Investigation of Functional Near Infrared Spectroscopy in Evaluation of Pilot Expertise Acquisition

Gabriela Hernandez-Meza[1(✉)], Lauren Slason[2], Hasan Ayaz[1], Patrick Craven[2], Kevin Oden[3], and Kurtulus Izzetoglu[1]

[1] School of Biomedical Engineering, Science & Health Systems, Drexel University, Philadelphia, PA, USA
{gh88,hasan.ayaz,ki25}@drexel.edu
[2] Applied Informatics Group, CCI, Drexel University, Philadelphia, PA, USA
{lrs75,plc35}@drexel.edu
[3] Lockheed Martin Corporation, Orlando, FL, USA
kevin.oden@lmco.com

Abstract. Functional Near-Infrared (fNIR) spectroscopy is an 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 examines the hemodynamic changes associated with expertise development during C-130j simulated flying missions.

Keywords: Near-infrared spectroscopy · Optical brain imaging · fNIR · Human performance assessment · Pilot training

1 Introduction

Improving the operational safety and efficacy of human-computer interactions is of interest for aerospace applications. Understanding the underlying neural processes that are associated with mental workload and expertise development is the first step in the development of a method for their accurate assessment. The current study is based on earlier work [24–30] that investigated the relationship of the hemodynamic response in the anterior prefrontal cortex to changes in mental workload, level of expertise, and task performance during learning of simulated piloting tasks utilizing functional near-infrared spectroscopy (fNIR).

fNIR is a safe, non-invasive and portable optical method that can be used to monitor activity within the prefrontal cortex of the human brain [15–22]. Making use of specific wavelengths of light fNIR provides measurements of oxygenated (oxy-Hb) and deoxygenated (deoxy-Hb) hemoglobin that are in direct relation with hemodynamic changes in the brain [2]. Research on brain-energy metabolism has elucidated the close link between hemodynamic and neural activity [3]. Traditional neuroimaging techniques, such as fMRI cannot be used to measure hemodynamic changes for a variety of

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real-life applications that could yield important discoveries and lead to novel uses. On the other hand, fNIR is well-suited for the flight simulator environment as it is capable of obtaining continuous measurements of the cerebral hemodynamics without restricting the testing location or the participant's movements.

In this paper we present an examination of the relationship between hemodynamic and performance measures as a C-130j pilot develops expertise during a flight simulator task. The main goals of this study is to understand the hemodynamic changes occurring in the pre-frontal cortex as an individual's expertise increases during flight simulator missions. Based on earlier work we hypothesize that a decrease in brain activity, measurable by fNIR, will occur as a result of skill acquisition in a flight simulator task.

To examine our hypothesis, 10 healthy adult individuals volunteered for a one day session consisting of eight trials in the flight simulator. Throughout the session the participants faced scenarios that reflected typical flying tasks while their behavioral and anterior prefrontal cortex (PFC) brain activation were recorded by Prepar3D and fNIR respectively.

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 [4]. 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 [4]. Oxygen is necessary for the metabolism of glucose and therefore for energy production. Oxygen is transported to the neural tissue via oxy-Hb which gives up the oxygen to the surrounding tissues in the capillary bed and is transformed to deoxy-Hb. The need for oxygen in active brain regions is satisfied by a rise in local cerebral blood flow (CBF) [23]. Based on the brain energy metabolism fNIR is capable of providing correlates of brain activity through the oxygen consumption of neurons via measurements of deoxy and/or oxy-Hb [27–34]. 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 increased 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 [5]. This spectral

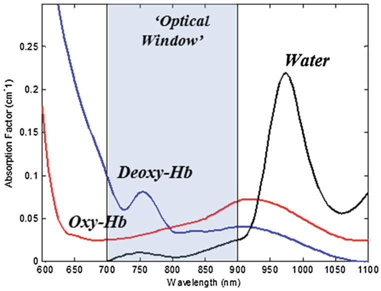

Fig. 1. Absorption spectrum in NIR window: spectra of oxy-Hb and deoxy-Hb in the range of 700 to 900 nm allows spectroscopy methods to assess oxy-Hb and deoxy-Hb concentrations, whereas water absorption becomes substantial above 900 nm, and thus majority of photons are mainly absorbed by water [5].

band is often referred to as the 'optical window' for the non-invasive assessment of brain activation [6].

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 [1]. By measuring absorbance/scattering changes at two wavelengths (730 nm and 850 nm), one of which is more sensitive to deoxy-Hb and the other to oxy-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 [7–11].

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 [5], the light intensity after absorption and scattering of the biological tissue is expressed by the equation:

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

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:

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

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

$$Oxygenation = \Delta C_{HBO_2} - \Delta C_{HB} \tag{3}$$

$$BloodVolume = \Delta C_{HBO_2} - \Delta C_{HB} \tag{4}$$

1.3 Near-Infrared Spectroscopy Based Brain Imaging Systems

The continuous wave (CW) fNIR system used in this study was originally described by Chance et al. [7]. The current generation consists of a flexible headband sensor with 4 LED light sources and 10 detectors (Fig. 2) and was developed in the Drexel's Optical Brain Imaging laboratory. 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 [33].

CW systems have a number of advantageous properties that have resulted in wide use by researchers interested in brain imaging. Compared to other near-infrared systems it is minimally intrusive and portable, affordable, and easy to engineer relative to frequency and time domain systems [12].

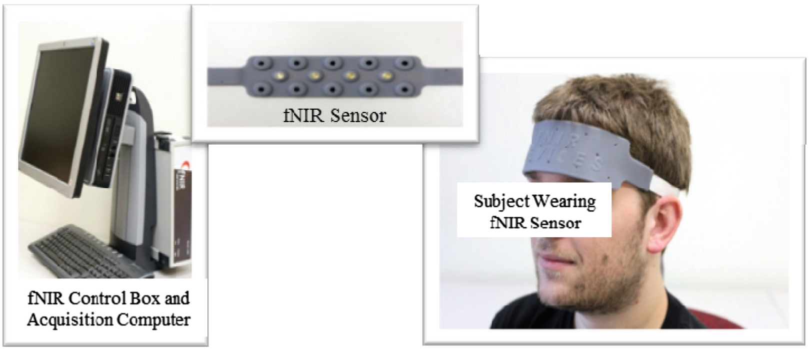

Fig. 2. Overview of the continuous wave 16-channel fNIR system

The fNIR sensor, illustrated in Fig. 2, reveals information in localizing brain activity, particularly in dorsolateral prefrontal cortex. Figure 3 shows the spatial map of the 16-channel fNIR sensor on the curved brain surface, frontal lobe [13].

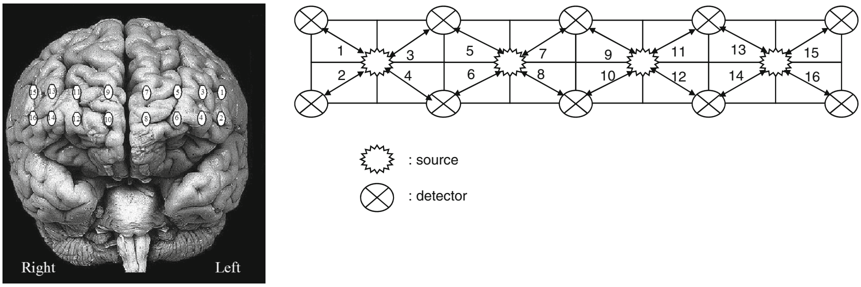

Fig. 3. Spatial map of the 16-channel fNIR sensor on the curved brain surface, frontal lobe

2 Method: Brain Activity Monitor During C-130j Flight Simulations

During each session the prefrontal cortex of the subjects was monitored using a 16 channel CW-fNIR system from the start until the end of the session. The simulation environment was constructed using Prepar3D (©2014, Lockheed Martin Corporation) with a model of a C-130 J airplane. The flight scenarios were developed to allow for the evaluation of skill development during a series of eight scenarios within the mission. The simulated scenarios reflect typical flying tasks such as adhering to a heading and altitude provided by an air traffic controller, navigation to way points, controlling vertical speed, completion of smooth turns, and following safety guidelines for the C130-J.

Fig. 4. Screenshot of prepared3D C-130j flight simulation

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 GT × 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. 4).

The C-130 J simulator is controlled using the Saitek Pro Flight Yoke System. The research team developed customized logging software that tracked specific performance-related values within the simulator environment, and real-time algorithms calculated feedback to the participants during the course of the trials as well as logged

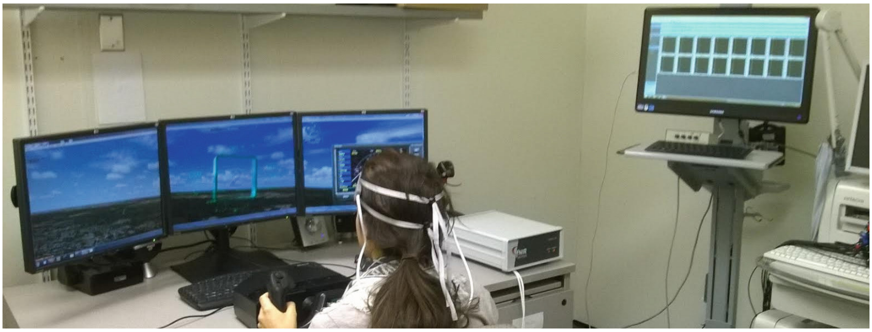

Fig. 5. Subject operating the C-130j simulator with fNIR sensor attached and data acquisition apparatus on far right.

performance values for later analysis. This custom software then communicated specific events for fNIR recording via serial port which allows time synchronization and the delivery of markers to the fNIR data acquisition computer (Fig. 5).

2.1 Experimental Procedure

Prior to the study, all participants are given an overview of the experiment and signed approved informed consent statements. After being given an overview of the experiment and providing informed consent, each subject completes (a) the Edinburgh Handedness Inventory, (b) a background questionnaire, and (c) a brief questionnaire regarding previous flight and video game experience. The flight scenarios were developed in conjunction with both an experienced C-130 pilot and an air traffic controller, and was designed to simulate a circuit (e.g., see Fig. 6). The scenarios require the subject to adhere to a heading and altitude provided by an air traffic controller, navigate to way points, control vertical speed, complete smooth turns, and follow safety guidelines for the C-130 J in the vicinity of New Castle Airport, home of the 166th Airlift Wing of the Delaware Air National Guard.

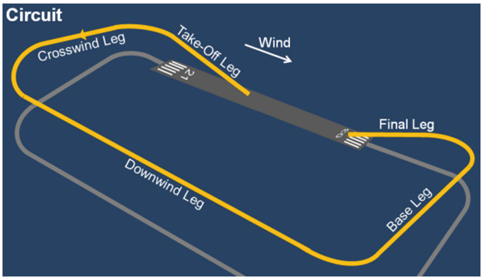

Fig. 6. Example of flight circuit around an airport

Each subject performs one flight session lasting approximately one hour. During the session the participants are first presented with a theoretical introduction to promote familiarization with the controls, a brief explanation of select aviation concepts, flight tasks within the scenario and how to complete these tasks. Subjects then proceed to fly the C-130 J plane in a mock scenario where they can familiarize themselves with the flight controls and expected task. The fNIR sensor is then placed on the participant's forehead and they fly the plane during a one hour session that contains eight scenarios or trials. The scenarios consist of a series of gates placed on a flight path that the participants will attempt to reach by flying the C-130 J plane. The subject begins at a heading of five degrees and an altitude of 950 feet shortly beyond the end of the runway 10 at the beginning of every scenario. From there, the subject begins a box pattern with waypoints marked to assist in following the pattern. In order to guide the inexperienced participants, the waypoints are displayed as large gates floating in space. The participant will complete more sections of the box pattern with each successive scenario by adding additional gates along the flight path. By the sixth and seventh scenario, the participant is expected to complete a full box pattern and pass through 10 gates. The subject is then presented with a modified flight path and gates for the 8th scenario. A schematic of the gates completed in each trial is presented in Fig. 7.

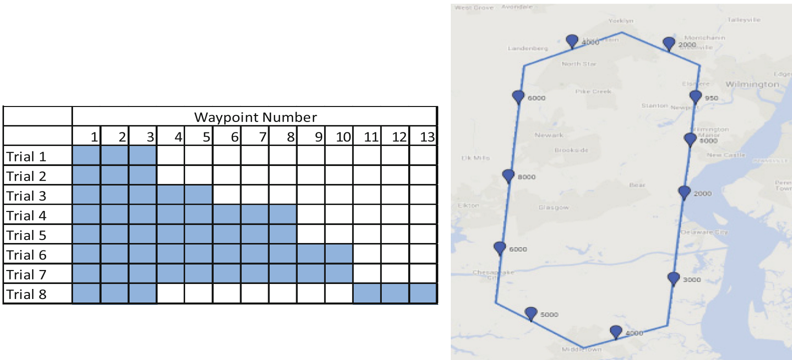

Fig. 7. Schematic of gates/waypoints per trial and map of flight circuit with labeled waypoints

2.2 Data Acquisition

Throughout the entire session, the following physiological and performance measures were collected: i. fNIR sensor recordings acquired at every half second; ii. events including the heading, bearing, relative bearing, distance from gate center and scores for heading, altitude, and smoothness of the approach upon gate completion within the Prepar3D scenario, iii. events including the C130-J's altitude, heading (true and magnetic), bearing, relative bearing, bank, pitch, latitude, longitude, airspeed, vertical speed, roll and yaw in addition to the gear, flaps, throttle and yoke controller positions recorded at 1/8 s intervals. A flexible fNIR sensor pad (Figs. 2 and 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.

2.3 Participants

Ten participants between ages of 18 and 28 with varying levels of 3D videogame experience volunteered for this study. The volunteers consisted of five male and five female participants. Prior to the study all participants signed informed consent forms approved by the Drexel University Institutional Review Board.

2.4 Data Analysis

For each participant, raw light intensity measures (16 optodes x 2 wavelengths) were low-pass filtered with a finite impulse response, linear phase filter with order of 20 and cut-off frequency of 0.1 Hz to attenuate the high frequency noise, respiration and cardiac cycle effects. Saturated and undervalued channels were excluded from analysis. fNIR data epochs for each task period were extracted using event markers recorded during task execution. Oxygenation (Oxy) within each of the 16 optodes was calculated from the difference between the calculated oxy-Hb and deoxy-Hb values using the modified Beer Lambert Law for each waypoint task period with respect to a 10 s baseline.

The main effect of expertise acquisition during the tasks was tested using two-way repeated measured analysis of variance (ANOVA), with subject, waypoint and trial as fixed effects. Greenhouse-Geisser (G-G) correction was used when violations of sphericity occurred in the omnibus test. The False Detection Rate (FDR) was applied to control for type I error [31, 32]. For this analysis, only the first 3 waypoints were evaluated as they are ones purposely repeated across all trials. Intergroup differences for significant optodes were examined using Tukey's post hoc test with a significance criterion of $\alpha = 0.05$. Additionally, to determine differences in oxygenation related to skill acquisition or expertise level in the flight simulator task, the trials were divided into *Initial* trials (mean of the first 3 waypoints during the first 3 scenarios) and *Final* trials (mean of the first 3 waypoints during the last 3 scenarios). Differences in oxygenation between the Initial trials and Final trials groups were tested in significant optodes using repeated measures ANOVA with subject and expertise level as fixed effects.

A variety of behavioral measures were generated from the logged simulator data in order to determine the participant's skill in navigating the scenario trials. These measures included *average heading difference*, *average altitude difference*, *average deviation from x and y* in coordinate space, and *average distance* from the gate. Average scores were calculated for each of these measures as high level view of an individual's overall performance, and these scores were compared (correlated using Pearson's product-moment correlation coefficient) with the survey results to see how demographic information relates to performance.

3 Results

3.1 fNIR Measures

The average oxygenation (Oxy) concentration change throughout the first 3 waypoints in each trial was analyzed using two-way repeated measures ANOVA for each optode. The response was significant after applying FDR for Trial in optodes 4 and 6 ($F(7,49) = 4.609$, $p = 0.001$ and $F(7,49) = 5.268$, $p < 0.001$ respectively) and reveals a decrease in oxygenation across trials as expected from previous result and in support of the hypothesis of this study (see Fig. 8A). The effect of the waypoints was not found to be significant ($p > 0.05$). Tukey Post hoc test for optode 6 revealed significant differences between trial 1 ($M = 0.50$, $SD = 0.96$) and trials 5 ($M = -0.17$, $SD = 0.42$), 6 ($M = -0.013$, $SD = 0.46$) and 8 ($M = -0.01$, $SD = 0.49$). A decrease in brain oxygenation as a function of expertise development was observed, see Fig. 8B where oxygenation is calculated as a function of *Initial* trials and *Final* trials. The difference in oxygenation between *Initial* and *Final* trials was found to be significant in optode 4 ($F(1,1) = 8.879$, $p = 0.021$) and optode 6 ($F(1,1) = 10.782$, $p = 0.013$).

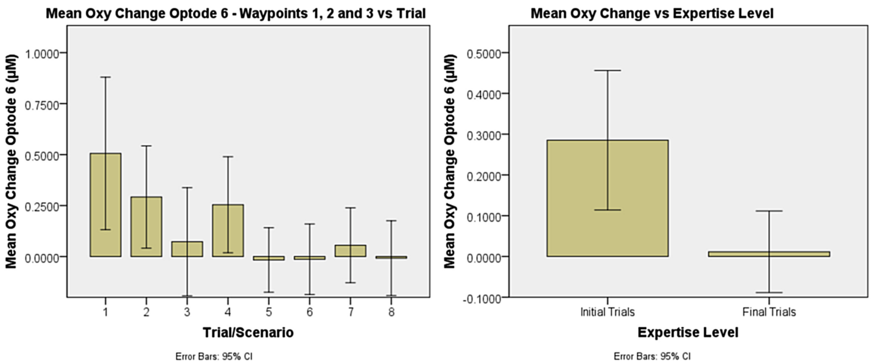

Fig. 8. A and B. (A). Mean Oxygenation Change in Optode 6 for Waypoints 1, 2 and 3 during 8 Trials. (B) Mean Oxy Change for Waypoints 1, 2 and 3 during Initial and Final Trials. Error bars represent the 95 % Confidence interval.

3.2 Behavioral Measures

The questionnaire responses were related to the prime behavioral measures, and the following results were observed. Participants' reported hours playing video games was correlated with both altitude difference ($r = -.246$, $p < .05$) and heading difference ($r = -.252$, $p < .05$), with smaller differences (i.e., better performance) were associated with more hours playing video games. These results were echoed in the more specific question asking participant's hours playing first-person video games in which the response was related to deviation from the airplane's optimal x ($r = -.295$, $p < .05$) and y ($r = -.303$, $p < .05$) position in coordinate space. Finally, performance results suggest that age matters and that a participant's age correlated with heading difference

($r = -.312$, $p < .01$), x deviation ($r = -.305$, $p < .05$), and y deviation ($r = -.272$, $p < .05$). It must be noted that all of the participants were between 18 and 28 years of age.

4 Discussion

The goal of this study was to examine the influence of pilot expertise development on the hemodynamic response in the prefrontal cortex during the complex cognitive task of flying a plane using a flight simulator.

The neurophysiological measures captured by fNIR show a decrease in oxygenation as the subjects become more proficient in the task. The oxygenation pattern that occurs in the process of skill acquisition during flight simulator task is consistent with neurophysiological results from previous work that examined expertise development using fNIR [24, 26, 27]. The significant differences observed between *Initial* and *Final* trials are hypothesized to be the result of expertise development, which is associated with lower brain activation in the prefrontal areas of the brain [14].

The results obtained in this study support the hypothesis that brain activity decreases (measured as Oxygenation by fNIR) as the level of expertise of a subject increases during flight simulator tasks.

The initial investigation of behavioral measures and how they relate to demographic survey responses reveal correlations in the expected direction. For example, a participants' reported hours playing video games was related to better performance, and reported hours playing first-person video games was related to one's ability to better maintain an ideal plane position in coordinate space. These results are in-line with similar studies revealing improved ability to manipulate objects in 3D space [34]. In addition, within the 18–28 age range of the participant population, age was positively related to performance. These results would be expected as the older participants within this range may benefit from increased experiences across a variety of domains without any associated decline of neural processing speed.

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