Correction of Stress-Induced States Using Sensory Stimulation Automatically Modulated by Endogenous Human Rhythms

A. I. Fedotchev

Translated from Zhurnal Vysshoi Nervnoi Deyatel'nosti imeni I. P. Pavlova, Vol. 72, No. 1, pp. 3–10, January–February, 2022. Original article submitted January 18, 2021. Accepted April 26, 2021.

This article considers the dynamics of the development of a potential approach to correcting stress-induced states in humans, i.e., adaptive neurostimulation. The approach consists of presenting sensory stimulation automatically modulated by intrinsic rhythmic human processes such as the respiratory rhythm, the heart-beat rhythm, and electroencephalograph (EEG) rhythms. Many examples have shown that real-time self-adjustment of the stimulation parameters by these rhythms leads to a high level personalization of therapeutic stimulation and increases in its efficacy in suppressing stress-induced states. The publications reviewed here point to the advantages of this approach for developing innovatory technologies using complex feedback from endogenous human rhythms to correct a wide spectrum of functional disorders.

Keywords: sensory stimulation, closed-loop feedback, automatic modulation, EEG rhythms, heartbeat rhythm, respiratory rhythm, self-tuning of stimulation parameters, correction of functional disorders.

In current conditions, humans are exposed to the continuous actions of acute and chronic stress, which lead to the formation of multiple stress-induced functional disorders [Esin et al., 2020]. Chronic complex exposure to industrial, social, and psychoemotional stress factors leads to impairment of adaptation mechanisms, failure of the body’s protective systems, and development initially of stable functional impairments, followed by serious diseases [Dillon et al., 2016]. In periods of crisis in the development of a society, where requirements for mobilization of adaptive potential are increased and there is a risk of loss of stable work and material and social status, development of state-of-the-art non-medication-based methods of correction of stress-induced functional impairments is particularly relevant [Leonova, 2016; Can et al., 2020].

In the COVID-19 pandemic, increases in stress-inducing disorders such as PTSD and professional burnout syndrome were of particular concern to specialists [Restauri and Sheridan, 2020]. Significant stressogenic factors were the potential for infection by the virus, media coverage of events, changes in the accustomed way of life, and the economic consequences of the pandemic [Bykhovets and Kogan-Lerner, 2020]. Among the most widespread signs of post-traumatic stress disorder and professional burnout are psychological maladaptation and depression, subjective feelings of helplessness and anxiety, loss of work motivation, and negative feelings regarding work results [Nagornova, 2019; Petrikov et al., 2020]. Prompt psychotherapeutic correction of functional states formed in response to stress is extremely important in these conditions [Solov’eva et al., 2020].

Neurobiocontrol Techniques in Correcting Stress-Induced Disorders. Analysis of the literature shows that the best developed means of correcting stress-induced disorders consist of biocontrol techniques with feedback – neurobiocontrol. These have been shown to be successful in overcoming daily stress and anxiety [Kotozaki et al., 2014; Goessl et al., 2017] and can be used in complex with stress control sessions [De Witte et al., 2019], which are widely used in the treatment of post-traumatic stress disorders [Chiba et al., 2019; Steingrimsson et al., 2020; Leem et al., 2020] and professional burnout syndrome [Reed et al., 2020; Kacem et al., 2020]. In these techniques, a person is presented with sensory stimuli (visual, auditory, tactile, electrical) reflecting the ongoing activity in particular nerve structures underlying his or her behavior or pathology [Papo, 2019;
Hampson et al., 2020]. Closed-loop feedback signals from a person’s own bioelectrical potentials allow causal relationships between brain activity and behavior to be identified, providing neurobiocontrol techniques with advantages such as a high level of personalization of therapeutic procedures and the opportunity to learn the conscious control of physiological functions which are normally controlled involuntarily [Sitaram et al., 2017; Dzhos and Men’shikova, 2019].

Despite these advantages, a significant drawback of neurobiocontrol techniques is that a significant proportion (up to 30%) of patients are unable to acquire the skill of conscious modification of intrinsic biopotentials to achieve the required therapeutic effects, while others need very prolonged training [Alkoby et al., 2017]. Judging from reviews this “ability to learn problem” is due to difficulty in correct decoding of mental commands and the use of ineffective learning strategies [De Vico Fallani and Bassett, 2019], as well as the dependence of learning success on motivation and the person’s mood [Kadosh and Staunton, 2019].

Thus, the insufficient efficacy of neurobiocontrol techniques using sensory feedback connections from a person’s own biopotentials to form the skill of voluntary control of physiological functions is due to factors linked in one way or another with the need for awareness and appropriate use of these signals. Thus, increasing the efficacy of neural interfaces requires alternative approaches to organizing feedback excluding conscious processing of the sensory stimuli presented.

From Adaptive Biocontrol to Adaptive Neurostimulation: Automatic Modulation of Sensory Stimulation by Rhythmic Human Processes. The approach later termed “adaptive neurostimulation” [Zanos, 2019] was proposed in the pioneering studies of Bekhtereva, who developed a method for continuous photostimulation of humans at the rhythm of their own brain biopotentials [Bekhtereva and Usov, 1960]. Rhythmic light stimulation automatically modulated by electrical signals from the patient’s brain lead to increases in the power of the electroencephalogram (EEG) α rhythm and is a more effective type of functional load than the usual types of photostimulation. Considering the advantages of automatic modulation of sensory stimulation by the person’s own brain biopotentials, Bekhtereva regarded such stimulation as “very gentle, very effective, and analogous to the brain and body’s own protective mechanisms” [Bekhtereva, 1990].

The advantages of automatic modulation of sensory stimulation not only using EEG rhythms, but also using other human rhythmic processes such as the respiratory rhythm and the heartbeat rhythm, were later put on theoretical grounds [Fedotchev, 1996]. In fact, all these rhythmic processes interact closely and are the source of interoceptive signals of vital importance for people [Gentsch et al., 2019; Gibson, 2019]. Endogenous rhythms form the basis for the homeostatic stability and effectiveness of physiological processes [Riganello et al., 2019] and take part in the rhythmic facilitation of sensory processing [Haegens and Columbic, 2018] and neurorehabilitation processes [Abiri et al., 2019]. Automatic modulation of the parameters of sensory therapeutic stimulation by these rhythms can be accompanied by marked physiological effects, which are due to dynamic self-adjustment of sensory stimulation on physiological changes taking place in the human body [Zhou and Miller, 2019; Fleming et al., 2020].

Effectiveness of Self-Adjustment of Stimulation by Human Rhythmic Processes. The advantages of using automatic feedback from endogenous human rhythms for effective correction of stress-induced states have now been demonstrated in a whole series of studies (Table 1).

Thus, for example, the “Biomusic” neural interface was developed for monitoring and correction of the states of anxiety and stress; in this system, the body’s ongoing physiological parameters are converted to musical characteristics: electrotactaneous activity into melody, skin temperature to musical tonality, heart rate to the sound of a drum, and the respiratory rhythm to rhythmic acoustic signals reminiscent of sounds on exhalation [Cheung et al., 2016]. It has also been shown that presentation of acoustic stimuli generated in real time by transformation in software of the subject’s dominant EEG rhythms into sound sequences induces clinically significant decreases in the symptoms of posttraumatic stress [Tegeler et al., 2017; Shaltout et al., 2018]. These authors came to the conclusion that rapid updating of their own rhythmic patterns and resonance between heard sound signals and oscillatory neural networks presents the body with the opportunity for self-calibration and self-adjustment to achieve relaxation and overcome resistant pathological states [Tegeler et al., 2020].

In our initial studies, musical stimulation automatically controlled by the ongoing amplitude of EEG rhythms was used with the aim of correcting stress-induced complications of pregnancy [Fedotchev and Kim, 2009]. The experimental basis of this line of research consists of extensive data showing that oscillations in brain electrical activity can be synchronized by the time patterns of external influences and lead to the therapeutic influences of music on cognitive or motor symptoms [Laffont and Dalla Bella, 2018]. In addition, musical stimulation is known to have a number of cognitive, psychosocial, and behavioral advantages, especially for people with neurological disorders, providing the basis for the development of nonmedication-based treatment methods [Brancatisano et al., 2020]. However, because of the high level of heterogeneity in the conventional EEG rhythms used (α, θ, β), positive effects were achieved only after numerous treatment sessions. This led to the conclusion that there is a need to use narrow-frequency spectral components of the EEG (EEG oscillators) of particular significance to the subject rather than the previously employed very wide-band conventional EEG rhythms.

This approach was realized by developing a double feedback method using human EEG oscillators providing
for simultaneous modulation of sound and light stimuli by narrow-frequency rhythmic spectral components (EEG oscillators) in the EEG \( \theta \) and \( \alpha \) ranges detected in each patient in real time [Fedotchev and Bondar’, 2008]. Automatic tuning of this audiovisual stimulation to the intrinsic activity rhythms of a person’s brain led to significant correction of stressogenic states after use of 2–4 treatment sessions.

The “Brain Music” project was later developed, with successful demonstration of the ability to suppress stress-induced states using musical or music-like actions automatically modulated by the patient’s EEG oscillators. In this project, the dominant spectral peak at the EEG \( \alpha \) rhythm or the EEG \( \alpha \) oscillator is determined in each subject. Its ongoing amplitude during correction procedures is transformed by computer into music-like signals whose timbre is reminiscent of flute sounds with smoothly varying pitch and loudness [Fedotchev et al., 2016].

We then suggested that the efficacy of music-like stimulation could be increased if controlled automatically not only by the patient’s EEG oscillators, but also by the patient’s heartbeat rhythm. This comes from the fact that brain and heart biopotentials are sources of interoceptive signals, which play a key role in maintaining people’s optimum physical, emotional, and mental health [Quadt et al., 2018; Dubrushina et al., 2020], and their use in biocontrol procedures with feedback is the “roadmap” for the development of neurotechnologies [Khalsa et al., 2018]. A neural interface was developed in which music-like signals formed using the algorithms described above on the basis of EEG oscillators were supplemented with weak clicks corresponding to the frequency of the subject’s pulse [Fedotchev et al., 2018]. Even single use of this neural interface in subjects in the state of tension and stress produced positive shifts in assessments of well-being and mood and decreased emotional maladaptation.

The ability to suppress stress-induced states using rhythmic light stimulation automatically modulated by a person’s intrinsic EEG has also been studied. This organization of stimulation is achieved by normalization of digitized ongoing EEG values, the greatest negative values of the EEG signal corresponding to the lowest light stimulation intensity and the greatest positive values to the highest levels of light stimulation. Strictly controlled experiments established that in subjects in the state of anxiety and stress, significant increases in EEG \( \alpha \)-rhythm power, decreases in stress levels, and improvements in subjective indicators were seen only when automatic modulation of rhythmic light stimulation was by the person’s ongoing total EEG recording [Fedotchev, 2019]. This led to the conclusion that the key role in these effects was played by resonance mechanisms of brain activity mediated by the interaction of endogenous brain oscillations with periodic external actions [Lefebvre et al., 2017].

These data provided grounds for developing another variant of a musical neural interface in which musical stimulation was formed on the basis of a person’s rhythmic EEG components and heartbeat rhythm simultaneously with presentation of rhythmic light stimuli controlled by the subject’s total EEG. The efficacies of three types of actions were compared: control, without feedback from the EEG and heart; musical, controlled by EEG oscillators and the heartbeat rhythm; and light/musical, where musical stimuli were supplemented by LED flashes formed on the basis of the total EEG. Stimulation using this complex feedback from brain biopotentials and the heart produced significant positive effects in the form of maximal increases in EEG

### TABLE 1. Development of Methods of Adaptive Neural Stimulation Successfully Using Automatic Modulation of Sensory Stimulation by People’s Rhythmic Processes for Correction of Stress-Induced States

| Study objective | Stimulation modality | Modulating rhythm | Reference |
|-----------------|----------------------|-------------------|-----------|
| Correction of stress-induced complications of pregnancy | Classical music | \( \theta, \alpha, \beta \) EEG rhythms | Fedotchev and Kim, 2009 |
| Correction of stress-induced states | Fixed sound frequencies and light | \( \theta \) and \( \alpha \) EEG oscillators | Fedotchev and Bondar’, 2008 |
| Correction of anxiety and stress states | Music-like stimulation | Heart and respiratory rhythms | Cheung et al., 2016 |
| Correction of stress-induced states | Music-like stimulation | \( \alpha \) EEG oscillators | Fedotchev et al., 2016 |
| Treatment of posttraumatic stress | Acoustic stimuli | Dominant EEG rhythms | Tegeler et al., 2017 |
| Treatment of posttraumatic stress | Acoustic stimuli | Dominant EEG rhythms | Shaltout et al., 2018 |
| Correction of stress-induced states | Music-like stimulation | \( \alpha \) EEG oscillators + heart rhythm | Fedotchev et al., 2018 |
| Correction of stress-induced states | Rhythmic light stimulation | Native EEG | Fedotchev, 2019 |
| Correction of stress-induced states | Music-like and rhythmic light stimulation | \( \alpha \) EEG oscillators + heart rhythm + native EEG | Fedotchev et al., 2019 |
| Treatment of posttraumatic stress | Acoustic stimuli | Dominant EEG rhythms | Tegeler et al., 2020 |
| Correction of stress-induced states | Music-like and rhythmic light stimulation | \( \alpha \) EEG oscillators + heart rhythm + native EEG | Fedotchev et al., 2020 |
α-rhythm power, increases in assessments of wellbeing and mood, and decreases in subjects’ emotional maladaptation after a single treatment procedure [Fedotchev et al., 2019]. In addition, questioning of participants on their subjective feelings during the experiments showed that most (75%) gave the best evaluations to stimulation with complex feedback from the EEG and heart, where music-like sound stimuli were supplemented with pleasant flooding with multicolored light obtained by perceiving EEG-controlled light flashes through closed eyes. The physiological basis of the effects recorded consists of multisensory integration mechanisms [Roy et al., 2019] and the mechanisms of neuroplasticity [Piravadov et al., 2018; Voropaev et al., 2019; Naryshkin et al., 2020], which are involved in the processes of normalizing subjects’ functional status as influenced by biosensory therapeutic stimulation.

Controlled studies were performed to obtain more detailed analysis of possible mechanisms, and these addressed the effects of light/musical stimulation controlled by the subject’s own brain and heart biopotentials, comparing them with the effects of stimulation modulated by brain and heart biopotentials from another person. This study design excluded the involvement of interoceptive signals when light/musical stimulation was controlled by another person’s brain and heart biopotentials. Only light/musical stimulation controlled by the subject’s own brain and heart biopotentials showed statistically significant increases in the power of the main EEG rhythms accompanied by significant improvements in EEG test measures and positive emotional reactions to stimulation [Fedotchev et al., 2020]. The data were explained by the integration of perception and processing of interoceptive signals of significance to the person and resonance mechanisms in the CNS supporting normalization of functional status in response to therapeutic stimulation.

Conclusions. The publications presented here show that adaptive neural stimulation methods using automatic modulation of sensory stimulation by a person’s endogenous rhythms for correction of stress-induced states have undergone intense development in recent years. Judging from the data presented, the most effective methods were those using bimodal stimulation automatically modulated by multiple rhythmic processes in humans. The potential of this approach is determined by the following characteristic features:

- highly personalized due to the use of feedback from the subject’s own bioelectrical characteristics;
- involvement of perception and processing of interoceptive signals of significance for the person in the mechanisms of multisensory integration, neuroplasticity, and brain resonance mechanisms supporting normalization of the functional state under the influences of stimulation procedures;
- automatic – without any conscious effort on the part of the patient – control of the therapeutic sensory stimuli, providing the opportunity to use adaptive neural stimulation to correct unfavorable shifts in status in patients with altered levels of consciousness, elderly people, and children.

These characteristics have the result that this approach can be employed in a wide range of rehabilitation measures, in educational institutions to activate people’s cognitive activity and learning processes, and in military and sports medicine, disaster medicine, and scientific research.

This work was supported by the Russian Foundation for Basic Research (Grant No. 19-013-0095).

REFERENCES

Abiri, R., Borhani, S., Sellers, et al., “A comprehensive review of EEG-based brain–computer interface paradigms,” J. Neural Eng., 16, 016001 (2019), https://doi.org/10.1088/1741-2552/aaf12e.

Alkoby, O., Abu-Rnileh, A., Shriki, O., and Toddler, D., “Can we predict who will respond to neurofeedback? A review of the inefficacy problem and existing predictors for successful EEG neurofeedback learning,” Neuroscience, 378, 155–164 (2018), https://doi.org/10.1016/j.neuroscience.2016.12.050.

Bekhtereva, N. P. and Usov, V. V., “A method for continuous photostimulation at the rhythm of intrinsic brain potentials during EEG recording,” Fiziol. Zh. SSR, 46, No. 1, 108–111 (1960).

Bekhtereva, N. P., Electrical Stimulation of the Brain and Nerves in Humans, Nauka, Leningrad (1990).

Brancatisano, O., Baird, A., and Thompson, W. F., “Why is music therapeutic for neurological disorders? The Therapeutic Music Capacities Model,” Neurosci. Biobehav. Rev., 112, 600–615 (2020), https://doi.org/10.1016/j.neubiorev.2020.02.008.

Bykhovets, Yu. V. and Kogan-Lerner, L. B., “The COVID-19 pandemic as a multifactorial psychotraumatizing situation,” Sots. Ekonom. Psikhol., 5, No. 2, 291–308 (2020), https://doi.org/10.38098/ipran.sep.2020.18.2.010.

Can, Y. S., Ilev-Smith, H., Chalabianloo, N., et al., “How to relax in stressful situations: a smart stress reduction system,” Healthcare (Basel), 8, No. 2, 100 (2020), https://doi.org/10.3390/healthcare8020100.

Cheung, S., Han, E., Kushki, A., et al., “Biomusic: An auditory interface for detecting physiological indicators of anxiety in children,” Front. Neurosci., 10, 401 (2016), https://doi.org/10.3389/fnins.2016.00401.

Chiba, T., Kanazawa, T., Koizumi, A., et al., “Current status of neurofeedback for post-traumatic stress disorder: A systematic review and the possibility of decoded neurofeedback,” Front. Hum. Neurosci., 13, 233 (2019), https://doi.org/10.3389/fnhum.2019.00233.

De Vico Fallani, F. and Bassett, D. S., “Network neuroscience for optimizing brain–computer interfaces,” Phys. Life Rev., 31, 304–309 (2019), https://doi.org/10.1016/j.plrev.2018.10.001.

De Witte, N. A. J., Buyck, I., and Van Daele, T., “Combining biofeedback with stress management interventions: A systematic review of physiological and psychological effects,” Appl. Psychophysiol. Biofeedback, 44, No. 2, 71–82 (2019), https://doi.org/10.1007/s10484-018-09427-7.

Dillon, A., Kelly, M., Robertson, I. H., and Robertson, D. A., “Smartphone applications utilizing biofeedback can aid stress reduction,” Front. Psychol., 7, No. 832, 1–7 (2016), https://doi.org/10.3389/fpsyg.2016.00832.

Dobrushina, O. R., Dobrynina, L. A., Arina, G. A., et al., “Interaction of interoceptive perception and emotional intelligence: a functional neuroimaging study,” Zh. Vychisl. Nerv. Dyeyat., 70, No. 2, 206–216 (2020), https://doi.org/10.31857/S0044467720020069.

Dzhos, Yu. S. and Men’shikova, I. A., “The possibility of using neurobio-control to increase the functional capacity of the brain,” Zh. Med. Biol. Issled., 7, No. 3, 338–348 (2019), https://doi.org/10.17238/issn2542-1298.2019.7.3.338.

Esin, R. G., Esin, O. R., and Khakimova, A. R., “Stress-induced disorders,” Zh. Nevrol. Psikhiatr., 120, No. 5, 131–137 (2020), https://doi.org/10.17116/jnepiro2020120051131.
Fedotchev, A. I., Bondar’, A. T., “A method for double feedback from a patient’s EEG oscillators for correction of stress-induced functional disorders,” Zh. Vyssh. Nerv. Deyat., 58, No. 3, 376–381 (2008).

Fedotchev, A. I. and Kim, E. V., “Characteristics of treatment sessions using biocontrol with electroencephalogram feedback in normal and complicated pregnancy,” Zh. Vyssh. Nerv. Deyat., 59, No. 4, 421–428 (2009).

Fedotchev, A. I., “Effects of photostimulation controlled by the human EEG,” Biофизика, 64, No. 2, 358–361 (2019), https://doi.org/10.1134/S0006302919020157.

Fedotchev, A. I., Bondar’, A. T., Bakhhchina, A. V., et al., “Transmutation of patients’ EEG oscillators into music-like signals in the correction of stress-induced functional states,” Sovrem. Tekhnik. Med., 8, No. 1, 93–98 (2016), https://doi.org/10.17691/stm2016.8.2.01.

Fedotchev, A. I., Parin, S. B., Gromov, K. N., et al., “Complex feedback from brain and heart biopotentials in the correction of stress-induced states,” Zh. Vyssh. Nerv. Deyat., 69, No. 2, 187–193 (2019), https://doi.org/10.1134/S0006302919020059.

Fedotchev, A. I., Parin, S. B., Savchuk, L. V., and Polevaya, S. A., “Mechanisms of light/musical stimulation controlled by own or other’s brain and heart biopotentials,” Sovrem. Tekhnik. Med., 12, No. 4, 23–29 (2020), https://doi.org/10.17691/stm2020.12.4.03.

Fedotchev, A. I., Zhuravlev, G. I., Eksina, K. I., et al., “Assessment of the efficacy of a musical EEG neural interface with an additional heart rhythm control circuit,” Ros. Fiziol. Zh., 104, No. 1, 122–128 (2018).

Fleming, J. E., Orłowski, J., Lowery, M. M., and Chaillet, A., “Self-tuning deep brain stimulation controller for suppression of beta oscillations: Analytical derivation and numerical validation,” Front. Neurosci., 14, 639 (2020), https://doi.org/10.3389/fnins.2020.00639.

Gentsch, A., Seli, A., Marshall, A. C., and Schütz-Bosbach, S., “Affective interoceptive inference: Evidence from heart-beat evoked brain potentials,” Hum. Brain Mapp., 40, No. 1, 20–33 (2019), https://doi.org/10.1002/hbm.24352.

Gibson, J., “Mindfulness, interoception, and the body: A contemporary perspective,” Front. Psychol., 10, 2012 (2019), https://doi.org/10.3389/fpsyg.2019.02012.

Goessl, V. C., Curtiss, J. E., and Hofmann, S. G., “The effect of heart rate variability biofeedback training on stress and anxiety: a meta-analysis,” Psychol. Med., 47, No. 15, 2578–2586 (2017), https://doi.org/10.1017/s0033291717001003.

Haegens, S. and Golombic, E. Z., “Rhythmic facilitation of sensory processing: A critical review,” Neurosci. Biobehav. Rev., 86, 150–165 (2018), https://doi.org/10.1016/j.neubiorev.2017.12.002.

Hampson, M., Ruiz, S., and Ushiba, J., “Neurofeedback,” NeuroImage, 218, 116473 (2020), https://doi.org/10.1016/j.neuroimage.2019.116473.

Kacem, I., Kahoul, M., El Arem, S., et al., “Effects of music therapy on occupational stress and burn-out risk of operating room staff,” Libyan J. Med., 15, No. 1, 1768024 (2020), https://doi.org/10.1080/19932820.2020.1768024.

Kadosh, K. C. and Staunton, G., “A systematic review of the psychological factors that influence neurofeedback learning outcomes,” NeuroImage, 185, 545–555 (2019), https://doi.org/10.1016/j.neuroimage.2018.10.021.

Khalsa, S. S., Adolphs, R., Cameron, O. G., et al., “Interoception and mental health: A roadmap,” Brain. Cogn. Neurosci. Neuroimaging, 3, No. 6, 501–513 (2018), https://doi.org/10.1016/j.bscj.2017.12.004.

Kotozaki, Y., Takeuchi, H., Sekiguchi, A., et al., “Biofeedback-based training for stress management in daily hassles: an intervention study,” Brain Behav., 4, No. 4, 566–579 (2014), https://doi.org/10.1002/bbr3.241.

Laffont, J. and Dalla Bella, S., “Music, rhythm, rehabilitation and the brain: From pleasure to synchronization of biological rhythms,” Ann. Phys. Rehabil. Med., 61, No. 6, 363–364 (2018), https://doi.org/10.1016/j. reabh.2018.10.001.

Lee, J., Cheong, M. J., Yoon, S. H., et al., “Neurofeedback self-regulating training in patients with Post traumatic stress disorder: A ran-
Voropaev, A. A., Ivanova, G. E., and Kotenko, N. V., “Use of noninvasive neural modulation in the rehabilitation of patients with traumatic brain disorders,” Vestn. Vosstan. Med., 1, No. 89, 29–32 (2019).

Zanos, S., “Closed-loop neuromodulation in physiological and translational research,” Cold Spring Harb. Perspect. Med., 9, No. 11, a034314 (2019), https://doi.org/10.1101/cshperspect.a034314.

Zhou, X. and Miller, J. P., “The emerging role of biomarkers in adaptive modulation of clinical brain stimulation,” Neurosurgery, 85, No. 3, E440–E441 (2019), https://doi.org/10.1093/neuros/nyz097.