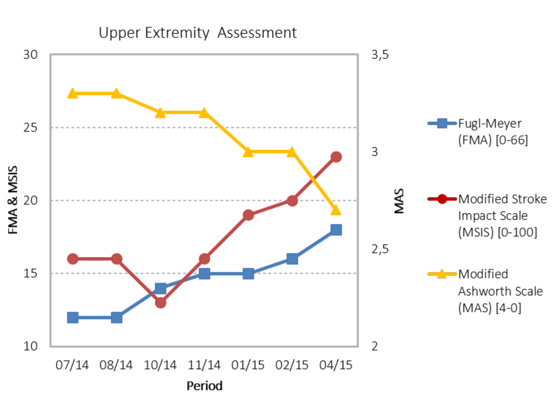
Mirror Therapy: *Pre-training (black) vs. post-training (red) averaged harmonic part of the EEG power spectrum for the eyes-closed condition, pre-trainng (black). Each plot is an average computed over 50 sessions (days).*

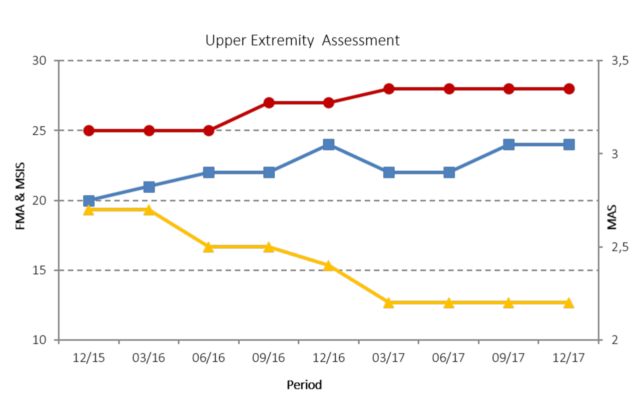


Robotic Splint: *Pre-training (black) vs. post-training (red) averaged Mu rhythm harmonic part of the EEG power spectrum for the eyes-closed condition. Each plot is an average computed over 132 sessions (days).*

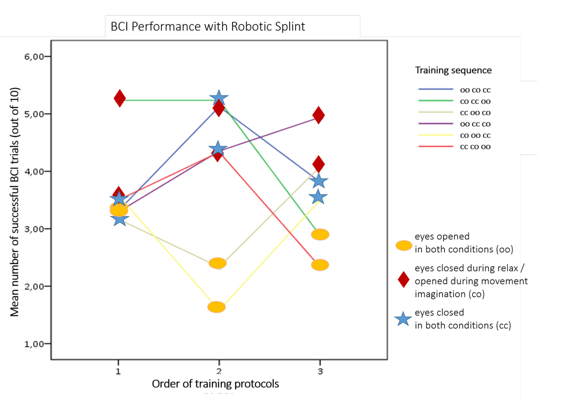
Clinical & Behavioural Results

A clinical evaluation of the subject's upper limb movement abilities was carried out. The undertaken clinical tests indicate a slight improvement in movement and spasticity of the arm but without a detectable progress for wrist and fingers. It is worth noting that the subject entered the study as late as two years after stroke with severe plegic hand. Subjectively, we observed an improvement in subject's speech and social communication, but this was not clinically tested. The subject showed strong enthusiasm to participate.





For the rehabilitation training with the robotic splint we compared 3 different protocols. We observed that it was the most difficult when the subjects was instructed to keep eyes open during the robotic splint control.



Conclusions

To our knowledge, this is the first longitudinal study (over 9 months long) of the mirror-box therapy showing effects on the modulation of sensorimotor EEG oscillatory rhythms. We observed significant short-term (a single session pre- versus post-training) and longer-term EEG effects lasting from day-to-day as well as spanning the whole period of the experiment. Analysis of the EEG data recorded during the mirror therapy sessions reveals stable day-to-day space-spectral atomic EEG representation of dominant sensorimotor oscillatory rhythms. The atomic representation of EEG allowed us to develop and test an efficient and flexible BCI protocol for the control of the constructed robotic splint for neuro-rehabilitation. Longitudinal robotic splint training of a 58-years-old man who had a right-hand hemiplegia due to an ischemic stroke is promising and although it is a single case study, it is used as a proof of concept, not as a population based statistical proof. Clinical efficiency of this procedure requires further evaluation by considering a wider, clinically heterogeneous population of patients with motor impairment.

References

[1] Ramachandran V. S., Rogers-Ramachandran D. C., Cobb S. Touching the phantom. *Nature*, 377:489–490, 1995.
[2] Mulder T. Motor imagery and action observation: cognitive tools for rehabilitation. *Journal of Neural Transmission.* , 114:1265–1278, 2007.
[3] Bro R. PARAFAC. Tutorial and applications. *Chemometrics and Intelligent Laboratory Systems*, 28:149–171, 1997.
[4] Rosipal R., Trejo L.J., Nuñez P.L. Application of multi-way EEG decomposition for cognitive workload monitoring. In *Proc. of the 6th ICPRM*, Beijing, pp. 145-149, 2009.
[5] Wen H, Liu Z. Separating Fractal and Oscillatory Components in the Power Spectrum of Neurophysiological Signal. *Brain Topography.* , 29:13–26, 2016.

Acknowledgement

The work was supported by the Slovak Research and Development Agency (projects APVV-16-0202 and APVV-0668-12) and by the Slovak Grant Agency for Science (projects VEGA-2/0011/16 and VEGA 2/0151/18).