Using S-transform in EEG analysis for measuring an alert versus mental fatigue state

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Abstract— **This paper presents research that investigated the effects of mental fatigue on brain activity using electroencephalogram (EEG) signals. Since EEG signals are considered to be non-stationary, time-frequency analysis has frequently been used for analysis. The S-transform is a time-frequency analysis method and is used in this paper to analyze EEG signals during alert and fatigue states during a driving simulator task. Repeated-measure MANOVA results show significant differences between alert and fatigue states within the alpha (8-13Hz) frequency band. The two sites demonstrating the greatest increases in alpha activity during fatigue were the Cz and P4 sites. The results show that S-transform analysis can be used to distinguish between alert and fatigue states in the EEG and also supports the use of the S-transform for EEG analysis.**

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I. INTRODUCTION

Fatigue is a major cause of accidents and injury when driving and when performing boring or repetitive process work tasks [1,2]. Assessing brain wave activity is a viable strategy for monitoring mental fatigue and numerous studies have been conducted in this area (eg. monitoring drivers' fatigue) [1,2]. Mental fatigue is also a common symptom of many illnesses and disabilities. It has mental and physical components, and has been described as a change in a person's psychophysiological state due to sustained mental performance [3]. Mental fatigue symptoms consist of tiredness, drowsiness and consequent elevated risks of performance decrements [3]. The occurrence of mental fatigue has been shown to alter brain activity signals. For instance, increases in electroencephalography (EEG) alpha (8-13Hz) and theta (3-7.5Hz) activity have been commonly reported at the onset of mental fatigue [4,5].

The electroencephalogram (EEG) signal reflects the electrical activity of the brain and has been assessed by a range of signal processing techniques such as time domain analysis, frequency domain analysis, time-frequency domain analysis, nonlinear analysis and artificial neural network analysis [6]. Since EEG signals are considered to be non-stationary, time-frequency analysis is a viable method to analyze these signals. One common method of time-frequency analysis for EEG signals is the short time Fourier transform (STFT) analysis. In STFT analysis, Fourier analysis (FFT) is performed on out on small sections of the signal, referred to as windowing the signal. This gives the time-frequency representation of the signal, however, the precision of the information obtained is determined by the size of the window. The wavelet transform (WT), corrects this by using a windowing technique with variable size regions. In the WT, time–scale maps are obtained whereby the information at a particular time can be obtained by translating the wavelet in that time while the information at different scales is obtained by dilating the wavelet. Another time-frequency method, the S-transform, was developed on the basis of STFT and continuous WT involving a direct time-frequency map being produced without any translation or dilation. It localizes the amplitude and retains the phase information referenced to time t=0. Thus the phase information is absolutely referenced and is similar to what is obtained in the conventional Fourier transform. Further the S-transform has a direct relation to the Fourier transform where the integral of the S-transform over time results in the Fourier transform. This direct relationship to the Fourier transform simplifies the task of inversion to the time domain [7]. The S-transform has many advantages such as linearity, lossless reversibility, multi-resolution, and good time-frequency resolution [6].

Driver fatigue is a prevalent problem and a major risk for road safety accounting for approximately 20-40% of all motor vehicle accidents [2]. One strategy to prevent fatigue related accidents is through the use of countermeasure devices. The countermeasures that measure physiological signals are considered more reliable as they provide a direct measure of physiological changes as the driver becomes fatigued. Research on countermeasure devices have focused on methods that detect physiological changes associated with fatigue, with the fast temporal resolution from EEG brain signals. The EEG is an excellent candidate given its fast temporal resolution and is now believed to be a promising technique for detecting real-time mental fatigue [8]. However, as argued above, it is believed the S-Transform offers many advantages in the assessment of physiological changes associated with fatigue. Therefore,

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this paper presents the results of using the time-frequency technique of S-Transforms to measure changes in brain activity during a simulated driving task in adults who have a current drivers license.

II. METHODS

A. Participants

Thirty-six participants (19 males, 17 females) non professional drivers were entered into the study. The mean age for male participants was 29.7 (SD 11.4) and for female participants 32.1 (SD 12.5). All participants consisted of volunteers from the community. All participated in a structured interview immediately prior to the study in order to determine their health status. Participants were included only if they reported they were free of viral or bacterial disease, and reported no prior psychopathology. Participants were also included if they were not taking any medication that could potentially affect the recording of the EEG. The study was approved by the institutional research ethics committee and participants were only entered into the study after informed consent.

B. Simulated Driving Task

Participants performed a driving simulator task that included driving along a straight road with minimal stimulation. This task was aimed at reducing their cognitive load and leading them towards boredom and fatigue. Simulated driving tasks are used in fatigue studies, both in clinical and research settings as they provide a measure to detect fatigue by means of decreased vigilance [11]. In this study we used Divided Attention Steering Simulator (DASS) (Stowood Scientific Instruments), according to the manufacturer's instructions. The DASS has been used reliably in other studies [11]. The program measures decreasing vigilance and hence fatigue, by the means of increased deviation of steering the car and poor reaction time. The aim of the task was to steer an image of a car down the centre of the road using a game steering wheel (Grandprix 1, Thrustmaster, USA). In addition, during the driving task, numbers or digits, which changed randomly, were displayed at the corner of the screen. To test vigilance and reaction time, participants were also required to identify the number "2" when it appeared by pressing a button on the side of the steering wheel where the digit appeared on the screen. The task was considered monotonous because the participants were required to drive on a straight road on a constant slow speed for an extended period of time in a noise, stimulus and temperature controlled laboratory. The task was set for a maximum of 1 hour of driving. Fatigue onset was confirmed by reaction time results, video monitoring and self-reported feedback using validated questionnaire (Chalder Fatigue Scale) [9].

C. Data Acquisition and Pre-processing

The Biosemi$^{\text{TM}}$ Active-Two System was used in this study for recording EEG signals from each person. Raw data was acquired using 32-channels at a sampling rate of 2048Hz with 24-bit digital resolution per channel, using the biopotential measurement system and active electrodes. The signal was down sampled to 256Hz. Twelve channels were chosen and used for the analysis in this paper, that covered the left, right and midline as well as frontal, central, parietal and occipital cortical scalp regions (F3, F4, Fz, C3, C4, Cz, P3, P4, Pz, O1, O2, and Oz). The recording of the EEG signals was conducted in a dedicated temperature controlled research laboratory (22°C). Several pre-processing steps were also performed on the raw EEG prior to S-Transform analysis. High pass filter was applied at 1Hz to remove movement artifact (drift in the electrical signals). In addition, artifacts such as eye and muscle movements, which are non-cerebral in origin, were removed from the recorded EEG data using Independent Component Analysis (ICA) using EEGLab version 10 [10].

Two sets of 10 second artifact free EEG data were taken and analyzed from an alert state during the start of the task where the participants were engaged to the task but not fatigued and during fatigue as determined by video monitoring, physiological symptoms and performance decrements from the driving task.

E. The S-Transform

The S-transform is a time-frequency technique proposed by Stockwell, Mansinha and Lowe, 1996 [11]. It has been successfully used in other fields of engineering such as electrical engineering and geological engineering [6]. Since it is based upon STFT and WT, the method inherits the advantages of both the STFT and continuous WT in that it is a new windowed Fourier transform and has the "phase correction" of continuous WT [6].

The S-transform of a continuous time signal *h (t)* is defined as:

$$S(\tau, f) = \int_{-\infty}^{\infty} h(t) w(\tau - t, f) \exp(-i2\pi f t) dt \qquad (1)$$

where

$$w(\tau - t, f) = \frac{|f|}{\sqrt{2\pi}} \exp(-0.5(\tau - t)^2 f^2) \qquad (2)$$

f being the frequency, *t* the time and τ the delay with

$$\int_{-\infty}^{\infty} w(t, f) dt = 1 . \qquad (3)$$

E. Extracting information from the S-transform

In order to study in more detail the changes that occur during fatigue, additional information was extracted from the alpha band (8-13Hz) where major changes are known to occur [ref]. Two parameters are extracted, the first being the maximum amplitude ($A_{\alpha}^{\max}(t)$) for each time (t), where the suffix α refers to the alpha band and *max* to the maximum amplitude in that band at time t. The other parameter that was computed is the sum of the amplitudes in the alpha band at time (t), this was denoted by $A_{\alpha}^{sum}(t)$.

III. RESULTS

A. *Time-Frequency Distributions*

The EEG signal from all 36 participants was analysed. Fig. 1 shows the raw EEG signal for alert and fatigue from one representative participant. The fatigue state plot (bottom) shows the clear presence of alpha spindles. The x-axis shows the EEG data points such that 1 second of data equals 256 points. The alert (top) and fatigue (bottom) are both of 10 second lengths.

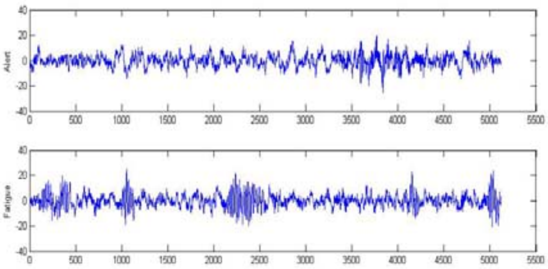

Fig 1: Shows the raw EEG signal (Pz site) for the alert state (top) and fatigue state (bottom).

Fig. 2 shows the time-frequency distributions of S-transform based on the above EEG signal (in Fig. 1). The two 10 second EEG segments from the alert and fatigue state were concatenated to form a 20 second segment so that the distribution can be shown on the one scale for comparisons. The alert segment runs from 0 to 10 seconds and the fatigue segment runs from 10 to 20 seconds. Visually, there are distinct differences seen between the fatigue and alert phase especially in the alpha (8-13Hz) and beta (14+ Hz) frequency bands.

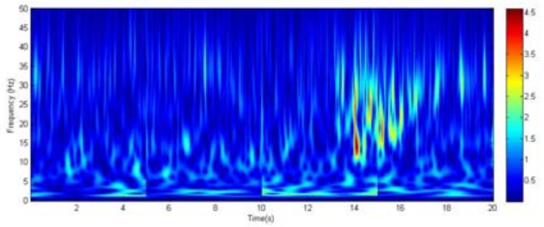

Fig 2: Shows the time-frequency distributions using S-transform in the alert (0-10s) and fatigue (10-20s) state during the simulated driving task.

B. *Maximum Amplitude Analysis ($A_\alpha^{\max}(t)$)*

A repeated-measures MANOVA was conducted on the sample of 36 participants, to test for differences between alert and fatigue states in the twelve sites covering the major cortical regions (F3, F4, Fz, C3, C4, Cz, P3, P4, Pz, O1, O2, and Oz). There were significant differences between alert and fatigue states, with a Wilks (df=12, 24) of 0.45, (F=2.42, P<0.05). Post-hoc analysis using Bonferronni testing showed significant differences (p<0.05) in the P4 and Cz sites. Although there were statistical differences in only two sites there was a definite trend towards increases in maximum alpha activity in most of the cortical sites. Nonparametric Sign Test on the means show that the increase in maximum alpha in the 12 sites was significant (Z=2.6, p<0.01). See Table 1 for mean and standard deviations for $A_\alpha^{\max}(t)$ in alert and fatigue states.

TABLE I. MEAN AND STANDARD DEVIATION OF $A_\alpha^{\max}(t)$ FOR ALERT AND FATIGUE STATES

*significant p<0.05

C. *Sum of Amplitude Analysis ($A_\alpha^{sum}(t)$)*

EEG site	Alert $A_\alpha^{\max}(t)$ Mean (SD)	Fatigue $A_\alpha^{\max}(t)$ Mean (SD)	p
F3	0.88 (0.26)	0.91 (0.34)	0.18
Fz	1.01 (0.34)	1.04 (0.40)	0.18
F4	0.91 (0.28)	0.92 (0.37)	0.69
C3	0.73 (0.22)	0.81 (0.44)	0.07
CZ	0.90 (0.28)	0.97 (0.32)	0.002*
C4	0.77 (0.23)	0.79 (0.28)	0.09
P3	1.02 (0.33)	1.05 (0.40)	0.27
Pz	1.12 (0.39)	1.17 (0.57)	0.25
P4	1.01 (0.35)	1.09 (0.46)	0.007*
O1	1.30 (0.38)	1.28 (0.45)	0.642
Oz	1.17 (0.33)	1.17 (0.41)	0.963
O2	1.22 (0.41)	1.25 (0.41)	0.370

To test for differences between an alert and fatigue state of the $A_\alpha^{sum}(t)$, which measures the entire alpha frequency band, repeated-measures MANOVA was also conducted. The results for the 36 participants, in the twelve sites (F3, F4, Fz, C3, C4, Cz, P3, P4, Pz, O1, O2, and Oz) was significantly different between the alert and fatigue states. (Wilks (df=12, 24) of 0.45, (F=2.42, P<0.05)). Post-hoc analysis using Bonferronni testing also showed significant differences (p<0.05) in the P4 and Cz sites. Once again there was a definite trend towards increases in the alpha band in all but one site (O2). Nonparametric Sign Test on the mean changes was also significant (Z=2.6, p<0.01). See Table 2 for mean and standard deviations for $A_\alpha^{sum}(t)$ in alert and fatigue states.

IV. DISCUSSION

Given the fast temporal changes occurring in the brain during a consciousness state such as during mental fatigue, a reliable measure that can capture these changes is required if early indications/ warning of the onset of fatigue can be provided. EEG has been shown to measure accurately changes in brain activity in different physiological stages such as alert and mental fatigue states [2,5]. In this paper, mental fatigue during a simulated driving task was found to be associated with increases in maximum alpha activity ($A_\alpha^{\max}(t)$) and increases in the sum of alpha amplitude

($A_{\alpha}^{sum}(t)$). This was seen generally across the cortex, and found to be significant in the Cz and P4 sites ($p<0.05$). This finding is similar to other studies using STFT for analysis [2].

The results show that significant differences in alert and fatigue states can be detected using S-transform analysis. The S-transform proposed by Stockwell et al., 1996 was developed for the analysis of geophysics data [11]. However, since it extends from the STFT and continuous WT, both used extensively in EEG analyses, and inherits the advantages of these two methods [6], this paper demonstrates its feasibility in EEG analysis. In a previous study, Ai et al., 2010 [6], also demonstrated the used of S-transform analysis on EEG data. Ai and colleagues showed differences in the time-frequency distribution in alert and fatigue states. Zhang & Huang, 2013 [12], also applied the S-transform to EEG data and compared the three transform methods, STFT, WT and the S-transform. They found the S-transform to have the best energy distribution in the time-frequency field from the three methods [12].

This paper also extends from the prior study by Ai et al., 2010 [6] by quantifying the S-transform results, in order to provide a test for statistical significance between the two states. This paper explored alpha changes only, given previous studies showing greatest changes in this frequency band [2], however future studies can easily extend to other frequency bands of interest using the same technique.

TABLE II. MEAN AND STANDARD DEVIATION OF $A_{\alpha}^{sum}(t)$ FOR ALERT AND FATIGUE STATES

*significant $p<0.05$

EEG site	Alert $A_{\alpha}^{sum}(t)$ Mean (SD)	Fatigue $A_{\alpha}^{sum}(t)$ Mean (SD)	p
F3	15.33 (4.59)	16.00 (6.09)	0.09
Fz	17.32 (5.80)	17.96 (6.96)	0.14
F4	15.93 (4.98)	16.08 (6.62)	0.74
C3	12.88 (4.08)	14.48 (8.01)	0.05
CZ	15.62 (4.75)	16.88 (5.73)	0.002*
C4	13.53 (4.32)	13.97 (5.09)	0.14
P3	17.98 (5.89)	18.55 (7.45)	0.24
Pz	19.71 (7.24)	20.72 (10.49)	0.21
P4	17.81 (6.31)	19.21 (8.24)	0.01*
O1	22.76 (6.41)	22.06 (7.90)	0.79
Oz	20.47 (5.86)	20.66 (7.40)	0.70
O2	21.26 (7.22)	22.06 (9.55)	0.002*

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