Applications of Functional Near Infrared Imaging: Case Study on UAV Ground Controller

Kurtulus Izzetoglu[1], Hasan Ayaz[1], Justin Menda[1], Meltem Izzetoglu[1], Anna Merzagora[1], Patricia A.Shewokis[1,2], Kambiz Pourrezaei[1], and Banu Onaral[1]

[1] School of Biomedical Engineering, Science & Health Systems
[2] College of Nursing and Health Professions, Drexel University
Drexel University, Philadelphia, PA, U.S.A
{kurtulus.izzetoglu,ayaz,jm973,meltem,am396,shewokis, kambiz,banu.onaral}@drexel.edu

Abstract. Functional Near-Infrared (fNIR) spectroscopy is an emerging optical brain imaging technology that enables assessment of brain activity through the intact skull in human subjects. fNIR systems developed during the last decade allow for a rapid, non-invasive method of measuring the brain activity of a subject while conducting tasks in realistic environments. This paper introduces underlying principles and various fNIR designs currently applied to real-time settings, such as monitoring Unmanned Aerial Vehicle (UAV) operator's expertise development and cognitive workload during simulated missions.

Keywords: Near-infrared spectroscopy, optical brain imaging, fNIR, human performance assessment.

1 Introduction

Near infrared spectroscopy (NIRS) has been increasingly applied for the noninvasive measurement of changes in the relative ratios of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) during brain activation. In the late 1980s, Delpy designed and tested an NIRS instrument on newborn heads in neonatal intensive care [1]. In the late 1980s and early 1990s, Dr. Britton Chance and his colleagues, using pico-second long laser pulses, spearheaded the development of time-resolved spectroscopy techniques in an effort to obtain quantitative information about the optical characteristics of the tissue [2]. These efforts by Chance, Delpy [3] and others [4], expedited the translation of NIRS based techniques into a neuroimaging modality for various cognitive studies [5-9]. Based on the NIRS technique, the Drexel Optical Brain Imaging team has developed a functional brain monitoring prototype, called fNIR. The portable fNIR system enables the study of cortical cognition-related hemodynamic changes in various field conditions.

Neural activity has a direct relation with hemodynamic changes in the brain [10]. Research on brain-energy metabolism has elucidated the close link between hemodynamic and neural activity [11]. Traditional neuroimaging techniques, such as fMRI cannot be used to measure these hemodynamics for a variety of real-life applications that could yield important discoveries and lead to novel uses. By

D.D. Schmorrow and C.M. Fidopiastis (Eds.): FAC 2011, HCII 2011, LNAI 6780, pp. 608–617, 2011.

contrast, the fNIR system can be deployed to assess hemodynamic responses and help understand human brain activation by providing neurophysiological markers derived from neural responses to different experimental settings under field conditions. However, research should be conducted to establish the validity of the fNIR signal as well as to demonstrate the acquisition of accurate and viable signals under real-life conditions. Hence, in addition to general review of underlying principles and various fNIR designs currently applied to real-time settings, this paper also introduces the deployment of this emerging fNIR device to human performance assessment, such as monitoring the changes in UAV operator's level of expertise during simulated missions.

1.1 Physiological Principles of fNIR in Brain Activity Assessment

Understanding the brain energy metabolism and associated neural activity is important for realizing principles of fNIR spectroscopy in assessing brain activity. The brain has small energy reserves and the great majority of the energy used by brain cells is for processes that sustain physiological functioning [12]. Ames III [12] reviewed the studies on brain energy metabolism as related to function and reported that the oxygen (O_2) consumption of the rabbit vagus nerve increased 3.4-fold when it was stimulated at 10 Hz and O_2 consumption in rabbit sympathetic ganglia increased 40% with stimulation at 15 Hz. Furthermore, glucose utilization by various brain regions increased several fold in response to physiological stimulation or in response to pharmacological agents that affect physiological activity [12]. These studies provide clear evidence that large changes occur in brain energy metabolism in response to changes in activity. Moreover, based on this brain energy metabolism, methods and imaging modalities that measure deoxy-Hb and/or oxy-Hb, such as fNIR and fMRI, are implemented to provide correlates of brain activity through oxygen consumption by neurons. Because oxy-Hb and deoxy-Hb have characteristic optical properties in the visible and near-infrared light range, the change in concentration of these molecules during increase in brain activation can be measured using optical methods.

1.2 Physical Principles of fNIR in Brain Activity Assessment

Most biological tissues are relatively transparent to light in the near infrared range between 700-900 nm, largely because water, a major component of most tissues, absorbs very little energy at these wavelengths (Fig. 1). Within this window the spectra of oxy- and deoxy-hemoglobin are distinct enough to allow spectroscopy and measures of separate concentrations of both oxy-Hb and deoxy-Hb molecules [13]. This spectral band is often referred to as the 'optical window' for the non-invasive assessment of brain activation [14].

If wavelengths are chosen to maximize the amount of absorption by oxy-Hb and deoxy-Hb, changes in these chromophore concentrations cause alterations in the number of absorbed photons as well as in the number of scattered photons that leave the scalp. These changes in light intensity measured at the surface of the scalp are quantified using a modified Beer–Lambert law, which is an empirical description of optical attenuation in a highly scattering medium [3]. By measuring absorbance/scattering changes at two (or more) wavelengths, one of which is more sensitive to oxy-Hb and the other to deoxy-Hb, changes in the relative concentration of these chromophores can be calculated. Using these principles, researchers have demonstrated that it is possible to assess hemodynamic changes in response to brain activity through the intact skull in adult human subjects [15-19].

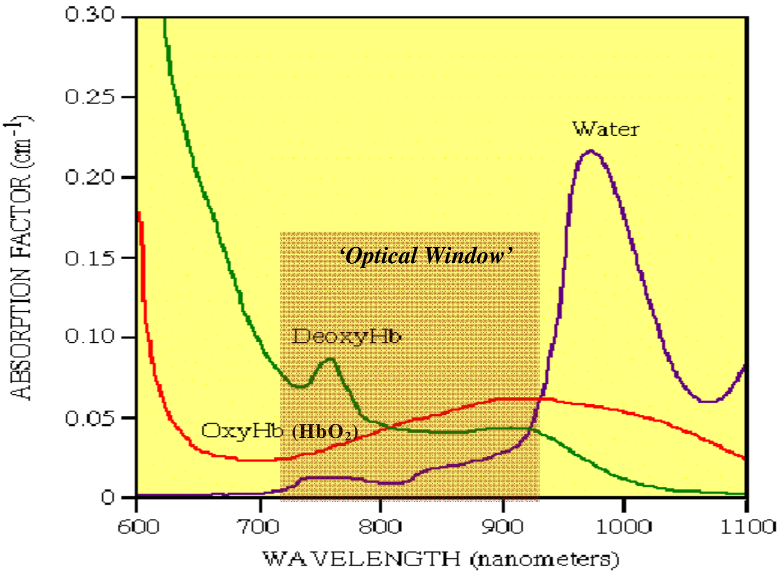

Fig. 1. Absorption spectrum in NIR window: spectra of oxy-Hb and deoxy-Hb in the range of 700 to 900 nm allow spectroscopy methods to assess oxy-Hb and deoxy-Hb concentrations, whereas water absorption becomes substantial above 900 nm, and thus majority of photons are mainly absorbed by water [13].

Typically, an optical apparatus consists of a light source by which the tissue is radiated and a light detector that receives light after it has interacted with the tissue. Photons that enter tissue undergo two different types of interaction, namely absorption and scattering. According to the modified Beer-Lambert Law [13], the light intensity after absorption and scattering of the biological tissue is expressed by the equation:

$$I=GI_o e^{-(\alpha_{HB} C_{HB} + \alpha_{HBO2} C_{HBO2})*L} \quad (1)$$

where G is a factor that accounts for the measurement geometry and is assumed constant when concentration changes. I_o is input light intensity, α_{HB} and α_{HBO2} are the molar extinction coefficients of deoxy-Hb and oxy-Hb, C_{HB} and C_{HBO2} are the concentrations of chromophores, deoxy-Hb and oxy-Hb respectively, and L is the photon path which is a function of absorption and scattering coefficients μ_a and μ_b.

By measuring optical density (OD) changes at two wavelengths, the relative change of oxy- and deoxy-hemoglobin versus time can be obtained. If the intensity measurement at an initial time is I_b (baseline), and at another time is I, the OD change due to variation in C_{HB} and C_{HBO_2} during that period is:

$$\Delta OD = \log_{10} \frac{I_b}{I} = (\alpha_{HB} \Delta C_{HB} + \alpha_{HBO_2} \Delta C_{HBO_2})L \quad (2)$$

Measurements performed at two different wavelengths allow the calculation of ΔC_{HB} and ΔC_{HBO_2}. Change in oxygenation and blood volume or total hemoglobin (Hbt) can then be deduced:

$$Oxygenation = \Delta C_{HBO_2} - \Delta C_{HB} \quad (3)$$

$$BloodVolume = \Delta C_{HBO_2} - \Delta C_{HB} \quad (4)$$

1.3 Near-Infrared Spectroscopy Based Brain Imaging Systems

The combined efforts of the researchers [3, 4, 15] led to the development of three distinct NIRS implementations, namely, time resolved spectroscopy (TRS), frequency domain and continuous wave (CW) spectroscopy [20]. In TRS systems, extremely short incident pulses of light are applied to tissue and the temporal distribution of photons that carry the information about tissue scattering and absorption is measured. In frequency domain systems, the light source is amplitude modulated with frequencies in the order of tens to hundreds of megahertz. The amplitude decay and phase shift of the detected signal with respect to the incident are measured to characterize the optical properties of tissue. In CW systems, light is continuously applied to tissue at constant amplitude. The CW systems are limited to measuring the amplitude attenuation of the incident light[20].

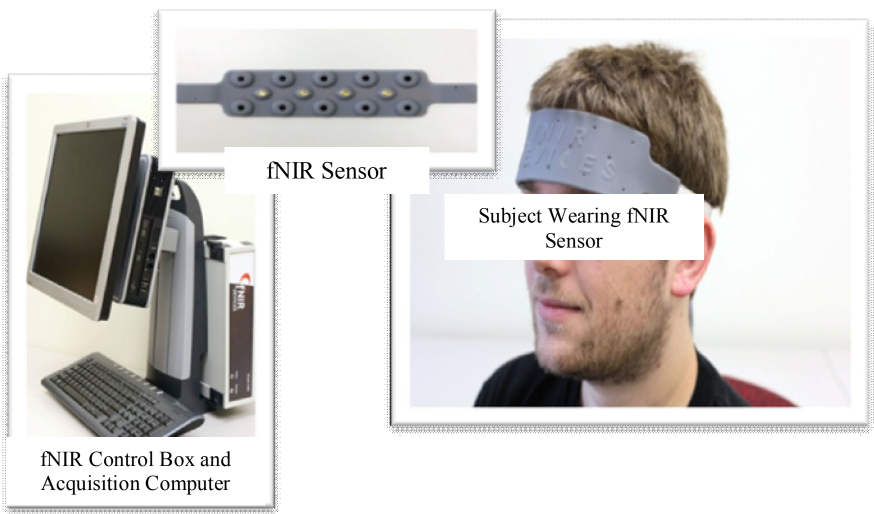

Fig. 2. Overview of the continuous wave 16-channel fNIR system

CW systems have a number of advantageous properties that have resulted in wide use by researchers interested in brain imaging relative to other near-infrared systems; it is minimally intrusive and portable, affordable, and easy to engineer relative to frequency and time domain systems [21]. These CW systems hold enormous potential for research studies and clinical applications that require the quantitative measurements of hemodynamic changes during brain activation under ambulant conditions in natural environments.

The continuous wave fNIR system used in this study was originally described by Chance et al. [15]. The current generation, flexible headband sensor developed in the Drexel's Optical Brain Imaging laboratory, consists of 4 LED light sources and 10 detectors (Figure 2).

The fNIR sensor, illustrated in Fig. 2, reveals information in localizing brain activity, particularly in dorsolateral prefrontal cortex. Fig. 3 shows the spatial map of the 16-channel fNIR sensor on the curved brain surface, frontal lobe [22].

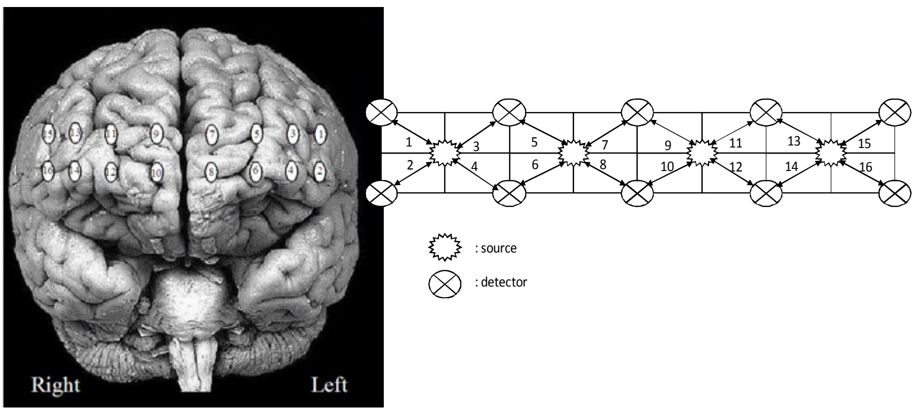

Fig. 3. Spatial map of the 16-channel fNIR sensor on the curved brain surface, frontal lobe

2 Method: Brain Activity Monitor during UAV Simulations

A 16-channel CW- fNIR system (Fig. 2) has been utilized to monitor the prefrontal cortex during simulated missions. An integrated simulation environment is constructed to allow novice participants to operate a simulated MQ-1 Predator UAV (Fig. 4). Missions and scenarios have been developed to represent a variety of tasks typical of UAV training and Predator operations, such as visual search/target categorization tasks and flight maneuvers [23].

To run the simulation reliably and with a high degree of realism, high performance hardware is specified, including an Intel Core i7 925 CPU and an nVidia GeForce GTX 280 graphics processor. The simulation is presented on a triple-display system by Digital Tigers, using 19" LCD monitors with 4:3 aspect ratios in a horizontal configuration (Fig. 5).

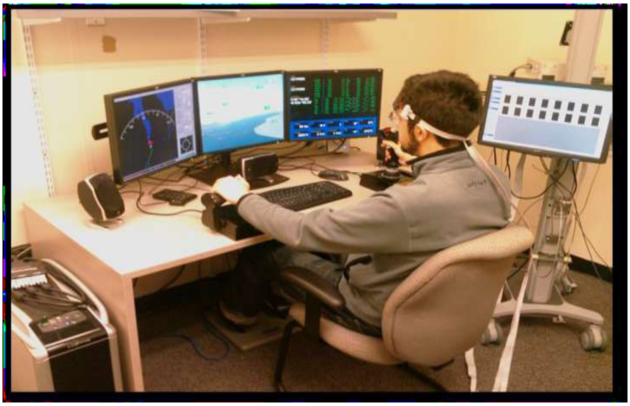

Fig. 4. Subject operating the Predator UAV simulator with fNIR sensor attached and data acquisition apparatus on far right

Fig. 5. Screenshot of flight simulation interface with Predator UAV add-on

Subjects control the simulated Predator UAV using a Thrustmaster HOTAS Cougar joystick-and-throttle system and a CH Pro Pedals rudder pedal system. FS Recorder, an add-on for Flight Simulator X, is implemented to record behavioural data during the simulated flights [23]. The time synchronization between fNIR recording and task events is facilitated by a custom application implemented to send event markers to the fNIR data acquisition computer via RS232.

2.1 Experimental Procedure

Prior to the study, all participants signed informed consent statements approved by the Human Subjects Institutional Review Board at Drexel University and by the U.S. Army Medical Research and Materiel Command (USAMRMC), Office of Research Protections (ORP), Human Research Protection Office (HRPO). The flight scenarios have been designed to represent a variety of tasks required of UAV operators (coordinate-based navigation, landing, visual search/target categorization, etc.) and to incorporate workload factors (e.g. crosswinds, cloud cover, fuel constraints, etc.). After an "introduction" session for the purpose of familiarization with the protocol and simulation, subjects fly these scenarios during eight subsequent flight sessions. Each subject performs one flight session per day, each lasting approximately two hours, for a total of 18 hours over 9 days per subject.

In the first session, after being given an overview of the experiment and providing informed consent, each subject completes the Edinburgh Handedness Inventory and a brief questionnaire regarding previous flight and video game experience. Then, the fNIR sensor is attached and subjects perform an intro flight of up to 1.5 hours, during which they are introduced to the UAV simulation. In sessions 2 through 9, each subject attempts one or more of the flight scenarios, with the fNIR sensor attached to the forehead and gathering data during the flight. At the end of each session, a confidence survey and the NASA-TLX are administered to allow subjects to self-rate overall performance.

2.2 Data Acquisition

Throughout the entire sessions, the following physiological and behavioral data were collected; i. fNIR sensor recordings acquired at every half second; ii. events including position, orientation, and velocity of the simulated aircraft in all three axes, and positions of all flight controllers (joystick, rudder pedals, throttle) recorded at 1/8 seconds intervals. A flexible fNIR sensor pad (Figs. 2 & 3) hosting 4 light sources with built in peak wavelengths at 730 nm and 850 nm is placed over subject's forehead to scan cortical areas. With a fixed source-detector separation of 2.5 cm, this configuration generates a total of 16 measurement locations per wavelength. For data acquisition and visualization, COBI Studio software (©2010, Drexel University) was used. Raw light intensity measures were low-pass filtered with a finite impulse response, linear phase filter with order of 20 and cut-off frequency of 0.1Hz to attenuate the high frequency noise. Using filtered raw fNIR measures, we calculated oxy-Hb, deoxy-Hb and blood volume (totalHb) using the formulas 1,2,3, and 4.

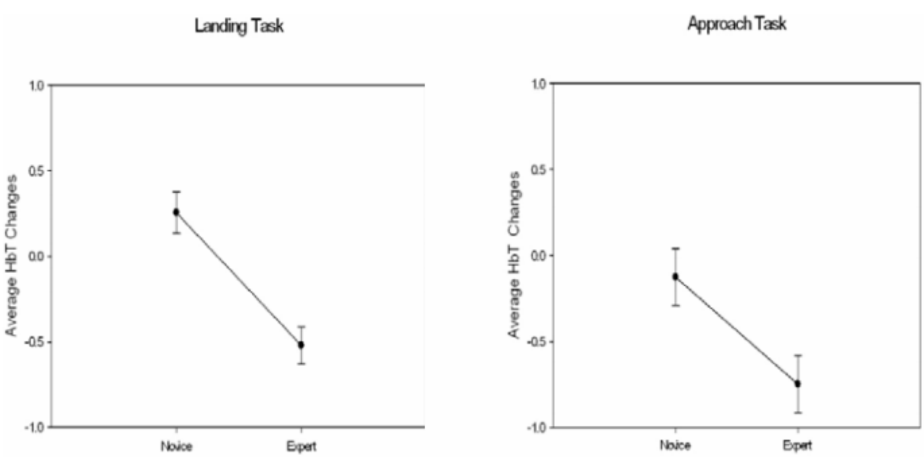

Fig. 6. Average blood volume (totalHb) changes in channel 2 during the transition from novice to expert. Left: Flight landing, and Right: Flight approach tasks. Error bars represent the standard error of the mean.

3 Results

For statistical analysis, repeated-measures ANOVA was used for the fNIR data to compare within subject factor of two expertise levels: novice (sessions 2, 3 & 4) versus expert (sessions 7, 8 & 9). The significance criterion for the tests was $\alpha = 0.05$. The same statistical analyses were performed for the flight approach and landing tasks.

There is a significant decrease in totalHb during the transitioning from novice to expert for both flight landing task ($F(1,4) = 13.00$; $p<0.005$) and flight approach task ($F(1,4) = 9.22$; $p<0.005$) (Fig. 6). The results also reveal that channel 2 (see Fig.3 for the spatial mapping) is the significant activation location. This area, left inferior frontal gyrus, was also reported to be sensitive to working memory by Ayaz et al [24] in the cognitive workload monitoring study for the air traffic controllers.

4 Discussion

This paper introduces a case study with a preliminary finding that fNIR, a portable optical brain imaging system, can monitor changes in level of expertise by measuring activation in the prefrontal areas relative to task performance. Decrease in the fNIR measures, shown in Fig. 6, is significant and a valid hypothesis can be derived from the evidence that expertise tends to be associated with overall lower brain activity relative to novices, particularly in prefrontal areas [25]. Both practice and the development of expertise typically involve decreased activation across attentional and control areas, freeing these neural resources to attend to other incoming stimuli or task demands. As such, measuring activation in these attentional and control areas relative to task performance can provide an index of level of expertise and illustrate how task-specific practice influences the learning of tasks. The differences in activation of the attentional and control regions of the prefrontal cortex may also indicate neural plasticity as a function of task-specific practice [26].

In summary, a field deployable optical brain imaging (fNIR) holds enormous potential for research studies and clinical applications that require the quantitative measurements of hemodynamic changes during brain activation under ambulant conditions in natural environments. As such, fNIR has been already deployed in many field settings for objective measurements of cognitive state and expertise development which will, among other advantages, allow for dynamic interventions in the training process, and helping to assure robust performance under adverse circumstances. Other fNIR application areas include, but are not limited to, brain computer interface for cognitive enhancement, neurological and gaming applications, pediatric solutions, education and training and cognitive aging.

Acknowledgments. The U.S. Army Medical Research Acquisition Activity, 820 Chandler Street, Fort Detrick, MD 21702-5014 is the awarding and administering acquisition office. This investigation was funded under a U.S. Army Medical Research Acquisition Activity; Cooperative Agreement W81XWH-08-2-0573. The content of the information herein does not necessarily reflect the position or the policy of the U.S. Government or the U.S. Army and no official endorsement should be inferred.

References

1. Delpy, D.T., Cope, M.C., Cady, E.B., Wyatt, J.S., Hamilton, P.A., Hope, P.L., Wray, S., Reynolds, E.O.: Cerebral monitoring in newborn infants by magnetic resonance and near infrared spectroscopy. Scand J. Clin. Lab. Invest Suppl. 17, 9–17 (1987)
2. Patterson, M.S., Chance, B., Wilson, B.C.: Time resolved reflectance and transmittance for the non-invasive measurement of tissue optical properties. Appl. Opt. 28, 2331–2336 (1989)
3. Cope, M., Delpy, D.T.: System for long-term measurement of cerebral blood and tissue oxygenation on newborn infants by near infra-red transillumination. Medical & Biological Engineering & Computing 26, 289–294 (1988)
4. Fishkin, J.B., Gratton, E.: Propagation of photon-density waves in strongly scattering media containing an absorbing semi-infinite plane bounded by a straight edge. J. Opt. Soc. Am. A 10, 127–140 (1993)
5. Okada, F., Takahashi, N., Tokumitsu, Y.: Dominance of the nondominant hemisphere in depression. J. Affect Disord. 37, 13–21 (1996)
6. Villringer, A., Chance, B.: Non-invasive optical spectroscopy and imaging of human brain function. Trends in Neurosciences 20, 435–442 (1997)
7. Obrig, H., Villringer, A.: Near-infrared spectroscopy in functional activation studies. Can NIRS demonstrate cortical activation? Advances in Experimental Medicine and Biology 413, 113–127 (1997)
8. Boas, D.A., Gaudette, T., Strangman, G., Cheng, X., Marota, J.J.A., Mandeville, J.B.: The accuracy of near infrared spectroscopy and imaging during focal changes in cerebral hemodynamics. NeuroImage 13, 76–90 (2001)
9. Izzetoglu, K., Bunce, S., Onaral, B., Pourrezaei, K., Chance, B.: Functional optical brain imaging using near-infrared during cognitive tasks. International Journal of Human-Computer Interaction 17, 211–227 (2004)
10. Kruggel, F., von Cramon, D.Y.: Temporal properties of the hemodynamic response in functional MRI. Hum Brain Mapp 8, 259–271 (1999)
11. Magistretti, P.J.: Cellular bases of functional brain imaging: insights from neuron-glia metabolic coupling. Brain Res. 112, 108–112 (2000)
12. Ames, A.: CNS energy metabolism as related to function. Brain Res. Rev. 34, 42–68 (2000)
13. Cope, M.: The application of near infrared spectroscopy to non-invasive monitoring of cerebral oxygenation in the newborn infant. vol. Ph.D. University of London (1991)
14. Jobsis, F.F.: Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. Science 198, 1264–1267 (1977)
15. Chance, B., Zhuang, Z., Unah, C., Alter, C., Lipton, L.: Cognition-Activated Low-Frequency Modulation of Light-Absorption in Human Brain. P. Natl. Acad. Sci. 90, 3770–3774 (1993)
16. Gratton, G., Corballis, P.M., Cho, E., Fabiani, M., Hood, D.C.: Shades of gray matter: noninvasive optical images of human brain responses during visual stimulation. Psychophysiology 32, 505–509 (1995)
17. Hoshi, Y., Tamura, M.: Dynamic multichannel near-infrared optical imaging of human brain activity. J. Appl. Physiol. 75, 1842–1846 (1993)
18. Kato, T., Kamei, A., Takashima, S., Ozaki, T.: Human visual cortical function during photic stimulation monitoring by means of near-infrared spectroscopy. J. Cereb. Blood Flow Metab. 13, 516–520 (1993)

19. Villringer, A., Planck, J., Hock, C., Schleinkofer, L., Dirnagl, U.: Near infrared spectroscopy (NIRS): a new tool to study hemodynamic changes during activation of brain function in human adults. Neurosci. Lett. 154, 101–104 (1993)
20. Strangman, G., Boas, D.A., Sutton, J.P.: Non-invasive neuroimaging using near-infrared light. Biol. Psychiatry 52, 679–693 (2002)
21. Chance, B., Anday, E., Nioka, S., Zhou, S., Hong, L., Worden, K., Li, C., Murray, T., Ovetsky, Y., Pidikiti, D., Thomas, R.: A novel method for fast imaging of brain function, non-invasively, with light. Opt. Express 2, 411–423 (1998)
22. Ayaz, H., Izzetoglu, M., Platek, S.M., Bunce, S., Izzetoglu, K., Pourrezaei, K., Onaral, B.: Registering fNIR data to brain surface image using MRI templates. Conf. Proc. IEEE Eng. Med. Biol. Soc. 1, 2671–2674 (2006)
23. Menda, J., Hing, J.T., Ayaz, H., Shewokis, P.A., Izzetoglu, K., Onaral, B., Oh, P.: Optical Brain Imaging to Enhance UAV Operator Training, Evaluation, and Interface Development. J. Intell. Robotics Syst. 61, 423–443 (2011)
24. Shewokis, P.A., Izzetoglu, K., Hah, S., Deshmukh, A., Onaral, B.: Cognitive Workload Assessment of Air Traffic Controllers Using Optical Brain Imaging Sensors. In: Marek, T., Karwowski, W., Rice, V. (eds.) Advances in Understanding Human Performance: Neuroergonomics, Human Factors Design, and Special Populations, pp. 21–32. CRC Press, Boca Raton (2010)
25. Milton, J.G., Small, S.S., Solodkin, A.: On the road to automatic: dynamic aspects in the development of expertise. J. Clin. Neurophysiol. 21, 134–143 (2004)
26. Kelly, A.M., Garavan, H.: Human functional neuroimaging of brain changes associated with practice. Cereb Cortex 15, 1089–1102 (2005)