REVIEW ARTICLE

Pol J Aviat Med Bioeng Psychol 2019; 25(2): 24-37
DOI: 10.13174/pjambp.15.12.2020.03

NEAR-INFRARED SPECTROSCOPY IN HEALTHY SUBJECTS: POSSIBLE APPLICATION IN AVIATION AND AVIATION MEDICINE

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Source of support: The preparation of this manuscript was partially supported by the National Science Centre grant no 2016/23/B/HS6/03860 and the Institute of Psychology, PAS.

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Abstract: Functional near-infrared spectroscopy (fNIRS) is a non-invasive optical brain monitoring technology for mapping the functioning of the human cortex in response to sensory or motor activation. There is a growing interest in implementing fNIRS to monitor the cognitive performance of military pilots. The method relies on differences in hemoglobin absorption spectra depending on blood oxygenation. However, this method was relatively rarely utilized in aviation and aviation medicine. Therefore, we will provide a broad review of applying this method in various avenues of medicine and cognitive psychology, as well as cover its documented use in aviation and aviation medicine.

In this review, we cover the following topics: 1) fNIRS in comparison to most commonly used neuroimaging methods, 2) fNIRS in the evaluation of human performance, 3) fNIRS application in aviation and aviation medicine, and 4) fNIRS-based Brain-Computer-Interface (BCI) to overcome cognitive restrictions and for optimizing pilot training.

In conclusion, over the years, fNIRS has become a neuroimaging technique that contributes to making advances toward understanding the functioning of the human brain.

Keywords: neurocognition, functional studies, functional neuroimaging, brain activity, near-infrared spectroscopy (NIRS), aviation operator performance

Figures: 6 • **References:** 116 • **Full-text PDF:** http://www.pjambp.com • **Copyright** © 2020 Polish Aviation Medicine Society, ul. Krasińskiego 54/56, 01-755 Warsaw, license WIML • **Indexation:** Index Copernicus, Polish Ministry of Science and Higher Education

INTRODUCTION

The military nature of the currently undertaken activities aimed at achieving the objectives of the mission is related to the necessity of controlling modern, high-maneuver machines, fighter planes. Piloting this kind of aircraft requires strong and specific operator skills. They involve the pilot's interaction with controls, including pilot-navigation devices or maintaining regular radio communications with the crew members. The rapidly changing situation makes it essential to maintain a high level of awareness [15,16]. Thus, pilots are particularly exposed to excessive psychophysical strain manifested by overloaded cognitive function, especially working memory. Human-factor studies emphasize that a variety of environmental stressors may have a negative impact on pilots' skills and decrease their performance to execute a task with high precision [21]. Therefore, it is important to understand the neural activity underlying the process of operating aircraft during military tasks. Previously, electroencefalography (EEG) was used for this.

On the other hand, cognitive processes and neural activity associated with them are related to localized changes in cerebral blood flow. Monitoring cerebral blood flow changes induced by neuronal activity is commonly referred to as functional neuroimaging, which is used to understand the relationship between activity in certain brain areas and specific mental functions. Recently, increasingly more neuroimaging studies employ functional near-infrared spectroscopy (fNIRS) also to monitor brain functions during flight [31].

Functional near-infrared spectroscopy (fNIRS) is an optical brain imaging method that measures the cortical hemodynamic response which is used to estimate the mental workload level in an operational context. fNIRS provides a safe, user-friendly system, with near-zero run-time costs, for measuring cognitive functions under field conditions [18]. It can also index the level of mental demand associated with a given task as it provides continuous and unobtrusive monitoring of the operator and does not interfere with the operator's work.

The use of near-infrared spectroscopy (NIRS) for non-invasive brain oxygenation was proposed in 1977 by Frans Jöbsis in Duke University [52]. In 1991 it was demonstrated that increasing the emitter-detector distance increases tissue penetration, allowing for brain cortex imaging. In 2002, Japanese researchers used multi-channel fNIRS to monitor changes in the volume of cerebral blood use during EEG in patients with seizures to diagnose an epileptic outbreak [109].

fNIRS offers some advantages over the most commonly used methods, namely functional magnetic resonance imaging (fMRI) and electroencephalography (EEG). Both fNIRS and fMRI rely on detecting the hemodynamic response, which starts around 2s after the event (or onset of the task in the block-design) and peaks around 6s after stimulus onset [56]. However, fNIRS has a better temporal resolution than fMRI. Specifically, the sampling rate of fMRI is around 0.5 Hz whereas that of fNIRS can be over 100Hz. On the other hand, EEG has an even higher temporal resolution, up to 1000 Hz, making it possible to measure the activity of neural networks at a millisecond timescale. The hemodynamic response of the brain (to an event) is much slower than the activity it reflects, and thus, like fMRI, fNIRS provide worse temporal resolution than EEG.

fNIRS has been promoted in a number of fields in which fMRI is limited due to the constraints induced by the scanning environment and the experimental measurements take place in a more comfortable and natural environment. The method is compact and easy to administer. Headgear, usually in the form of an elastic band or EasyCap, houses light sources and detectors. The light is transmitted through optic fibers connected to a somewhat small system. Participants are relatively free to move while the data is collected. In most studies, participants are seated and the system is placed beside or behind them, see figure 6. Although facial movements, such as smiling or raising eye-brows, may cause artifacts, the method is much more robust to motion than fMRI or EEG. Therefore, participants can engage in real-life interactions with others, or even perform difficult tasks. Only fNIRS can be utilized in simultaneous brain activation studies on multiple subjects during interaction, and it is the preferred method for infant and children neurodevelopmental studies as well as neuro-rehabilitation assessment. The dimensions and weight of a standard fNIRS device fit comfortably in the cabin of an airplane, therefore, it can be utilized in aviation [14]. Unlike the relatively light and portable fNIRS device, the standard fMRI magnet weighs several tons, which precludes using fMRI for on-the-flight research. Although movement during testing might cause unwanted motion artifacts, fNIRS is less motion-susceptible than other brain imaging techniques, such as fMRI. This is accomplished thanks to probe design, with optodes tightly held in position by the headgear. Motion artifacts are not as big of an issue as in other neuroimaging techniques, and secure placement of the headgear allows the measurement to be completed successfully even during activity (e.g. [116]). Given the system's portability, relative resistance to motion artifacts, and non-invasiveness, cortical activations can be measured during task performance, e.g., in surgeons performing surgical tasks [94].

Currently, fMRI is the most popular method of neuroimaging that measures hemodynamic responses elicited by event (elementary parts of the experimental task). The main reason behind such popularity of fMRI lies in its capacity to measure neural activity across the entire brain with very high spatial resolution [34]. In comparison to fMRI, fNIRS can cover only a limited region beneath the skull, therefore, deep white matter and subcortical structures cannot be observed. Near-infrared light cannot penetrate deeper brain structures, such as subcortical regions. As a result, fNIRS studies have to be limited to cortical measurements [29]. Given the limits of light propagation in opaque tissue (skull, brain), the exact volume of illuminated tissue is unknown, while the spatial resolution of fNIRS is relatively low, from 0.5 to 1 cm, which is less than the standard resolution used in fMRI of 3×3×3mm3. NIRS spatial resolution additionally depends on the headgear geometry of the array of the sourcedetectors, where the separation distance between source-detector pairs dictates the ''banana-shaped'' sensing volume intrinsic to diffusing light transport (see figure 1). The brain hemodynamic responses (to the events) are depicted on the MRI template of the brain. The spatial localization of observed responses is only as accurate as the headgear positioning on the head and co-registration of observed responses to MRI templates. However, shifts in headgear position result in the measurement of different cortical regions. Hence, the initial positioning of the headgear and its stability during the testing session affect spatial accuracy. Moreover, the technique allows for limited head coverage due to the size of the fiber bundles and the required distance between sources and detectors. This limitation is overcome in newer systems, such as Lumo (Gowerlabs; https://www.gowerlabs.co.uk/).

With the development of the hyperscanning wireless fNIRS system, which enables simultaneous interpersonal brain scanning, it is now possible to measure the synchronization of the hemodynamic responses from multiple subjects [51]. Recent studies have shown that a simultaneous increase in activity in the left inferior frontal cortex and the right temporoparietal junction is more common in subjects who are singing or playing computer games while facing each other than in subjects who perform the same task while looking at the walls [79,99]. Hyperscanning studies can be conducted in freely moving subjects. This can be important in sports science or to monitor the interactions between the crew members on the airplane.

Functional Mapping of Human Cortex: Overview of fNIRS

The fNIRS method for mapping the functioning of the human cortex relies on differences in hemoglobin absorption spectra depending on blood oxygenation [106]. It was demonstrated that increasing the emitter-detector distance increases tissue penetration and determined a penetration depth of about 1/3 the emitter-detector distance [19]. Therefore, fNIRS makes it possible to monitor important physiological parameters including: a) HbO (oxygenated hemoglobin); b) HbR (deoxygenated hemoglobin); c) HbT (total hemoglobin HbT=HbO+HbR, HbT is strictly proportional to cerebral blood volume by the hematocrit); and d) HbO saturation. Near-infrared light is shone through the skull (see figure 1) into the brain at two wavelengths (usually between 650 and 900 nm).

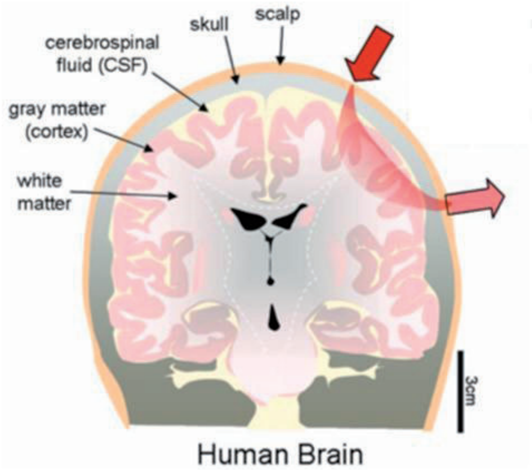

Fig. 1. The "banana shape" of light illuminated and detected with adjacent NIRS optodes [43].

The choice of these wavelengths depends on the accuracy of HbO and HbR measurements. The majority of NIRS systems use wavelengths on either side of the HbO/HbR isosbestic point, with the lower wavelength located below and the higher wavelength above the isosbestic point (i.e. the point where the extinction coefficients of HbO and HbR are equal, see figure 2). As environ-

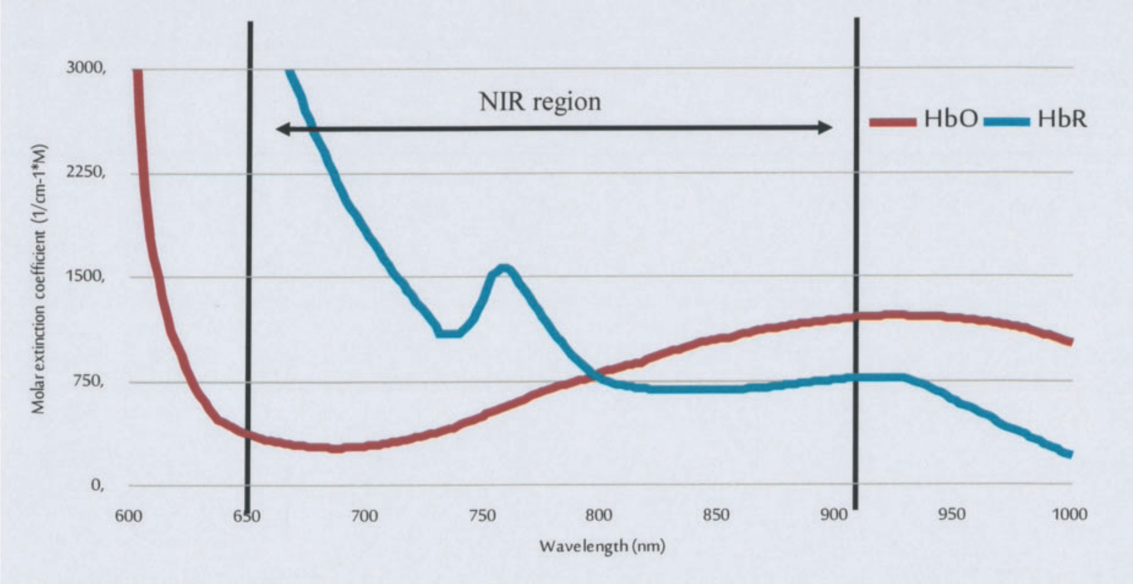

Fig. 2. Absorption spectra of hemoglobin (oxygenated - HbO, deoxygenated - HbR) in the near-infrared (NIR) region.

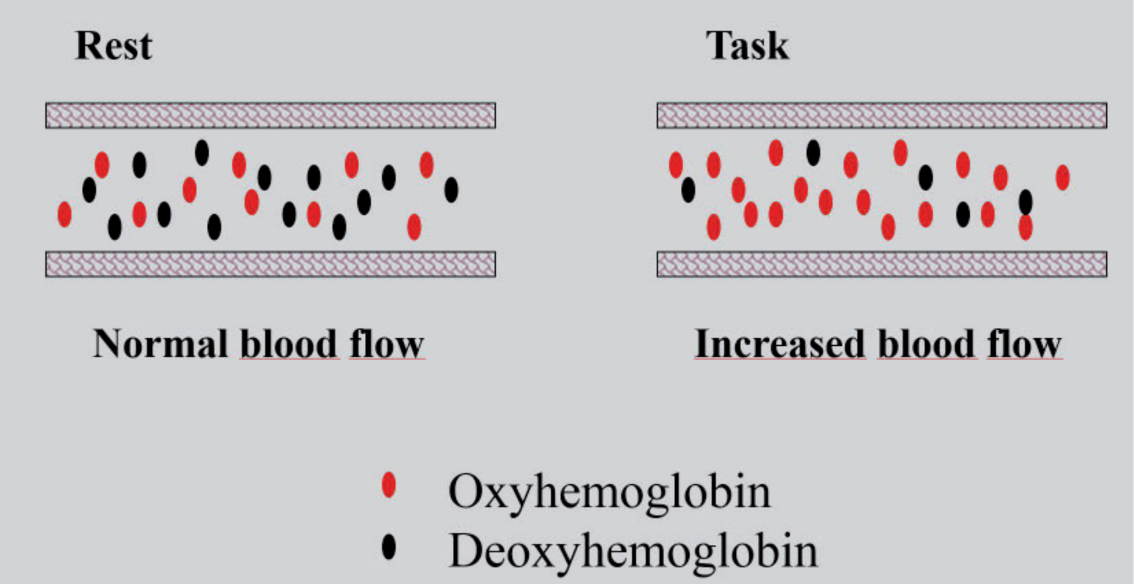

Fig. 3. Changes in cerebral blood oxygenation in hemodynamic response to neural activity.

mental light sources modulate at a significantly different frequency than laser, ambient illumination during the experiment (e.g. from the visual stimuli or surroundings) does not interfere with the laser signals [28].

Illuminated light is detected by co-located detectors, the separation between source and detector pairs affects the depth sensitivity of the measurement. However, the greater the distance between sources and detectors (optodes), the lower the signal strength. Therefore, typically in adult studies, optodes are separated by 30mm, while in infant studies – by 20mm. The exact depth of penetration is provided by the manufacturers of the apparatus and validated by the manufacturer for each model of the device. The penetration distance is affected by various factors: wavelength and energy, attenuation coefficient (composed of dissipation, reflection, and absorption factors), area of the intensity of radiation, and wavelength coherence [42]. Such distance allows the measurement of cortical structures. Measuring the light intensity modulation of oxygenated and deoxygenated blood during the experiment enables to quantify a hemodynamic response, which is related to neural activity [35].

In adults, an increase in regional neural activity results in an increase in blood flow to the activated region [5]. This coupling between neural activity and cerebral blood flow is referred to as neurovascular coupling. The inflow of oxygenated blood is, however, higher than the consumption, leading to a localized increase in oxygenated hemoglobin over the activated region. The observed change in blood oxygenation is called a hemodynamic response (see figure 3).

fNIRS takes changes in blood-oxygenation following stimulation as an index of neural activation. The hemodynamic response observed in fNIRS studies is typically characterized by a noticeable increase in oxygenated hemoglobin (HbO) accompanied by a slightly less pronounced decrease in deoxygenated hemoglobin (HbR), thus showing an increase in total hemoglobin (HbT) [78] (see figure 4).

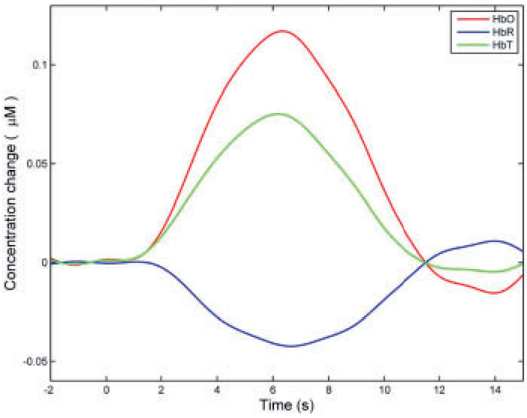

Fig. 4. Average hemodynamic response function (HRF).

While fairly uncommon, a negative hemodynamic response, characterized by a decrease in HbO and an increase in HbR, following stimulus presentation, has been observed in adults during task performance (e.g. [26,108,114].

Common study designs

fNIRS experiments typically employ either a block or an event-related design (see figure 5). In the block design participants are presented with longer periods of stimulation. Activation is measured as average from all presented control stimuli subtracted from the average of all presented experimental stimuli. On the other hand, in event-related designs, stimuli are presented as isolated events of short duration but activation is measured as a change from the preceding control period. Lastly, the two designs can be combined within a single experiment. The mixed design is a combination of block and event-related designs, which allows measuring "maintained" versus "transient" neural activation (e.g. [24,81]. However, this design requires more assumptions and problematic HRF shape estimation [23].

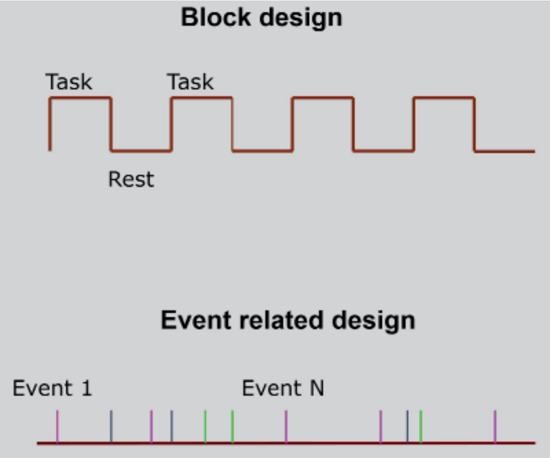

Fig. 5. Block design and event-related design. Color lines indicate events from various conditions.

Fig. 6. On the left: Gowerlabs NTS system, On the right: NIR-X NIRScout (https://www.gowerlabs.co.uk/nts, https://nirx.net/nirscout/).

EXAMPLES OF APPLICATIONS

Infant studies

Functional near-infrared spectroscopy (fNIRS) has recently become one of the most commonly used neuroimaging techniques for infant studies (for a review see [112]. First of all, both color and amount of hair, as well as scalp thickness, may affect the absorption and scattering of light. Infants have considerably less hair and thinner scalps than adults, which allows the near-infrared light to effectively reach the cortex. Secondly, infants move a lot and cannot be instructed to stay still. fNIRS testing procedures do not require lying down, infants can move relatively freely once the headband is securely positioned on the head. This way, testing can be completed both when infants sit on the parent's lap and in a high-chair. Even if they do move a lot, thanks to the secure and tight placement of the headgear, fNIRS is relatively robust to movement artifacts. Thirdly, current fNIRS systems are relatively low-cost and portable, wireless instruments (compared to fMRI), which allows using this technique in several settings, including hospitals [73].

Although quite stable in adults, the process of neurovascular coupling is not as consistently observed in infants [11]. Infant hemodynamic response can have different shapes and sizes, which could be related to developmental changes in signaling pathways, vascular physiology, or structure [20,40,59]. In infant fNIRS studies, both a typical and a negative hemodynamic response can be observed [60,63,73]. This effect can be related to developmental changes, for example, in enzymes regulating neuromuscular coupling [40], a greater proportional increase in consumption of oxygen compared to regional cerebral blood flow increase [10], or vascular constriction and decreases in cerebral blood flow [59]. However, most studies on language and social visual stimuli perception with 4-11-month-old infants observed an increase in HbO (e.g. [13,36-39,45,46,63-66,75,80,88,89,98,110,113]. Therefore, the presence of a negative hemodynamic response could potentially be difficult to interpret (for a review see [59]).

However, combining some of the benefits of both EEG and fMRI, fNIRS is the preferred method for studying infant cortical development (for a review see [4]). Like EEG, fNIRS does not require participants to stay in a fixed position, it is noiseless and easily applied as the headgear is stretched over the infant's head during testing. Similarly to fMRI, it allows relatively good spatial resolution imaging of the brain and provides an indirect measure of neural activation by measuring blood oxygenation.

Developmental studies require implementing creative alternations to adapt paradigms for infant testing. Infants cannot be instructed to attend to stimuli for long periods of time, therefore, it is important to design shorter tasks. Moreover, the presented stimuli need to be engaging enough to capture and maintain infant attention for the duration of the task. Therefore, instead of using a blank screen or fixation cross (as often employed in adult neuroimaging studies) during control tasks, infant studies often show still images of toys (e.g. [64]). Within the experimental paradigm, short sounds (e.g. laughter, toy rattle) are infrequently presented or music is played on selected trials to help maintain infant attention to the screen (e.g. [64]). Infant behavior during testing is typically recorded for later coding of looking at the screen. Trials where infants did not attend to the presented stimuli for a longer period of time (e.g. > 60% of the trial's duration) are marked as invalid and excluded from analyses. Experiment duration depends on the infant's behavior, typically lasting around 5-10 minutes. Most infant studies show that HRF can be observed from 3-5 valid trials (e.g. [64]).

fNIRS responses were found to be related to behavioral outcomes in infants. For instance, in a recent study, Altvater -Mackensen and Grossmann [1] observed that inferior frontal gyrus activation during perception of audiovisual speech is related to viewing behavior in 6-month-olds. Specifically, they found that infants who preferred to look at the mouth of a talking face had higher left IFG activation than infants who preferred to look at the speaker's eyes. Cortical activation during face processing was also found to be related to infant temperament [86]. Whereas infants with low negative emotionality had preferential left hemisphere activation when observing happy faces [86]. These studies show the use of fNIRS in measuring how individual differences in visual scanning or temperament might modulate neural responses during cognitive processing in infancy.

Because it is safe and flexible, fNIRS is well suited for studies on infants and children. Recent studies have demonstrated that lateral activation of the cerebral cortex occurs during language development [104]. Additionally, it has been reported that the activity of the medial PFC [103] and inferior frontal and temporal regions [66] 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), which occur mainly in infants and children. ADHD is characterized by persistent symptoms of inattention, hyperactivity, and impulsivity [27]. 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 several regions, including the PFC, inferior prefrontal gyrus, middle prefrontal gyrus, supramarginal gyrus, and angular gyrus [2].

Application of fNIRS in medicine

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 also in identifying abnormalities in neuronal activity in the brain of patients suffering from neurological and psychiatric disorders.

Many studies indicate the possibility of fNIRS being used in neurology. This is linked to many of the advantages of this method: cerebral oximetry, providing information on regional brain oxygen saturation, reflects local metabolism and balance between the oxygen delivered and required by the brain [55]. Furthermore, regional saturation is a sensitive indicator of hypoperfusion or cerebral ischemia. The non-invasive device is portable, wireless and especially easy to use at the patient's bedside [92].

fNIRS has become an excellent tool for investigating conditions such as stroke and Parkinson's disease that are primarily characterized by impaired movements. It has been shown that a significant increase in asymmetrical hemodynamic response occurs in several regions mediating motor functions, including the sensorimotor cortex, supplementary motor area, premotor cortex, and prefrontal cortex, when patients suffering from either stroke or Parkinson's disease perform motor-related tasks, including treadmill walking and postural perturbation tasks [30,68].

fNIRS imaging has also been used in patients suffering from schizophrenia and affective disorders such as depression, panic disorder, and post-traumatic stress disorder (PTSD) to explore cortical regions showing abnormal activity that may account for the inappropriate emotional responses observed in patients with these disorders. Exposure to extreme stress can have long-lasting effects including memory deficits and poor health. It has been reported that the PFC of patients suffering from PTSD exhibit complex changes in brain response, in that cortical activity increases dramatically when the person encounters an object associated with traumatic events [70,71] but decreases when the person performs tasks requiring cognitive functions [71].

fNIRS studies have found that patients suffering from depression disorder show hypoactivation in PFC during cognitive tasks, suggesting the importance of the prefrontal function in symptoms associated with this disorder [85]. Similarly, hypoactivation of the frontal brain region has been found in panic disorder patients during cognitive tasks as well as a word fluency test [77].

Recently, there has been considerable interest in using near-infrared spectroscopy as a potential noninvasive method for clinical testing. NIRS and fNIRS are broadly applied in various areas, such as pain assessment [116], to study a range of diverse conditions including epilepsy [96], metabolic myopathy [8], skin carcinoma [62], type 1 and 2 diabetes mellitus [93], valvular heart disease [58], transient ischemic attack [53], aging [44], pigmented skin [61], breast cancer [95], pulmonary disease [50] and chronic fatigue syndrome (CFS) [90], virus infection [91], migraine [77], cervical dysplasia [47], atherosclerotic plaques [107], rheumatoid arthritis [12], glioma [3], intraocular pressure [111], hemorrhagic shock [101], brain edema [69,100], and optic neuritis [74].

Application of fNIRS in aviation medicine

There is a growing interest in implementing fNIRS to monitor cognitive performance in the occupational environment. The method has been successfully used to measure changes in cerebral oxygen status (COS) of fighter pilots during aircraft missions [57]. fNIRS was also found to be useful for assessing brain oxygenation during orthostatic stress [33]. Such an assessment is essential for screening and training to improve G-tolerance in air force pilots. The method has also been implemented to monitor cortical oxygenation during helicopter flights [54]. FNIRS also helps to investigate cortical activity including memory workload in a variety of human tasks, out of the laboratory, particularly when piloting supermaneuverable aircraft in real-time. Gateau et al. [32] found that a pilot's mental state estimated from fNIRS data with a real-time algorithm matched the pilot's actual state. Experienced human operators can maintain performance at required levels for a while through increased effort and motivation or strategy changes. Sustained tasks lead to performance breakdown and increased mental workload which can predicate performance failure. Thus, the implementation of monitoring technology in the cockpit to infer a state of cognitive limitation could represent a promising approach to enhance flight safety [87,105]. Consequently, it is important to assess mental workload independently of performance measures. Neuroergonomic approaches based on measures of human brain hemodynamic activity using fNIRS can provide a reliable assessment of human mental workload in a composed activity such as aviation [82]. Recently, Durantin et al. [25] developed improved filters that allow signal improvement for fNIRS in neuroergonomics. Moreover, fNIRS allows a more objective measure of cognitive workload in air traffic controllers than measures using the workload assessment keypad [41]. The use of fNIRS has been gaining popularity recently as the sensors have been miniaturized, become portable, and wireless [6].

Advantages of fNIRS for aviation studies

The fNIRS system provides several advantages compared to traditionally used EEG such as a high signal-to-noise ratio, as sensors are relatively more robust to motion artifacts, eye-blinks, and facial muscles [48]. It is also possible to run experiments with active and mobile subjects, and even outdoors [72]. Specifically, it is less sensitive to the noisy electromagnetic environment in the aircraft (radio transmission, radio-navigation beacons, GPS) than EEG, making it a candidate to measure a pilot's brain activity during real flight.

fNIRS enable to assess and measure operator mental workload in situations where performance failures could result in catastrophic losses (military command and control, air traffic control). It can help in preventing operator error and allow for pertinent intervention by predicting performance decline that can arise from either work overload or understimulation [83]. fNIRS helps to facilitate optimal performance in critical mission systems by dynamically matching the momentary mental capabilities of the operator to the imposed task demands [115].

fNIRS's capacity for spatial resolution has important benefits for use as a measure of mental workload as pilots develop flying activities. Human operators in work settings typically have developed considerable expertise in the tasks they have to perform in their job, whereas laboratory studies usually examine the performance of untrained participants on artificial tasks.

This technology attempts to understand brain mechanisms underlying performance in operators during operationally-relevant tasks. fNIRS is very often used in studies for assessing mental workload in a complex cognitive task of experienced air traffic controllers (ATCs). Pilots have to face compounding interaction with the flightdeck. For them, working memory abilities is the key executive function for handling the flightpath, maintain high situation awareness, or adapting the flight plan [16]. Working activity indeed requires the memorization process of critical flight information, such as heading, altitude, or speed [21]. It is also an important component when interacting with ground control instructions [76]. Many studies have revealed that several factors, such as message length and complexity, affect the pilot's memory capacity necessary for following ATC instructions, as well as their ability to execute commands [101]. Erroneous execution of the ATC clearances may considerably jeopardize the flight safety of the crew [9]. Thus, prompting the need for an enhanced pilot-system with fNIRS technology is inevitable. The result obtained by Izzetoglu et al. [49] with the use of fNIRS, showed that the hemodynamic response over the dorsolateral and ventrolateral prefrontal cortex was responsive to mental workload in a realistic command and control task. Further studies indicate that text-based communications required less brain activation of the operator than voice-based communication systems [49].

The result obtained with the participation of experienced air traffic controllers demonstrates that the average oxygenation level, measured by fNIRS in the anterior medial prefrontal cortex PFC, increased monotonically with increased task difficulty. The results provide strong evidence that activation in this brain region provides a valid measure of mental workload in this realistic IATC task. Nevertheless, results must be interpreted with caution, because not all brain regions that are involved in IATC could be measured with fNIRS [7].

Evaluation of the effects of aging

The effects of aging on cognitive performance must be better understood, especially to protect older individuals who are engaged in risky activities such as aviation. Research with the use of fNIRS suggests that brain compensatory mechanisms may counter cognitive deterioration due to aging for certain task load levels. Results obtained by Causse et. al. confirmed an overall effect of the difficulty level in the three pilot age groups with a decline in task performance and an increase in prefrontal HbO signal [14]. The performance of older pilots, compared to younger pilots, was impaired in tasks, with the greatest impairment observed for the highest load spatial working memory task. Consistent with this behavioral deficit in older pilots, a plateau of prefrontal activity was observed at this highest-load level, suggesting that a ceiling in neural resources was reached. Finally, older pilots with extensive flying experience tend to show better preserved spatial working memory performance when compared to those mildly-experienced from the same age group.

fNIRS-based Brain Computer Interfaces

Future studies aim to develop an online fNIRS based on BCI (Brain Computer Interface) for the assessment of working memory of aircraft pilots during real-time flight. Nevertheless, solutions have to be explored to speed up response detection on the fNIRS signal that can drastically reduce latency in detecting a change in mental state. Further studies have to be conducted to discriminate a gradient of working memory levels from underload to overload [102] and consider the effect of accelerations and headband motion on the fNIRS signal [67].

The development of fNIRS and BCI technology provides interesting prospects to continuously monitor and take advantage of the brain dynamics and the neural mechanisms underlying cognition. It offers a unique insight into the development of the human-system interactions to overcome cognitive limitations. While several of them have been successfully implemented in driving [22] and flight simulators [105], few have attempted to test these systems in more realistic settings.

fNIRS based BCI could be first used for civilian application as highly automated high-tech aircraft prevents pilots from exceeding 1g maneuvers for passenger comfort and to avoid going against the flight envelope protection. Future studies should consider the use of fNIRS-based BCI to improve training via neurofeedback [84] and to tailor the flight sessions to the trainee [17]. The next step is to stream the fNIRS data to the flight data recorder for analyses of accidents. It would provide additional insights on the crew's cognition during these critical events, prevent them from distraction, and help accident investigators [31]. The objective is to improve task allocation to enable better task switching, interruption management, and multi-tasking [97].

CONCLUSIONS

In the field of emerging neuroimaging techniques, it is essential to investigate the advantages of fNIRS and its utility in future aviation applications. In terms of interdisciplinary research, the use of fNIRS promotes an understanding of the brain in complex real-life activities. This approach combines knowledge from cognitive psychology, neuroscience, or system engineering [83]. Sensitive and reliable mental state assessment of human operators navigating complex systems is a prime goal of neuroergonomics that aims to measure the "brain at work" [83]. Understanding the essential neurocognitive processes of such interaction could be used to improve the safety and efficiency of the overall human-machine pairing. This could be achieved by the augmentation of aviation operators' performance and its translation to improved functioning in the real flight task. Since fNIRS technology allows the development of wireless, non-invasive, and miniaturized devices, it has the potential to be deployed in future training environments to personalize the learning process and to assess the effort of human operators expended in crucial multitasking environments.

Furthermore, with new technologies such as wireless and wearable devices, including the hyperscanning system, fNIRS has great potential to provide novel insights into brain function. In the near future, the development of fNIRS will achieve such high reliability of signals that even a single brain activation can be detected. This opens a new field in brain-computer interface, which will lead to many everyday life applications. Additionally, fNIRS can be developed into a low-cost option that would allow researchers to diagnose brain disorders using a more objective method based on brain activity. Finally, it would help them to monitor the effects of therapeutic approaches during treatment.

To conclude, over the years fNIRS has become a neuroimaging technique that contributes to making advances toward the understanding of the functioning human brain. It is clear that today we have merely reached the tip of an iceberg. fNIRS will become an indispensable clinical method and also enter our daily lives.

AUTHORS' DECLARATION:

Study Design: Anna Przewodzka, Aleksandra Dopierała. **Data Collection:** Aleksandra Dopierała, Anna Przewodzka. **Manuscript preparation:** Aleksandra Dopierała, Anna Przewodzka. **Funds Collection:** Przemysław Tomalski. The Authors declare that there is no conflict of interest.

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Cite this article as: Dopierała A, Przewodzka A, Tomalski P. Near-Infrared Spectroscopy In Healthy Subjects: Possible Application In Aviation And Aviation Medicine. Pol J Aviat Med Bioeng Psychol 2019; 25(2): 24-37. DOI: 10.13174/pjambp.15.12.2020.03