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Changes in Behavior of Evoked Potentials in the Brain as a Possible Indicator of Fatigue in People

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Abstract— **Many professions place significant mental and/or physical strain on their workers. Some professionals (such as firefighters, soldiers, and pilots) have an inherent responsibility for the safety of others. Making sure that workers in these remain fit for duty is an important health/safety concern for the workers and those they serve. This paper explores the viability of using EEG as a non-invasive, cost efficient method for assessing fatigue, sleep deprivation, physical exertion and stress. Specifically, P300 evoked potentials are generated in response to certain stimuli. Variations in the response characteristics (magnitude, shape, and peak shift) are explored in relation to sleep deprivation, caffeine usage, and physical exertion. Preliminary data suggests that there are quantifiable changes to the P300 response that may be attributed to fatigue.**

I. Introduction

Professions such as firefighting, mining, construction and the military service subject their workers to periods of intense physical and/or mental pressure in harsh work environments that frequently includes potential for physical harm. Under such challenging conditions mental and/or physical fatigue can affect task performance and in some cases jeopardize the health of the workers [1]. This can have a severe negative impact on the wellbeing of the professionals and those that they serve. Thus, the ability to monitor fatigue in real-time can be a critical need. Of particular interest is the identification of reliable methods for detecting the onset of critical fatigue (i.e. the threshold where fatigue significantly impairs the health and well being of the worker and the people they serve) [2][3].

Previous psychological, imaging and kinesthetic studies have demonstrated measurable physical and mental changes associated with fatigue [4][5]. Unfortunately, the Computer Tomography (CT) scanners or Magnetic Resonance Imaging (MRI) machines used to conduct these studies are expensive, bulky, require the subject to remain motionless and may include radiation exposure which renders them inappropriate for use as platforms for continuous monitoring of worker fatigue. In contrast, electroencephalography (EEG) is a non-invasive technology that can be used to continuously assess a subject's neurological status [6]. Further, recent advances in EEG technology have made it possible to design mobile system that can potentially be integrated into existing equipment that is worn continuously during the full duration of work activities.

Brain Computer Interface (BCI) research utilizes neurological feedback, like EEG and event related potentials (ERP), to defined stimuli to perform tasks like writing, prosthetic movement and playing games. A much-studied ERP is the P300 (P3) wave that is formed as a component of recognition when the subject responds to a target stimulus [7]. There have been studies demonstrating that sleep deprivation, medication and time of day are among several factors that can produce changes to the P3 wave [8][9][10]. In this work we build on these findings and include the impact of caffeine usage and the impact of physical exertion.

II. Experimental Methods

In this study, five research subjects were evaluated. While they were not blinded to the study, they had no prior experience with BCI or EEG testing. The subjects were healthy volenteer students between the ages of 21-30.

After connecting the EEG system to a subject, 5 minutes of EEG was aquired where subjects were asked to perform specific tasks such as to focus on an object, close their eyes and relax, blink and move their eyes. The baseline sessions were recorded to enable evaluation of the EEG responses to ensure appropriate set up. Next, a P300 Speller program was used to capture the P3 response pattern for the subject. At this point it was confirmed that each subject was able to spell accurately using the P300 Speller program; using their individulized response . Finally, the P3 responses collected under different conditions were analyzed offline to extract characteristic features.

A: Experimental Set Up

Two 16-channel g.tec USB amplifiers were used along with a standard EEG-Cap to obtain 19 channels of EEG data with a single Ground and Reference as illustrated in Fig. 1. The amplifiers were connected to a Windows™ laptop with a CRT monitor connected for use as a test display. BCI2000 and Matlab™ with the EEGLab™ plug-in were used for data acquisition,

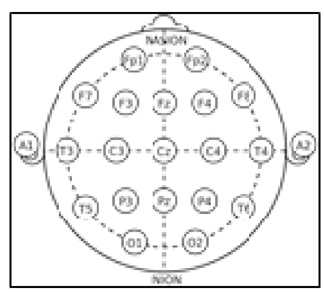

Figure 1 Showing Experimental Electrode Configuration

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signal processing, and data analysis [9].

B: EEG Set-up

The subject was asked to sit facing the CRT monitor with their legs uncrossed and arms resting comfortably at their sides. An elastic EEG-Cap pre-configured to follow the International 10-20 system for electrode placement was stretched over the subject's scalp to place 19 Tin electrodes as shown in Fig. 1. The ground electrode was located between FP1 and FP2 and the reference electrode was connected to the ear at either position A1 or A2. A syringe with a blunt tipped needle was used to gently abrade the subject's scalp before injecting conductive gel into the gap between the electrode and the skin. This prepping process was performed for all electrodes connected to the g.tec USB amplifiers. Finally, the subject was asked not to make any sudden movements and to keep as still as possible during the 1-5 minute test cycles. A complete set of tests for a single test subject takes ~1.5 hr. [12].

C: P300 Speller

The BCI2000 P300 Speller is a spelling application that uses the P3 wave to determine which letter the subject is focusing their attention on during a set of stimulus flashes. The user interface of the P300 Speller is composed of a 6X6 grid containing the letters of the alphabet, numbers one through nine and an underscore representing a space. Based on the application settings, every row and column of the matrix flashes for a specific length of time and a specific number of times.

The speller application [12] can be modified for the specific amplifier and number of channels used. Table 1 shows some of the relevant experimental parameters used for the experiments reported here. A Classifier Builder program generates a number of useful parameters including, the minimum number of flashes for accurate spelling, a weighted matrix based on the feature response time and the specific channels where the P300 response is the strongest. A customized parameter file that enabled spelling with 100% accuracy was constructed for each test subject.

During the experiments reported here, a demonstration of the P300 Speller was performed before each session to make subjects familiar with the speed and letter grid. The subject was instructed to focus on the letter they were trying to spell and count the number of time it flashes. By comparing the difference in the response to every flash in a pre-defined set to the flashes at the target letter the P300 response can be characterized and later searched for. The speller application uses the "oddball paradigm" to build a classifier that associates the counting of flashes to appropriate letters [13].

For each subject a classifier was built based on spelling "THE" "QUICK" "BROWN" "FOX" (i.e. each word run separately with no spaces included) with 30 flashes per letter. Thus the classifier is based on the application of 2880 stimuli of which 480 are on target. This allows for a robust individualized classifier to be built and the P300 waveform for the test subject to be characterized.

Table 1 Experimental parameters used for P300 Speller

Parameter	Values
Sampling Rate	256Hz
Gain	1
High Pass Filter	70Hz
Low Pass Filter	0.1Hz
Notch Filter	58-62Hz
Number of Flashes	30
Flash Duration	32.5ms
Inter Flash Interval	61.5ms
Surface Impedance	<10 kΩ

D: Experimental States

During the testing, each subject was evaluated under the following states:

Control: Subjects slept at least 6 hours the previous night and the testing was done 6-8 hours after waking up. Subjects were advised to avoid caffeine, physical exercise and any medication (if possible) for 12 hours preceding the test.

Sleep Deprivation: Subjects were directed to document time of waking and then not sleep for 24 hours. Subjects were also asked to avoid caffeine, medications (if possible) and strenuous physical exercise prior to testing. Testing was conducted at 25-26 hours after waking.

Physical Fatigue: Subjects were instructed to be at the Control state prior to testing. Subjects were tested with the Control Classifier to ensure that they were at the Control state. Subjects were then instructed to run down and up 6 flights of stairs twice (more if the heart rate was not greater than 90 beats per minute (bpm) monitored by pulse counts and breathing not greater than 20 breaths per minute) per timed observation.

Caffeine: Subjects were instructed to be at control state 6-8 hours before testing. They were then instructed to drink an 8oz. caffeinated beverage upon waking up and then another within 1 hour prior to testing.

E: Analysis of P300 Under All Test Conditions

The BCI2000 Offline Analyzer was used to analyze the classifier generated for experiment. An r^2 plot was generated by the BCI200 analysis and then post processed using Matlab™ to find the peak times, areas under the peak and peak voltage. The r^2 value of the response to the P300 stimulus is plotted based on equation (1).

$$r^2 = SS_{reg} / SS_{tot} \qquad (1)$$

Where SS_{tot} is the sum of squares of all values and SS_{reg} is the regression sum of squares.

The proportion incorrect is then subtracted from the proportion correct giving the response for that particular experiment. A moving window average with a window size of 7 was performed to smooth the data over the range where the P300 response was present. Formula for averaging is generated by equation (2).

$$A_n = (x_n + x_{n-1} + \ldots x_{n-k+1}) / k \qquad (2)$$

Where A_n is the moving average after n points and k is the window size.

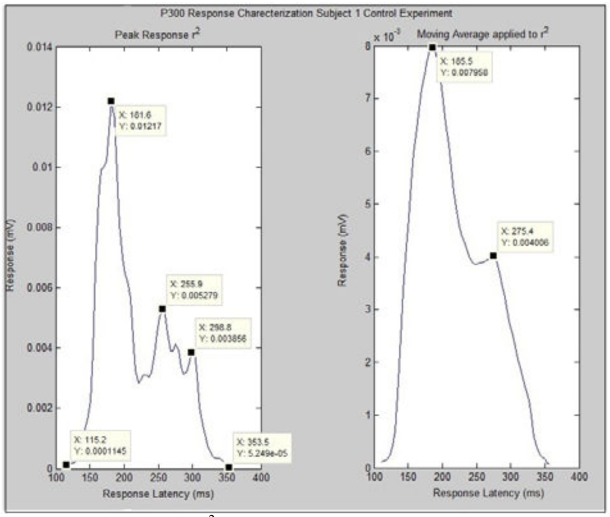

Figure 2 Example of an r^2 plot showing raw data and smoothed data over range of the P3 response.

Full duration half max (FDHM) is then calculated for the original and averaged r^2 plots using equation (3).

$$f(x) = (1 / (\sigma*(2\pi)^{1/2})) * \exp (- (x-x_0)^2/(2 \sigma^2)) \quad (3)$$

Where sigma is variance and x_0 is the mean.

Finally, the area under the curve (AUC) is calculated using a trapezoidal approximation given in equation (4).

$$Ar = (b-a)* ((f(a) + f(b)) / 2) \quad (4)$$

Where a and b are the lower and upper limit of the function

Figure 2 shows a typical r^2 plot for a subject in the Control State. The r^2 plot on the left is generated using equation (1) applied to the raw data. The smoothed version of the r^2 plot is shown based on applying equation (2). As expected, smoothing the r^2 plot reduces local variability in the plot (i.e. fewer local maxima and minima) while simultaneously shortening and broadening the peak. The smoothed r^2 plot is used for determination of the Full Duration Half Max (FDHM) and Area Under the Curve (AUC) analysis.

III. Results

A. Control Condition Range and Location of P300

The P3 response is located in different regions of the brain for each person. Common locations for the P3 response include the Cz, Pz, T4, O1 which is consistant with data gathered from the subjects in this study. P300 response time in the 5 subjects that have been tested in the Control State have ranged between 170ms and 450ms. This compares well to the typical range of 200-500ms [7][11]. With system utilizing their individualized P3 response classifier parameters, all 5 of the test subjects were able to spell with 100% accuracy using the BCI2000 speller application and their individulized Classifier in each state. It is interesting to note that the number of stimuli it took to accuratly spell increased with sleep deprivation versus the control state.

Table 2 Averaged FDHM and AUC Results (standard error)

Condition	FDHM	AUC
Control	80.98 (3.69)	0.72 (0.36)
Sleep Deprivation	122.61 (22.84)	0.41 (0.22)
Caffeine	88.37 (20.62)	0.76 (0.52)
Physical fatigue	69.89 (9.61)	0.18 (0.11)

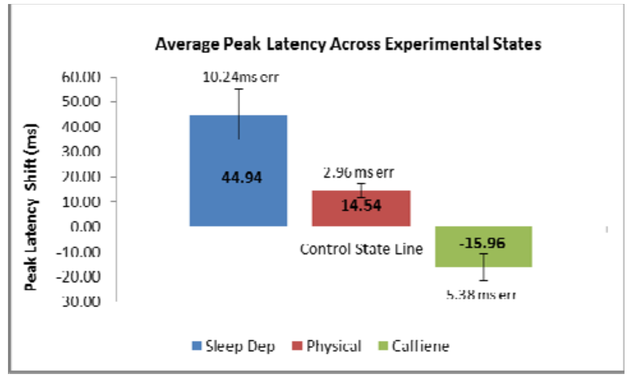

Figure 3: Peak Shift compared to Control Conditions

B. Impact Test States on P300

To date, only 5 subjects have been completely evaluated through all of the test states described in Section II.D. Table 2 shows the average Full Duration Half Max (FDHM) and Area Under the Curve (AUC) for these subjects for all 4 of the test states. In general, smaller magnitude r2 peaks are observed for all fatigued test conditions leading to significant reduction in the signal-to-noise value. A higher magnitude was typically observed in the caffeine tests. This observation along with the limited number of test subjects evaluated makes it difficult to draw conclusions regarding possible trends in this data. It is striking that under sleep deprivation, subjects typically showed an increase in the FDHM value.

Fig. 3 represents average peak latency shift with calculated standard error bars compared to the Control State. In this graph, positive latency shift represents a time delay in the peak of the P3 wave compared to the timing collected in the Control State. In contrast, negative latency shift is associated with an enhancement or speed up in timing of the P3 wave peek.

IV. Discussion

An increase in latency of the P300 response with sleep deprivation and physical fatigue (Fig.2) is consistent with previously observed results [9]. These results, correlate with decreased focus and slowing of responses that are associated with fatigue. Further, these results are consistent with other fatigue related neurological findings [14][15][16]. The fact that physical exertion in these experiments had less impact on latency than sleep deprivation can be attributed to the limited activity and the fact that the subject's heart rate fluctuated during the EEG assessment interval. It is believed that an increase in exercise intensity/duration would impact these results leading to changes in the P3 latency values.

Latency results associated with caffeine use also correlate with expectation. Caffeine binds to target receptors in the brain to make one feel energized and alert. The speeding up (i.e. negative latency) of the P300 response with caffeine usage is a logical result [9][15].

There were changes seen in EEG activity in terms of alpha bands, blink rate and SNR which could also be useful to serve as fatigue indicators [2]. While the sample size evaluated in this data set is small, seeing changes consistent with expected results is an encouraging result that warrants continued exploration.

V. CONCLUSIONS

Changes in P300 peak response time and EEG artifacts are quantifiable and have been shown to vary with conditions that induce fatigue. Deviations from the average could be attributed to subject differences terms of activity intensity and physical fitness. Thus there is utility in the creation of an individualized application for fatigue assessment. More data is required to show generalizability of the results. The study methodology described is appropriate for the research question being asked.

VI. FUTURE DIRECTIONS

More data is needed to draw conclusions about fatigue responses over time across conditions and about critical fatigue indications. Thus, we are continuing to test and analyze subjects with the primary goal being to identify characteristics of the P300 that exhibit significant modification based on fatigue, sleep deprivation and stimulants like caffeine. While use of caffeine appears to heighten attention and awareness, it is not clear if this improvement would overcome deficits associated with fatigue. Exploration of the relationship between caffeine and fatigue is part of our ongoing work.

The version of the P300 speller used in initial experiments is a visual stimulus test. An audio based test with different sound frequencies has been developed and is undergoing testing. Comparing results from both testing methods will aid in developing practical comprehensive systems for given applications [13][17]. The ultimate goal of this project is to develop a mobile, system to assess work-induced fatigue in professions where fatigue can significantly impact the performance and safety of the worker. As shown in fig. 4 the ultimate system would be integrated directly into the workers existing equipment and enable continuous real-time monitoring of fatigue through applied stimuli and then measuring changes in response remotely [18]. Such a system would enable monitoring by a supervisor/manager allowing for more effective rotation active workers and/or scheduling of rest periods.

Figure 4. Concept for Fatigue Assessment Application

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