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Functional Optical Brain Imaging Using Near-Infrared During Cognitive Tasks

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A symbiotic relation between the operator and the operational environment can be realized by an advanced computing platform designed to understand and adapt to the cognitive and the physiological state of the user, especially during sensitive and cognitively demanding operations. The success of such a complex system depends not only on the efficacy of the individual components, but also on the efficient and appropriate integration of its parts. Because near infrared technology allows the design of portable, safe, affordable, and negligibly intrusive monitoring systems, the functional near infrared (fNIR) monitoring of brain hemodynamics can be of value in this type of complex system, particularly in helping to understand the cognitive and emotional state of the user during mentally demanding operations. This article presents the deployment and statistical analysis of fNIR spectroscopy for the purpose of cognitive state assessment while the user performs a complex task. This article is based on data

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collected during the Augmented Cognition—Technical Integration Experiment session. The experimental protocol for this session used a complex task, resembling a video game, called the Warship Commander Task (WCT). The WCT was designed to approximate naval air warfare management. Task difficulty and task load were manipulated by changing the following: (a) the number of airplanes that had to be managed at a given time, (b) the number of unknown (vs. known) airplane identities, and (c) the presence or absence of an auditory memory task. The fNIR data analysis explored the following: (a) the relations among cognitive workload, the participant's performance, and changes in blood oxygenation levels of the dorsolateral prefrontal cortex; and (b) the effect of divided attention as manipulated by the secondary component of the WCT (the auditory task). The primary hypothesis was that blood oxygenation in the prefrontal cortex, as assessed by fNIR, would rise with increasing task load and would demonstrate a positive correlation with performance measures. The results indicated that the rate of change in blood oxygenation was significantly sensitive to task load changes and correlated fairly well with performance variables.

1. INTRODUCTION

The sophistication and complexity of modern military systems place significant cognitive demands on military operators under stressful conditions. The Defense Advanced Research Projects Agency (DARPA) Augmented Cognition (AugCog) program is currently one of the major programs of the Department of Defense funding research designed to facilitate a symbiotic relation between the operator and the operational environment. The primary objective of this program is to enable the development of a futuristic computing platform designed to understand and adapt to the cognitive and physiological state of the user (Schmorrow & Kruse, 2002). The utility of human brain imaging sensors and their capacity to integrate with other neurobehavioral and physiological measures position them to play a key role in achieving a reliable platform for use during sensitive and cognitively demanding operations, particularly in assessing of the cognitive state of the operator.

Human brain imaging techniques such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have dramatically increased knowledge about the neural circuits that underlie cognitive and emotional processes (Cabeza & Nyberg, 2000; Davidson & Sutton, 1998). However, these techniques are expensive, highly sensitive to motion artifact, confine the participants to restricted positions, and may expose individuals to potentially harmful materials (PET) or loud noises (fMRI). These characteristics make these imaging modalities unsuitable for many uses, including the monitoring of ongoing cognitive activity under routine working conditions.

More recently, near infrared (NIR) spectroscopy (NIRS) has been widely used in functional brain studies as a noninvasive tool to monitor changes in the concentration of oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (deoxy-Hb; Boas, Franceschini, Dunn, & Strangman, 2001; Chance et al., 1998; Chance, Zhuang, UnAh, Alter, & Lipton, 1993; Obrig & Villringer, 1997; Villringer & Chance, 1997). Furthermore, NIR technology allows the design of portable, safe, affordable, and negligibly intrusive monitoring systems. This makes NIRS suitable for the study of cortical cognition-related hemodynamic changes under many working conditions, including military field deployment.

Photons that enter tissue may interact with the tissue in several ways, including (a) absorption, which can lead to a loss of energy to the tissue, or, alternatively, induce either fluorescence or phosphorescence; and (b) scattering, among others (Villringer & Chance, 1997). Scattering may occur at an unchanged frequency when the tissue is stationary, or, in the case of moving particles in the tissue (e.g., blood cells), the scattering may be accompanied by a Doppler shift. Biological tissues are relatively transparent to light in the NIR range between 700 to 900 nanometers (nm). However, as illustrated in Color Plate 4, Figure 1, two chromophores in this "optical window" from 700 to 900 nm, oxygenated and deoxygenated hemoglobin, have two important characteristics: (a) because of their optical properties, they tend to scatter light back to the surface of the tissue, and (b) they can serve as biologically relevant markers with which to monitor neural activity (Cope, 1991). Specified wavelengths in the optical window easily pass through most tissue, reflect back off oxy- and deoxy-HbO, and can be measured at the surface of the skin. The relative levels of absorption and backscatter provide information about neural activity, including, for instance, motor and visual activation, auditory stimulation, and the performance of cognitive tasks (K. Izzetoglu et al., 2003; Villringer & Chance, 1997).

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 (Cope, 1991), the light intensity after absorption and scattering of the biological tissue is expressed by the equation:

$$I = GI_o e - (\alpha_{HB} C_{HB} + \alpha_{HBO2} C_{HBO2}) \times L \qquad (1)$$

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 HbO_2, C_{HB} and C_{HBO2} are the concentrations of chromophores, deoxy-Hb and HbO_2, respectively, and L is the photon path which is a function of absorption and scattering coefficients $_{\alpha}$ 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_{HBO2} during that period is

$$\Delta OD = \log_{10} \frac{I_b}{I} = \alpha_{HB} \Delta C_{HB} + \alpha_{HBO2} \Delta C_{HBO2} \qquad (2)$$

Measurements performed at two different wavelengths allow the calculation of ΔC_{HB} and ΔC_{HBO2}. Oxygenation and blood volume can then be deduced:

$$Oxygenation = \Delta C_{HBO2} - \Delta C_{HB} \quad (3)$$

$$BloodVolume = \Delta C_{HBO2} + \Delta C_{HB} \quad (4)$$

Three distinct types of NIRS implementation have been developed: time domain, frequency domain, and continuous wave spectroscopy measurements. In time domain systems, also referred to as time resolved spectroscopy (TRS), 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 to the 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 (Boas et al., 2002). In continuous wave systems, light is applied to tissue at constant amplitude. The continuous wave (CW) systems are limited to measuring the amplitude attenuation of the incident light (Boas et al., 2002).

This study was conducted for the DARPA AugCog program to evaluate the ability of a fNIR sensor to assess cognitive workload during a complex task. The 'Warship Commander Task' (WCT), developed by the Pacific Science & Engineering Group under the direction of the Space and Naval Warfare Systems Center in San Diego, California, was designed as a cognitive multitasking environment to manipulate workload while simulating actual military commands and tasks (St. John & Kobus, 2002). The primary objective of this experiment was to use physiological measures to predict changes in cognitive workload during a complex cognitive task. The principal hypothesis, derived from preliminary data on a working memory task (the "n-back" task; K. Izzetoglu, Yurtsever, Bozkurt, & Bunce, 2003), was that blood oxygenation in the dorsolateral prefrontal cortex, as assessed by fNIR, would increase with increasing task difficulty and sustained cognitive effort in a working memory task. That is, blood oxygenation was expected to increase with increasing workload as long as the participant was attentive and engaged in the task. However, at the point when the task became too difficult, and the participant broke his or her attention or engagement in the task, the blood oxygenation was expected to decrease. Similar to the Yerkes–Dodson law, blood oxygenation was expected to increase with increasing workload to the point of overload, after which it would decline. This hypothesis is consistent with preliminary data using fNIR in the n-back task. Participants in the 3-back condition reported losing their concentration in this taxing working memory task, which tended to be coincident with a decrease in blood oxygenation. In this study, in addition to fNIR data, several other physiological measures were obtained simultaneously during the experimental session, as illustrated in Color Plate 5, Figure 2. These other physiological measures included EEG (Advanced Brain Monitoring's wireless EEG sensor headset; Levendowski & Berka, 2002), eye tracking, pupillometry, skin conductance, respiration, and heart rate (Marshall, Pleydell–Pearce, & Dickson, 2003).

2. SYSTEM IMPLEMENTATION

2.1. CW Functional Near Infrared System

A number of functional brain imaging techniques have been established for the noninvasive mapping of human brains during responses to sensory, cognitive, and emotional stimulation. CW NIRS has a number of advantageous properties that have resulted in wide use by researchers interested in brain imaging relative to other NIR systems: it is minimally intrusive and portable, affordable, and easy to engineer relative to frequency and time domain systems (Boas, Franceschini, Dunn, & Strangman, 2002; Chance et al., 1998). 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.

The fNIR system used in this study was originally described by Chance et al. (1998). The current flexible sensor developed in the Drexel Biomedical Engineering laboratory consists of four LED light sources and 10 detectors. Figure 3 shows a block diagram of the CW fNIR sensor system to monitor brain activity. The main components are the sensor that covers the entire forehead of the participant, a control box for data acquisition, a power supply for the control box, and a computer for the data analysis software. The communication between the data analysis computer and the task presentation computer is established via serial port to time-lock the fNIR measures to the task events.

The flexible sensor is a modular design consisting of two parts: a reusable, flexible circuit board that carries the necessary infrared sources and detectors, and a disposable, single-use cushioning material that serves to attach the sensor to the participant (see Color Plate 5, Figure 4). The flexible circuit provides a reliable integrated wiring solution, as well as consistent and reproducible component spacing and alignment. Because the circuit board and cushioning material are flexible, the components move and adapt to the various contours of the participant's head,

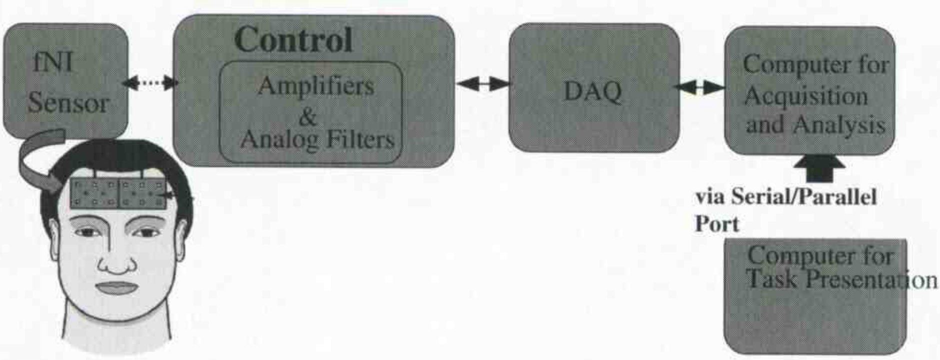

FIGURE 3 Block diagram of functional near infrared (fNIR) sensor system. The control box hosts analog filters and amplifies, and the data acquisition board (DAQ) is used for switching the LED light sources and detectors, which collect the reflected light.

thus allowing the sensor elements to maintain an orthogonal orientation to the skin surface, dramatically improving light coupling efficiency and signal strength.

The sensor contains four light sources and 10 photodetectors and divides the forehead into 16 voxels as illustrated in Figure 5. The source detector separation is 2.5 cm.

The light sources are controlled by the data acquisition software and turned on and off sequentially. The time multiplexing operation, turning sources on and off, is required to utilize two wavelengths in the system. This procedure does not alter the nature of the CW fNIR system due to the sampling process carried out during the digitization of data (Strangman, Boas, & Sutton, 2002; Villringer & Chance, 1997).

2.2. Data Presentation System

The fNIR system has both online and offline data presentation capacities:

1. Online—16-channel gauges simultaneously monitor real-time hemodynamic changes during data collection (Figure 6). The behavioral events (e.g., onset of stimu-

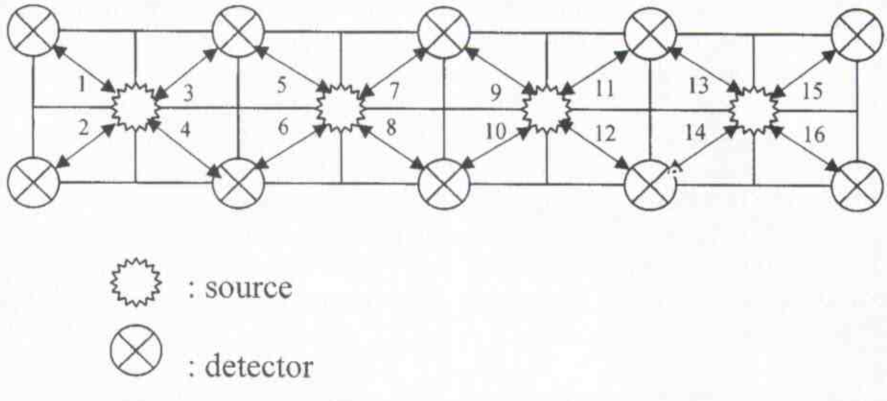

FIGURE 5 Illustration of functional near infrared probe design.

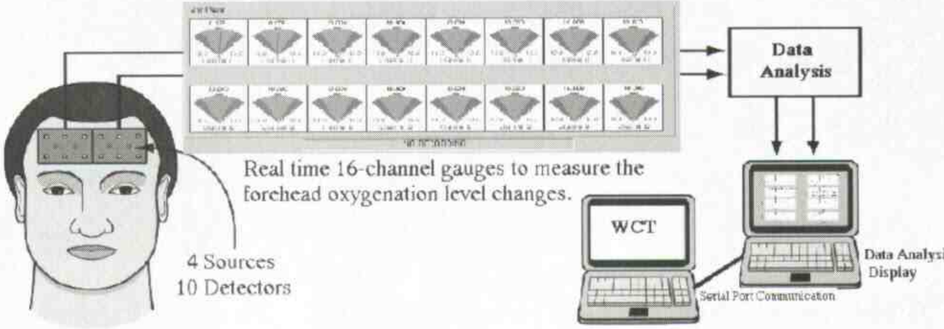

FIGURE 6 Data analysis and presentation system flow.

lus, type of stimulus, onset of response, and type of response) are synchronized with the fNIR measures for further event-specific quantification and analysis.

2. Offline—A testing and analysis platform has been designed for postexperimental data processing and presentation. The WCT data was processed using this offline platform, revealed in Figure 7.

2.3. Signal Preprocessing and Conditioning

To increase the signal to noise ratio of the fNIR device during the extraction of the hemodynamic response during cognitive tasks, signal processing algorithms were implemented to identify, eliminate, or compensate for noise and other signal distortions, such as electronic drift. Optical data are particularly vulnerable to artifacts caused by head motion. Head movement may displace the sensors, causing them to capture ambient light or light that has passed directly from source to detector without passing through the tissue. An adaptive filtering technique was implemented to remove motion artifacts from the fNIR data. As shown in Color Plate 6, Figure 8, the motion artifact can be removed successfully from the fNIR measurements. This procedure provides more reliable measurements of the hemodynamic response (M. Izzetoglu, Izzetoglu, Bunce & Onaral, 2003). Functional near infrared is not as sensitive to muscle tension as EEG, and eye-blinks produce virtually no artifact over dorsolateral prefrontal cortex (M. Izzetoglu & Bunce, n.d.).

2.4. Data Processing and Feature Extraction

As explained in section 2.3, the testing and analysis platform incorporates algorithms which enumerate, sort, and average the event segments marked during

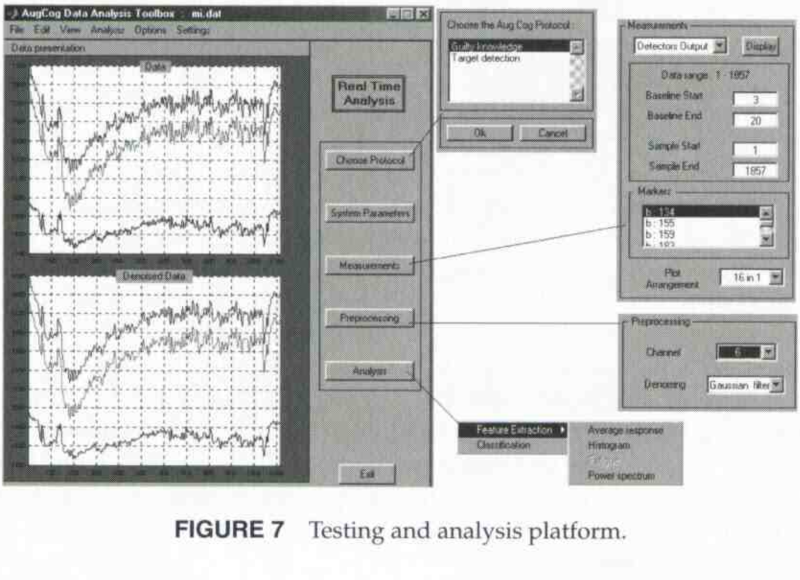

FIGURE 7 Testing and analysis platform.

data collection. Each marker embedded into the fNIR data represents an event and thus the algorithm is able to extract these segments and to sort them to calculate averaged response across trials within participants. Using equations 2 and 3, the blood oxygenation is calculated to assess the response to each stimulus. The calculated blood oxygenation changes are relative changes from baseline, determined as 15 to 20 sec prior to an event marker. Feature extraction and pattern recognition algorithms provide the tools to test the hypotheses that underlie specific experimental protocols and to perform trend analysis. A feature extraction module is under development as part of the testing and analysis platform (Figure 7) and automatically calculates averaged oxygenation and rate of oxygenation change over time. This study employed an algorithm that calculated the rate and slope of oxygenation change in the fNIR data. Because of the dynamic nature of the WCT, this feature was chosen to provide a "calculus" to describe the relative direction and speed of change in blood oxygenation during complex cognitive activity versus the baseline state. (The specific algorithm is currently proprietary.)

3. METHOD

3.1. Participants

A total of eight healthy participants, three women and five men, ranging in age from 18 to 50, participated in the DARPA AugCog Technical Integration Experiment study. The study was conducted at Pacific Science & Engineering in San Diego, California. The participants, recruited by Pacific Science & Engineering, had a range of experience with the WCT, ranging from 1 day to 300 hr. Prior to the study, all participants signed informed consent statements approved by the Human Subjects Institutional Review Board at Drexel University.

3.2. WCT

The WCT has been described as a quasi-realistic, ship-based, navy command and control environment task that requires spatial and verbal working memory and decision-making processes (St. John & Kobus, 2002). The version of the WCT employed in this experiment was comprised of two component tasks: Air Warfare Management and the Ship Status (SS) task. Air Warfare Management required the user to monitor "waves" of incoming airplanes, to identify them as friendly or hostile, and to warn and then destroy hostile airplanes using rules of engagement. Each wave lasted 75 sec. The level of cognitive effort in the Air Warfare Management component was manipulated by (a) increasing the number of planes per wave (6, 12, 18, or 24 planes), and (b) changing the proportion of planes whose identity was unknown, that is, whether hostile or friendly. Airplanes with unknown status require more decision and processing time, and therefore make the task more difficult. The WCT had two levels of difficulty relative to the proportion of unknown planes: low, in which 33% of the planes were unknown; and high, in which 67% of the planes were unknown.

A third task load factor used to manipulate cognitive workload was the presence or absence of a secondary verbal task labeled the SS task. The SS task was comprised of auditory messages containing information about the ship and its operation (encoding), and periodic queries, or "recall" about earlier auditory messages. In this auditory task, the participants were required to listen to sporadic auditory messages and memorize various ship status data while answering periodic queries that appeared on the computer screen. The Air Warfare Management task involves spatial and verbal working memory and decision-making processes, whereas the SS task is primarily a verbal memory task. When both tasks are operational, the WCT becomes a divided attention task. Although there is no universally accepted definition of cognitive workload, please see St. John et al. (St. John & Kobus, 2002) for the rationale behind this definition of workload.

For this study, each participant completed four sets of WCT. Each set was comprised of 12 waves, with three repetitions of each wave size in the order of 6, 18, 12, and 24 planes. The factors of wave size (6, 12, 18, or 24 planes), complexity (*high* vs. *low* percentage of unknown airplanes), and *full* versus *divided* attention (secondary SS task On or Off) were crossed to create a $4 \times 2 \times 2$ repeated-measures design.

Performance was assessed using two measures. The Reaction Time to Identify Friend or Foe, or RTIFF, indicated the time from when a plane appeared on the screen until the participant selected the plane and pressed the identification button. The Percent Game Score, or PctGS, was calculated as the percentage of game points that a participant did accumulate during any given wave relative to the total game points that were possible for that wave. Previous work on the WCT has demonstrated that RTIFF is a reasonable predictor of cognitive task load and of overall performance, and can be used as a behavioral measure of participant workload (DARPA, 2003).

3.3. Analyses

For each wave of 75 sec, the rate of change in the oxygenation was calculated from the fNIR measurements. For the purpose of these analyses, blood oxygenation values were averaged across the eight channels or pixels covering left and right hemispheres. To test the primary hypothesis that increased workload would be associated with relative increases in blood oxygenation in the frontal poll and dorsolateral prefrontal cortex, a 4 (wave size) × 2 (high vs. low complexity) × 2 (Second Verbal Task) × 2 (left vs. right hemisphere) repeated measures ANOVA was computed. To test the hypothesis that blood oxygenation would predict performance, within-subject Pearson product–moment correlation coefficients were computed between blood oxygenation levels and their RTIFF scores for each wave.

4. RESULTS

4.1. Task Load and Performance Analysis

In support of the primary hypothesis, the results indicated a main effect for wave size across both hemispheres ($F = 16.24$, $p < 0.001$). Post hoc analyses revealed that the 6-, 12-, and 18-plane waves differed from each other; 12-plane > 6-plane, $t = 2.29$, $p = .03$; 18-plane > 12-plane, $t = 3.52$, $p = .002$. The 18- and 24-plane waves did not differ (Figure 9). This main effect did not interact with hemisphere, ($F = 0.54$, ns) suggesting both hemispheres were responsive to wave size.

Independent analyses of left ($F_{left} = 14.87$, $p < 0.01$) and right ($F_{right} = 11.73$, $p < 0.01$) hemispheres indicated that both left and right dorsolateral prefrontal cortexes were responsive to wave size (see Color Plate 6, Figure 10, and Color Plate 6, Figure 11). No other main effect obtained significance (all p values > 0.10).

The main effect for wave size was qualified by one significant interaction between wave size and the Secondary Verbal Task ($F = 3.10$, $p < 0.05$); no other interaction obtained conventional levels of significance (all p values > 0.10). Post hoc analyses of the wave size × Secondary Verbal Task interaction revealed that the primary effect occurred in the 24-plane wave. When the Secondary Verbal Task was off (the less difficult condition), blood oxygenation exhibited a linear relation with wave size. In contrast, when the Secondary Verbal Task was on, blood oxygenation exhibited a quadratic relation with wave size, with the mean for the 24-plane wave dropping below that of the 18-plane wave (see Figure 12).

In line with the stated hypothesis, a preliminary interpretation of this finding was that a number of participants had reached their maximal level of performance in this most difficult level of the task, lost their concentration or effort in the task, and consequently their blood oxygenation dropped. The hypothesis also predicts that individuals who were able to stay on task and continue to perform in this difficult condition should demonstrate increased oxygenation relative to both (a) their own oxygenation levels in the 18-plane wave, and (b) individuals who became overwhelmed and disengaged. Because sustained concentration and engagement in the task should result in increased performance, a positive correlation between performance and blood oxygenation would provide support for this interpretation. A Pearson prod-

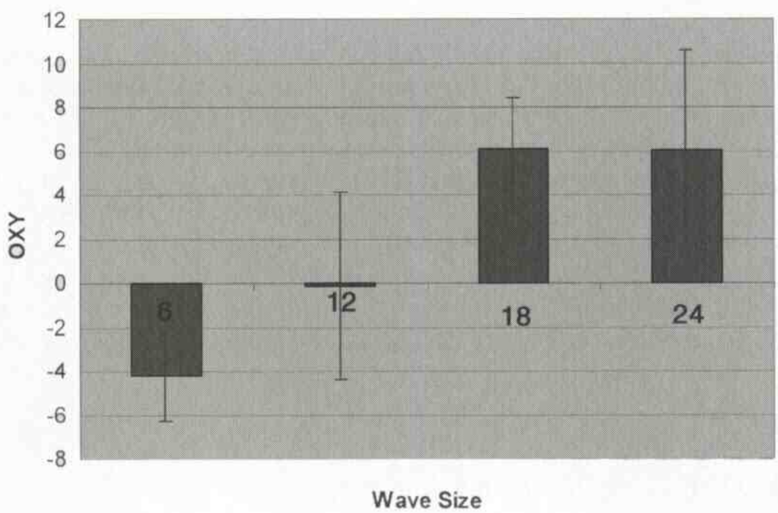

FIGURE 9 Averaged oxygenation versus wave size ($n = 8$).

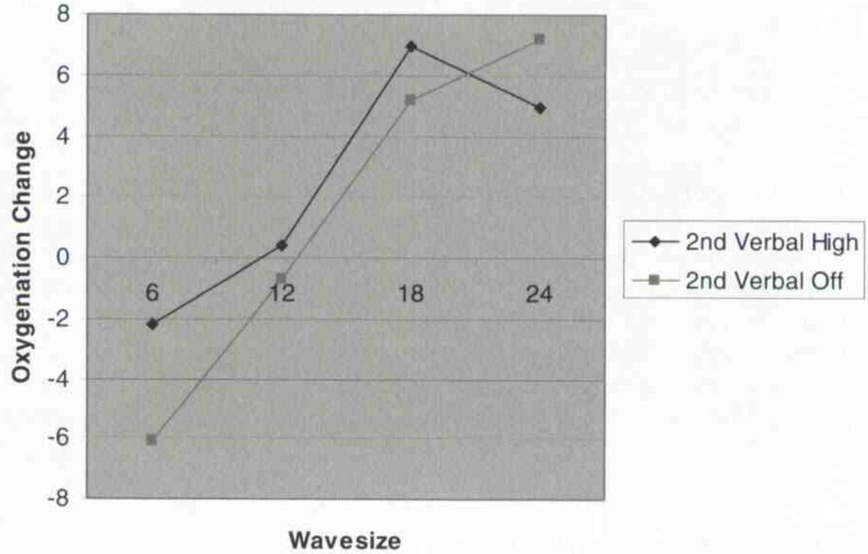

FIGURE 12 Wave size by Second Verbal Task for oxygenation change.

uct–moment correlation coefficient indicated a very strong positive relation between blood oxygenation and performance, indexed by the Percentage Game Score, in the 24-plane condition (Pearson's $r = .89$, $p = .003$; see Figure 13).

A median split on the Percentage Game Score provided further evidence of the hypothesized relation between cognitive effort and the blood oxygenation response. As can be seen in Color Plate 7, Figure 14, the mean levels of oxygenation were higher for both high and low performers in the 24-plane wave than the 18-plane wave when the Secondary Verbal Task was off, the easier condition. How-

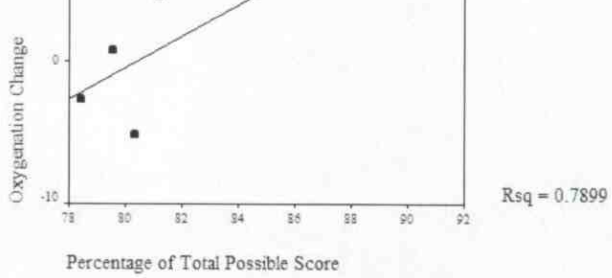

FIGURE 13 A Pearson product–moment correlation coefficient between performance and oxygenation change.

ever, when the Secondary Verbal Task was on, the more difficult condition, the individuals who performed well on the 24-plane wave showed a higher mean level of oxygenation for the 24-plane wave than for the 18-plane wave, whereas those who performed more poorly showed a decrease in oxygenation relative to the 18-plane wave.

Performance measures computed for each wave, including RTIFF, warn and destroy airplanes, and total game scores (as a percentage of possible points) correlate directly with workload levels (number of airplanes) and can be used as behavioral measures of participant workload (St. John & Kobus, 2002). A Pearson product–moment correlation coefficient between fNIR gauge output and the RTIFF performance measure confirmed a positive relation between prefrontal blood oxygenation and performance across all conditions (left hemisphere, Pearson's $r = .31$; right hemisphere, Pearson's $r = .32$). These data are graphically represented by wave size in Figures 15 and 16.

4.2 Individual Participant Analysis

To measure correlation between number of airplanes and the fNIR gauge values for each participant, the authors calculated 48 mean values of the blood oxygenation change rates for three waves of 6, 12, 18, and 24 airplanes within each WCT session.

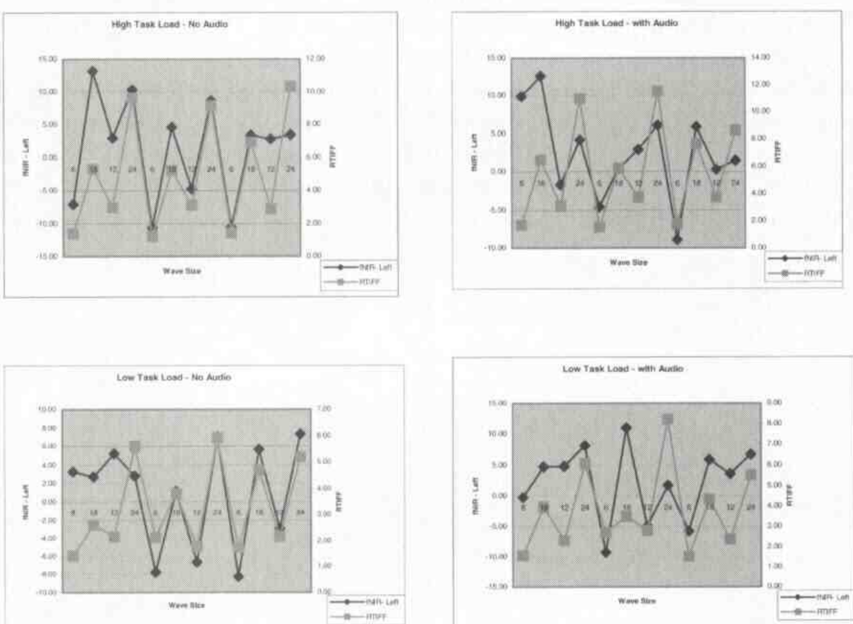

FIGURE 15 Functional near infrared (fNIR; Left) measurements versus the Reaction Time to Identify Friend or Foe (RTIFF; $n = 8$). The plot reflects the correlation between rate of change in left prefrontal oxygenation and performance measure RTIFF for each of the 12 waves of the scenario.

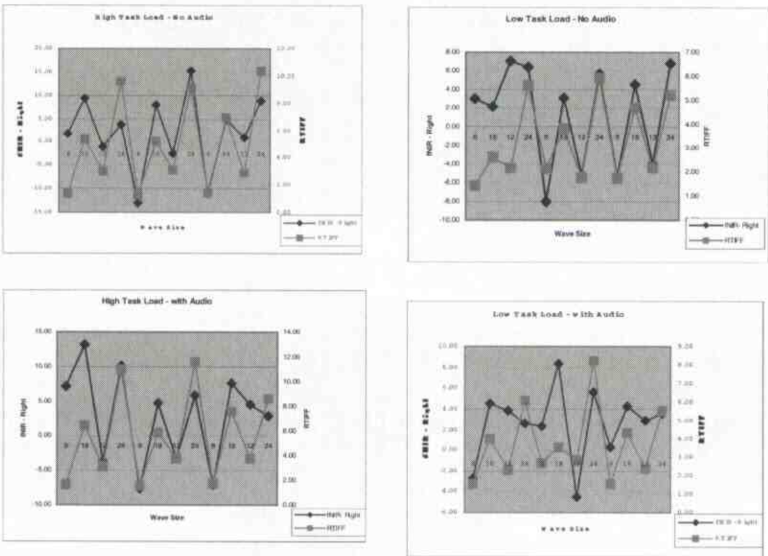

FIGURE 16 Functional near infrared (fNIR; Right) measurements versus the Reaction Time to Identify Friend or Foe (RTIFF; $n = 8$). The plot reflects the correlation between rate of change in right prefrontal oxygenation and performance measure RTIFF for each of the 12 waves of the scenario.

These values were analyzed using repeated measures ANOVA and the results are presented in Tables 1 and 2.

The individual analysis in Tables 1 and 2 suggests that the fNIR gauge is significantly sensitive to number of airplanes per wave in at least one hemisphere for seven participants. For participant P6, both left and right fNIR measurements failed. The correlation between fNIR measurements and number of airplanes per wave is provided in the third column of Tables 1 and 2 designated by R. Two individual participants (P1 and P2) show significantly strong correlation (Pearson's $r > 0.6$, $p < 0.01$).

5. CONCLUSION

FNIR spectroscopy—a portable, safe, affordable, and negligibly intrusive optical imaging system—can be used to measure hemodynamic changes in the cortex. The purpose of this study was to use fNIR as a gauge of cognitive workload in a complex, "realistic," command and control task. Changes in blood oxygenation in relevant areas of the frontal poll and dorsolateral prefrontal cortex were predicted to be associated with increasing cognitive workload defined as attention in a verbal and spatial working memory and decision task. The results, acquired in the context of the WCT, suggest a reliable, positive association between cognitive workload and increases in the oxygenation responses under circumscribed conditions. The re-

Table 1: Effects of Wave Size on the Functional Near Infrared (fNIR; Left)

Participants	*F*	*p*	*R*
P1	14.929	0.000	0.621
P2	19.980	0.000	0.672
P3	3.1550	0.034	0.363
P4	1.931	0.138	0.306
P5	5.258	0.030	0.428
P6	0.312	0.817	–0.023
P7	2.769	0.053	0.395
P8	3.597	0.021	0.300

Note. *R* = Mean correlations between number of airplanes and the fNIR gauge.

Table 2: Effects of Wave Size on the Functional Near Infrared (fNIR; Right)

Participants	*F*	*p*	*R*
P1	13.196	0.000	0.649
P2	8.331	0.000	0.537
P3	0.574	0.635	0.064
P4	3.006	0.040	0.342
P5	2.527	0.070	0.308
P6	1.151	0.339	0.169
P7	1.491	0.230	0.290
P8	2.152	0.107	0.281

Note. *R* = Mean correlations between number of airplanes and the fNIR gauge.

sults support the hypothesis that rate of oxygenation change in dorsolateral prefrontal cortex as measured by fNIR can provide an index of sustained attention in a complex working memory and decision-making task. The results also suggested that a drop in the rate of oxygenation change in dorsolateral prefrontal cortex under high workload conditions may be able to predict some participant's decline in performance. As an initial endeavor, these results are promising for the use of fNIR in the creation of a symbiotic relation between the operator and the operational environment.

One assumption in this interpretation of the data is that individuals became overwhelmed and that there was a mental shift which resulted in a decrease in oxygenation. Although the performance scores provide some evidence that participants became overwhelmed or lost their concentration in the task, the participants' mental states were not directly assessed. Future studies are needed to better articulate and verify this aspect of the hypothesis.

A number of individual differences could play a role in these results. One individual difference of particular interest for these results is that of expertise, or practice. Overall "expertise" was not quantified by Pacific Science & Engineering Group, although participants had a wide range of exposure to the task. However, performance in a complex, rule-driven task like the WCT can reasonably be assumed to be highly influenced by practice. As such, practice would appear to be an important variable for this type of task, and should be quantified in future studies.

Actual performance provides an index of skill that may reasonably serve as a correlate of practice. Nevertheless, oxygenation levels in both skilled and neophyte participants appeared to conform to the hypotheses in this study. Those with less competence simply hit their maximal level of performance sooner than those with better skills, with an associated drop in cortical oxygenation. It may be, however, that some individuals are more adept at such tasks as the WCT. It is well known that there are individual differences in personality, such as extraversion and neuroticism, that influence competencies in various tasks, and also differentially influence physiological measures, for example (Broke & Battmann, 1992; Razoumnikova, 2003). The influence of these individual differences remains for future studies to explore.

The main effects for complexity and for the Secondary Verbal Task, despite increasing perceived cognitive effort (DARPA, 2003), were not associated with significant changes in blood oxygenation. There are a number of potential reasons for these findings. First, the sample size was small, which limits the power of these analyses. It is possible that a larger sample could result in more reliable results. Indeed, the small sample size is a significant limitation in this study, and all results, although promising, should be considered preliminary. Second, these analyses focused on only two fNIR parameters: average change in oxygenation and rate of change of oxygenation. It is possible that other parameters could add predictive power in these complex cognitive tasks. We are currently working on developing a parametric model for the HbO_2 pulse to extract additional features such as peak amplitude, pulse width, latency, and so forth. Hence, further development in the algorithm, fine-tuning, and increasing the number of features are expected to enhance consistency and efficacy of the gauge. Third, the current sensor was applied over a limited area of the frontal poll and dorsolateral prefrontal cortex. Some of these manipulations may have had effects in areas of the cortex that are accessible to fNIR, but were not measured with the current sensor. This question remains for future generations of the sensor to determine.

In this study, significant effects were found across both hemispheres. Although fNIR has many advantages over fMRI for field deployment, it does not have the same spatial resolution as fMRI or PET. In addition, because the depth of fNIR imaging is dependent on the distance between the source and detector, these distances must be fixed. The current sensor is fixed with respect to all sources and detectors across both hemispheres. As forehead dimensions differed among individuals, the additional variance associated with different spatial locations combined with variations among individual brains, may have contributed to these widespread effects. As such, interpretations about the precise neural sources of these hemodynamic effects should be further investigated using fMRI technology in combination with fNIR for such complex tasks as the WCT. Having more independent source-detector arrays in future generations of the sensor, and more precise localization algorithms, may help to mitigate this limitation. Finally, the WCT itself is complex, and numerous cognitive and emotional functions are occurring during the execution of the task. It is possible that these various tasks have differential effects on the hemodynamic response. For example, recent research using PET indicates that various areas of the cortex show increases in oxygenation during a divided attention task relative to a full attention task, whereas other areas demonstrate decreases in oxygenation during the same task (Iidaka, Anderson, Kapur, Cabeza, & Craik, 2000). Further work is needed to more fully explicate our understanding of brain function during what may be common everyday, and yet extremely complex, tasks.

Our finding, that fNIR can predict cognitive workload, defined as sustained attention in a complex working memory task, holds promise for the use of fNIR in the creation of a symbiotic human–computer interface. As our knowledge about the neural underpinning of attention and working memory yields to scientific investigation, so will our ability to use this information to increase human cognitive and emotional capacities in a number of critical work and educational environments.

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