Detection of Attentional State in Long-Distance Driving Settings Using Functional Near-Infrared Spectroscopy

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ABSTRACT

Self-driving cars have the potential to drastically improve the efficiency and safety of personal cars. However, despite recent significant improvements in the field, fully autonomous car technology will not likely be ready in the near future. A derivative architecture, instead of full autonomy, is one where automated technology provides driver assistance, and thus incorporates a human who is expected to intervene in the case of a problem or an emergency. Humans, however, have difficulty sustaining vigilance for long periods of time, which is of concern if a human driver is expected to monitor automation for extended periods of time during long distance drives. We investigated a method to detect this lapse in sustained attention, otherwise known as the vigilance decrement, in long-distance driving by analyzing oxygenated hemoglobin concentrations (HbO) collected by functional near infrared spectroscopy (fNIRS). A total of 27 subjects in a four hour simulated driving scenario reached an HbO plateau, and thus potentially the vigilance decrement point, in 20.55 minutes on average. Driver performance, on average, was poorer in the phase after the vigilance decrement compared to the performance before the decrement point, as measured by maximum lane deviation. Such an approach could eventually enable self-driving cars to detect the attentional state of human drivers, which is critical if the car needs to determine whether the human can intervene in a timely fashion.

Keywords: self-driving cars, fNIRS, vigilance decrement, highway driving

INTRODUCTION

Self-driving cars have the potential to drastically improve personal transportation in terms of both safety and efficiency (*1*). However, there are no self-driving cars that have achieved the National Highway Traffic Safety Administration's "Level 4" certification (*2*). Level 4 automation is defined as full self-driving automation, where the driver is not expected to be available to control the car at any point during the trip (*3*). There are still a number of technical obstacles that have to be addressed before these cars can obtain this classification, including inclement weather, construction zone traversing, large-scale mapping of U.S. roadways, and vulnerabilities associated with the GPS and other technology in the car (*4, 5*).

Due to the number of technological and policy related hindrances associated with self-driving cars, it is within reason to postulate that a human will have to be involved in the self-driving paradigm for the immediate future (*6, 7*). The human would provide supervisory oversight and intervene when the self-driving car experienced an error or encountered a problem (*7)*. Humans, however, are not perfect operators of motor vehicles, and would experience new challenges as supervisors of a highly automated system (7). The inability for humans to maintain sustained attention for prolonged periods of time, known as the vigilance decrement, has been shown in multiple supervisory domains to wane during the first 20-30 minutes (but up to 45 minutes) of a monitoring task (*8, 9*). A decrease in human attention could render the driver ineffective in the event of an emergency, which will be particularly problematic in long distance driving settings. Thus, for humans to be sufficient monitors of a self-driving car, there needs to be a reliable way to monitor a human's vigilance in real time.

One potential avenue to monitor vigilance in real-time is through the utilization of frequency domain functional Near-Infrared Spectroscopy (fNIRS). This technology measures the quantity of oxygenated-hemoglobin (HbO) and deoxygenated- hemoglobin (HbR) utilizing light in the 650- 900 nanometer range (*10, 11*). These two states of hemoglobin can be measured because HbO and HbR absorb near-infrared light uniquely at different wavelengths. Absorption of the light is then converted into a micromolar concentration value for HbO and HbR by utilizing the modified Beer-Lambert law. This type of functional neuroimaging could be advantageous for two reasons. First, this method compared to other functional neuroimaging techniques is more robust against motion artifacts (*11)*. Secondly, fNIRS is capable of collecting data very quickly and providing information about the subject with high temporal resolution (*11*).

There have been a few experiments that attempt to explain vigilance utilizing fNIRS (*12, 13*). Warm et al. were able to detect a decline in vigilance based on task performance results, but they were unable to detect blood oxygenation changes utilizing fNIRS that matched the decline in task performance (*12*). Bogler et al. demonstrated that variations in reaction times for task performance were correlated with HbO changes in the frontal and parietal regions of the brain (*13*). However, the method has not been demonstrated in a continuous vigilance setting, where there are no intermittent tasks to assess cognitive performance (*13*). Below, we present a method that attempts to estimate the time at which the vigilance decrement occurs, through the use of functional near- infrared spectroscopy, based on the concentration of HbO or HbR in the pre-frontal cortex. Moreover, we attempt to link these physiologic attention measures to performance.

Materials and Methods

Twenty-seven human subjects participated in this experiment, 13 male and 14 female. The average age is 25.3 years old, with a standard deviation of 5.8 years. The average boredom proneness scale (bps) score for all subjects is 85.3, with a standard deviation of 16.4. The range of typical bps scores is 81-117 for the general population, with an average bps score of 99 (*14*). The subjects volunteered for the study and were compensated one hundred dollars for four hours of testing. Solicitation of the experiment consisted of flyers and online announcements.

The experiment involved each subject completing a long distance driving simulation in a STISIM™ four-lane highway environment that lasted approximately four hours. The physical environment of the simulation included an automobile bucket chair, acceleration and brake pedals, a steering wheel, an LCD monitor projecting the simulation, and an fNIRS device secured to the subject's forehead. The subjects operated the car via a 48-inch display with the steering wheel and pedals. Each side of the four-lane highway was 18 feet wide, with occasional traffic passing by in the opposite lane (Figure 1).

Subjects were instructed to behave exactly as they would if driving on the road. Therefore, mobile phone usage, reading, eating, etc. were permitted. Time spent using a mobile phone was observed and recorded during the experiment. Drivers and their simulation environments were recorded during the experiment to allow more precise analysis of behavior while driving the car. Metrics collected included car velocity, car acceleration, lateral lane position, number of times the white line at the edge of the road (right or left) was crossed, number of times the double yellow line was crossed, and number of times the car crashed.

The functional near-infrared spectroscopy instrument utilized was an ISS Imagent with a modulation frequency of 110 MHz. The fiber-coupled laser diodes operated at 690 nm and 830 nm. The two probes were placed on the subject's forehead (pre-frontal cortex), secured with a black neoprene bandage, and then each

FIGURE 1 Photograph of the Experiment in Progress

subject was fitted with a black polyester swimming cap to ensure the sensors were securely fixed and insulated against incoming light. Each probe contained 4 linearly spaced light sources and a single detector.

The ISS Imagent instrument collected and stored data utilizing a software package called "BOXY." Before each experiment, BOXY and calibration blocks were utilized to ensure the instrument was calibrated before placed on the subject's forehead. BOXY was utilized for both a low-pass filter and the modified Beer-Lambert law data calculation. The low-pass filter eliminated high-frequency instrument noise, fast cardiac oscillations, and artifacts caused by respiration (15).

All subject data was analyzed offline. A low-pass filter of .15 Hz was applied to the raw data after collection (*16*). After the low-pass filter, a discrete wavelet transform was applied to the data in order to reduce the number of motion artifacts in the data (*16*). The discrete wavelet transform was executed in MATLAB. The Modified Beer-Lambert law was applied to the data after filtering to produce HbO and HbR values.

HbO concentration plateau points in the data were determined utilizing a method relying on the calculation of the percent change of two slopes, with each slope calculated from a finite window size. The slope of the line connecting the first and last points in the first 5-second window was calculated. A 5-second window was selected since fNIRS measures have an approximate 5-second delay (17). The percent change of the two slopes was calculated and when the change was less than 5%, the time point in the center of the 5-second windows was determined to be the plateau point. If the percent change of the two slopes was greater than a 5% change, the latter 5-second window slope was compared to a newly calculated slope for the window immediately following the latter 5-second window. The calculation continued until a change in slopes of less than five percent for this rolling 5-second average was discovered in each subject's data, which was labeled as a plateau.

Various metrics were computed across two different time ranges, defined as pre-plateau and post-plateau for each subject (Tables 1 and 2). Each time range lasted the same amount of time, and was dependent on when the subject's HbO reached a plateau point. Therefore, if the subject's HbO plateau point was calculated at 10 minutes, pre-plateau period was from 2-10 minutes, and the post-plateau period was from 10-18 minutes. The first two minutes were excluded to account for the subject acclimating to the simulation environment. Percent change calculations found in Table 2 were calculated based on the percent change from an average baseline period in the beginning of the data from 2:00-2:05 to an average of five seconds of HbO data around the maximum lane deviations in a given phase.

Results

Various metrics were collected from both the STISIM driving simulation and fNIRS. Table 2 shows the descriptive statistics for the dependent variables of average and maximum lane deviation before and after the HbO plateau time point, the road excursions pre and post plateau, and the percent changes in HbO and HbR pre and post plateau. HbR concentration values did not offer the same magnitude of signal fluctuation that HbO produced, which is typical of fNIRS systems. Data for mobile phone usage was calculated for each subject via the recording of each subject during the experiment.

Dependent t-tests were not significant for any of the before and after paired variables in Table 2, except for maximum lane deviation ($p = 0.025$, $\alpha = 0.05$). These data indicate that the HbO plateau point, on average, is capable of highlighting degeneration in driving ability during this experiment with respect to maximum lane deviation.

The data in Table 3 include the number of driver errors and mobile phone usage before and after the HbO plateau point. No before and after pairing dependent t test for individual behaviors was statistically significant. However, while drivers did not cross the centerline more while on the phone pre or post the HbO plateau point, even though not statistically significant, they were willing, on average, to tolerate more road edge excursions post HbO plateau. Time to HbO plateau from Table 1 was significantly correlated with road edge line crossings pre-plateau ($\rho = .389$, $p = .045$) and also marginally with the amount of time spent on the phone pre-plateau ($\rho = .374$ $p = .054$).

TABLE 1 Individual Subject's Observed HbO Time to Plateau and Summary Statistics

Subject Number	HbO Plateau Times (minutes)	Subject Number	HbO Plateau Times (minutes)
1	15.25	17	6.42
2	28.25	18	38.08
3	11.42	19	32.42
4	11.25	20	31.08
5	20.08	21	5.92
6	21.25	22	10.42
7	7.25	23	10.75
8	46.08	24	6.75
9	24.58	25	29.75
10	24.75	26	27.08
11	40.58	27	28.25
12	25.08		Mean: 20.55
13	14.58		Median: 20.08
14	19.42		Stan. Dev: 11.21
15	9.92		Minimum: 5.20
16	8.25		Maximum: 46.08

TABLE 2 Dependent Variables and Descriptive Statistics

Metric	Minimum Value	Maximum Value	Mean Value	Median Value	Standard Deviation	t- Statistic
Average Lane Deviation: Pre-Plateau (Feet)	0.54	1.95	1.09	1.07	0.35	0.125
Average Lane Deviation: Post-Plateau (Feet)	0.69	1.94	1.18	1.18	0.31	
Maximum Lane Deviation: Pre-Plateau (Feet)	2.04	13.13	6.23	5.10	3.24	0.025
Maximum Lane Deviation: Post-Plateau (Feet)	3.31	19.01	7.53	5.06	4.29	
Percent Change HbO: Pre-Plateau	-1.65	1.25	0.046	0.00	0.65	0.156
Percent Change HbO: Post-Plateau	-3.07	1.43	-0.236	-0.130	1.032	
Percent Change [HbR]: Pre-Plateau	-1.58	1.84	0.09	0.00	0.81	0.807
Percent Change [HbR]: Post-Plateau	-2.00	2.36	0.05	0.14	0.89	

TABLE 3 Aggregate Driver Behavioral Data Before and After The HbO Plateau Point

Incident	**Pre-Plateau**	**Post-Plateau**	**Difference Between Post- and Pre-Plateau**
Number of times center line was crossed	21	18	-3
Number of times center line was crossed while using mobile phone	9	10	1
Number of times the road edge line was crossed	64	86	22
Number of times road edge line was crossed while using a mobile phone	23	31	9
Average percentage of time spent on mobile phone while driving	4.5%	9.8%	5.3%

Discussion The average HbO plateau time of 20.55 minutes falls within the range of time values (20-35 minutes) accepted as the window where the vigilance decrement traditionally occurs (*8*). However, the standard deviation of the data set, equal to 11.21 minutes, indicates that not every subject had a plateau point falling within the 20-30 minute vigilance decrement window. The vigilance decrement has been reported to occur in the first fifteen minutes of cognitive activity, all of the way up to 45 minutes (*9*). In this data set, there is only one HbO plateau point, 46.08 minutes, which is greater than 45 minutes. The large standard deviation of the saturation points suggests that the saturation points, and therefore possible vigilance decrements, vary from person to person by a noticeable margin. This could be due to the fact that vigilance decrement is not fixed for all people given the same task (12).

Simply discovering a plateau point or event in HbO data does not necessarily guarantee a difference in a human cognitive state. Theoretically, if a person experiences a vigilance decrement, then presumably there should be a performance metric indicating a change in task performance that would correlate with some measurable physiologic change. Past studies have attempted to correlate HbO events with the performance in a particular task (13, 14). Bogler et al. were able to correlate decreased reaction times with changes in HbO concentration and they correlate these observed neural events to decreases in vigilance (14). Similarly, our data indicates a decreased performance in long-distance driving after the calculated HbO plateau point, but only for the maximum lane deviation distance. Therefore, HbO plateau points during the first 45 minutes of long-distance driving may provide a threshold for marking when a driver's performance could begin to decrease due to a loss of sustained attention.

Regardless of whether the HbO plateau is truly indicative of the vigilance decrement, there was a detectable difference in performance before and after our calculated HbO plateau for the maximum lane deviation variable with an average deviation of 6.231 feet before but 7.531 feet after the HbO plateau. While there were not statistically significant differences for the other performance variables, the trends generally indicated decreases in performance post the HbO plateau.

The significant increase in maximum lane deviation distances and the number of road excursions after the HbO plateau, while not statistically significant, may indicate that after the HbO plateau point, drivers may be more susceptible to distractions that consume attention, and therefore result in poorer driving performance. Also, while not statistically significant, there is an almost two-fold increase in the percentage of time spent using a mobile phone in the post-plateau phase versus the pre-plateau phase, demonstrating an increased propensity for distraction after the HbO plateau point. In addition, those people that spent more time on the phone look longer to reach an HbO plateau, possibly because their mental activity was higher than those not on the phone. However, the penalty was that these drivers were more likely to have a road excursion.

Current analysis is underway to look not just at the performance immediately before and after the HbO plateau, but also the remaining three hours of driving which included a response to a surprise event (a moose crossing the roadway). It is not clear if and how the time to vigilance, or possibly the percent changes in either oxygenated or deoxygenated blood, has an impact on performance and whether there is any kind of predictive relationship that could assist a driverless car in assessing the attention state of the driver.

More study is needed to both replicate these findings in driving settings as well as other domains that require sustained attention. In the only other known study that has looked at relating the vigilance decrement to a blood oxygenation/deoxygenation plateau, Boyer et al. saw similar trends. In this study that looked at operators monitoring a military display for signs of incoming missiles, the HbO plateau for 26 subjects occurred at 32.6 minutes, with a standard deviation of 17.1 (19).

The monitoring task in the missile study was uniquely different from the driving task in that there were no continuous physical interactions and subjects were not allowed to use cell phones, yet as a group, they took much longer to reach their HbO plateau. Thus, interesting future questions are whether the automaticity of the driving task (and conversely, the complexity of the missile task) led to shorter HbO plateau times, and whether there are clear performance benefits in delaying the onset of an HbO plateau.

In addition, more work is needed to examine the impact of individual differences, including how and why time to the HbO plateau differs. One confounding issue in this study was that the average BPS value for this experiment was 85.3, and the average BPS range for the general population is 81-117, with higher scores indicating a propensity towards boredom (*15*). So the subjects in this study were in general low on the boredom scale, which may have influenced the results. Future studies should potentially select those people who are on the higher end of the scale to see how results compare.

There are also difficulties in conducting fNIRS studies that cause both experimental issues as well as issues for future potential operational use which include compression headaches as well as difficulties fitting the system to smaller foreheads. In addition, when percent change between adjacent slopes was calculated, the 5% change threshold was chosen to represent a relative plateau. Each five-second sub-window, which together creates the ten-second window analyzed, was chosen due to the hemodynamic signal latency following stimulus onset. There is a similarity between measurement capabilities for fNIRS and fMRI. However, fNIRS is not capable of obtaining the same type of spatial resolution found with fMRI. Therefore, this restricts the ability for one to utilize fNIRS and report that signals are related to very specific areas of the brain. Thus, the fNIRS results are more generalized to define the origin of the signal as the pre-frontal cortex.

Conclusion The purpose of this study was to determine if it is possible to detect the physiological phenomenon known as the vigilance decrement in a long-distance driving simulator, utilizing HbO concentrations obtained from a functional near infrared spectrometer placed on the driver's forehead. Utilizing a novel algorithm that detects if adjacent slopes are less than 5% different in a 10 second window, we were able to calculate a single plateau point corresponding to an HbO plateau time for 27 subjects. Using the calculated plateau point, maximum lane deviation after the plateau point is significantly greater than the maximum lane deviation before the plateau point, indicating a clear performance difference. This plateau point also showed an increase in the driver's average lane deviation, mobile phone usage, and road edge line crossings, although not statistically significant. Therefore, it is possible that the calculated physiologic plateau point aligns with the psychological construct of a vigilance decrement point. Regardless of whether this is a tangible expression of such a phenomenon, this physiologic measure could be an important metric for self-driving cars because it would potentially allow computers to determine if a human is cognitively capable of intervening in a scenario where the self-driving car requires human intervention.

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