

Estimation of Cognitive Workload during Simulated Air Traffic Control Using Optical Brain Imaging Sensors

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Abstract. Deployment of portable neuroimaging technologies to operating settings could help assess cognitive states of personnel assigned to perform critical tasks and thus help improve efficiency and safety of human machine systems. Functional Near Infrared Spectroscopy (fNIR) is an emerging non-invasive brain imaging technology that relies on optical techniques to detect brain hemodynamics within the prefrontal cortex in response to sensory, motor, or cognitive activation. Collaborating with the FAA William J. Hughes Technical Center, fNIR has been used to monitor twenty four certified professional controllers as they manage realistic Air Traffic Control (ATC) scenarios under typical and emergent conditions. We have implemented a normalization procedure to estimate cognitive workload levels from fNIR signals during ATC by developing linear regression models that were informed by the respective participants' prior n-back data. This normalization can account for oxygenation variance due to inter-personal physiological differences. Results indicate that fNIR is sensitive task loads during ATC.

Keywords: Optical Brain Imaging, Air Traffic Control, Cognitive Workload, Functional Near Infrared Spectroscopy, fNIR.

1 Introduction

Increasing air traffic in the United States has placed the current air traffic control (ATC) system under stress. To alleviate this stress, the Next Generation Air Transportation System (NextGen, Joint Planning and Development Office) has outlined a series of transformations designed to increase the capacity, safety, and security of air traffic operations [1]. Towards achieving this vision, sophisticated new features and systems are designed or will be implemented for future air-traffic management. Brain based measures of operator's cognitive workload could help

assess utility of interfaces in human machine systems operating in complex environments and provide objective measures in addition to behavioral performance and subjective self-reported feedback [2-4]. The use of human brain imaging sensors and their capacity to integrate with behavioral and physiological measures, position them to play a key role in the development and operation of futuristic 'brain-in-the-loop' systems.

Significant progress has occurred over the last decade in understanding the physiological and neural bases of cognitive processes and behavior. New and improved brain imaging tools are used to monitor brain activity noninvasively and assess neurophysiological markers of human performance in various settings. Functional magnetic resonance imaging (fMRI), positron emission tomography (PET) and Magneto-encephalography (MEG) have enabled studying localized brain activity in humans and carry out studies for better understanding the neural basis of mental states [5-8]. However, these techniques are not amenable to ecologically valid, regular operating settings as they are expensive, highly sensitive to motion artifact, require participants in confined positions and may expose individuals to potentially harmful materials or loud noise. More recently, functional near-infrared (fNIR) spectroscopy has been used as a noninvasive tool to monitor concentration changes of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) at the cortex [9-11]. fNIR technology allows the design of ambulatory, safe and affordable monitoring systems. These qualities pose fNIR as an ideal candidate for monitoring cognitive activity related hemodynamic changes not only in laboratory settings but also under working conditions [12-15].

In this study, we have incorporated fNIR into ongoing studies at the FAA's William J. Hughes Technical Center (WJHTC) where certified controllers were monitored with fNIR while they managed realistic ATC scenarios under typical and emergent conditions. A critical transition defined in NextGen involves augmenting the current auditory-based communications between ATC and the flight deck with text-based messaging, or DataComm systems. DataComm systems are expected to allow ATC to manage more air traffic at a lower level of cognitive load, thereby increasing both the capacity of national airspace system and safety of passengers. Self-report measures of workload suggest that DataComm systems require less cognitive effort than voice-based systems to manage the same amount of traffic [16, 17], and this has been recently corroborated with objective brain based measures as the first part of the current study [14].

The objective of this experiment was to use physiological measures to predict changes in cognitive workload during a complex cognitive task: ATC. The hypothesis derived from a standardized working memory task (n-back) [14] was that blood oxygenation in the dorsolateral prefrontal cortex (DLPFC), as measured by fNIR would increase with increasing task difficulty and sustained cognitive effort.

2 Cognitive Workload

There is no singular definition of cognitive workload [18]. There are at least two major theoretical approaches to the construct: 1) mental workload may be defined such that a given task's requirements are viewed as an independent, external variable

with which the working subjects have to cope more or less efficiently; or 2) mental workload may be defined in terms of an interaction between task requirements and human capabilities or resources [19, 20]. In either of these paradigms, the definition of workload involves the “objective” effects of task difficulty on the participant, and the participant’s effort involved in maintaining performance. Workload is an intervening variable between task and environmental demands and the operator’s performance, defined by the relationship between task demand and the participants resource supply, i.e., the portion of operator’s limited mental capacities actually required to perform a particular task. That is, workload can be defined in terms of some “objective” criteria for task difficulty (e.g., managing 6 aircrafts versus 12 aircrafts), or in terms of the participant’s capacities to perform the identified task. As such, workload can be dissociated from performance. Two people performing the same task can have identical performance, yet one operator may have significant cognitive resources free to allocate to concurrent tasks, whereas the second operator may be just on the brink of performance failure. The difference between the required capacity and the available capacity of an individual is referred to as the mental or cognitive reserve.

There are four basic methodologies for the assessment of workload. The first category includes subjective assessment that use self-reported rating scores such as Modified Cooper-Harper Scale [21], Subjective Workload Assessment Technique (SWAT) [22], NASA Task Load Index [23] and self-reported mental effort [24]. The second category of cognitive workload assessment methods compares behavior and primary task performance measures of the participant, recorded during the task, to identify any workload effects within them. Accuracy and speed of response are widely in use [25]. The third category includes secondary task measures where participant’s mental workload is evaluated based on the performance on the additional secondary task [26]. The final group of cognitive workload assessment methods is based on physiological measures such as eye movements [27], eye blinks [28], pupil dilation [29], skin temperature [30], galvanic skin response [31], heart rate [32], blood pressure [28], and respiration rate [33].

Primary task performance measures are critical in that they define the task that needs to be accomplished. However, they are only sensitive to changes in workload at the limits of mental capacity, which is not very useful for ATC. If operators can compensate for increased workload by increasing effort, then the task performance measure is insensitive. Finally, task performance measures do not provide any direct evidence about the participant’s degree of effort or level of arousal. Subjective ratings provide an important measure of the operator’s perceived load, and have good face validity. However, they are intrusive to collect while on task, and are often dissociated from actual performance and potential failure. Secondary tasks techniques can give some sense of cognitive or mental reserve, but they are often intrusive, and cannot reasonably be employed during actual ATC activities. Physiological measures can be unobtrusive, and provide an “objective” measure of workload. However, many of the typical physiological systems measure autonomic responses, i.e., the fight or flight system, which assesses stress and emotion, whereas some of the difference in workload may more appropriately be measured using a measure of cognitive workload, rather than stress.

On the other hand, technologies that assess Central Nervous System functioning can provide measures of cognitive functioning as well as measures of stress or emotion. Commonly employed techniques such as electroencephalography (EEG), event-related brain potentials (ERPs), MEG, PET and fMRI have dramatically increased our understanding of a broad range of cognitive and emotional states. EEG have been applied for mental workload assessment of air traffic controllers [34] and operators [35]. Methods that directly measure the summation of neural function, such as EEG, ERP and MEG allow researchers to observe neuronal activation related electromagnetic signals with temporal resolution on the order of milliseconds and have been utilized for workload assessment. However, these technologies also have limited spatial resolution [11] and are susceptible to electromagnetic field artifacts. In contrast, PET and fMRI monitor the hemodynamic and metabolic changes associated with neural activity with impressive spatial resolution, but are limited in temporal resolution and are associated with neuronal activity through a poorly-understood neurovascular coupling function [11]. In addition, PET do not allow for continuous or repeated measurements because they require the use of radioactive isotopes, which also limits their use in children. fMRI is currently considered the “gold standard” for measuring functional brain activation because it offers safe, noninvasive neuroimaging with high spatial resolution. However, fMRI is expensive to operate, requires massive installations and a large team of technicians to operate. In addition, fMRI is highly sensitive to motion artifact and confines participants to restricted positions, and exposes participants to loud noises.

fNIR is an emerging optical brain imaging modality that measures hemodynamic response, similar to fMRI, by using near infrared light [36, 37]. fNIR has been demonstrated to be sensitive to cognitive workload [12-14, 36, 37]. fNIR technology allows devices to be miniaturized, portable and battery-operated, making them field deployable. These qualities make fNIR suitable for the study of cognitive- and affect-related hemodynamic changes under field conditions.

3 Method

3.1 Participants

Twenty-four certified professional controllers (CPC) between the ages of 24 to 55 volunteered. All participants were non-supervisory CPC with a current medical certificate and had actively controlled traffic in an Air Route Traffic Control Center between 3 to 30 years. Prior to the study, all participants signed informed consent forms.

3.2 Experiment Protocol

All participants were asked to complete two types of tasks: n-back and ATC tasks. The n-back task is a standardized working memory and attention task with four incremental levels of difficulty. Participants were asked to monitor stimuli (single letters) presented on a screen serially and click a button when a target stimulus arrives. Four conditions were used to incrementally vary working memory load from zero to three items. In the 0-back condition, participants responded to a single target

letter (e.g., “X”) with their dominant hand (pressing a button to identify the stimulus). In the 1-back condition, the target was defined as any letter identical to the one immediately preceding it (i.e., one trial back). In the 2-back and 3-back conditions, the targets were defined as any letter that was identical to the one presented two or three trials back, respectively. The total test included seven sessions of each of the four n-back conditions (hence, a total of 28 n-back blocks) presented in a pseudo-random order. The task was designed and presented in E-prime (Psychology Software Tools).

For the ATC task, each CPC controlled traffic on workstations with a high-resolution (2,048 x 2,048), 29” radarscope, keyboard, trackball, and Direct Access Keypad for 10 minutes. To display the air traffic, the DESIREE ATC simulator and the TGF systems that were developed by software engineers at the WJHTC were used.

Six simulation pilots were used within scenarios by supporting one sector or two sectors and entering data at their workstations to maneuver aircraft, all based on controller clearances. Two types of communications, either voice (VoiceComm) or data (DataComm) communications were used in separate sessions in a pseudo-random order. For each communication type, task difficulty was varied by the number of aircraft in each sector, containing 6, 12 or 18 aircraft.

3.3 fNIR Device

The continuous wave fNIR system (fNIR Devices LLC; www.fnirdevices.com) used in this study is connected to a flexible sensor pad that contains 4 light sources with built in peak wavelengths at 730 nm and 850 nm and 10 detectors designed to sample cortical areas underlying the forehead. With a fixed source-detector separation of 2.5 cm, this configuration generates a total of 16 measurement locations (voxels) [38]. For data acquisition and visualization, COBI Studio software (Drexel University) was used. The sampling rate of the system is 2Hz. During the n-back task, serial cable between the fNIR data acquisition computer and E-prime stimulus presentation computer was used to transfer time synchronization signals (markers) that indicate the start of sessions and onset of stimuli.

4 Data Analysis

For each participant, raw fNIR data (16 voxels x 3 wavelengths) was 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. Saturated channels (if any), in which light intensity at the detector was higher than the analog-to-digital converter limit were excluded.

Using time synchronization markers, fNIR data segments for rest periods and task periods (28 sessions per participant for n-back task and 6 sessions per participant for ATC task) were extracted. Blood oxygenation changes within dorsolateral prefrontal cortex for 16 voxels were calculated using the Modified Beer Lambert Law (MBLL) for task periods with respect to rest periods at beginning of each task [13, 14]. Average oxygenation change for each session was used as the dependent measure. For statistical analysis, 2 (Communication: Data-based, Voice-based) X 3 (Task Difficulty: 6, 12, 18 aircraft) ANOVA with repeated measures on both factors for

average self-reported ratings and oxygenation changes were applied. Geisser-Greenhouse correction was used with Tukey's post hoc tests to determine the locus of main effects. The significance criterion was 0.05.

4.1 Normalization by Linear Modeling

A separate first order polynomial regression model was established for each participant and the model parameters were estimated by using min and max of the respective participant's n-back data. This individualized model, mapped oxygenation (of ATC task) through an affine transformation that kept the collinearity, in other words it applied the same scaling and translation for all conditions for that subject. This model transforms ATC oxy values on a standardized n-back conditions (0 to 3) axis by using the min and max nback oxy values as scale. The general model:

$$Y_i = \beta_0 + \beta_1 X_i \quad (1)$$

where X is the oxygenation value and Y is the normalized output response. β_0 and β_1 are scalar model parameters (of a participant) estimated by using two (nback-oxygenation, nback-condition) coordinates, where nback-condition is either 0, 1, 2 or 3. Using minimum and maximum oxygenation (and respective condition), parameters can be solved from the following equation set:

$$\begin{bmatrix} n_{min} \\ n_{max} \end{bmatrix} = \beta_0 + \beta_1 \begin{bmatrix} oxy_{min} \\ oxy_{max} \end{bmatrix} \quad (2)$$

Finally, using this model, ATC oxygenation values for all 6 (2 communication x 3 task difficulty) conditions of the participants were transformed.

5 Results

N-back behavioral and fNIR results were reported in [14]. For the self-assessment data of ATC tasks, there were two significant main effects, Task Difficulty denoted by number of aircraft [$F_{2,46} = 6.79$, $p < 0.05$] and Communication [$F_{1,23} = 4.53$, $p < 0.05$] which is depicted in Figure 1. Tukey post hoc tests for Task Difficulty ($q_{0.05/2, 46} = 3.43$, $p < 0.05$) showed that the 18 aircraft condition had significantly higher oxygenation change than the 6 and 12 aircraft conditions. Also, the interaction between aircraft number and communication type was significant [$F_{2,46} = 4.66$, $p < 0.05$].

For the fNIR data of ATC tasks, two subjects were excluded from the analyses because of high motion artifact and low signal-to-noise ratios. The most significant measurement location was voxel 8 in the medial prefrontal cortex, and there were two significant main effects, Task Difficulty [$F_{2,42} = 4.52$, $p < 0.05$] and Communication [$F_{1,21} = 5.03$, $p < 0.05$] which are depicted in Figure 1. Tukey post hoc tests for Task Difficulty ($q_{0.05/2, 42} = 3.44$, $p < 0.05$) showed that the 18 aircraft condition had significantly higher oxygenation change than the 6 aircraft condition.

The individualized linear model trained by nback data used to normalize oxygenation changes (See Figure 2). Fitted ATC responses indicate that this normalization improved the spatial localization of activity pattern in DLPFC and represent a monotonic increase with increasing task difficulty within anterior medial prefrontal cortex (PFC) [$F_{2,21} = 11.26$, $p < 0.05$].

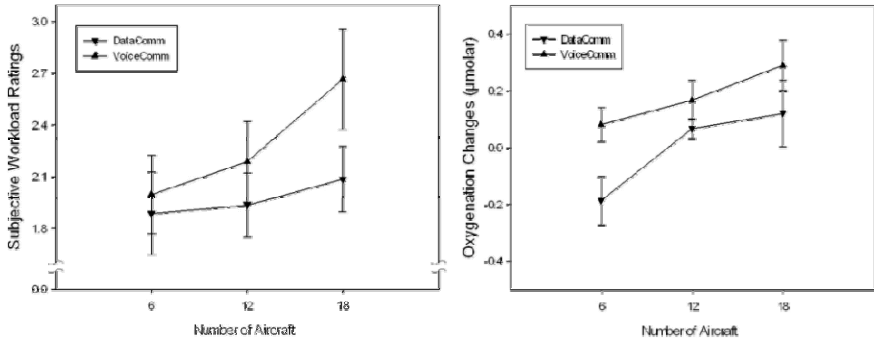


Fig. 1. Self-reported difficulty ratings (left) and average oxygenation changes (right) for each condition (6, 12 and 18 aircraft). Error bars are standard error of the mean.

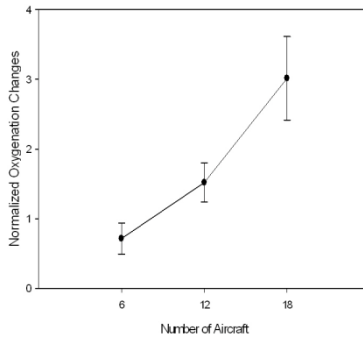


Fig. 2. Average Oxygenation changes normalized by the individualized linear model

6 Discussion

In this study, ATC brain responses under highly regulated and well-known experimental conditions were assessed for comparison with simulated air traffic control tasks. Changes in blood oxygenation in dorsolateral prefrontal cortex, as measured by fNIR, were shown to be associated with increasing cognitive workload. The results further indicate that an individualized linear model improved contrast for comparing responses across task difficulty.

The hypothesis was that, for increasing task difficulty, there would be increasing oxygenation as measured by fNIR. ATC results supported the hypothesis as n-back and earlier results [12, 14]. Average oxygenation in the anterior medial prefrontal cortex, imaged at voxel 8, increased monotonically with our manipulation of increasing task difficulty (number of aircrafts) as illustrated in Figure 1, suggesting this cortical area could provide a valid measure of workload for the air traffic control task. Furthermore, applying normalization resulted in response across larger spatial area by including voxels 7, 9 and 10. For voxel locations please see [38]. The distinction of focal regions for n-back (working memory) and ATC (planning/decision making) are also in parallel

with the fMRI findings of functional dissociation of lateral and medial PFC [39-41]. The fNIR results from the main effect of communication type ($p < 0.05$), confirms that VoiceComm condition results in higher oxygenation compared to DataComm with a small to moderate effect size ($d = 0.28$ for voxel 8, and $d=0.25$ for voxel 6). These results are consistent with the idea that, given the same cognitive workload (identical scenarios), DataComm required fewer cognitive resources.

These results must be interpreted with caution, as not all areas of the brain that are involved in ATC could be measured with fNIR technology. It is possible that workload was shifted to other areas of the brain that were not being monitored under the DataComm condition, rather than a reduction in working memory resources. This hypothesis requires further evaluation. However, combined with performance evaluations, the fNIR data provides preliminary evidence that DataComm may require fewer cognitive resources than VoiceComm by lowering the demand on working memory and attentional resources.

In summary, fNIR is a portable, safe, affordable and negligibly intrusive optical brain monitoring technology that can be used to measure hemodynamic changes in the prefrontal cortex. Changes in blood oxygenation in the dorsolateral prefrontal cortex, as measured by fNIR, were shown to be associated with increasing cognitive workload. The results further indicate that text-based communications required less brain activation of the operator than legacy voice based communication systems. These fNIR results corroborate with subjective assessments of operators and earlier studies.

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