Brain plasticity and rehabilitation by using Near-Infrared Spectroscopy

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Abstract

The present review elucidated the use of optical imaging technique (Near-Infrared Spectroscopy, NIRS) to better explain the brain plasticity for learning mechanisms, rehabilitation and post-traumatic brain recovery. Some recent applications were discussed, with specific focus on the usability of integrated measures (such as electroencephalography, EEG-NIRS; Transcranial Magnet Stimulation, TMS-NIRS) to study plasticity and its dynamic effects. NIRS-Neurofeedback and NIRS-BCI (Brain Computer Interface) were also explored as possible tools to produce a specific long-lasting learning in relationship with a specific cognitive domain. Finally a proficient domain where NIRS was found to be useful to test neuroplasticity is the interpersonal brain-to-brain coupling, termed "hyperscanning", a new emerging paradigm in neuroscience which measures brain activity from two or more people simultaneously.

Keywords: Brain plasticity; NIRS; Rehabilitation; Hyperconnection

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1. Optical imaging measure: Near Infrared Spectroscopy (NIRS)

A number of recent researchers have used Near-Infrared Spectroscopy (NIRS) and functional NIRS (fNIRS) to produce new insights about the neural mechanisms underlying cognitive, emotive and perceptual functions (Hoshi, 2007; Balconi, Vanutelli, Bartolo & Cortesi, 2015). This technique was developed to be non-invasive, easy-to-use, portable, restraint-free and replicable (Kono et al., 2007). A recent review summarized the main domains where NIRS technique was found to be more usefull (Ferrari & Quaresima, 2012). Indeed NIRS enables the non-invasive measurement of spatiotemporal characteristics of brain function, which are assumed to reflect regional Cerebral Blood Flow (rCBF). The relationship between neural activity and changes in blood oxygenation can result from the interplay of multiple factors. Regional brain activation leads to an increasing oxygen demand by neurons and consequent increase in regional metabolism. In turn, increased oxygen consumption induces increased rCBF. Researchers have documented that the increased rCBF exceeds the tissue's demand for oxygen, which leads to increased (O2Hb) and to decreased (HHb) as a sign of activation (Fox & Raichle, 1986).

The conception of NIRS as a novel technique for measuring neural activation is attributable to some unique characteristics, which may be summarized in two main points: the technical advantages and the experimental and ecological validity of this measure (Balconi & Molteni, 2015). Indeed NIRS is considered to impose considerably reduced physical limitations than those of classical neuroimaging techniques. Indeed the ecological value of this measure, the ease of use, and the possibility to be integrated with other measures (such as electroencephalographic, EEG; or neurostimulation – Transcranial Magnetic Stimulation, TMS – measures) make this technique highly powerful to improve the quality of the cognitive and emotional studies. In addition, contraindications of applications by using other measures (such as fMRI) (claustrophobia, pacemakers, metal implants, etc.) may be bypassed by NIRS. Moreover, it produces separate measures of oxygenated and deoxygenated hemoglobin species and also provides additional information about total hemoglobin and changes in local blood volume. A relevant feature is that it has higher temporal resolution with respect to other neuroimaging techniques (such as fMRI, PET or SPECT). Moreover, when compared to fMRI, NIRS offers the advantage of measuring hemodynamic activity in environments with greater ecological validity. This is especially crucial, as studies have shown that simulated tasks do not always generate the same brain activations as do their real-life counterparts (Okamoto et al., 2004). Thus, NIRS is a useful technique for measuring neural activation under less constrained and more ecologically valid settings (Tuscan et al., 2013).

2. NIRS and brain plasticity: some applications to the lifespan

One of the most recent and promising domain where NIRS has shown to be useful is the exploration of neural plasticity. Indeed, in comparison with other classical imaging techniques, NIRS offers the opportunity to monitor in a dynamic and ecologically valid setting the cortical modification induced by a spontaneous (task-induced) or modulated (device-induced, i.e. by neurofeedback) setting.

The investigation of plasticity can be synthesized taking into account three different assumptions, that is that brain plasticity is a physiological process which mainly takes place during the earliest period of life, and comes along with the organization of several cognitive functions and with the development of the emotional asset during childhood; secondly, that brain plasticity can intervene as an effect of cerebral damage (as a traumatic, hemorrhagic, surgical or infectious damage to the brain), thus allowing an either adaptive or maladaptive repair or reconnection of certain neural networks; thirdly, that brain plasticity can arise from the training of brain networks, as a result of task execution or rehabilitation activity.

From one hand, physiological brain plasticity during early phases of life has been investigated showing the functional maturation and organization of cortical networks that mediate perceptual and cognitive processing in the infants' developing brain. The NIRS data revealed age-related changes in patterns of activation to featural information (shape) and spatiotemporal information (speed of motion), mostly involving posterior parietal areas (Kobayashi et al., 2012). It was suggested that these changes reflect age-related differences in the perceptual and/or cognitive processes engaged during the task. From the other hand, a recent application was related to older age and the evolution of the cognitive functions. For example a recent study evaluated the influence of reading habits on cerebral plasticity in the performance of a discourse comprehension task in aging (Martin, Desrochers, Demers, Scherer & Ska, 2012). The main hypothesis was that participants with higher frequency and quality of reading habits should exhibit reduced brain activity because the task should be easier for them. The results showed that the more experienced readers had higher activation in the superior left region of the prefrontal cortex while they were reading but lower activation in the same region when they were retrieving the information. Thus, more effort is required to acquire and maintain the information needed to answer, and this effort makes it easier to give the answer. These results reinforce the hypothesis that brain plasticity is promoted by cognitive activities throughout the lifespan.

3. The advantages to integrate NIRS with other neurophysiological measures for studying plasticity

Combined NIRS/EEG measurements allow for the complementary examination of neural as well as hemodynamic aspects of brain activation (Biallas, Trajkovic, Haensse, Marcar & Wolf, 2012), and EEG and NIRS integration is not only economically and ecologically favorable, but it is also particularly useful for studies on plasticity. It should be considered that the combination of NIRS and EEG measurements does not involve technical interferences as both methods rely on different working-principles: whereas EEG assesses the electrical neural, NIRS is based on the local hemodynamic changes based on the distinct optical properties of oxygenated and deoxygenated hemoglobin species. In addition, the evoked paradigms, usable in the case of NIRS and EEG acquisition, may furnish a specific overview on the brain activity more directly task- or stimulus-related.

From a second perspective, also some neuromodulation and neurostimulation techniques (such as Transcranial Electrical Stimulation – TES – and TMS) in co-registration with NIRS may furnish important information about the effect of brain plasticity induced by cortical increased/decreased excitability. Specifically, TMS is a non-invasive technique for stimulating the human cerebral cortex using a brief high-current pulse applied via an electromagnetic coil placed above the scalp (Hallett, 2000). Depending on the stimulation parameters, the produced magnetic field can either inhibit or excite a focal cortical area, most likely by inducing changes in synaptic plasticity linked to learning and memory (Hoogendam, Ramakers & Di Lazzaro, 2010). TMS, in its repetitive applications (rTMS), may produce effects beyond the time of stimulation and exceeding the targeted area (Ilmoniemi et al., 1997; Guse, Falkai & Wobrock, 2010).

A relevant potentiality of NIRS/TMS coregistration is the chance to explore the intrinsic dynamic of cerebral plasticity. Indeed, TMS was used to induce long-lasting modifications of structural and functional connections within the brain networks. The online monitoring of the way this plasticity may be effective is well supported by NIRS. For example, Baeken and colleagues (2010) investigated one session of 10 Hz rTMS applied to the right dlPFC in healthy volunteers while passively viewing emotional faces. The application of NIRS may point out the underlying mechanisms related to subcortical structures (i.e. amygdala) modulation across the time, allowing for a stable and long-lasting effect on emotional response. However, it has to be noted that some imaging studies investigating rTMS mediated hemodynamic consequences revealed inconsistent results, mainly due to differences in rTMS parameters and technical difficulties with simultaneous recordings during rTMS. For this reason some recent study applied a specific TMS paradigm, a Quadri-pulse rTMS (QPS) to induce bidirectional long-term plasticity of the human primary motor cortex (M1). To evaluate its on-line effects, NIRS recordings were performed, supposing that on-line effects during QPS are different from long-term aftereffects. This new TMS-NIRS setup may be valuable to investigate TMS induced neurovascular coupling mechanisms in humans (Groiss et al., 2013). The authors found that QPS can significantly alter cortical hemodynamics depending on the stimulation frequency. While bidirectional long-term aftereffects of QPS reflect synaptic efficacy changes, unidirectional on-line effects during QPS may represent pure electrophysiological property changes within the cell membrane or synapse. Since neuronal postexcitatory inhibitory postsynaptic potentials typically peak within the first 10-20 ms, only pulses delivered at higher frequencies may lead to summation of the inhibitory effects, resulting in (oxy-Hb) decrease.

4. Optical imaging and rehabilitation

The potential use of NIRS in the monitoring of brain plasticity resulting from rehabilitation programs has been considered by some recent research that observed the change of cortical activation pattern induced by sessions of Neuromuscular Electrical Stimulation (NMES) in the motor areas (Jang et al., 2014). Other study focused on the long-term enhancement of brain function and cognition using cognitive training and brain stimulation by Transcranial Random Noise Stimulation (TRNS) (Snowball et al., 2013). For example TRNS of the bilateral dorsolateral Prefrontal Cortex (dlPFC) was coupled with NIRS to measure online hemodynamic responses within the PFC. It was shown that TRNS-accompanied cognitive training enhanced the speed of both calculation – and memory-recall-based arithmetic learning. These behavioral improvements were associated with more efficient neurovascular coupling within the left dlPFC, and testing many months after training revealed long-lasting behavioral and physiological modifications. It was speculated that such findings have significant implications for basic and translational neuroscience, highlighting stimulation techniques as a viable approach to enhancing learning and high-level cognition by the long-term modulation of neuroplasticity.

A second proficient field of application was the study of motor learning, neuroplasticity and functional recovery after the occurrence of brain lesion. New findings in basic neuroscience provided stimuli for research in motor rehabilitation. Electrical stimulation can be applied in a variety of ways to the neurological impairment. Especially, electromyography (EMG) initiated electrical muscle stimulation improves motor dysfunction of the hemiparetic arm and hand. Triggered electrical stimulation is reported to be more effective than non-triggered electrical stimulation in facilitating upper extremity motor recovery. It was shown by using NIRS that combined modulation of voluntary movement, proprioceptional sensory feedback and electrical stimulation might play an important role to facilitate impaired sensory-motor integration in power-assisted electrical stimulation therapy (Hara, 2010; 2011). For a review on NIRS application to brain recovery after motor impairment see also Schaechter (2004) and Kato et al. (2002).

On the other hand, neurofeedback (NF) and Brain Computer Interface (BCI) technique may be used to produce a specific long-lasting learning in relationship with a specific cognitive domain. While in both BCI and NF the participant's brain signals are directly displayed to the participant in real-time, these applications differ conceptually. BCI can be seen as a direct communication pathway between a human brain and an external device such as a computer or prosthesis (Kropotov, 2009). In BCI, the recorded brain signal is translated in real-time into commands that operate a computer display or other device (Wolpaw, Birbaumer, McFarland, Pfurtscheller & Vaughan, 2002). In NF applications, the feedback parameters are used for self-regulation of the brain (Kropotov, 2009). Indeed participants learn to control brain activity by contingent feedback of measures of the brain activity (Weiskopf, 2012).

A few studies investigated if the NIRS signal can be used as control signal for BCI purposes. These studies successfully used different mental strategies, such as motor imagery or mental arithmetic, to control a NIRS-based BCI. Compared to growing body of NIRS-based BCI research, NIRS-based NF studies are rare. In a recent research, Sakatani and colleagues (2013) planned a NIRS-based neurofeedback system to modulate activity in the PFC. Interestingly the dlPFC exhibited enhanced activity after neurofeedback training. NF has been found to be also effective in modifying brain function and producing significant improvements in clinical symptoms in several clinical areas, including epilepsy, ADD/ADHD, learning disabilities, and head injuries. The integration with hemodynamic measures may better explain the evidences and the reasons to apply this methodic to induce significant changes in brain responsiveness to emotions.

Also robotics was a proficient application field for NIRS. Indeed clarification of the relationship between external devices applications and brain response has been an important topic in plasticity and brain rehabilitation. For example, recently cortical activation patterns generated during execution of a rehabilitation robotic hand was monitored (Chang et al., 2014). Passive movements of the right fingers were performed using a rehabilitation robotic hand at a frequency of 0.5 Hz while values of 02Hb, HHb and total-hemoglobin (HbT) were registered. 02Hb and HbT values indicated significant activation in the some motor areas during execution of the rehabilitation robotic hand.

5. Brain plasticity and "hyperconnections"

A domain where NIRS was found to be a useful measure to test neuroplasticity is related to the interpersonal brain-to-brain coupling, a new emerging paradigm in neuroscience which measures brain activity from two or more people simultaneously, termed "hyperscanning". The hyperscanning approach has the potential to reveal inter-personal brain mechanisms underlying interaction-mediated brain-to-brain coupling (Villringer & Chance, 1997; Rolfe, 2000; Lloyd-Fox et al., 2009; Minagawa -Kawai et al., 2009; Grossmann & Johnsons, 2010; Grossmann, Oberecker, Koch & Friederici, 2010; Suda et al., 2010). These mechanisms are engaged during real social interactions, and cannot be captured using single-subject recordings. In particular NIRS hyperscanning is a promising new method. Although the "social brain" (Gazzaniga, 1985; Brothers, 2002; Frith, 2007; Fujii, Hihara & Iriki, 2007) has been studied by many researchers, it is mostly measured by adopting a "summative approach" measuring only one brain at a time by using various neuroimaging or electrophysiological modalities, such as EEG (Gao et al., 2009; Cheung, Rutherford, Mayes & McPartland, 2010), PET (Fletcher et al., 1995; Goel, Grafman, Sadato & Hallett, 1995; Gallagher et al., 2002) or fMRI (McCabe, Houser, Ryan, Smith & Trouard, 2001; Mitchell, Banaji & Macrae, 2005; Fukui et al., 2006; Schippers, Roebroeck, Renken, Nanetti & Keysers, 2010; Stephens, Silbert & Hasson, 2010). Consequently, little is known about how social functions are processed in interacting brains of multiple participants. Therefore, as classical neuroimaging approaches, such as fMRI studies, are unable to test the interpersonal dynamic relationships, alternative methodologies are needed (Funane et al., 2011). Another technology, EEG, has also been employed, which enabled the study of social interaction in a more naturalistic environment (Lindenberger, Li, Gruber & Müller, 2009; Astolfi et al., 2010; Dumas, Nadel, Soussignan, Martinerie & Garnero, 2010). However, EEG reveals the inability to precisely localize the origin of the neuroelectrical signal (Michel et al., 2004). As we have previously underlined, NIRS offers an easy-to-use, non-invasive cortical imaging technology capable of measuring brain activity in a more naturalistic environment than EEG or fMRI experiments. At this regard, a useful measure, the interbrain coherence, that is the correlation between two signals of brain activity, was applied in recent studies showing increases during cooperation, but not during competition interpersonal situations (Egetemeir, Stenneken, Koehler, Fallgatter & Herrmann, 2011).

6. Conclusion

NIRS technique contributed to the advanced understanding of the functioning human brain in and its underlying mechanisms related to plasticity functions. There are some weel known challenges when using NIRS to explore brain plasticity. Indeed NIRS is a reliable technique for quantifying several aspects of brain functioning and modifications, induced by learning mechanisms, external device applications of cortical damages recovery. Finally, interpersonal contexts may offer a valid test bench to explore the plastic behavior of interconnected-brains.

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