

Estimation for Driver Fatigue with Phase Locking Value

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Abstract. This paper aims at detecting driver fatigue during driving by means of EEG technique. A novel and efficient method is proposed in this paper. The proposed method calculated the phase synchronization index between two EEG channels and the phase locking value (PLV) which is an average value for phase synchronization index in certain regions with selected pairs of channels in gamma band. Our work demonstrates that the PLV in gamma band is responsible for cognitive mental state of the brain. And the PLV can significantly distinguish different mental states such as alert and fatigue.

Keywords: Driver; Fatigue; EEG Signal; Phase Synchronization; Phase Locking Value; Gamma Band

1. Introduction

In recent years, with car ownership and the number of motor vehicle drivers increased rapidly, the road safety problem has been highlighted. As a major cause of fatal traffic accidents, the detection of driver fatigue has become one of most popular research topics. Earlier researches have concluded that fatigue is responsible for 15-20% of all fatal accidents [Connor et al., 2002]. Hence, driver fatigue assessment and taking corresponding actions, e.g. informing and warning the driver accordingly, are essential for increasing traffic safety.

Recently, many methods have been proposed to estimate the drowsiness. Some studies used subjective measurements and psychomotor tests such as reaction time, concentration and sleepiness scale [Caldwell et al., 2003]. A recent tendency to assess the mental fatigue is to choose more objective measures as physiological variables like Electroencephalogram (EEG), Electrooculogram (EOG), Electromyogram (EMG), Electrocardiogram (ECG) [Papadelis et al., 2007; Jeong et al., 2007; Knaflitz and Morinari, 2010]. Among these physiological indicators, EEG is considered to be the most significant and reliable because it is closely associated with mental and physical activities [Kar et al., 2010].

The classical methods using EEG are generally based on power spectral analysis of four bands. Jap demonstrated that algorithm $(\alpha + \beta) / \theta$, α / β , $(\theta + \alpha) / (\alpha + \beta)$ and θ / β of the EEG signal can indicate driver fatigue [Japa et al., 2009]. Simon employed EEG alpha spindles as an objective measure for assessing driver fatigue and the result showed that it is superior to EEG band power [Simon et al., 2011]. Liu et al. used two complexity parameters to characterize the complexity and irregularity of EEG data under different mental fatigue states [Liu et al., 2010]. Furthermore, five types of entropies including Shannon's entropy have been considered as possible indicators of fatigue [Kar et al., 2010] and the result shows that these parameters can quantify the level of fatigue in human drivers or human operators in safety critical human-machine interactions.

Phase synchronization analysis is an important and effective method examining the relationship of instantaneous phase between EEG signals but neglecting the influence of their amplitudes [Sun et al., 2012]. Synchronization phenomenon in EEG, especially the oscillation in the high frequency bands, is a key part to establish a different brain regions information exchange. Gysels investigated the performance of features derived from the PLV and from the spectral coherence for classifying mental

tasks [Gysels and Celka, 2004]. Bhattacharyaa et al. studied the phase synchronization pattern in the gamma band and found the that synchronization between frontal cortex and right parietal cortex is significantly increased during mental rotation tasks with respect to rest [Bhattacharyaa et al., 2001]. Hence, in this paper, we proposed a novel method that can quantify mental fatigue and has a more direct neurophysiological meaning: the phase locking value (PLV). The proposed method calculated the phase synchronization index between two EEG channels and the phase locking value (PLV) which is an average value for phase synchronization index in certain region with some pairs of channels in gamma band. Our work demonstrates that the PLV in gamma band is responsible for some mental states (alert or fatigue) of the brain.

2. Material and Methods

2.1. Experimental Design

2.1.1. Experiment setup

In our experiment, we need at least two separated computers to perform the experiment. One for running the software of the driving simulations and a program called *WorldRecord* which can collect all data related to the cars during games. Specifically speaking, the driving simulation software involved in our work is *Need For Speed - Shift 2 Unleashed* (NFS – S2U). The other computer is used for supporting the program of TAV task and EEG signal acquiring. Concerning with the TAV task, it consists in an alert task in which subject has to press a button every time when an “X” is shown on the screen and in a vigilance task in which subject has to identify the same acoustical frequency of consecutive tone impulses by pressing the other corresponding button respectively. In the experiment, we also need a projector and a driving simulator system with Logitech. The outline of the experiment is shown in Figure.1.



Figure.1 Outline of experiment setup

2.1.2. Experimental protocol

In order to collect valid EEG signals for assessment of driver fatigue, subjects were involved in training and experimental sessions. And the whole duration for one subject may last 2 or more days, it depends on his or her training performance. The experiments were performed after dinner and between 18:00-21:00. As soon as the subject is ready for the experiment, he or she has to perform the selected track under different conditions with priority of the driving control. Any condition includes a race of 2 laps. The experimental session, in this paper, consisted of eight conditions or stages. In the first condition (TASK_1-WUP) the subjects did not receive any additional tasks and they were told to do the laps normally as the previous day. The TASK_2 -PERFO, it is basically like the TASK_1 but the subjects were asked to improve the performance of 2%. Differently from the previous two conditions, in the third condition (TASK_3-TAV3), TAV task is involved, and subjects need to carry out the TAV meanwhile he/she was performing the driving task. The following four conditions are the same as TASK_3. However, the stimuli frequency is different from TAV1 to TAV5. In our experiment, the

sequence of the five conditions is TAV3, TAV1, TAV5, TAV2 and TAV4. While TAV3 has higher stimuli frequency than TAV1 and TAV2. The aim of extra TAV tasks during these five conditions is to enhance the workload for the driver. The last condition (TASK_8-DROW) was a monotonous driving, in which the subject had to drive on the same track carefully at the speed of 60Km/h at most. This monotonous condition was designed to make the driver drowsy. At the end of each condition the subject had to fill the NASA-TLX questionnaire for the subjective workload assessment. The TAV performance was recorded and evaluated by the computer automatically. Furthermore, the operator also needs to record the number of rushing out road during each condition for each subject.

2.2. Phase Synchronization and Phase Locking Value

Phase synchronization is the process by which two or more cyclic signals tend to oscillate with a repeating sequence of relative phase angles. The mathematical formula of Phase synchronization index [13] can be described as below.

Given a continuous time signal $x(t)$, we first define the analytic signal

$$Z_x(t) = x(t) + i\tilde{x}(t) = A_x(t)e^{i\theta_x(t)} \quad (1)$$

where $A_x(t)$ is instantaneous amplitude of $x(t)$ and $\theta_x(t)$ is the instantaneous phase of $x(t)$.

$\tilde{x}(t)$ is the Hilbert transform of $x(t)$ and can be defined as follow

$$\tilde{x}(t) = \frac{1}{\pi} P \int_{-\infty}^{+\infty} \frac{x(\tau)}{t - \tau} d\tau \quad (2)$$

where P means that the integral is taken in the sense of the Cauchy principal value .

Analogously, we define $Z_y(t) = A_y(t)e^{i\theta_y(t)}$ for signal $y(t)$.

The phase locking value (PLV) is then defined as the average value:

$$PLV = \frac{1}{N} \left| \sum_{n=1}^N \exp(i\theta(t)) \right| \quad (3)$$

where $\theta(t)$ is the phase difference $\theta_x(t) - \theta_y(t)$, and N is the number of selected pairs' channels.

PLV will be zero if the signal $x(t)$ and $y(t)$ are not synchronized at all and will be one if the phase difference is constant (perfect synchronization).

In this work, we studied phase synchronization pattern on whole brain region in the gamma band for estimating driver fatigue. A gamma wave is a pattern of neural oscillation in humans with a typical frequency band between 25 and 40 Hz [Gold, 1999]. The gamma band was chosen because there are numerous evidences that neuronal oscillations and synchronization in the high frequency range (>30 Hz) provide a general framework of large scale cognitive integration [Bhattacharyaa et al., 2001; Rodriguez et al., 1999]. Fatigue may affect the neuronal oscillations in the gamma band.

According to Dr. Sun's research [Sun et al., 2012], in order to get the best performance of phase synchronization, we should set the segmentation length as 5-12 times of its cycle. Considering with the low sample rate with 256 Hz in this paper, the segmentation length for computing the phase locking value is 1s. In the experiment, for each stage or condition, there are M non-overlap segmentations. Therefore, for the overall PLV during the certain stage is the mean of M PLV corresponding to its segmentation in gamma band. It can be denoted as

$$PLV_g = \frac{1}{M} \frac{1}{N} \left| \sum_{m=1}^M \sum_{n=1}^N \exp(i(\theta_x^g(t) - \theta_y^g(t))) \right| \quad (4)$$

Where $\theta_x^g(t)$ is instantaneous phase of $x(t)$ filtered by gamma band.

3. Results

12 right-dominated Chinese students, between 23 and 25 years old (M=23.7 years, SD = 0.78), participated in this experiment. They had no personal history of neurological or psychiatric disorder and they were prohibited to drink alcohol, coffee and tea one day before the experiment. All the subjects own their driving license and they are used to drive the cars with manual gear. We collected the EEG

data by a 16 channels system with the gUSBamp amplifier (g.Tec medical engineering GmbH) at a sampling rate of 256Hz while the impedances kept below 5k Ω . The electrode cap we used was built according to the 10-20 international system. The 16 electrodes are: Fz, Pz, Oz, Fp1, Fp2, F7, F3, F4, F8, C3, C4, P7, P3, P4, P8 and EKG. The EKG electrode is placed in the pulse position on left wrist to record the EKG data. Right ear was used as reference.

The EEG recordings were also band-pass filtered (low-pass filter cut-off frequency: 40 (Hz), high-pass filter cut-off frequency: 1 (Hz)) and then the Independent Component Analysis (ICA) was used in order to remove the artifacts from the data. The data are then filtered in gamma band and finally the PLV is computed in each condition for each subject.

3.1. Phase Synchronization Index

Figure 2 shows Phase Synchronization Index in 4 different conditions for one subject. The conditions sequence is: WUP, PERFO, TAV3, TAV1, TAV5, TAV2, TAV4 and DROW.

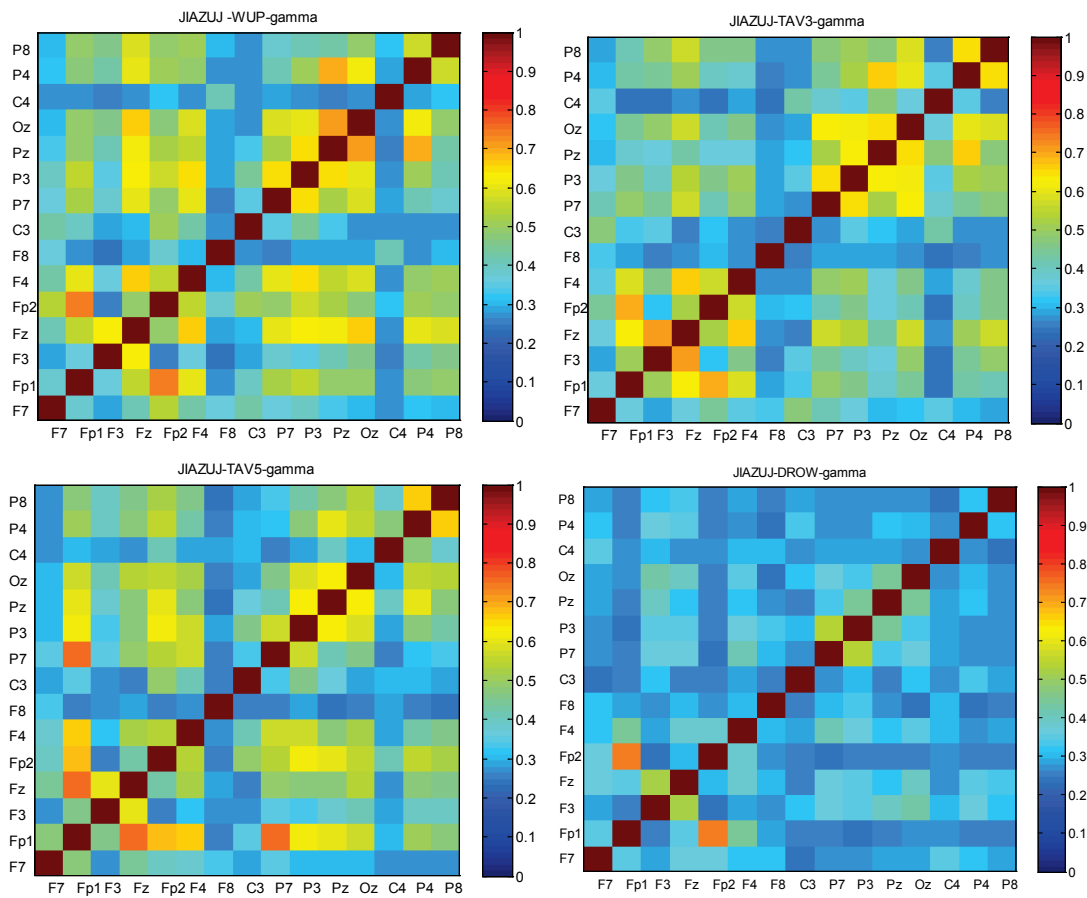


Figure.2 Phase synchronization index computed in 4 different conditions.

Hence, for the WUP condition, it is at the beginning of the task. It should be less fatigue than other conditions. From Fig.2, we can conclude that the phase synchronization index in the WUP is generally bigger than other 3 conditions. Concerning for the TAV3 condition, it is the first time that the subject need do extra cognitive task besides of driving, and the brain for subjects should contain much more cognitive involvement. Fig.2 shows that the phase synchronization index distribution is still keep at a relatively high level. As the condition boosts, the workload exerts on the subject, and the subject is going to be fatigue. Finally, in the last condition, due to both exhausted mental and monotonous driving condition, the driver is easily to fall into the fatigue or drowsy stage. Refer to Fig.2, we can find that the phase synchronization index distribution is dramatically decreased with previous 3 conditions. Therefore, we can believe that the phase synchronization index is an efficient way to estimate the degree of driver fatigue.

3.2. Phase Locking Value

In order to distinguish the fatigue condition more intuitively, we employed the phase locking value based on phase synchronization index. It is also useful for comparing indexes of TAV and NASA-TLX clearly. In the total 12 subjects, we have 8 valid subjects. The other four may not cooperate with the experimental protocol very well, the performance of their TAV task was incompatible with common knowledge. Figure 3 shows respective mean parameters of TAV tasks in 8 valid subject. And, we can conclude that as the step of experiment move forward, the mean accuracy of reaction to the alert and vigilance during driving is decreased gradually. However, it is interesting that the reaction time also decreases. Fig.4 shows the mean PLV, off-load number, and NASA-TLX score in 8 conditions for 8 valid subjects. From the start condition WUP to the end condition DROW, the NASA-TLX score is generally increased. It indicated that the workload for subjects is accumulated gradually. For off-load (rushing out) number, there are none of off load in the last condition for 8 valid subjects. And for other conditions, it is basically related with the frequency of stimuli in TAV tasks.

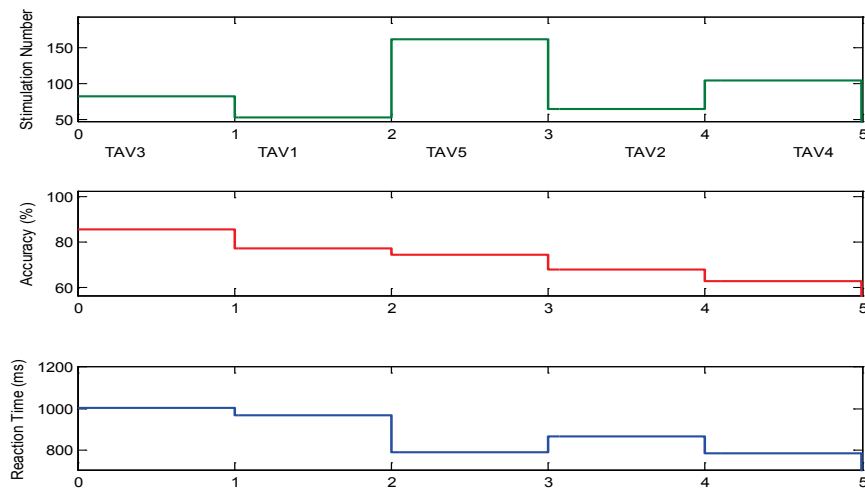


Figure.3 The mean index in 5 TAV tasks for 8subjects

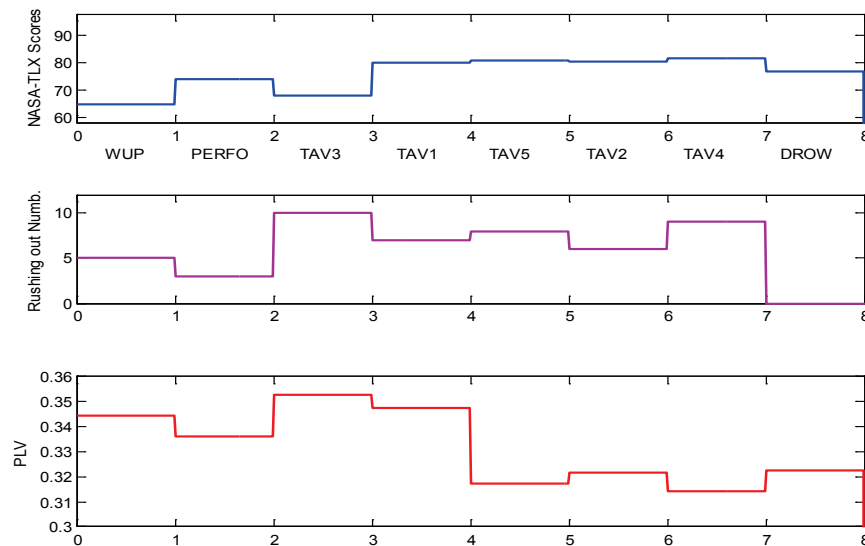


Figure.4 The mean PLV and driving parameters in 8 conditions for 8 subjects

Finally, concerning with the PLV, it is the most high in the condition when subject first involved in the TAV task. It is reasonable, because it is near the start step and alert with the stimuli making the subject refreshable. While for the TAV2, TAV4, though there is stimuli, but they are near the end condition and far from start. The workload has accumulated gradually, possibly makes subject fatigue. And their corresponding PLV indexes are relatively low. While in the last condition, the subjects are expecting drowsy according to the experimental protocol, and its PLV is also lower than the first 4 conditions.

Hence, we can conclude that the PLV index in gamma band is related to cognitive mental state, While the higher PLV is, the more alert subject is, Or the more fatigue the subject is.

4. Conclusions

A novel method was proposed to detect driver fatigue in this paper. We studied phase synchronization pattern in whole brain region in the gamma band for estimating driver fatigue. The experiment demonstrates that phase synchronization index and phase locking value in gamma band is an efficient way to estimate the degree of driver fatigue. They not only can tell difference between the alert and drowsy two stages clearly, but portray the trend when driver's condition changing from alert to fatigue. Furthermore, if we decrease the duration of segmentation for computing the Phase synchronization, we may find a real-time approach to evaluate the driving fatigue online. In order to portray the driving fatigue more effectively, it is our future work to discover in certain spatial-frequency pairs of channels and determine the length of segmentation to compute phase locking value.

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References

- Connor J, Norton R, Ameratunga S, Robinson E, Civil I, et al. Driver sleepiness and risk of serious injury to car occupants: population based case control study. *BMJ* 324: 1125.1. 2002.
- Caldwelll JA, Prazinko B, Caldwell JL. Body posture affects electroencephalographic activity and psychomotor vigilance task performance in sleep deprived subjects. *Clinical Neurophysiology*, 114(1): 23-31, 2003.
- Papadelis C, Chen Z, Kourtidou-Papadeli C, et al. Monitoring sleepiness with on-board electrophysiological recordings for preventing sleep-deprived traffic accidents. Elsevier, Oxford, ROYAUME-UNI, 118(9): 1906-1922,2007.
- Jeong IC, Lee DH, Park SW, Ko JI, Yoon HR. Automobile drivers stress index provision system that utilizes electrocardiogram.In Proceedings of the 2007 IEEE intelligent vehicle symposium, Istanbul, Turkey, June 13-15, 652-656 2007.
- Knaflitz M, Molinari F. Assessment of muscle fatigue during biking. *IEEE Trans Neural Syst Rehabil Eng*, 11(1): 17-23 2003.
- Kar S, Bhagat M, Routray A. EEG signal analysis for the assessment and quantification of driver's fatigue. *Transportation Research Part F: Traffic Psychology and Behaviour*, 13(5): 297-306, 2010.
- Japa BT, Lala S, Fischerb P, Bekiarisc E. Using EEG spectral components to assess algorithms for detecting fatigue. *Expert Systems with Applications*, 36(2): 2352-2359, 2009.
- Simona M, Schmidt EA, Kincses WE, et al. EEG alpha spindle measures as indicators of driver fatigue under real traffic conditions. *Clinical Neurophysiology*, 122(6): 1168-1178, 2011.
- Liu J, Zhang C, Zheng C, et al. EEG-based estimation of mental fatigue by using KPCA-HMM and complexity parameters. *Biomedical Signal Processing and Control*, 5(2): 124-130, 2010.
- Sun J, Li ZJ, Tong SB. Inferring Functional Neural Connectivity with Phase Synchronization Analysis A Review ofMethodology. *Computational and Mathematical Methods in Medicine*, 2012: 13, 2012.
- Gysels E, Celka P. Phase synchronization for the recognition of mental tasks in a brain computer interface. *IEEE Trans Neur Syst Rehab Eng*, 12(4): 406-415 2004.
- Bhattacharyaa J, Petscheb H, Feldmanna U, Rescherb B. EEG gamma-band phase synchronization between posterior and frontal cortex during mental rotation in humans. *Neuroscience Letters*, 311(1): 29-32, 2001.
- Gold I. Does 40-Hz Oscillation Play a Role in Visual Consciousness. *Consciousness and Cognition*, 8(2): 186-195, 1999.
- Rodriguez E, George N, Lachaux JP, et al. Perception's shadow: long-distance synchronization of human brain activity. *Letters to Nature*, 397: 430-433, 1999.