EEG-Based Driving Fatigue Alleviation Using Multi-Acupoint Electrical Stimulation Combine Music Conditioning Method

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EEG-based driving fatigue alleviation using multi-acupoint electrical stimulation combine music conditioning method

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Abstract: In the present work, we propose the multi-acupoint electrical stimulation (stimulating the Láogóng point (劳宫 PC8) and acupuncture points on waist, shoulders, buttocks of the human body) combined with music conditioning (MESCMC) to alleviate driving fatigue. In our study, the complexity of α and β rhythms of EEG of the drivers, the relative power spectrum of θ and β, as well as two relative power spectrum ratio θ/β and $(\theta+\alpha)/(\alpha+\beta)$ are used as fatigue features during driving. The features of the complexity, which can effectively reflect brain activity information, were used to detect the change of driving fatigue over time. Combined with the traditional relative power spectrum features, the changes in driving fatigue features were comprehensively analyzed. The results show that the MESCMC method can effectively alleviate the mental fatigue of drivers. Besides, compared with the single-acupoint electrical stimulation[only stimulating the Láogóng point (劳宫 PC8)] (SES) method, the MESCMC method is more effective in relieving driving fatigue.The mitigation equipment is low in cost and practical, and the MESCMC method is individualized and improves the universality of driving fatigue detection and relieve, so will be practical to use in actual driving situations in the future.

1. Introduction

Many factors cause traffic accidents, among which traffic accidents caused by driving fatigue account for a considerable proportion [1,2]. Therefore, it is particularly important for safe driving to accurately and quickly detect the fatigue state of drivers and relieve the fatigue state in time in the process of long-term driving. EEG signals can accurately represent the fatigue states of people [3], which is an ideal method of objectivity and accuracy among many detection methods, is regarded as the "gold standard" [4-7]. Ma et al proposed a feature extraction method based on a deep learning model to obtain higher classification accuracy and efficiency in EEG-based driving fatigue detection [8]. Ren et al proposed a two-level learning hierarchy RBF network that allows for global optimization of the key network parameters, aims to enhance the accuracy and efficiency of the EEG-based driving fatigue detection model [9]. Min et al using the multi-entropy fusion method analyzed the multi-channel area EEG to effectively detect the fatigue state of drivers, which achieved high-precision and high-sensitivity driving fatigue detection[10].

Merely detecting driver fatigue can sometimes not reduce safety hazards, so it needs to be alleviated in time to reduce the incidence of traffic accidents. At present, the methods to relieve driving fatigue mainly include reducing work intensity, taking short breaks, drinking caffeinated beverages, drugs, etc. These methods may affect normal work or harm the body. In recent years, a new method of relieving human fatigue called electrical stimulation has been widely used. Due to the advantages of small side effects of electrical stimulation, it has recently begun to be used to alleviate human physical and mental fatigue [11,12]. Tsay et al conducted acupressure and transcutaneous acupoint electrical stimulation on patients, the result showed that the fatigue level of patients in the transcutaneous acupoint electrical stimulation group was significantly relieved [13]. Dong et al analyzed the effect of acupoint electrical stimulation to relieve fatigue, the result showed that transcutaneous acupoint electrical stimulation can significantly relieve fatigue [14]. Wang & Hong et al used electrical stimulation on the Láogóng point (劳宫PC8) to relieve the mental fatigue of drivers. The study showed that electrical stimulation of the Láogóng point (劳宫 PC8) can effectively relieve driver fatigue during long-term driving [12]. Uenal et al analyzed the impact of listening to music on the driver when driving in a low-complexity traffic environment. The results show that listening to music in a monotonous car following task will not affect driving, and can improve driving ability such as alertness[15]. Yuan et al analyzed the α rhythm power spectrum of the subjects who listened to different rhythms of music, focusing on the corresponding relationship between EEG and music rhythm. The research showed that music rhythm is an important factor affecting the α rhythm [16]. Trumbo et al adopted song naming games to relieve driving fatigue in monotonous environments. The research showed that using song naming games as an alleviation countermeasure can effectively alleviate driving fatigue [17]. Guo et al analyzed whether listening to relaxing music can help alleviate mental fatigue and to maintain performance after a continuous performance task. The results show that listening to relaxing music can reduce mental fatigue when performing persistent cognitive tasks[18]. Li et al analyzed the influence of music rhythm on driver fatigue and attention quality in a long-distance monotonous highway environment. The study showed that middle-speed music was the best choice to relieve fatigue and maintain long-distance driving attention [19].

In this study, the MESCMC method was used to relieve the mental fatigue of the subjects. This method uses a conductive cloth that is fixed on the steering wheel of the car as the stimulation electrode. In the MESCMC method, the music player plays a mid-rhythm (70-100 BPM) song while the subject is receiving electrical stimulation. Nowadays, listening to music has become a habit of many drivers. Compared with traditional electrical stimulation, this method does not require patch electrodes and is convenient to use. The music adjustment method and electrical stimulation are activated at the same time to relieve fatigue. The MESCMC method is individualized and improves the universality of driving fatigue detection and relieve. This method will have broad application prospects in the future.

2. Experiment

2.1. Subjects

A total of 10 healthy subjects (8 males and 2 females; aged 24 ± 1.6 (S.D.)), were recruited to perform a monotonous driving simulator experiment. All subjects have no hearing impairment. Also, none of them have received professional music training. In the simulation experiment, all subjects are prohibited from taking drugs and any type of stimulants, such as alcohol, tea or coffee. All subjects have no history of neurological diseases, hearing impairment and sleep-related diseases, who were familiar with the procedure and purpose of the experiment. Additionally, they all volunteered to participate in the experiment and agreed in writing to include it in the scope of the study. The Ethics Committee at the Northeast Electric Power University Hospital endorsed the study protocol, which accords to The Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Experimental procedure and EEG acquisition equipment

The Emotiv, as a portable EEG acquisition device with a sampling rate of 128Hz, is very convenient to be used in real driving conditions. Its sensor electrodes are placed on the corresponding scalp surfaces of human brain regions according to the international 10-20 system (14 channels=AF3, AF4, F3, F4, FC5, FC6, F7, F8, T7, T8, P7, P8, O1 and O2). In the experiment, the Emotiv device is chosen for EEG signals recording. Each subject collected seven stages of EEG signals. The EEG signals recording for each stage lasts 5 minutes. Recordings are performed with the ears mastoids (right and left) used as the common reference. In the experiment, it should be ensured that all leads are in a normal connection state during recording EEG signals for each stage. In addition, the electrical stimulation and music plays must be suspended during EEG recording. The whole experiment lasted three hours (2:00 p.m.~ 5:00 p.m.). In the experiment of the MESCMC method to relieve driving fatigue, the flowchart of this method is shown in Fig.1, k is the adjustment factor, which is adjusted according to the individual's fatigue resistance. Considering the convenience of electrode placement and the efficiency of alleviating fatigue, we tried to use Multi-acupoint electrical stimulation to alleviate driver fatigue. The location of the Láogóng point (劳宫PC8) and multi-acupoint is shown in *Fig. 3.* Giving all subjects one hour (00:30 p.m.~1:30 p.m.) to rest to eliminate the interference caused by mental fatigue at noon. The experiment was divided into seven stages (stage 1-2:00 p.m., stage 2-2:30 p.m., stage 3-3:00 p.m., stage 4-3:30 p.m., stage 5-4:00 p.m., stage 6-4:30 p.m., stage 7-5:00 p.m.).

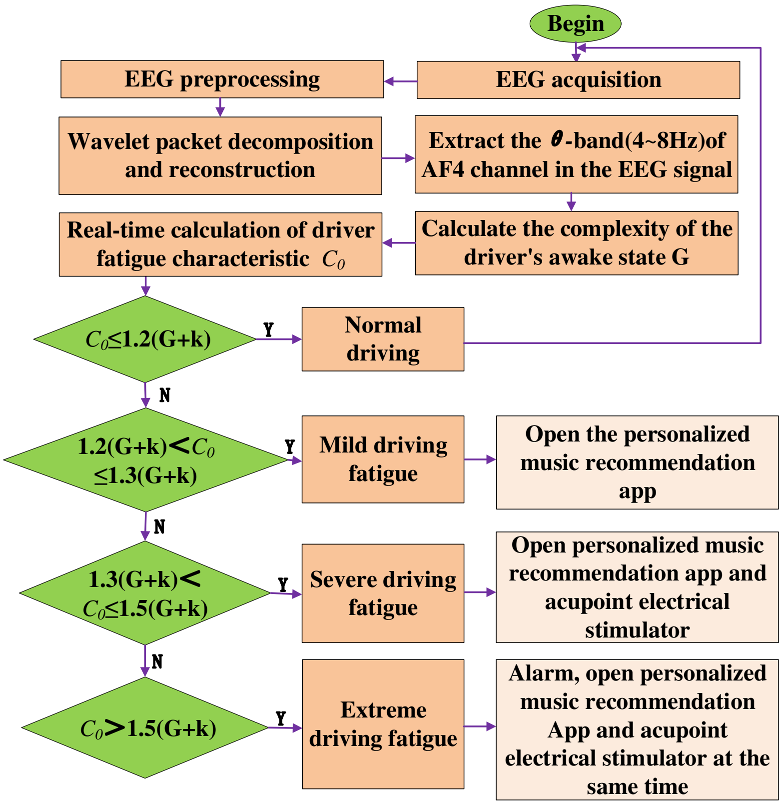


Figure 1. The MESCMC method to relieve driving fatigue flow chart

The experimental platform can be divided into four parts: car simulator, Emotiv, electric stimulator and music player. In the experiment, the car simulator is used to simulate the real driving environment; Emotiv that an EEG acquisition device was used to collect EEG of the subjects; Electric stimulator and music player are used to relieve driver fatigue. The following is a brief introduction to the components of the experimental platform. Fig.2 shows the experimental set-up.

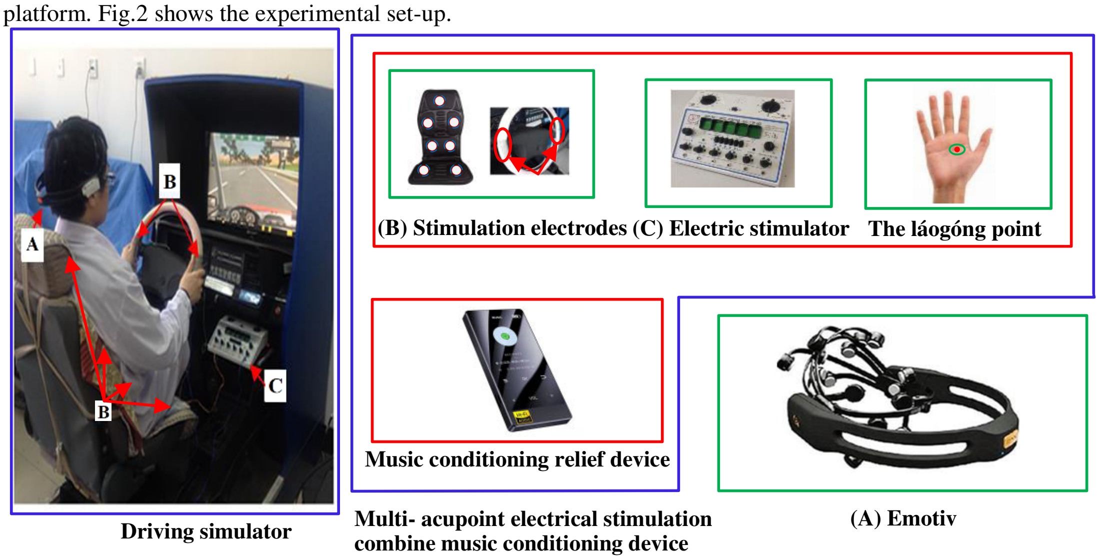


Figure 2. Experimental set-up

In the experiment, a multifunctional electrical stimulator (KWD-808I) was used to stimulate the acupoint with a current of 1~3mA (Subject to the strength that the participant can bear and is more comfortable), the pulse frequency of the electric stimulation is 1Hz, and the intermittent wave, triangle wave and continuous wave are alternately stimulated. In the experiment, the intensity of electrical stimulation must be lower than the level of nerve damage that causes the human cortex to stimulate. The actual electrical stimulator is shown in Fig. 2.

In the experiment, Amoi Mp3 is used as the car music player. The player has 5D surround sound effects and BOX shocking external playback. It supports TF card playback mode to meet various listening needs. Fig. 2 shows the experimental set-up.

In our study, the subjects were asked to drive at 70Km-90Km/h on the highway, and drive along the route that was told before the experiment. In addition, the experiment chose a low-complexity traffic setting as the driving environment, and the weather was sunny. The research includes three types of driving experiments, namely driving in normal driving conditions, driving with MESCMC method to alleviate driving fatigue, and driving with SES method to alleviate driving fatigue. Each subject was tested in three driving states. In the normal driving experiment, the subjects drive without electrical stimulation and music regulation. In the experiment of using the SES method to relieve driving fatigue, the subjects turned on the electric stimulator after normal driving to the third stage, and do not turn on the music player. In the experiment of using the MESCMC method to relieve driving fatigue, after the normal driving to the third stage, the MESCMC method (shown in Fig. 1.) is used to relieve driving fatigue. In this study, medium-speed music（70~100 BPM）that the subjects are interested in and have a good effect on alleviating driving fatigue is selected.

3. Analytical Method

In this paper, wavelet packet decomposition (four-layer decomposition of frequency bands) is used to extract δ(0~4Hz), θ(4~8Hz), α(8~12Hz) and β(12~32Hz) rhythms of EEG signals. Then, the complexity of α and β rhythms of EEG signals of the drivers, the relative power spectrum of θ and β, as well as two relative power spectrum ratio θ/β and $(\theta+\alpha)/(\alpha+\beta)$ are used as fatigue characteristics during driving. Finally, the efficiency of the MESCMC method and the SES method in alleviating driving fatigue is analyzed. The following sections describe these methods in detail.

3.1. EEG signals preprocessing

Since EEG signals collected in the driving environment contain strong interference, EEG must be preprocessing. The WPD can overcome the defect that the frequency resolution of wavelet transform will decrease with the increase of signal frequency, and then conduct more detailed analysis of the signal, can adaptively select the frequency band, and better reflect the essential characteristics of the signal [20]. In this study, the WPD was used for the preprocessing of EEG signals. The schematic diagram of the WPD is shown in Fig. 3, which is a four-layer WPD.

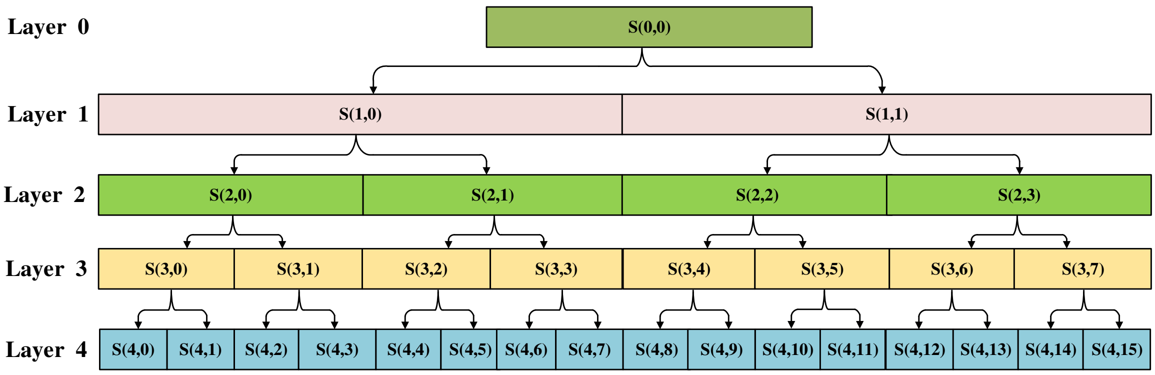


Figure 3. Experimental set-up

The WPD can decompose the time series signals from the time domain to the frequency domain layer by layer according to the resolution level. As the decomposition proceeds, the resolution in the time domain decreases, while the resolution in the frequency domain increases. The WPD formula is as:

Let $f(t)$ denote the source signals, after wavelet packet decomposition, 2i sub-bands are obtained in the ith sub-level, so the original signals can be expressed as:

$$f(t)=\sum_{j=0}^{2^i-1} f_{i,j}(t_j)=f_{i,0}(t_0)+f_{i,1}(t_1)+\cdots+f_{i,2^i-1}(t_{2^i-1}) \quad (1)$$

where j=0,1,2,…,2i-1,$f_{i,j}(t_j)$ is the reconstructed signals of the WPD on the node (i,j) of the ith layer. According to Parseval's theorem and formula (1), the energy spectrum of signals $f(t)$ wavelet packet decomposition can be calculated as:

$$E_{i,j}(t_j)=\int_\Gamma |f_{i,j}(t_j)|^2\, dt=\sum_{k=1}^{m}|x_{j,k}|^2 \quad (2)$$

where $E_{i,j}(t_j)$ is the frequency band energy decomposed by the $f(t)$ wavelet packet to the node (i,j); $x_{i,j}$(j=0,1,2,…,2i-1, k=0,1,2,…,m) is the amplitude of the discrete points of the reconstructed signals $f_{i,j}(t_j)$; m is the number of signals sampling points. In this paper, according to the WPD algorithm, binary scale transformation is used to decompose the resampled EEG signals into the fourth layer to obtain the low-frequency sub-band of the EEG, as shown in Table 1.

Table 1. Wavelet packet sub-band with corresponding EEG signals band

Wavelet sub-band	s(4,0)	s(4,1)	s(4,2)	s(4,3)	s(4,4)	s(4,5)	s(4,6)	s(4,7)
Frequency band/Hz	0~4	4~8	8~12	12~16	16~20	20~24	24~28	28~32

In this study, the 4-layer decomposition is made using the WPD to extract δ(0~4Hz), θ(4~8Hz), α(8~12Hz) andβ(12~32Hz) rhythms. The δ rhythm(0~4Hz) reconstructed using the sub-band $s(4,0)$, the θ rhythm(4~8Hz) reconstructed using sub-band $s(4,1)$, the α rhythm(8~12Hz) reconstructed using sub-band $s(4,2)$, and β rhythm(12~32Hz) reconstructed using sub-bands $s(4,3)$, $s(4,4)$, $s(4,5)$, $s(4,6)$, and $s(4,7)$. The waveform of each rhythm after reconstruction is shown in Fig. 4.

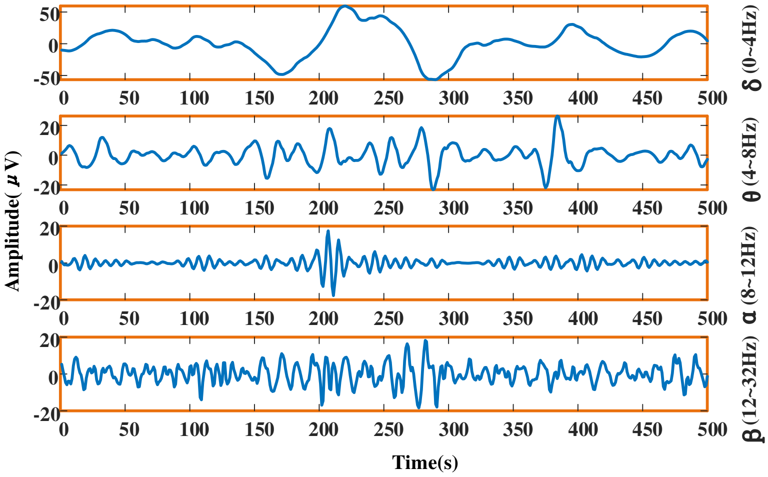


Figure 4. Waveform diagram of δ, θ, α and β rhythms

3.2. Driving Fatigue detection Indicators

This study uses the complexity feature to analyze the tested EEG signal (non-stationary signal), and combines the traditional relative power spectrum feature to comprehensively analyze the driving fatigue change process to improve the accuracy and reliability of driving fatigue detection.

3.2.1. The complexity

The research showed that the higher the LZC (Lempel-Ziv complexity, LZC) value, the higher the probability of the emergence of the new model, it also shows that the dynamic behavior is more complex [21,22]. Therefore, LZC can reflect the changes of physiological signals with the state of body fatigue. The Lempel-Ziv complexity algorithm proposed by Lempel and Ziv to measure the increase of new patterns as the sequence length increases. The algorithm characterizes the rate at which new patterns appear in a time series. The calculation method of C_0 complexity is as:

Define $\{f(x), k=0,1,2,\ldots,N\text{-}1\}$ as a time sequence of length N, then the corresponding Fourier transform sequence is:

$$F_N(j)=\frac{1}{N}\sum_{k=0}^{N-1} f(k)e^{-2\pi i(kj/N)} \tag{3}$$

where j=0,1,2$\cdots$,N-1, $i=\sqrt{-1}$ is the imaginary unit. For the formula (3), define W_N=e$^{-2\pi i/N}$, then there is:

$$F_N(j)=\frac{1}{N}\sum_{k=0}^{N-1} f(k)W_N^{-kj} \tag{4}$$

where j=0,1,2,…,N-1. Assuming that the mean square value of $\{F_N(j), j=0,1,2,\ldots,N\text{-}1\}$ is:

$$G_N=\frac{1}{N}\sum_{j=0}^{N-1}\left|F_N(j)\right|^2 \tag{5}$$

Definition:

$$\tilde{F}_N(j)=\begin{cases} F_N(j), & \left|F_N(j)\right|^2 > G_N \\ 0, & \left|F_N(j)\right|^2 \le G_N \end{cases} \tag{6}$$

Perform inverse Fourier transformation on sequence $\{\tilde{F}_N(j), j=0,1,2\cdots,N\text{-}1\}$:

$$\tilde{f}_N(k)=\sum_{k=0}^{N-1}\tilde{F}_N(j)W_N^{-kj}, k=0,1,2,\ldots,N-1 \tag{7}$$

The C_0 complexity formula is:

$$C_0 = \frac{\sum_{k=0}^{N-1}\left|f(k)-\tilde{f}(k)\right|^2}{\sum_{K=0}^{N-1}\left|f(k)\right|^2} \tag{8}$$

Assuming that $c(n)$ is the C_0 complexity of sequence $S(s_1,s_2,\ldots, s_n)$, Lempel and Ziv have proved that when $n\to\infty$, $c(n)$ approaches the fixed value $n/log_l n$, then the normalized formula is:

$$C_0 = \frac{c(n)n/\log_l n}{n} \tag{9}$$

where l is the number of coarse-grained stages (in traditional binarization, l=2).

3.2.2 Relative power spectrum

The studies have shown that when the driver is fatigued, the fast-wave (α and β) activity gradually decreases, the slow-wave (δ and θ) activity gradually increases. Besides, the characteristics of the EEG power spectrum can intuitively reflect the energy changes of EEG in different rhythms [23]. In this paper, the relative power spectrum is used as a feature to detect the driving fatigue state. Assuming that the autocorrelation function of the random signal is known, the power spectral density function can be defined as:

$$P(\omega) = \sum_{k=-\infty}^{\infty} r(k)e^{-j\omega k} \tag{10}$$

where $r(k)=E[x(n)x^*(n+k)]$; E represents mathematical expectation; * represents complex conjugate.

In the experiment, the EEG signals of each subject were collected 7 times. The relative power spectrum of the rhythm of the EEG signals refers to the ratio of the power spectrum in each rhythm of the EEG signals to the total power spectrum of the EEG signals (0～32Hz), as shown in formula (11):

$$P_i = \frac{E_i}{E_\alpha + E_\beta + E_\theta + E_\delta} \tag{11}$$

where P_i is the relative power spectrum of i rhythm, $i = \alpha, \beta, \theta, \delta$.

The study showed that when adults change from a normal state to a fatigued state, the slow-wave of EEG gradually increases, and the fast-wave gradually decreases (Borghini et al., 2014). Therefore, the sum of the slow-wave θ and the fast wave α can be combined with the fast wave, the ratio of the sum of slow-wave θ and fast-wave α to the sum of fast-wave β and α energy can be used as an index to judge the fatigue state, denoted as F, and the formula is:

$$F = \frac{E_\theta + E_\alpha}{E_\beta + E_\alpha} \tag{12}$$

where E_θ, E_α and E_β represent the energy of θ, α and β rhythms respectively.

In this experiment, as driving time increases, the changes in θ and β rhythms are more regular than the changes in the δ and α rhythms. In this experiment, β wave is selected as fast-wave, and θ wave is slow-wave. The formula for selecting the index F to judge the fatigue state is simplified as:

$$F = \frac{E_\theta}{E_\beta} \tag{13}$$

In this experiment, the relative power spectrum average value of the β rhythm $\overline{P_\beta}$ is used to replace the energy E_β of the β rhythm in formula (11), and the relative power spectrum average value of the θ rhythm $\overline{P_\theta}$ is used to replace the energy E_θ of the θ rhythm. The formula (11) can be expressed as:

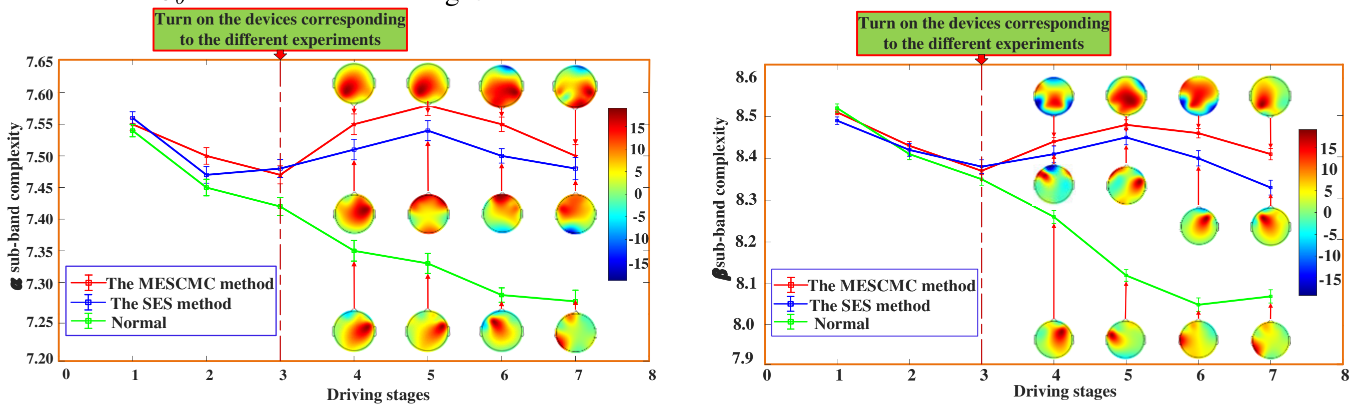
$$F = \frac{\overline{P_\theta}}{\overline{P_\beta}} \tag{14}$$

In section 4.2 of this article, the linear fitting method is adopted. The relative power spectrum ratios and the C_0 values of the subjects who used the SES method and the MESCMC method to relieve driving fatigue are calculated respectively. The linear slope indexes of the fitting are compared, which compared the efficiency of the SES method and the SESCMC method to relieve driving fatigue.

4. Results

4.1. The Complexity

Studies have shown that the complexity of EEG signals reflects the amount of EEG information and can reveal the laws of brain activity [25-27]. Lempel-Ziv complexity (LZC) relates the complexity of a particular sequence to the gradual emergence of new patterns in a given sequence [28]. The smaller the LZC of the EEG signal sequence, the more fatigued the driver[29,30]. In this paper, the C_0 values of α and β rhythms of one subject were calculated, as well as the variation of the C_0 values of the subjects as driving over time were analyzed. The trends of the C_0 value are shown in Fig. 5.



(a)The C_0 values(mean ± S.D.) of α sub-band (b) The C0 values(mean ± S.D.) of β sub-band

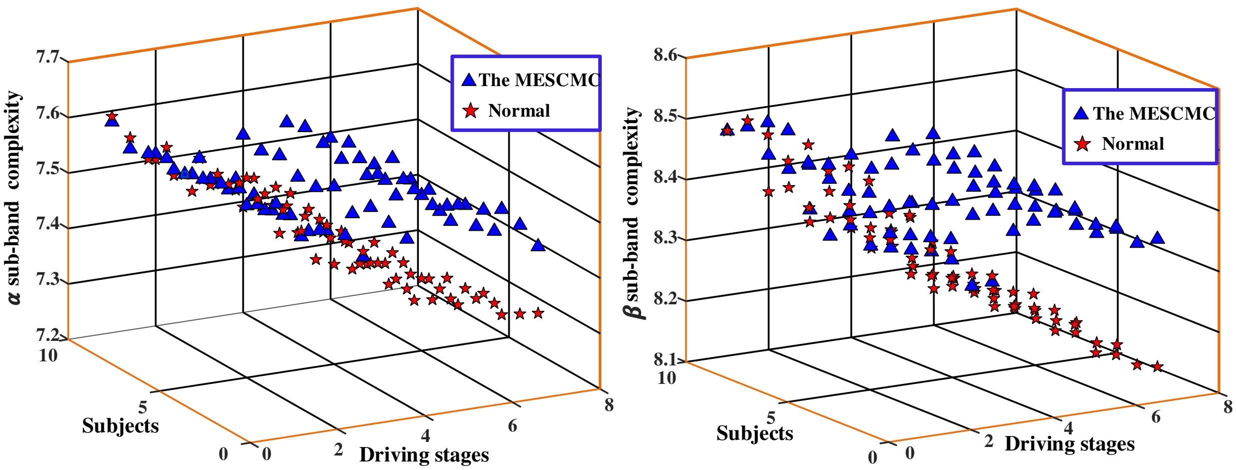
Figure 5. The C_0 values (mean ± S.D.) of α and β sub-bands of one subject in three experiments

It can be concluded from Fig. 5(a) and Fig. 5(b) that the C_0 values of the α and β sub-bands of the subjects corresponding to the three (normal driving group, MESCMC method group and SES method group) decreased from starting the experiment to the third stage, which means that the fatigue of the subjects will gradually deepen over time. From the fourth to seventh stages of the experiment, the C_0 values corresponding to α and β sub-bands of the subjects continued to decrease for the normal group.

From the third stage of the experiment, as shown in Fig. 5, the MESCMC method is used to relieve driving fatigue for the MESCMC method relief group, the subjects received multi-acupoint electrical stimulation and music relieve for the MESCMC method relief group. The C_0 values of α and β bands of the subjects were an upward trend after the fourth stage. For the SES method relief group, as shown in Fig. 6, only the single-acupoint electrical stimulator was turned on after the third stage. The subjects in the SES method relief group received single-acupoint electrical stimulation. The C_0 values of the α and β sub-bands of the subjects also have an upward trend. The increase of C_0 values indicates that the driving fatigue of the 10 subjects (MESCMC method relief group and SES method relief group) is alleviated. Moreover, the C_0 values, which subjects driving in the MESCMC method relief group, are always greater than that of the SES method relief group, which means that the MESCMC method is more effective in relieving driving fatigue compared with the SES method.

Fig. 5(a) and Fig. 5(b) show the brain topographic maps of the α and β sub-band the complexity when one subject is in the MESCMC method relieves driving fatigue, the SES method relieves driving fatigue and normal driving. The high complexity of the brain nerve is shown by a red shaded area, as well as the low complexity of the brain nerve is shown by a blue shaded area. Fig. 5(a) and Fig. 5(b) show that the complexity of brain regions of α and β sub-bands of the subjects show a significant downward trend in the 4-7 stages of normal driving. The complexity of brain regions of α and β sub-bands of the subjects show a significant upward trend for the MESCMC method relief group and the SES method relief group during the 4-7 stages of driving, which means the MESCMC method and the SES method can alleviate driving fatigue. In addition, the α and β sub-bands of the subjects in the relief group using the MESCMC method are significantly higher the complexity than the SES method relief group, which means that the MESCMC method is superior to the SES method to relieve driving fatigue.

In our study, we analyzed the C_0 values of α and β sub-bands of the 10 subjects of the two experiments(the MESCMC method relief group and the normal driving group) in the 4-7 stages of the experiment, the trends are shown in Fig. 6.

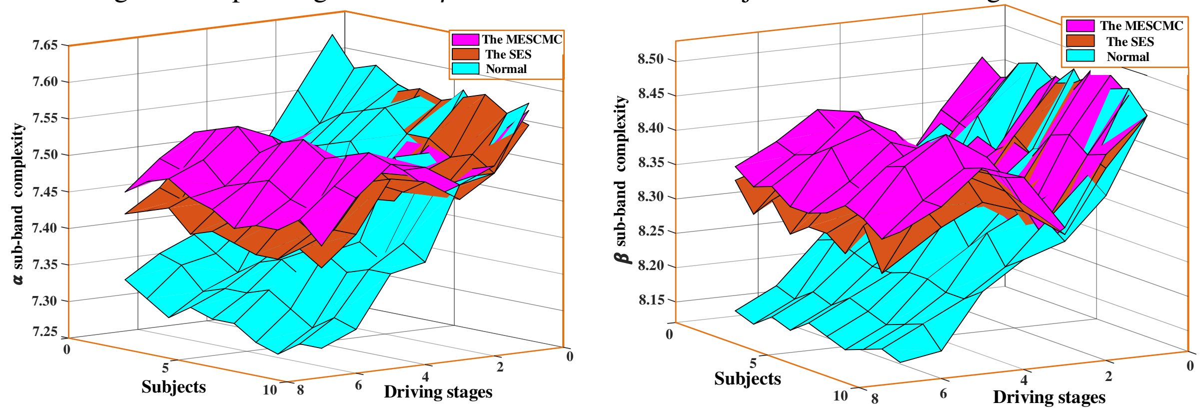


(a) The C_0 values of α sub-band of the two experiments (b) The C_0 values of β sub-band of the two experiments

Figure 6. Trends of the C_0 values of α and β sub-bands of the 10 subjects as driving over time

It can be concluded from Fig. 6(a) and Fig. 6(b) that the C_0 values corresponding to the α and β sub-bands of the 10 subjects continue to decrease over time in the normal driving group, which means that the fatigue degree of subjects gradually deepened over time. It can also be concluded from Fig. 6(a) and Fig. 6(b) that the C_0 values corresponding to the α and β sub-bands of the 10 subjects showed an overall upward trend from the fourth to the seventh stage of the experiment in the MESCMC method relief group. The conclusion is attributed to the fact that the multi-acupoint electric stimulator and the music player are turned on after the third stage. Moreover, the C_0 values corresponding to α and β sub-bands of the 10 subjects driving in the MESCMC relief group, are always greater than the normal driving group, which means that the MESCMC method can effectively alleviate driving fatigue.

Studies have shown that EEG can reflect the neural activity of the human body [31,32]. In our study, the C_0 values corresponding to the α and β bands of the 10 subjects are calculated to describe the changing trends of the fatigue state of the three experiments (the normal driving stage, the MESCMC method relief group and the SES method relief group) of 10 subjects. In these three experiments, the C_0 values changes corresponding to α and β sub-bands of the 10 subjects are shown in Fig. 7.



(a) The C_0 values of α sub-band of the 10 subjects (b) The C_0 values of β sub-band of the 10 subjects

Figure 7. Comparison of the C_0 values of α and β sub-bands of the 10 subjects in three experiments

It can be concluded from Fig. 7 that there is a significant difference in the C_0 values of α and β sub-bands of the 10 subjects between the MESCMC method relief group and the normal driving (p<0.01). From the fourth to seventh stages of the experiment, the C_0 values corresponding to α and β sub-bands of the subjects continued to decrease for the normal group. While the C_0 values of the α and β bands of the subjects who were arranged to participate in two experiments(the MESCMC method relieve group and the SES method relieeve group) also were an upward trend after the fourth stage. It means that the MESCMC method and the SES method can effectively alleviate driving fatigue. Moreover, the C_0 values corresponding to α and β sub-bands of the 10 subjects driving in the MESCMC relief group, are always greater than that of the SES relief group, which means that the MESCMC method is more effective in relieving driving fatigue compared with the SES method.

4.2. The Linear Fitting Method

The power spectrum and relative power spectrum analysis of each rhythm of EEG is considered to be one of the most commonly used methods to distinguish driving fatigue state [33]. In our study, the linear fitting method is used to calculate the fitting slopes of fatigue alleviation indicators of the two experiments(the MESCMC method relief group and the SES method relief group) in the 4-7 stages of the experiment. Meanwhile, the slope of the fitted line is used as the evaluation index, and the same detection index of the two experiments (the MESCMC method relief group and the SES method relief group) is compared, and the effect of the two methods(the MESCMC method and the SES method) to relieve driving fatigue is obtained. Firstly, to make various data comparable, the data is normalized. Taking the relative power spectrum index of θ sub-band of one subject as an example, the least-squares method is used to fit the relative power spectrum value of θ sub-band after the MESCMC method is used to relieve driving fatigue. The fitted line is shown in Fig. 8.

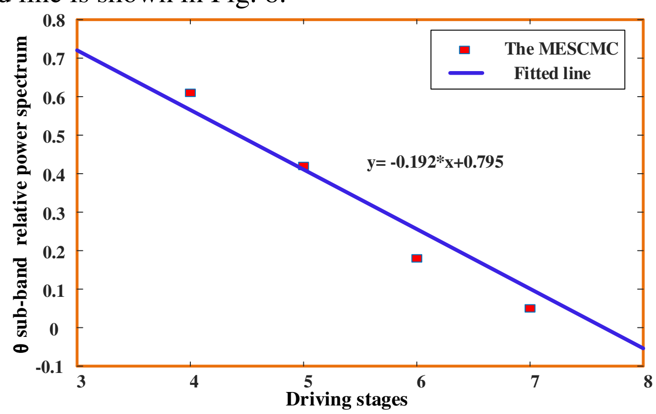


Figure 8. Relative power spectrum the fitted line in the driving fatigue relief stages

The SPSS software was used for analysis, the fitting line of the relative power spectrum of the θ sub-band of the subjects in the fatigue relief stage was obtained: y=-0.192*x+0.795, F-test p=0.027, which passed the significance test and accorded with the linear relationship. According to the same method, linear fitting was performed on the driving fatigue alleviation stage indicators of the two experiments (MESCMC method relief group and SES method relief group), and the slope of the fitting line is shown in *Table 2*.

Table 2. The slope of the fitted line of the driving fatigue parameter index of different experiments

Driving fatigue parameter index	The slope of the fitted line of SES method	The slope of the fitted line of MESCMC method	The MESCMC method P-value of the F test	The SES method P-value of the F test
θ relative power spectrum	-0.168	-0.192	0.027*	0.034*
β relative power spectrum	0.203	0.305	0.005**	0.033*
Relative power spectrum ratio(θ/β)	-0.172	-0.196	0.047*	0.054
Relative power spectrum ratio $(\theta+\alpha)/(\beta+\alpha)$	-0.206	-0.273	0.031*	0.041*
C_0 values of α sub-band	0.015	0.025	0.041*	0.052
C_0 values of β sub-band	0.019	0.031	0.039*	0.048*

Note: *: Indicates a significant difference (p<0.05)
**: Indicates that the difference is very significant (p<0.01)

In our study, the relative power spectrum of the θ and β sub-bands of the subject, the C_0 values corresponding to the α and β sub-bands of subject and the relative power spectrum ratio$(\theta+\alpha)/(\beta+\alpha)$ is used as the fatigue feature. *Table 2* shows the slope value of the fitting line corresponding to the fatigue feature after the MESCMC and the SES method is used to relieve driving fatigue. After the subjects received the MESCMC method to relieve fatigue, the absolute value of the slope of the fitting line of the fatigue feature was greater than the absolute value of the slope of the fitting line of the fatigue feature after the SES method was used to relieve the driving fatigue. Through the significance test, it is in line with the linear relationship. The result showed that the MESCMC method is more effective than the SES method in alleviating driving fatigue.

5. Discussion

Previous studies have shown that when the driver is fatigued, his reaction ability, cognitive ability and operation ability are severely affected, the judgment accuracy is reduced, and more and more errors occur, which poses a serious threat to safe driving [34,35]. Therefore, rapidly and accurately detect and relieve driving fatigue is particularly important for driving safety. The study has shown that stimulating the Láogóng point (劳宫 PC8) can effectively relieve the mental fatigue drivers during long-term driving [12]. The study has shown that music can relieve driving fatigue in a monotonous environment [36]. However, the traditional single method of relieving fatigue does not meet actual driving needs. The MESCMC method is to stimulate the multi-acupoint (the Láogóng point (劳宫 PC8) and acupuncture points on waist, shoulders, buttocks of the human body) with the electric stimulator while the music player is playing the music that the driver is interested in to relieve mental fatigue of the drivers. In our study, we propose the multi-acupoint electrical stimulation combined with music conditioning (MESCMC) to alleviate driving fatigue.

5.1. The Complexity and the Linear Fitting Method

Previous study indicated that there is a downward trend of the complexity as subjects' fatigue deepens [35,36]. This result is consistent with our research. The C_0 value reflects the probability of a new pattern in the brain, and indirectly reflects the driving fatigue states of the subjects. In our study, we analyzed the complexity, relative power spectrum, relative power spectrum ratio and linear fitting slope of different rhythms of EEG signals of the subjects, as well as used the four indicators to distinguish the fatigue state. We compared the effects of the SES method and the MESCMC method in alleviating driving fatigue. As shown in Fig. 6, the complexity of the subjects driving in normal mode also showed overall downward trends. However, from the fourth stage to the seventh stage of the experiment, the C_0 values of the α and β sub-bands of the subjects in the MESCMC relief group showed upward trends because the brain nerves were continuously stimulated at successive driving stages, which keep the nerves in a relatively exciting state. This means that the MESCMC method can effectively relieve driving fatigue. For two experiments (MESCMC method relief group and SES method relief group), subjects driving in the MESCMC state can stay awake more effectively than in the SES state. When the subject is driving in an awake state, the C_0 value is greater than the C_0 value in a fatigued state. From the fourth stage to the seventh stage of the experiment, the C_0 values of the α and β sub-bands of the subjects in the MESCMC relief group are greater than the C_0 values of the α and β sub-bands of the subjects in the SES relief group, as shown in Fig. 5 and Fig. 7.

The linear fitting method is used to fit the absolute value of the index slope from the 4-7 stages of the experiment. The absolute value of the index fitting slope of the MESCMC method is greater than the absolute value of the index fitting slope of the SES method, as shown in *Table 2*, which means the MESCMC method is more efficient than the SES method in alleviating driving fatigue. Because the acupoint electrical stimulation can dredge the body's meridians, allow blood to pass through, protect internal organs, and relieve physical fatigue. In the MESCMC method, stimulating electrodes are arranged on the seat corresponding to the shoulders, waists, and buttocks of the human body to relieve body stiffness and numbness caused by long-term driving of the human body. Music can act on the limbic system and brainstem network structure of the human brain through human hearing. Meantime, music can regulate the cerebral cortex, so that visceral activities of the body and behaviors have a well-coordinated response. Furthermore, music relieves boredom and fatigue during driving. The MESCMC method is more effective than the single the SES method to relieve driving fatigue. Additionally, the mitigation equipment is low in cost and practical, and the electrical stimulation equipment of the MESCMC method used multi-acupoint electrical stimulation that can alleviate driving fatigue more effectively than traditional methods for relieving fatigue and improve driving safety. The MESCMC method is individualized and improves the universality of driving fatigue detection and relieve, so will be practical to use in actual driving situations in the future.

5.2. Novel Findings of This Study

This study adopted the MESCMC method to relieve driving fatigue. In the MESCMC method, stimulating electrodes are arranged on the seat corresponding to the shoulders, waists, and buttocks of the human body to relieve body stiffness and numbness caused by long-term driving of the human body. Our study shows that compared with the SES method, the MESCMC method can more effectively alleviate driving fatigue. In future research related to human mental fatigue, researchers can try to use the MESCMC method to relieve human mental fatigue. Additionally, listening to music during driving has become a driving habit of many drivers. The method adopts simple equipment and low cost, and can alleviate driving fatigue more effectively than traditional methods for relieving fatigue and improve driving safety. The MESCMC method is individualized and improves the universality of driving fatigue detection and relieve. This method of relieving driving fatigue has positive significance for practical applications in the future.

5.3. Limitations and Future Research Lines

In our experiments, when using an electric stimulator, how much stimulation current and stimulation frequency will be more effective in alleviating driving fatigue requires further research. As the driving fatigue state changes, when playing music, it is necessary to further study what rhythm of personalized music should be played in different fatigue states to achieve the purpose of personalized music recommendation. Electrical stimulators and music playback equipment need to be further integrated.

6. Conclusions

In our study, the MESCMC method was proposed for alleviating driving fatigue. The features of the complexity, which can effectively reflect brain activity information, were used to detect the change of driving fatigue over time. Combined with the traditional relative power spectrum features, the changes in driving fatigue features were comprehensively analyzed. The results show that the MESCMC method can effectively alleviate the mental fatigue of drivers. Besides, compared with the SES method, the MESCMC method is more effective in relieving driving fatigue. Moreover, the mitigation equipment is low in cost and practical, and the electrical stimulation equipment of the MESCMC method used multi-acupoint electrical stimulation that can alleviate driving fatigue more effectively than traditional methods for relieving fatigue and improve driving safety. The MESCMC method is individualized and improves the universality of driving fatigue detection and relieve, so will be practical to use in actual driving situations in the future.

Author Contributions

Fuwang Wang: Conceptualization, Methodology, Validation, Writing-review & editing, Supervision. **Xiaogang Kang:** Conceptualization, Methodology, devices, Validation, Writing-original draft. **Bin Lu:** devices, Investigation. **Hao Wang:** Investigation, Supervision. **Rongrong Fu:** Investigation, Supervision.

Conflicts of interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Ethics approval

The Ethics Committee at the Northeast Electric Power University Hospital endorsed the study protocol. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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