Application of Functional Near-Infrared Spectroscopy to the Study of Brain Function in Humans and Animal Models

Hak Yeong Kim1, Kain Seo1, Hong Jin Jeon2, Unjoo Lee3, and Hyosang Lee1,*

1Department of Brain and Cognitive Sciences, DGIST, Daegu 42988, Korea, 2Department of Psychiatry, Depression Center, Samsung Medical Center, Sungkyunkwan University, School of Medicine, Seoul 06351, Korea, 3Department of Electronic Engineering, Hallym University, Kangwon 24252, Korea
*Correspondence: hyosang22@dgist.ac.kr
http://dx.doi.org/10.14348/molcells.2017.0153
www.molcells.org

Functional near-infrared spectroscopy (fNIRS) is a non-invasive optical imaging technique that indirectly assesses neuronal activity by measuring changes in oxygenated and deoxygenated hemoglobin in tissues using near-infrared light. fNIRS has been used not only to investigate cortical activity in healthy human subjects and animals but also to reveal abnormalities in brain function in patients suffering from neurological and psychiatric disorders and in animals that exhibit disease conditions. Because of its safety, quietness, resistance to motion artifacts, and portability, fNIRS has become a tool to complement conventional imaging techniques in measuring hemodynamic responses while a subject performs diverse cognitive and behavioral tasks in test settings that are more ecologically relevant and involve social interaction. In this review, we introduce the basic principles of fNIRS and discuss the application of this technique in human and animal studies.

Keywords: brain recording, functional neuroimaging, fNIRS, functional near-infrared spectroscopy, neurovascular coupling

INTRODUCTION

In response to external stimuli or changes in the environment, the brain undergoes various electrophysiological and neurochemical reactions that are the result of the harmonious interactions of neurons and non-neuronal cells in the brain. The increase in local neuronal activity is usually accompanied by the consumption of glucose and oxygen (Villringer and Chance, 1997), which in turn leads to an increase in local blood flow and blood volume through the distension of the capillaries, eventually leading to the entry of oxygen-bound hemoglobin into the region (Roy and Sherrington, 1890). During this neurovascular coupling, the amount of oxygen supplied is typically greater than that consumed locally, resulting in a substantial increase in oxygenated hemoglobin and a slight reduction in deoxygenated hemoglobin in the region (Fox et al., 1988; Villringer and Dirnagl, 1995). Since the magnitude and location of both oxy- and deoxy-hemoglobin are tightly linked to the extent and location of neuronal activity, the hemodynamic response is often measured as an alternative marker of neuronal activity (Chance et al., 1993; Ogawa et al., 1990; Villringer and Chance, 1997).

Over the last several decades, a number of non-invasive or minimally invasive methods have been developed to measure neuronal activity in the brain. Neuropsychological techniques such as magnetoencephalography (MEG), electroencephalography (EEG), and event-related brain potentials offer the ability to measure the overall change in the electromagnetic field with an excellent time resolution of a thousandth of a second, but with very limited spatial resolution. On the other hand, brain imaging techniques such as positron...
emission tomography (PET), single-positron emission computed tomography, and functional magnetic resonance imaging (fMRI) allow indirect measurement of neuronal activity by monitoring local hemodynamic and metabolic changes. These techniques have excellent spatial resolution but limited temporal resolution (Irani et al., 2007).

**FUNCTIONAL NEAR-INFRARED SPECTROSCOPY**

Functional near-infrared spectroscopy (fNIRS) is an emerging optical imaging technique that measures the hemodynamic response in the brain using light in the near-infrared wavelength range (~700-900 nm), which is known to be permeable to biological samples (Fig. 1) (Fox and Raichle, 1986; Jobsis, 1977). The fNIRS system consists of two main components: a light source, such as a light emitting diode or laser, which irradiates near-infrared light at the surface of the subject’s head; and the nearby photodetector, which captures photons returning to the surface of the head after being scattered, reflected, and absorbed in the tissue (Bunce et al., 2006; Villringer and Chance, 1997). Some photons that leave the light source can reach the photodetector by typically following a banana-shaped path in the tissue, but the remaining photons are either dispersed away from the photodetector or absorbed by chromophores present in the tissue, including oxy- and deoxy-hemoglobin and cytochrome c oxidase (Bonner et al., 1987; Gratton et al., 1994). Because oxy- and deoxy-hemoglobin are the main absorbers of near-infrared light with distinct absorption spectra, the relative changes in these chromophores in a target region can be assessed by measuring the absorption of light at two wavelengths, one of which is more sensitive to oxy-hemoglobin and the other to deoxy-hemoglobin (Ferrari and Quaresima, 2012). In other words, the local changes in the hemodynamic response can be determined by using a modified version of the Beer-Lambert law, with the light intensities at the source and detector (León-Carrion and León-Domínguez, 2012). In order to measure the absolute amount of these chromophores in the tissue, rather than the relative changes, more sophisticated fNIRS approaches such as a time-resolved system are required. This technique has been validated by the strong correlation observed between the hemodynamic responses measured by fNIRS and by other standard imaging techniques such as fMRI (Ferrari and Quaresima, 2012; Kleinschmidt et al., 1996).

fNIRS has distinct strengths and limitations when compared to other neuroimaging techniques. The temporal resolution of this technique is better than that of fMRI and PET, whereas the spatial resolution is better than that of MEG and EEG, but lower than that of fMRI and PET. One of the major limitations of fNIRS is its shallow imaging depth, which is the result of an exponential attenuation of light intensity as it travels through the scalp and skull and then penetrates through the brain tissue (Bunce et al., 2006; Irani et al., 2007). It has been shown that the imaging depth is influenced by certain factors such as the wavelength and intensity of light, the optical properties of the tissue (such as skin color), and the distance between the light source and the photodetector (Ferrari and Quaresima, 2012; León-Carrion and León-Domínguez, 2012). In general, the more intense the light and/or the further the distance between the light source and the photodetector, the deeper the light can penetrate into the tissue (Ferrari and Quaresima, 2012). However, there are realistic constraints to these parameters, in that the light intensity should be kept much lower than the safety limit in order to avoid skin damage caused by the associated heat, and the distance between the light source and photodetector should be close enough to transmit and receive signals efficiently (Villringer and Chance, 1997). Thus, the imaging depth of fNIRS is generally limited to the surface of the cortex in the case of humans (Sakudo, 2016).

Despite these few limitations, fNIRS offers many advantages. Because it uses a safe, low-energy near-infrared light, fNIRS can continuously and repeatedly measure the
hemodynamic response: this type of measurement is not possible with other imaging techniques that require the use of radioisotopes or contrast reagents. Its quietness and tolerance of motion artifacts make fNIRS ideal for use in infants, children, and patients who are uncomfortable with conventional imaging techniques that require confinement in an fMRI magnet, physical constraints, or exposure to loud noise. In addition, other features of fNIRS, including its compact, portable, and wireless design, allow researchers to conduct more physiologically and clinically relevant studies under natural and socially interactive settings. It is also notable that the cost of the fNIRS device and of each test session are much lower than those of other functional neuroimaging methods. Finally, fNIRS can be readily used in conjunction with implanted devices such as cochlear implants and other recording and stimulating equipment, including EEG and the transcranial magnetic stimulator (Boas et al., 2014; Bunce et al., 2006; Irani et al., 2007; León-Carrón and León-Dominguez, 2012; Lloyd-Fox et al., 2010).

APPLICATIONS OF fNIRS TO HUMAN SUBJECTS

Over the years, the fNIRS technique has received increasing attention as a new approach to complement other standard imaging techniques such as fMRI. Given its unique strengths, combining fNIRS with a variety of behavioral tests that assess cognitive, motor, and emotional functions offers great advantages not only in studying basic brain function in normal human subjects but also in identifying abnormalities in neuronal activity in the brain of patients suffering from neurological and psychiatric disorders.

The main features of fNIRS, such as its portability and lower susceptibility to motion artifacts, allow researchers to measure changes in cortical activity during diverse motor tasks, ranging from moving the fingers and hands in clicking a mouse or keyboard during a Stroop task or computer game (Carrien et al., 2016; Harmat et al., 2015; Kashou et al., 2016; Shortz et al., 2015) to those body movements requiring coordination, such as juggling (Carius et al., 2016) and balancing on a board (Herold et al., 2017), and even to those requiring fine motor skills, such as simulating surgery (Andreu-Perez et al., 2016) and flight (Choe et al., 2016; Gateau et al., 2015). In addition, several recent studies have investigated the effects of bodily and road conditions, such as fatigue (Xu et al., 2017), age (Foy et al., 2016), and road curve (Oka et al., 2015), on the hemodynamic responses of subjects during a driving simulation test. These studies found an activation of a number of brain regions that are known to be involved in cognitive and motor functions, including the prefrontal cortex (PFC), motor cortex, premotor cortex (PMC), and supplementary motor area (SMA).

By the same token, fNIRS has become an excellent tool for investigating conditions such as stroke and Parkinson’s disease (PD) that are primarily characterized by impaired movements. It has been shown that a significant increase in asymmetrical hemodynamic response occurs in a number of regions mediating motor functions, including the sensorimotor cortex (SMC), SMA, PMC, and PFC, when patients suffering from either stroke or PD perform motor-related tasks, including treadmill walking and postural perturbation tasks (Al-Yahya et al., 2016; Fujimoto et al., 2014; Maidan et al., 2015; 2016; Mihara et al., 2007; Miyai et al., 2002; Niewhof et al., 2016).

Because it is safe and flexible, fNIRS is well suited to studies of infants and children. For example, recent studies have demonstrated that lateral activation of the cerebral cortex occurs during language development (Altvater-Mackensen and Grossmann, 2016; Vannasimg et al., 2016). In addition, it has been reported that the activity of the medial PFC (Urawakawa et al., 2015) and inferior frontal and temporal regions (Lloyd-Fox et al., 2015) increases when infants interact with their parents and other infants, respectively. fNIRS has also been used to study neurodevelopmental disorders, such as attention deficit hyperactivity disorder (ADHD) and autism spectrum disorder (ASD), that occur mainly in infants and children. ADHD is characterized by the persistent symptoms of inattention, hyperactivity, and impulsivity (Faraone et al., 2005). By using behavioral tasks requiring attentiveness and concentration, fNIRS imaging has demonstrated that these ADHD-related symptoms are associated with low cerebral cortical activity in a number of regions, including the PFC, inferior prefrontal gyrus, middle prefrontal gyrus, supramarginal gyrus, and angular gyrus (Araki et al., 2015; Ichikawa et al., 2014; Inoue et al., 2012; Ishii-Takahashi et al., 2015; Kochel et al., 2015; Monden et al., 2015; Moser et al., 2009; Nagashima et al., 2014a; 2014b; 2014c; Negoro et al., 2010; Schecklmann et al., 2011b; Tsujimoto et al., 2013; Weber et al., 2005; Xiao et al., 2012; Yasumura et al., 2014). Similarly, frontal hypoactivity has been observed in ASD patients during behavioral tasks designed to assess social relations and communicative abilities that are dysfunctional or inappropriate in these patients (Iwazuku et al., 2013; Kajumura et al., 2015; Kita et al., 2011; Kuwabara et al., 2006; Minagawa-Kawai et al., 2009; Tamura et al., 2012; Xiao et al., 2012; Yasumura et al., 2014). Furthermore, the effect of neurofeedback training to improve facial processing in ASD patients has been assessed using fNIRS (Liu et al., 2017).

fNIRS imaging has also been used in patients suffering from schizophrenia and affective disorders such as depression, panic disorder, and posttraumatic stress disorder (PTSD) in order to explore cortical regions showing abnormal activity that may account for the inappropriate emotional responses found in patients with these disorders. Exposure to extreme stress can have long-lasting effects that often lead to psychological symptoms of PTSD, including memory deficits and poor health. It has been reported that the PFC of patients suffering from PTSD, for example, victims of the Tokyo subway sarin gas attack, exhibit complex changes in brain response, in that cortical activity increases dramatically when the person encounters an object associated with tragic and traumatic events (Matsuo et al., 2003a), but decreases when the person performs tasks requiring cognitive functions (Matsuo et al., 2003b). Consistent with earlier findings using other imaging techniques, a majority of fNIRS studies have found that patients suffering from major depression disorder show hypoactivation in PFC during cognitive tasks, suggesting the importance of the prefrontal function in symptoms associated with this disorder (Herrmann et al., 2016).
The fNIRS technique has been used in a variety of model animals, including non-human primates, sheep, dogs, pigs, and rodents. The advantages of model animals include the ready availability of invasive techniques, diverse disease models, genetically engineered models, and advanced molecular genetic tools (Franceschini et al., 2008). The number of fNIRS studies performed using animals is still far lower than that of human studies, probably because the clinical applications of this technique has been the primary consideration, and there are many other non-invasive and invasive methods already available for animals. However, recent studies have shown a potential for utilizing fNIRS in non-humans, with broad applicability to model animals.

fNIRS studies on non-human primates have focused on customizing and cross-validating this technique with other well-established methods, such as electrophysiological recordings (Zaidi et al., 2015). Previous studies have found a strong correlation between visual stimulus-elicited responses in the primary visual cortex and PFC of monkeys when measured by fNIRS and via electrodes in the same experiment (Wakita et al., 2010; Zaidi et al., 2015). Interestingly, one study has shown that the activity of the frontal region of monkeys increases in response to various visual stimuli and that the magnitude of the response varies depending on the type of visual stimuli, such as a flower, monkey, snake, or food (Lee et al., 2017). One study has shown a significant correlation between the hemodynamic response measured by fNIRS and the cortical field potentials detected by the epidural electrodes during a delayed working memory task in monkeys (Fuster et al., 2005). However, another study using the same behavioral paradigm has demonstrated that electrophysiological responses measured by EEG exhibit characteristics of complexity and fragmentation of the electrical frequencies, whereas the hemodynamic response obtained with fNIRS increases homogeneously and cumulatively, suggesting that the two methods measure slightly different aspects of the neural responses (Ardestani et al., 2016).

Unlike the fNIRS system used for primates, a mobile, miniaturized 8-channel wireless fNIRS system has been typically used to study sheep (Guldemann et al., 2015; Vogeli et al., 2014), goats (Gygax et al., 2013), and dogs (Gygax et al., 2015). To investigate cortical activities representing the affective state, fNIRS imaging has been performed on animals exposed to rich and stable versus poor and unpredictable housing conditions, hot and cold stimuli (Vogeli et al., 2015a), gentle grooming (Muehlemann et al., 2011), or video clips showing positive versus negative social interactions (Vogeli et al., 2015b). Although the effects of these stimuli on the emotional responses of the animals were inconsistent among studies, fNIRS imaging was able to monitor changes in hemodynamic activity in response to such stimuli in the same animals.

In rodents, a set of miniaturized optodes consisting of a light source and photodetector was placed on either the surface of the skull or brain using variable interoptode distances (approximately 400 µm-1.5 cm) and diverse array formations, depending on the brain region being targeted. A previous study using an adapted electrocorticography (a combination of optode and electrode) has demonstrated a strong correlation between the signals measured by EEG and by
fNIRS in the somatosensory cortex and auditory cortex when the rats were stimulated with an electric shock on the forepaw and by the speech sounds of humans, respectively, validating the efficacy of fNIRS in this model animal (Mahmoudzadeh et al., 2017). fNIRS was also shown to be able to detect the sequential activation of the primary and secondary somatosensory cortices and the motor cortex when an electrical stimulus was applied to the whiskers of rats, indicating that fNIRS is capable of detecting a subtle difference in the time sequence, thanks to its high sampling rate (Im et al., 2010). In rats, fNIRS has been used in a wide range of experiments to investigate the effect of diverse stimuli on brain activity, such as electrical stimulation of the somatosensory cortex (Lee et al., 2012), subcutaneous injections of amphetamine and nicotine (Crespi et al., 2005), and the transcranial direct-current stimulation of the barrel cortex (Han et al., 2014). Furthermore, fNIRS imaging has been applied to rodents experiencing epilepsy (Hoshi et al., 1985; Lee et al., 2010; Roche-Labarbe et al., 2010), stroke (Chang et al., 2007; Wolf et al., 1997), brain damage (Abookasis et al., 2013), or pain (He et al., 2012). For example, fNIRS imaging is capable of measuring an increased activity in various cortical and subcortical regions that have previously been shown to mediate pain when the animals are treated with noxious stimuli (e.g., subcutaneous formalin or a noxious pinch on the hindpaw).

In mice, fNIRS has been shown to be capable not only of identifying the correlated activity change in multiple cortical regions during seizures but also of distinguishing between different types of seizures that are classified according to their EEG signal patterns (Lee et al., 2010). Typically, brain activity in mice is measured by non-invasive methods such as fMRI and intrinsic signal optical imaging (Cui et al., 2014), as well as by invasive methods such as multi-photon microscopy and microendoscopy. Because fMRI is susceptible to motion artifacts, it is mainly used for anesthetized or movement-restricted animals (Grandjean et al., 2014; Jonckers et al., 2011; Martin et al., 2013). Multi-photon microscopy and microendoscopy, on the other hand, measure the fluorescent signal emitted by an activity marker exogenously expressed in neurons, such as a genetically encoded calcium indicator GCaMP, at the cellular level by imaging a target region in head-fixed or freely moving animals (Ghosh et al., 2011; Helmchen, 2009). Fiber photometry is another technique measuring the collective changes in fluorescence of an activity marker expressed in a target region using a fiber-optic cable installed just above the target region in freely moving animals (Kim et al., 2016; Packer et al., 2015). These recording techniques offer the ability to directly measure neuronal activity at high resolution in an awake animal, but they have the disadvantage of requiring expensive equipment and the expression of a neuroactivity marker in a target region (Girven and Sparta, 2017). In contrast, fNIRS offers a low-cost alternative for non-invasively or invasively measuring changes in activity in the cortical and subcortical regions of awake, behaving animals by using a set of fiber-optic cables that either transmit or capture photons in the target region (Fig. 2). If fNIRS could be integrated with optogenetics, a method enabling the manipulation of neuronal activity using a light-responsive protein called an opsin, it might be possible to monitor and manipulate neuronal activity using the same fiber-optic cables installed in a target region; this approach would permit the examination of correlations and causal relationships between regional activity and physiological or behavioral changes in the same animal (Fig. 2). If the fNIRS and optogenetic equipment were designed to control each other, it would be possible to maintain regional activity by continuously manipulating the activity using optogenetics according to the change in regional activity measured by fNIRS; such an approach might be useful for patients with brain disorders who often suffer from a sudden activity change in the brain.

![Fig. 2. Potential integration of optogenetics and fNIRS](image-url)
CONCLUSIONS

Since fNIRS was first developed in 1985, its usage has been increasing gradually. Most studies have focused on establishing and improving fNIRS technology, developing data analysis methods, and confirming the validity of the technique by reproducing the results obtained via other imaging techniques. Taking advantage of the strengths of fNIRS allows researchers to perform experiments that are either impossible or limited with other imaging techniques. With the new fNIRS technologies such as wireless and wearable devices and the hyperscanning system, fNIRS has great potential to provide novel insights into brain function by allowing the use of the technique under more ecologically relevant testing conditions. Finally, fNIRS can be developed into a low-cost option that would permit us to diagnose brain disorders using a more objective method based on brain activity and also to monitor the efficacy of therapeutic approaches during the course of treatment.

ACKNOWLEDGMENTS

This work was supported by the Basic Science Research Program (2017R1A2B4003351, H.L.) and the Brain Research Program (2016M3C7A1947307, H.L., U.L., and H.J.J.) of the National Research Foundation of Korea (NRF), funded by the Ministry of Sciences, ICT, and Future Planning; and the KBRI basic research program through Korea Brain Research Institute, funded by the Ministry of Sciences, ICT, and Future Planning (17-BR-04, H.L.). We thank Dr. Deborah McClellan for editorial assistance.

REFERENCES

Abookasis, D., Shochat, A., and Mathews, M.S. (2013). Monitoring hemodynamic and morphologic responses to closed head injury in a mouse model using orthogonal diffuse near-infrared light reflectance spectroscopy. J. Biomed. Optics 18, 045003.

Akiyoshi, J., Hieda, K., Aoki, Y., and Nagayama, H. (2003). Frontal brain hypoxia as a biological substrate of anxiety in patients with panic disorders. Neuropsychobiology 47, 165-170.

Al-Yahya, E., Johansen-Berg, H., Kischka, U., Zarei, M., Cockburn, J., and Dawes, H. (2016). Prefrontal cortex activation while walking under dual-task conditions in stroke: a multimodal imaging study. Brain 133, 14-20.

Andreu-Perez, J., Leff, D.R., Shetty, K., Darzi, A., and Yang, G.-Z. (2016). Disparity in frontal lobe connectivity on a complex bimanual motor task aids in classification of operator skill level. Brain Connectivity 6, 375-388.

Araki, A., Ikegami, M., Okayama, A., Matsumoto, N., Takahashi, S., Azuma, H., and Takahashi, M. (2015). Improved prefrontal activation in AD/HD children treated with atomoxetine: a NIRS study. Brain Dev. 37, 76-87.

Ardestanti, A., Shen, W., Darvas, F., Toga, A.W., and Fuster, J.M. (2016). Modulation of frontoparietal neurovascular dynamics in working memory. J. Cogn. Neurosci. 28, 379-401.

Ayaz, H., ONaral, B., Izzetoglu, K., Shewokis, P.A., McKendrick, R., and Parasuraman, R. (2013). Continuous monitoring of brain dynamics with functional near infrared spectroscopy as a tool for neuroergonomics research: empirical examples and a technological development. Front. Hum. Neurosci. 7, 871.

Azechi, M., lwase, M., lkezawa, K., Takahashi, H., Canuet, L., Kurimoto, R., Nakahashi, T., Ishi, R., Fukumoto, M., Ohi, K., et al. (2010). Discriminant analysis in schizophrenia and healthy subjects using prefrontal activation during frontal lobe tasks: a near-infrared spectroscopy. Schizophr. Res. 117, 52-60.

Baker, J.M., Liu, N., Cui, X., Vrticka, P., Saggard, M., Hosseini, S.M.H., and Reiss, A.L. (2016). Sex differences in neural and behavioral signatures of cooperation revealed by fNIRS hyperscanning. Sci. Rep. 6, 26492.

Boas, D.A., Elwell, C.E., Ferrari, M., and Taga, G. (2014). Twenty years of functional near-infrared spectroscopy: introduction for the special issue. Neuroimage 85, 1-5.

Bonner, R., Nossal, R., Havlin, S., and Weiss, G. (1987). Model for photon migration in turbid biological media. JOSA A 4, 423-432.

Burce, S.C., Izzetoglu, M., Izzetoglu, K., Onaral, B., and Pourrezaei, K. (2006). Functional near-infrared spectroscopy. IEEE Eng. Med. Biol. Mag. 25, 54-62.

Chari, D., Andra, C., Clauss, M., Ragert, P., Bunk, M., and Mehnert, J. (2016). Hemodynamic response alteration as a function of task complexity and expertise - an fNIRS study in jugglers. Front. Hum. Neurosci. 10, 126.

Carrieri, M., Petracca, A., Lancia, S., Moro, S.B., Brigadoi, S., Spezialetti, M., Ferrari, M., Placid, G., and Quaresima, V. (2018). Prefrontal cortex activation upon a demanding virtual hand-controlled task: a new frontier for neuroergonomics. Front. Hum. Neurosci. 10, 53.

Chance, B., Zhuang, Z., UnAh, C., Alter, C., and Litton, L. (1993). Cognition-activated low-frequency modulation of light absorption in human brain. Proc. Natl. Acad. Sci. USA 90, 3770-3774.

Chang, G., Wang, K., Hsu, C., and Chen, J. (2007). Development of functional near infrared spectroscopy system for assessing cerebral hemodynamics of rats with ischemic stroke. J. Med. Biol. Eng. 27, 207.

Choe, J., Coffman, B.A., Bergstedt, D.T., Ziegler, M.D., and Phillips, M.E. (2016). Transcranial direct current stimulation modulates neuronal activity and learning in pilot training. Front. Hum. Neurosci. 10, 34.

Chou, P.H., Lin, W.H., Lin, C.C., Hou, P.H., Li, W.R., Hung, C.C., Lin, C.P., Lan, T.H., and Chan, C.H. (2015). Duration of untreated psychosis and brain function during verbal fluency testing in first-episode schizophrenia: a near-infrared spectroscopy study. Sci. Rep. 5, 18069.

Crespi, F., Bandera, A., Donini, M., Heidbreder, C., and Rotavi, L. (2005). Non-invasive in vivo infrared laser spectroscopy to analyse endogenous oxy-haemoglobin, deoxy-haemoglobin, and blood volume in the rat CNS. J. Neurosci. Methods 145, 11-22.

Cui, G., Jun, S.B., Luo, G., Pham, M.D., Lovinger, D.M., Vogel, S.S., and Costa, R.M. (2014). Deep brain optical measurements of cell type-specific neural activity in behaving mice. Nat. Protocols 9, 1213.

Cutini, S., and Brigadoi, S. (2014). Unleashing the future potential of type–specific neural activity in behaving mice. Nat. Protocols 9, 1213.

Dong, H., and Zhang, X. (2017). Deception detection by hybrid-pair wireless fNIRS system. Int. J. Dig. Crime Forensic. (IJDCF) 9, 15-24.

Egashira, K., Matsuo, K., Nakashima, M., Watanuki, T., Harada, K., Nakano, M., Matusbara, T., Takahashi, K., and Watanabe, Y. (2015).
Blunted brain activation in patients with schizophrenia in response to emotional cognitive inhibition: a functional near-infrared spectroscopy study. Schizophr. Res. 162, 196-204.

Ehls, A.C., Herrmann, M.J., Pichita, M.M., and Fallgatter, A.J. (2007). Cortical activation during two verbal fluency tasks in schizophrenic patients and healthy controls as assessed by multi-channel near-infrared spectroscopy. Psychiatry Res. Neuroimaging 156, 1-13.

Faraone, S.V., Perlis, R.H., Doyle, A.E., Smoller, J.W., Goralnick, J.J., Holmgren, M.A., and Sklar, P. (2005). Molecular genetics of attention-deficit/hyperactivity disorder. Biol. Psychiatry 57, 1313-1323.

Ferrari, M., and Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. Neuroimage 63, 921-935.

Fox, P.T., and Raichle, M.E. (1986). Focal physiological uncoupling of cerebral blood flow and oxidative metabolism during somatosensory stimulation in human subjects. Proc. Natl. Acad. Sci. USA 83, 1140-1144.

Fox, P.T., Raichle, M.E., Mintun, M.A., and Dence, C. (1988). Nonoxidative glucose consumption during focal physiologic neural activity. Science 241, 462-464.

Foy, H.J., Runham, P., and Chapman, P. (2016). Prefrontal cortex activation and young driver behaviour: a fNIRS study. PLoS One 11, e0156512.

Franceschini, M.A., Nissili, I., Wu, W., Diamond, S.G., Bonmassar, G., and Boas, D.A. (2008). Coupling between somatosensory evoked potentials and hemodynamic response in the rat. Neuroimage 41, 189-203.

Fujimoto, H., Mihara, M., Hattori, N., Hatakenaka, M., Kawano, T., Yagura, H., Miyai, I., and Mochizuki, H. (2014). Cortical changes underlying balance recovery in patients with hemiplegic stroke. Neuroimage 85, 547-554.

Fuster, J., Guiou, M., Ardestani, A., Cannestra, A., Sheth, S., Zhou, Y.D., Toga, A., and Bodner, M. (2005). Near-infrared spectroscopy (NIRS) in cognitive neuroscience of the primate brain. Neuroimage 26, 215-220.

Gateau, T., Durantin, G., Lancelot, F., Scannella, S., and Dehais, F. (2015). Real-time state estimation in a flight simulator using fNIRS. PLoS One 10, e0121279.

Ghosh, K.K., Burns, L.D., Cocker, E.D., Nimgerjaehn, A., Ziv, Y., El Gamal, A., and Schnitzler, M.J. (2011). Miniaturized integration of a fluorescence microscope. Nat. Methods 8, 871-878.

Girven, K.S., and Sparta, D.R. (2012). Probing deep brain circuitry: new advances in in vivo calcium measurement strategies. ACS Chem. Neurosci. 8, 243-251.

Grandjean, J., Schroeter, A., Batata, I., and Rudin, M. (2014). Optimization of anesthesia protocol for resting-state fMRI in mice based on differential effects of anesthetics on functional connectivity patterns. Neuroimage 102, 838-847.

Gratton, G., Maier, J.S., Fabiani, M., Mantulin, W.W., and Gratton, E. (1994). Feasibility of intracranial near-infrared optical scanning. Psychophysiology 31, 211-215.

Guldinmann, K., Vogeli, S., Wolf, M., Wechsler, B., and Gygax, L. (2015). Frontal brain deactivation during a non-verbal cognitive judgement bias test in sheep. Brain Cogn. 92, 35-41.

Gygax, L., Refemann, N., Pilheden, T., Scholkmann, F., and Keeling, L. (2015). Dog behavior but not frontal brain reaction changes in repeated positive interactions with a human: a non-invasive pilot study using functional near-infrared spectroscopy (fNIRS). Behav. Brain Res. 287, 172-176.

Gygax, L., Refemann, N., Wolf, M., and Langbein, J. (2013). Prefrontal cortex activity, sympatho-vagal reaction and behaviour distinguishing between situations of fee reward and frustration in dwarf goats. Behav. Brain Res. 239, 104-114.

Han, C.H., Song, H., Kang, Y.-G., Kim, B.-M., and Im, C.-H. (2014). Hemodynamic responses in rat brain during transcranial direct current stimulation: a functional near-infrared spectroscopy study. Biomim. Optics Exp. 5, 1812-1821.

Harmat, L., de Manzano, O., Theorell, T., Hogman, L., Fischer, H., and Ullen, F. (2015). Physiological correlates of the flow experience during computer game playing. Int. J. Psychophysiol. 97, 1-7.

He, J.-W., Tian, F., Liu, H., and Peng, Y.B. (2012). Cerebrovascular responses of the rat brain to noxious stimuli as examined by functional near-infrared whole brain imaging. J. Neurophysiol. 107, 2853-2865.

Helmenf, C. (2009). Two-photon functional imaging of neuronal activity. In Frostig, R.D., editor., In vivo optical imaging of brain function., 2nd ed., Boca Raton (FL) (CRC Press/Taylor & Francis)., Chapter 2.

Herold, F., Orlowski, K., Bormel, S., and Muller, N.G. (2017). Cortical activation during balancing on a balance board. Hum. Mov. Sci. 57, 51-58.

Herrmann, M.J., Ehls, A.C., and Fallgatter, A.J. (2004). Bilaterally reduced frontal activation during a verbal fluency task in depressed patients as measured by near-infrared spectroscopy. J. Neuropsychiatr. Clin. Neurosci. 16, 170-175.

Holper, L., Wolf, M. (2011). Single-trial classification of motor imagery differing in task complexity: a functional near-infrared spectroscopy study. J. Neuroerg. Rehabil. 8, 34.

Holper, L., Muehlmann, T., Scholkmann, F., Eng, K., Kiper, D., and Wolf, M. (2010). Testing the potential of a virtual reality neurorehabilitation system during performance of observation, imagery and imitation of motor actions recorded by wireless functional near-infrared spectroscopy (fNIRS). J. Neuroerg. Rehabil. 7, 57.

Holper, L., Shalom, D.E., Wolf, M., and Sigman, M. (2011). Understanding inverse oxygenation responses during motor imagery: a functional near-infrared spectroscopy study. Eur. J. Neurosci. 33, 2318-2328.

Holper, L., Kobashi, N., Kiper, D., Scholkmann, F., Wolf, M., and Eng, K. (2012a). Trial-to-trial variability differentiates motor imagery during observation by low versus high responders: a functional near-infrared spectroscopy study. Behav. Brain Res. 229, 29-40.

Holper, L., Scholkmann, F., Shalom, D.E., and Wolf, M. (2012b). Extension of mental preparation positively affects motor imagery as compared to motor execution: a functional near-infrared spectroscopy study. Cortex 48, 593-603.

Holper, L., Scholkmann, F., and Wolf, M. (2012c). Between-brain connectivity during imitation measured by fNIRS. Neuroimage 63, 212-222.

Holper, L., Goldin, A.P., Shalom, D.E., Battro, A.M., Wolf, M., and Sigman, M. (2013). The teaching and the learning brain: a cortical hemodynamic marker of teacher-student interactions in the Socratic dialog. Int. J. Edu. Res. 59, 1-10.

Holper, L., Wolf, M., and Tobler, P.N. (2014). Comparison of functional near-infrared spectroscopy and electrodermal activity in assessing objective versus subjective risk during risky financial decision. Neuroimage 84, 833-842.

Hoshi, Y., Kobayashi, N., and Tamura, M. (1985). Interpretation of near-infrared spectroscopy signals: a study with a newly developed perfused rat brain model. J. Appl. Physiol. 90, 1657-1662.

Ichikawa, H., Nakato, E., Kanazawa, S., Shimamura, K., Sakuta, Y., Sakuta, R., Yamaguchi, M.K., and Kakigi, R. (2014). Hemodynamic response of children with attention-deficit and hyperactive disorder (ADHD) to emotional facial expressions. Neuropsychologia 63, 51-58.

Ikezawa, K., Iwase, M., Ishii, R., Azechi, M., Canuet, L., Ohi, K., Hak Yeong Kim et al.
Yasuda, Y., like, N., Kurimoto, R., Takahashi, H., et al. (2009). Impaired regional hemodynamic response in schizophrenia during multiple prefrontal activation tasks: a two-channel near-infrared spectroscopy study. Schizophr. Res. 108, 93-103.

Im, C.-H., Jung, Y.-J., Lee, S., Koh, D., Kim, D.-W., and Kim, B.-M. (2010). Estimation of directional coupling between cortical areas using near-infrared spectroscopy (NIRS). Opt. Express 18, 5730-5739.

Inoue, Y., Sakihara, K., Gunji, A., Ozawa, H., Kimiya, S., Shinoda, H., Kaga, M., and Inagaki, M. (2012). Reduced prefrontal hemodynamic response in children with ADHD during the go/nogo task: a NIRS study. Neuroreport 23, 55-60.

Irani, F., Platek, S.M., Bunse, S., Ruocco, A.C., and Chute, D. (2007). Functional near-infrared spectroscopy (fNIRS): an emerging neuroimaging technology with important applications for the study of brain disorders. Clin. Neuropsychol. 21, 9-37.

Ishii-Takahashi, A., Takizawa, R., Nishimura, Y., Kawakubo, Y., Hamada, K., Okuhata, S., Kawasaki, S., Kuvabara, H., Shimada, T., Todokoro, A., et al. (2015). Neuroimaging-aided prediction of the effect of methylphenidate in children with attention-deficit hyperactivity disorder: a randomized controlled trial. Neuropsychopharmacology 40, 2676-2685.

Iwanaga, R., Tanaka, G., Nakane, H., Honda, S., Imamura, A., and Ozawa, H. (2013). Usefulness of near-infrared spectroscopy to detect brain dysfunction in children with autism spectrum disorder when inferring the mental state of others. Psychiatry Clin. Neurosci. 67, 203-209.

Jiang, J., Bai, B.H., Peng, D.L., Zhu, C.Z., Liu, L., and Lu, C.M. (2012). Neural Synchronization during face-to-face communication. J. Neurosci. 32, 16064-16069.

Jobis, F.F. (1977). Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. Science 198, 1264-1267.

Jonckers, E., Van Audekerke, J., De Visscher, G., Van der Linden, A., and Verhoye, M. (2011). Functional connectivity fMRI of the rodent brain: comparison of functional connectivity networks in rat and mouse. PLoS One 6, e18876.

Kajiume, A., Aoyama-Setoyama, S., Saito-Hori, Y., Ishikawa, N., and Kobayashi, M. (2013). Reduced brain activity during imitation and observation of others in children with pervasive developmental disorder: a pilot study. Brain Behav. Funct. 9, 21.

Kashou, N.H., Giacherio, B.M., Nahhas, R.W., and Jadcherla, S.R. (2016). Hand-grasping and finger tapping induced similar functional near-infrared spectroscopy cortical responses. Neurophotonics 3, 025006.

Kim, K.C., Yang, S.J., Pichamonthy, N., Young, N.P., Kauvar, I., Jennings, J.H., Lerner, T.N., Berndt, A., Lee, S.Y., and Ramakrishnan, C. (2016). Simultaneous fast measurement of circuit dynamics at multiple sites across the mammalian brain. Nat. Methods 13, 325-328.

Kita, Y., Gunji, A., Inoue, Y., Goto, T., Sakihara, K., Kaga, M., Inagaki, M., and Hosokawa, T. (2011). Self-face recognition in children with autism spectrum disorders: a near-infrared spectroscopy study. Brain Dev. 33, 494-503.

Kleinschmidt, A., Obhir, H., Requardt, M., Berboldt, K.D., Dinnagl, U., Villinger, A., and Fröhle, J. (1996). Simultaneous recording of cerebral blood oxygen changes during human brain activation by magnetic resonance imaging and near-infrared spectroscopy. J. Cereb. Blood Flow Metabol. 16, 817-826.

Kochel, A., Schongassner, F., Feiet-Gsodam, S., and Schienle, A. (2015). Processing of affective prosody in boys suffering from attention deficit hyperactivity disorder: a near-infrared spectroscopy study. Soc. Neurosci. 10, 583-591.

Koike, S., Takizawa, R., Nishimura, Y., Takano, Y., Takayanagi, Y., Kino, M., Araki, T., Harima, H., Fukuda, M., Okazaki, Y., et al. (2011). Different hemodynamic response patterns in the prefrontal cortical subregions according to the clinical stages of psychosis. Schizophr. Res. 132, 54-61.

Kubota, Y., Toichi, M., Shimizu, M., Mason, R.A., Coconcea, C.M., Findling, R.L., Yamamoto, K., and Calabrese, J.R. (2005). Prefrontal activation during verbal fluency tests in schizophrenia—a near-infrared spectroscopy (NIRS) study. Schizophr. Res. 77, 65-73.

Kuwabara, H., Kasai, K., Takizawa, R., Kawakubo, Y., Yamasue, H., Rogers, M.A., Ishijima, M., Watanabe, K., and Kato, N. (2006). Decreased prefrontal activation during letter fluency task in adults with pervasive developmental disorders: a near-infrared spectroscopy study. Behav. Brain Res. 172, 272-277.

Lee, S., Lee, M., Koh, D., Kim, B.-M., and Choi, J.H. (2010). Cerebral hemodynamic responses to seizure in the mouse brain: simultaneous near-infrared spectroscopy-electroencephalography study. J. Biomed. Opt. 15, 037010-037018.

Lee, S., Koh, D., Jo, A., Lim, H.Y., Jung, Y.J., Kim, C.K., Seo, Y., Im, C.H., Kim, B.M., and Suh, M. (2012). Depth-dependent cerebral hemodynamic responses following direct cortical electrical stimulation (DCES) revealed by in vivo dual-optical imaging techniques. Opt. Express. 20, 6932-6943.

Lee, Y.A., Pollet, V., Kato, A., and Goto, Y. (2017). Prefrontal cortical activity associated with visual stimulus categorization in non-human primates measured with near-infrared spectroscopy. Behav. Brain Res. 317, 327-331.

Lein-Carrion, J., and Lein-Dominguez, U. (2012). Functional near-infrared spectroscopy (fNIRS): principles and neuroscientific applications. Neuroimaging-Methods (InTech), 47-74.

Liu, N., Cliffer, S., Pradhan, A.H., Lightbody, A., Hall, S.S., and Reiss, A.L. (2017). Optical-imaging-based neurofeedback to enhance therapeutic intervention in adolescents with autism: methodology and initial data. Neurophotonics 4, 011003.

Lloyd-Fox, S., Blasi, A., and Elwell, C. (2010). Illuminating the developing brain: the past, present and future of functional near infrared spectroscopy. Neurosci. Biobehav. Rev. 34, 269-284.

Lloyd-Fox, S., Szeplaki-Kollod, B., Yin, J., and Cisbora, G. (2015). Are you talking to me? Neural activations in 6-month-old infants in response to being addressed during natural interactions. Cortex 70, 35-48.

Macnab, A., and Shadgan, B. (2012). Biomedical applications of wireless continuous wave near infrared spectroscopy. Biomed. Spectroscopy and Imaging 1, 205-222.

Mahmoudzadeh, M., Dehaene-Lambertz, G., and Wallois, F. (2017). Electrophysiological and hemodynamic mismatch responses in rats listening to human speech syllables. PLoS One 12, e0173801.

Maidan, I., Bernad-Elazari, H., Gazit, E., Giladi, N., Hausdorff, J.M., and Mirelman, A. (2015). Changes in oxygenated hemoglobin link freezing of gait to frontal activation in patients with Parkinson disease: an fNIRS study of transient motor-cognitive failures. J. Neurool. 262, 899-908.

Maidan, I., Nieuwhof, F., Bernad-Elazari, H., Reelick, M.F., Bloem, B.R., Giladi, N., Deutsch, I.E., Hausdorff, J.M., Claassen, J.A.H., and Mirelman, A. (2016). The role of the frontal lobe in complex walking among patients with Parkinson’s disease and healthy older adults: an fNIRS study. Neurorehabil. Neural Repair 30, 963-971.

Martin, C., Zheng, Y., Sibson, N.R., Mayhew, J.E., and Berwick, J. (2013). Complex spatiotemporal haemodynamic response following sensory stimulation in the awake rat. Neuroimage 66, 1-8.

Marumo, K., Takizawa, R., Kinou, M., Kawasaki, S., Kawakubo, Y., Fukuda, M., and Kasai, K. (2014). Functional abnormalities in the left ventrolateral prefrontal cortex during a semantic fluency task, and their association with thought disorder in patients with schizophrenia.

Brain Recording Using Functional Near-Infrared Spectroscopy
Hak Yeong Kim et al.
Neuroimage 85; 518-526.

Negoro, H., Sawada, M., Iida, J., Ota, T., Tanaka, S., and Kishimoto, T. (2010). Prefrontal dysfunction in attention-deficit/hyperactivity disorder as measured by near-infrared spectroscopy. Child Psychiatry & Hum. Dev. 47, 193-203.

Nieuwhof, F., Reelick, M.F., Maidan, I., Mirelman, A., Hausdorff, J.M., Rikkers, M.G.O., Bloem, B.R., Muthalib, M., and Claassen, J.A. (2016). Measuring prefrontal cortical activity during dual task walking in patients with Parkinson's disease: feasibility of using a new portable fNIRS device. Pilot and feasibility studies 2, 59.

Nishimura, Y., Tanii, H., Fukuda, M., Kajiki, N., Inoue, K., Kajiy, H., Nishida, A., Okada, M., and Okazaki, Y. (2007). Frontal dysfunction during a cognitive task in drug-naive patients with panic disorder as investigated by multi-channel near-infrared spectroscopy imaging. Neurosci. Res. 59, 107-112.

Nishimura, Y., Tanii, H., Hara, N., Inoue, K., Kajiy, H., Nishida, A., Okada, M., and Okazaki, Y. (2009). Relationship between the prefrontal function during a cognitive task and the severity of the symptoms in patients with panic disorder: a multi-channel NIRS study. Psychiatry Res. Neuroimaging 172, 168-172.

Nozawa, T., Sasaki, Y., Sakaki, K., Yokoyama, R., and Kawashima, R. (2016). Interpersonal frontopolar neural synchronization in group communication: an exploration toward fNIRS hyperscanning of natural interactions. Neuroimage 132, 484-497.

Ogawa, S., Lee, T.-M., Kay, A.R., and Tank, D.W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. Proc. Natl. Acad. Sci. USA 87, 9868-9872.

Ohta, H., Yamagata, B., Tomioka, H., Takahashi, T., Yano, M., Nakagome, K., and Mimura, M. (2008). Hypofrontality in panic disorder and major depressive disorder assessed by multi-channel near-infrared spectroscopy. Depress. Anxiety 25, 1053-1059.

Oka, N., Yoshino, K., Yamamoto, K., Takahashi, H., Li, S., Sugimachi, T., Nakan, K., Suda, Y., and Kato, T. (2015). Greater activity in the right curve driving. PLoS One 10, e0127594.

Otto, H., Yamagata, B., Tomioka, H., Takahashi, T., Yano, M., Nakagome, K., and Mimura, M. (2008). Hypofrontality in panic disorder and major depressive disorder assessed by multi-channel near-infrared spectroscopy. Depress. Anxiety 25, 1053-1059.

Packer, A.M., Russell, L.E., Dalgleish, H.W., and Hausser, M. (2015). Simultaneous all-optical manipulation and recording of neural circuit activity with cellular resolution in vivo. Nat. Methods 12, 140-146.

Piper, S.K., Krueger, A., Koch, S.P., Mehner, J., Habermehl, C., Steinbrink, J., Obrig, H., and Schmitz, C.H. (2014). A wearable multi-channel fNIRS system for brain imaging in freely moving subjects. Neuroimage 85, 64-71.

Pu, S., Yamada, T., Yokoyama, K., Matsushima, K., Kobayashi, H., Sasaki, N., Mitani, H., Adachi, A., Kaneko, K., and Nakagome, K. (2011). A multi-channel near-infrared spectroscopy study of prefrontal cortex activation during working memory task in major depressive disorder. Neurosci. Res. 70, 91-97.

Pu, S.H., Nakagome, K., Yamada, T., Yokoyama, K., Matsushima, H., Mitani, H., Adachi, A., Nagata, I., and Kaneko, K. (2012). The relationship between the prefrontal activation during a verbal fluency task and stress-coping style in major depressive disorder: a near-infrared spectroscopy study. J. Psychiatr. Res. 46, 1427-1434.

Quan, W.X., Wu, T.N., Li, Z.H., Wang, Y.D., Dong, W.T., and Lv, B. (2015). Reduced prefrontal activation during a verbal fluency task in...
Brain Recording Using Functional Near-Infrared Spectroscopy
Hak Yeong Kim et al.

Chinese-speaking patients with schizophrenia as measured by near-infrared spectroscopy. Prog. Neuro-Psychopharmacol. Biol. Psychiatry 58, 51-58.

Quaresima, V., Giosue, P., Roncone, R., Casacchia, M., and Ferrari, M. (2009). Prefrontal cortex dysfunction during cognitive tests evidenced by functional near-infrared spectroscopy. Psychiatry Res. Neuroimaging 171, 252-257.

Roche-Labarbe, N., Zaaimi, B., Mahmoudzadeh, M., Osharina, V., Wallous, A., Nehlig, A., Grebe, R., and Wallous, F. (2010). NIRS-measured oxy- and deoxyhemoglobin changes associated with EEG spike-and-wave discharges in a genetic model of absence epilepsy: the GAERS. Epilepsia 57, 1374-1384.

Roy, C.S., and Sherrington, C.S. (1890). On the regulation of the blood-supply of the brain. J. Physiol. 11, 85-158.

Sakudo, A. (2016). Near-infrared spectroscopy for medical applications: current status and future perspectives. Clin. Chim. Acta 455, 181-188.

Schecklmann, M., Dresler, T., Beck, S., Jay, J.T., Febres, R., Haeusler, J., Jarzok, T.A., Reif, A., Pilchta, M.M., Ehls, A.C., et al. (2011a). Reduced prefrontal oxygenation during object and spatial visual working memory in unipolar and bipolar depression. Psychiatry Res. Neuroimaging 174, 378-384.

Schecklmann, M., Schaldecker, M., Aucktor, S., Brast, J., Kirchgassner, K., Muhlberger, A., Warnke, A., Gerlach, M., Fallgatter, A.J., and Romanos, M. (2011b). Effects of methylphenidate on activation and frontal and temporal brain oxygenation in children with ADHD. J. Psychiatr. Res. 45, 1446-1470.

Shimodera, S., Imai, Y., Kamiura, N., Morokuma, I., Fujita, H., Inoue, S., and Furukawa, T.A. (2012a). Mapping hypo- and hyperfrontality during letter fluency task in schizophrenia: a multi-channel near-infrared spectroscopy study. Schizophr. Res. 136, 63-69.

Shortz, A.E., Pickens, A., Zheng, Q., and Mehta, R.K. (2015). The effect of cognitive fatigue on prefrontal cortex correlates of neuromuscular fatigue in older women. J. Neuroeng. Rehab. 12, 115.

Takeshi, K., Nemoto, T., Fumoto, M., Arita, H., and Mizuno, M. (2010). Reduced prefrontal cortex activation during divergent thinking in schizophrenia: a multi-channel NIRS study. Prog. Neuro-Psychopharmacol. Biol. Psychiatry 34, 1327-1332.

Takizawa, R., Kasai, K., Kawakubo, Y., Marumo, K., Kawasaki, S., Yamasue, H., and Fukuda, M. (2008). Reduced frontopolar activation during verbal fluency task in schizophrenia: a multi-channel near-infrared spectroscopy study. Schizophr. Res. 99, 250-262.

Tamura, R., Kitamura, H., Endo, T., Abe, R., and Someya, T. (2012). Decreased leftward bias of prefrontal activity in patients with senile aphasia revealed by functional near-infrared spectroscopy. Psychiatry Res. Neuroimaging 203, 237-240.

Tang, H.H., Mai, X.Q., Wang, S., Zhu, C.Z., Krueger, F., and Liu, C. (2016). Ipsilateral brain synchronization in the right temporoparietal junction during face-to-face economic exchange. Soc. Cogn. Affect. Neurosci. 11, 23-32.

Tsujimoto, S., Yasumura, A., Yamashita, Y., Torii, M., Kaga, M., and Inagaki, M. (2013). Increased prefrontal oxygenation related to distractor-resistant working memory in children with attention-deficit/hyperactivity disorder (ADHD). Child Psychiatry Hum. Dev. 44, 678-688.

Urakawa, S., Takamoto, K., Ishikawa, A., Ono, T., and Nishijo, H. (2015). Selective medial prefrontal cortex responses during live mutual gaze interactions in human infants: an fNIRS study. Brain Topogr. 28, 691-701.

Vannasing, P., Florea, O., Gonzalez-Frankenberg, B., Tremblay, J., Paquette, N., Safi, D., Wallous, F., Lepore, F., Beland, R., Lassonde, M., et al. (2016). Distinct hemispheric specializations for native and non-native languages in one-day-old newborns identified by fNIRS. Neuropsychologia 84, 63-69.

Villringer, A., and Dimagl, U. (1995). Coupling of brain activity and cerebral blood flow: basis of functional neuroimaging. Cereb. Brain Metabol. Rev. 7, 240-276.

Villringer, A., and Chance, B. (1997). Non-invasive optical spectroscopy and imaging of human brain function. Trends Neurosci. 20, 435-442.

Vogeli, S., Lutz, J., Wolf, M., Wechsler, B., and Gygax, L. (2014). Valence of physical stimuli, not housing conditions, affects behaviour and frontal cortical brain activity in sheep. Behav. Brain Res. 267, 144-155.

Vogeli, S., Wolf, M., Wechsler, B., and Gygax, L. (2015b). Housing conditions influence cortical and behavioural reactions of sheep in response to videos showing social interactions of different valence. Behav. Brain Res. 284, 69-76.

von Luhmann, A., Herff, C., Heger, D., and Schultz, T. (2015). Toward a wireless open source instrument: functional near-infrared spectroscopy in mobile neuroergonomics and BCI applications. Front. Hum. Neurosci. 9, 617.

von Luhmann, A., Wabnitz, H., Sander, T., and Muller, K.R. (2017). M3BA: a mobile, modular, multimodal biosignal acquisition architecture for miniaturized EEG-NIRS-based hybrid BCI and monitoring, IEEE Trans. Biomed. Eng. 64, 1199-1210.

Wakita, M., Shibasaki, M., Ishizuka, T., Schnackenberg, J., Fujiawara, M., and Masataka, N. (2010). Measurement of neuronal activity in a macaque monkey in response to animate images using near-infrared spectroscopy. Front. Behav. Neurosci. 4, 31.

Watanabe, A., and Kato, T. (2004). Cerebrovascular response to cognitive tasks in patients with schizophrenia measured by near-infrared spectroscopy. Schizophr. Bull. 30, 435-444.

Weber, P., Lutschg, J., and Fahnentrich, H. (2005). Cerebral hemodynamic changes in response to an executive function task in children with attention-deficit hyperactivity disorder measured by near-infrared spectroscopy. J. Dev. Behav. Pediatr. 26, 105-111.

Wolf, T., Lindauer, U., Reuter, U., Back, T., Villringer, A., Einhaupl, K., and Dimagl, U. (1997). Noninvasive near infrared spectroscopy monitoring of regional cerebral blood oxygenation changes during peri-infarct depolarizations in focal cerebral ischemia in the rat. J. Cereb. Blood Flow Metab. 17, 950-954.

Xiao, T., Xiao, Z., Ke, X.Y., Hong, S.S., Yang, H.Y., Su, Y.L., Chu, K.K., Xiao, X., Shen, J.Y., and Liu, Y.J. (2012). Response inhibition impairment in high functioning autism and attention deficit hyperactivity disorder: evidence from near-infrared spectroscopy Data. PloS One 7, e46569.

Xu, L.W., Wang, B.T., Xu, G.C., Wang, W., Liu, Z.A., and Li, Z.Y. (2017). Functional connectivity analysis using fNIRS in healthy subjects during prolonged simulated driving. Neurosci. Lett. 640, 21-28.

Yasumura, A., Kokubo, N., Yamamoto, H., Yasumura, Y., Nakagawa, E., Kaga, M., Hiraki, K., and Inagaki, M. (2014). Neurobehavioral and hemodynamic evaluation of Stroop and reverse Stroop interference in children with attention-deficit/hyperactivity disorder. Brain Dev. 36, 97-106.

Zaidi, A.D., Munk, M.H., Schmidt, A., Risueno-Segovia, C., Bernard, R., Fetz, E., Logothetis, N., Birbaumer, N., and Sitaram, R. (2015). Simultaneous epidural functional near-infrared spectroscopy and cortical electrophysiology as a tool for studying local neurovascular coupling in primates. Neuroimage 120, 394-399.