8th International IEEE EMBS Conference on Neural Engineering
Shanghai, China, May 25 - 28 , 2017

An Alpha Wave Pattern from Attenuation to Disappearance for Predicting the Entry into Sleep during Simulated Driving

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***Abstract*— Attenuation of alpha wave is considered as the most valid marker of sleep onset during sleep, but this has received little attention during driving. Interestingly, from our simulated driving experiments, a new alpha wave's attenuation-disappearance phenomenon was observed to frequently appear in eye closure events (ECEs), with an obvious split point, which divides ECE into alpha attenuation phase and alpha disappearance phase. Firstly, we used box plots to visualize the general distribution of the alpha wave's power spectrum density (PSD) values in each of the two phases. Secondly, more quantitative analysis method was used to examine the characteristics of change in alpha PSD values. In addition, we analyzed the duration distribution of ECEs with alpha attenuation-disappearance phenomenon to measure sleepiness level and calculated the percentage of these ECEs across four sub duration ranges. The experimental results indicate that there is a general sharp decline of alpha PSD values from the alpha attenuation phase to the alpha disappearance phase among all the ten subjects. This result is consistent with visual observations and verified the alpha wave's attenuation-disappearance phenomenon as a general pattern. Moreover, this alpha attenuation pattern was proved to be more likely to appear under the condition of higher sleepiness level, predicting the entry into sleep.**

I. INTRODUCTION

Driving sleepiness accounts for a sizeable number of car crashes. Due to too much shift-work or suffering from deprivation of sleep, the driver tends to precipitate an incident of "dozing off" during monotonous driving process [1], [2].

Therefore, finding a reliable physiological indicator for predicting the entry to sleep will be very meaningful. What is particularly worth noticing is that the attenuation of alpha rhythm is considered as the most valid electro-physiological marker for sleep onset [3], [4]. The 30-s epoch with less than 50% alpha activity is judged as belonging to stage 1 sleep according to the sleep scoring manual developed by Rechtschaffen and Kales [4]. The nine-stage Hori scoring system using 5-s epoch length is reported to be particularly useful to describe the sleep onset period. The change in alpha activity across Hori's first four sleep stages [4] is described as follows: "Stage 1. Alpha wave train: Epoch composed of a train of alpha activity. Stage 2. Alpha wave intermittent (A): Epoch composed of a train of more than 50% of alpha activity. Stage 3. Alpha wave intermittent (B): Epoch contained less than 50% alpha activity. Stage 4. EEG flattening." [5] However, the sleep process mentioned in the above studies is very different from driving process. The existing studies on driving fatigue detection fail to give a consistent conclusion about whether alpha activity increase during fatigue. Jap *et al.* reported a slight decrease in alpha activity over time during driving [6], but the opposite trend was reported in Eoh *et al.*'s study [7], in which alpha activity has an increasing slope. We think one reason for this inconsistent conclusion is that the eye states such as open and closed are ignored in data analysis. However, it is well known that under the condition of closing eyes the typical alpha blocking phenomenon appears during wakefulness [8]. Another reason may be the likely effect caused by alpha wave's attenuation during driving, which has not received enough attention and has not been fully investigated.

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In this study, we report a new alpha wave's attenuation-disappearance phenomenon frequently appearing in ECEs during simulated driving experiments. This phenomenon is different from the intermittent alpha wave form reported in Hori's sleep stages, as well as the alpha blocking phenomenon. Therefore, our goals of this study are to verify the new observed alpha attenuation-disappearance phenomenon by statistical analysis of alpha PSD change and to investigate the characteristics of this phenomenon during simulated driving.

II. MATERIALS

A. Experiment Procedure

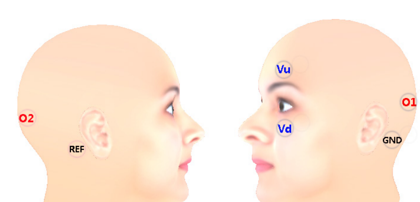

Fig. 1: The placements of all electrodes in our experiments.

Ten healthy subjects (6 males and 4 females, aged 23 $\pm$ 2.6) who had the siesta habit were recruited from Shanghai Jiao Tong University. All subjects had regular sleep schedule. They were asked to complete the Epworth Sleepiness Scale (ESS) [9]. Their ESS values were 9.8 $\pm$ 1.7. The starting time for the simulated driving experiment was half an hour before their regular sleep time at noon. Each experiment lasted for about 2 hours. All the subjects were instructed to drive a car in a virtual driving environment. The experimental task was just to keep the normal driving process like in real world, but

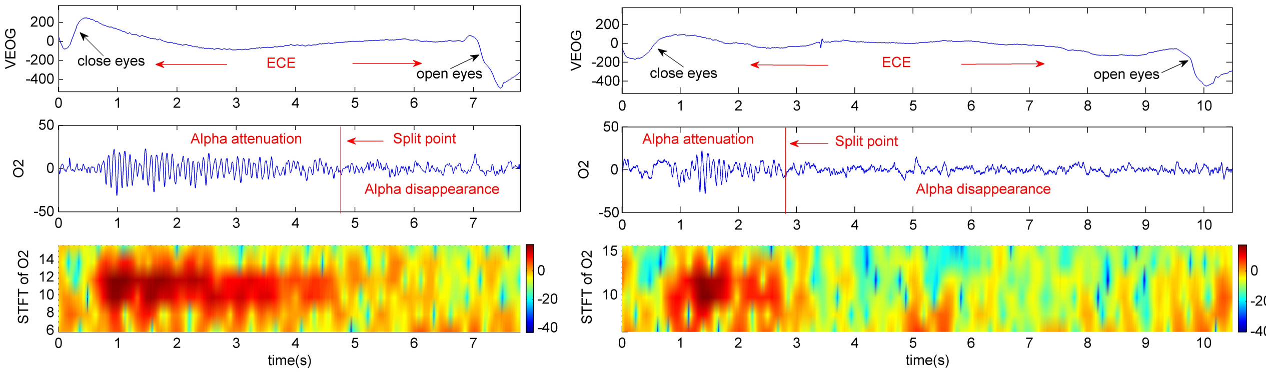

Fig. 2: Two examples of the alpha wave's attenuation-disappearance phenomenon in the eye closure events (ECEs) (The left ECE is about 7 s and the right ECE is about 10 s). The split point divides each ECE into two phases, alpha attenuation phase and alpha disappearance phase. Short time Fourier transform (STFT) is applied to the O2 channel to show the change in alpha PSD value over time. Here, VEOG=Vu-Vd.

closing eyes deliberately without feeling drowsy was strictly prohibited. Throughout the whole simulated driving, a lot of ECEs occurred. Most of them were within 1-15 s, some within 15-30 s, and few larger than 30 s.

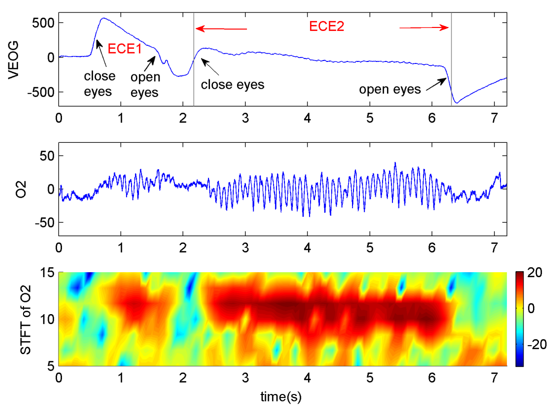

Fig. 3: The ECEs (ECE1 and ECE2) covered by continuous alpha wave corresponds to the alpha blocking phenomenon. Short time Fourier transform (STFT) of O2 shows the change in alpha PSD value over time.

B. Data Recording

EOG and EEG data were recorded at a 1000 Hz sampling rate using the ESI NeuroScan System. Totally, six electrodes were used, including two electrodes (Vu and Vd) for getting vertical EOG (VEOG), two occipital EEG electrodes (O1 as an alternative when O2 was corrupted by noise), one reference (REF) electrode and one ground (GND) electrode placed behind the ears, as shown in Fig. 1. The subjects were asked to wear a headband to fix electrodes. A video camera was set to monitor the subject's face. The facial image from the camera and the EOG/EEG signals displayed on the Scan software interface, both displaying on the same computer screen synchronously, were recorded into a video file. So we can review this video later to carefully check the eye movements corresponding to current EOG/EEG signals.

III. Methods

A. Alpha Wave's Attenuation-Disappearance Phenomenon

Alpha wave is within the range of 8-12 Hz. It is the dominant EEG rhythm with the maximum amplitude over the occipital regions (O2 channel) and is easy to recognize with the naked eye. By the visual observation of EOG/EEG recordings and reviewing the recorded video, eye closure event (ECE) as shown in Figs. 2 and Fig. 3 can be determined as the period between the upward trend line caused by closing eyes and the downward trend line caused by reopening eyes on VEOG. A new alpha wave's attenuation-disappearance phenomenon was observed to extensively exist in all the ten subjects. This phenomenon was often accompanied by slow eye movements on horizontal EOG signal [10]. Fig. 2 illustrates two examples of this alpha attenuation-disappearance phenomenon with alpha gradually attenuating before the split point but it almost disappears after the split point. The split point was determined as the mean value of three experts' scoring values. The split point divides an ECE into two phases: alpha attenuation phase and alpha disappearance phase. In addition, the typical alpha blocking phenomenon [8], which means that alpha rhythm (8-12 Hz) is prominent on the occipital area when eyes close but disappears when eyes open during wakefulness, could also be observed in ECEs during simulated driving as shown in Fig. 3. Online supplementary video materials are availble from http://bcmi.sjtu.edu.cn/research.html.

B. Statistical Analysis

In order to make statistical analysis, all the ten subjects who experienced at least 10 ECEs with alpha wave's attenuation were specially selected. According to the first ECE with the alpha wave's attenuation-disappearance phenomenon, the simulated driving process was divided into two main stages as shown in Fig. 4: non-sleep alpha stage and sleep alpha stage. We defined four different periods: (1) N-NEs: all data epochs without ECEs during driving; (2) N-Es: all the ECEs with continuous alpha wave during non-sleep alpha stage;

(3) S-Es: all the ECEs with continuous alpha wave during sleep alpha stage; and (4) S-Es*: all the ECEs with the alpha attenuation to disappearance phenomenon during sleep alpha stage. The S-Es* period has two sub periods: 1) S-Es*1: all the alpha attenuation phases of these ECEs during S-Es*; and 2) S-Es*2: all the alpha disappearance phases of these ECEs during S-Es*.

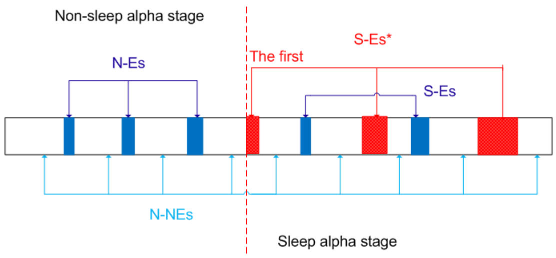

Fig. 4: The four different periods defined in simulated driving process.

Firstly, we analyzed the distributions of alpha PSD sample values during the above defined periods for each subject to verify the alpha attenuation-disappearance phenomenon commonly found in all the ten subjects. We applied short time Fourier transform with 1-s window length and 50% overlap into any data epoch in each period defined above, to get numerous 1-s alpha power spectral density (PSD) value samples for each period. Then, Z-score was done for all the samples from all periods for each subject. To reduce the effect of noise on samples, the sample whose alpha PSD values were more than the variance of all samples of this period was removed. Box plots were used to enable visualization of the distribution of alpha PSD sample values in different periods. Furthermore, Wilcoxon rank-sum test and more quantitative analysis were adopted to investigate the distribution characteristics of the alpha PSD sample values. Secondly, we used box plots to analyze the duration distribution of ECEs to measure the corresponding sleepiness level, especially for the ECEs with the alpha wave's attenuation-disappearance phenomenon. In addition, the percentage of ECEs with alpha wave's attenuation-disappearance was calculated across four sub duration ranges.

IV. Results

First, we obtained all 1-s alpha PSD sample values during each defined period in Fig. 4 for each subject. Then, we put together all subjects' alpha PSD sample values for each period to give a general distribution as shown in Fig. 5. The distribution of alpha PSD values has an obvious sharp decline trend from the S-Es*1 period with the median value 0.29 to the S-Es*2 period with the median value -0.45. The median value of the S-Es*1 period was significantly different from the S-Es*2 period with $p = 0$ by the Wilcoxon rank test. We also found that the N-Es and S-Es periods with ECEs corresponding to the alpha blocking phenomenon had higher alpha PSD value distributions than the S-Es*1 and S-Es*2 periods. The median values of the N-Es and S-Es periods were 2.29 and 1.59, higher than the median value 0.29 of the S-Es*1 period.

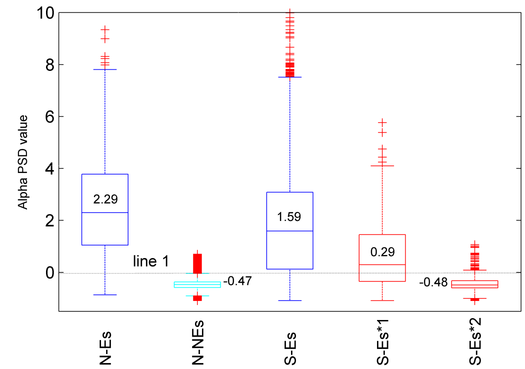

Fig. 5: The distribution of EEG alpha PSD sample values at different periods during simulated driving.

To give more quantitative analysis, we also calculated the percentage of alpha PSD values of each of the eye-closed periods which are higher than the *line 1* both for each subject and all the subjects as shown in Table. I. The *line 1* represents the maximum level of alpha PSD sample values of the eye-open period N-NEs. In fact, each subject's alpha PSD value distribution was very similar to the general distribution.

TABLE I: The percentage of alpha PSD values higher than the *line 1* for each of the eye-closed periods

Subject	Eye-closed periods			
	N-Es	S-Es	S-Es*1	S-Es*2
All	0.91	0.76	0.57	0.02
1	1.00	1.00	0.39	0.08
2	1.00	0.81	0.20	0.00
3	1.00	0.92	0.23	0.07
4	0.96	0.95	0.36	0.10
5	0.90	0.73	0.17	0.00
6	0.98	0.74	0.20	0.00
7	0.87	0.88	0.50	0.13
8	1.00	0.94	0.44	0.07
9	0.87	0.92	0.51	0.13
10	0.92	0.91	0.51	0.18

In Table I, for all the subjects' general distribution of alpha PSD values corresponding to Fig. 5, the N-Es, S-Es, S-Es*1 and S-Es*2 periods have 91%, 76%, 57% and 2% alpha PSD sample values higher than the *line 1*, respectively. This is similar in each individual from subject 1 to subject 10. For example, the N-Es, S-Es, S-Es*1 and S-Es*2 periods for the subject 1 have 100%, 100%, 39% and 8% alpha PSD sample values higher than the *line 1*, respectively. There is an obvious decline in the percentage of alpha PSD values higher than the *line 1* from the S-Es*1 period to the S-Es*2 period, indicating that the alpha wave's attenuation-disappearance phenomenon extensively exist in all the ten subjects.

All above results indicated the decrease in alpha activity from the N-Es and S-Es periods (corresponding to alpha blocking phenomenon) to the S-Es* (S-Es*1 and S-Es*2) period, especially from the S-Es*1 period to the S-Es*2 period, due to the occurrence of alpha wave's attenuation-disappearance phenomenon during S-Es* period. The consistency between the general distribution and each individual distribution for alpha PSD sample values may verify this new observed alpha attenuation-disappearance phenomenon as a general pattern during simulated driving experiments.

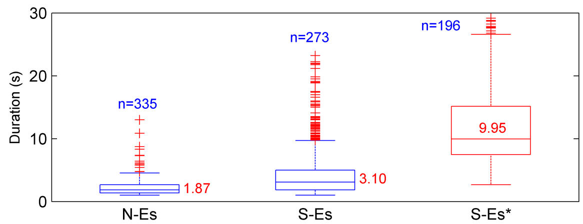

Fig. 6: The duration distributions of the ECEs during three different periods by box plots. Here, n is the number of each kind of ECEs.

Fig. 6 shows the distribution of the durations of ECEs from all ten subjects during three different periods. It is easy to understand that the longer the duration of ECE is, the sleepier the driver is in this current ECE. The ECEs with this alpha patern from attenuation to disappearance during the S-Es* period show the highest duration distribution, with the median value 9.95 s, and represent the highest sleepiness level. In contrast, the ECEs with continuous alpha wave during the N-Es and S-Es periods show the lower sleepiness level. It is worth noting that ECEs from N-Es and S-Es were the same type with continuous alpha wave, but in two different driving stages.

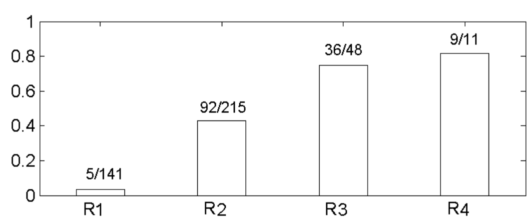

Fig. 7: The percentage of ECEs with the alpha wave's attenuation pattern over all the ECEs across four sub duration ranges during sleep alpha stage for all the subjects

Furthermore, we presented the change trend of percentage of ECEs with this alpha pattern from attenuation to disappearance across four sub duration ranges during sleep alpha stage: 2.5<R1<5 s, 5<R2<15 s, 15<R3<30 s, 30<R4<60 s, as shown in Fig. 7. Within the range R1, there were 141 ECEs in total and 5 of them were with this pattern. We can clearly see a significant increasing trend for the percentage of ECEs with this pattern from rang R1 to R4 with the percentage value increasing from 3.6% to 81.8%. This result further demonstrated that this pattern was more likely to appear at the higher sleepiness level.

V. Conclusions

The alpha wave's attenuation-disappearance pattern is different from the intermittent alpha wave form reported in Hori's nine-stage sleep scoring system, maybe due to the sleep deprivation caused by driving task at the usual sleep time of the subjects with siesta habit during our simulated driving experiments. Moreover, this alpha wave's attenuation pattern is more likely to appear at the higher sleepiness level, predicting driver's starting to enter sleep during driving. Considering these observations, we need to reassess fatigue measurements such as video rating and subject alertness rating [11], which ignore eye states and the possible appearance of alpha wave's attenuation. Meanwhile, simply judging whether alpha power increase over time during driving seems to have the limited significance, since the alpha wave's change is dynamic during driving.

Besides, it is worth noting that it is convenient to conduct the simulated driving experiment under the condition of sleep deprivation on the daytime by selecting the subjects with siesta habit. By the Epworth sleepiness scale for measuring daytime sleepiness level, the selected 10 subjects gave the relatively higher ESS scores. In future, various people need to be further investigated for achieving more comprehensive information about the change characteristics of alpha wave during simulated driving.

VI. Acknowledgment

This work was supported in part by grants from the National Natural Science Foundation of China (Grant Nos. 61272248 and 61673266), the National Basic Research Program of China (Grant No. 2013CB329401), the Major Basic Research Program of Shanghai Science and Technology Committee (Grant No. 15JC1400103), and the Technology Research and Development Program of China Railway Corporation (Grant No. 2016Z003-B).

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