Recurrence Quantification Analysis of EEGs for Mental Fatigue Evaluation

CHEN Lanlan, ZOU Junzhong, ZHANG Jian
Department of Automation, School of Information Science and Engineering,
East China University of Science and Technology, Shanghai, 200237, China
E-mail: {llchen, jzhzou, zhangjian}@ecust.edu.cn

Abstract: It is important to evaluate the level of mental fatigue by using electroencephalograms (EEGs). In this research, a recurrence quantification analysis (RQA) is proposed to reveal dynamical characteristics in EEGs of subjects suffering from mental fatigue. In contrast with traditional spectrum methods, the merits of RQA method is that it can measure the complexity of non-stationary and noisy signal without any assumptions such as linear, stationary and noiseless. In this study, eight channels of EEGs were collected in calculation-rest-calculation experiment. Both RQA measure i.e. determinism (%DET) and spectrum estimator i.e. central frequency (CenF) was computed. The test results show that %DET is sensitive to mental load and mental fatigue while CenF fails to track the change of mental fatigue. Particularly, %DET clearly reflects the rest effect in sustained mental work. Therefore, RQA could be a promising approach in evaluation and treatment for mental fatigue.

Key Words: Recurrence Quantification Analysis (RQA), EEGs, Mental Fatigue, Spectrum Estimation

1 Introduction

The increasing impact of mental fatigue on the quality of performance and health should be highlighted. Evaluation of human mental states is a complex task for which no single best way can be viewed as a standard. So far, several methods are available to measure the human mental fatigue. Questionnaire investigations and performance evidence are in common use. There are also increasing research using neurological signals. EEGs are recognized as the golden measures to detect mental fatigue [1]. So far, many methods have been proposed to analyze EEG data and recognize EEG pattern. In the last decade, visual inspection and spectral estimation are important clinic approaches for EEG analysis. In particular, spectral measures i.e. spectral power [2] and central frequency [3] are based on assumptions of stationary and linear signals. Actually, EEG data is evolving fluctuant which presents non-stationary and transient characteristic. Therefore, a useful tool which may help physiologists to detect significant patterns in fatigue EEGs is the recurrence quantification analysis (RQA). The main advantage of RQA is that it can provide useful information even for noisy and non-stationary data where other methods fail [4].

In this study, RQA is applied to quantify dynamics of EEG data across a long-term fatigue test. Both RQA measure i.e. determinism (%DET) and spectral estimator i.e. central frequency (CenF) are computed. The research results show that %DET is highly correlated with the change of vigilance level while CenF is not so sensitive to vigilance and fatigue level in this experiment. Therefore, RQA could be a promising approach in the evaluation of mental fatigue.

2 Materials and Data Acquisition

2.1 Subjects and Experiment Design

Two healthy male students, aged 24-25 years old, were recruited from East China University of Science and Technology. The subjects were instructed to abstain from alcohol and caffeine 24 hours before experiments. On the experiment days, the subjects were settled in a dimly lit, sound-attenuated, electrically shield room. Before the start of experiments, they fulfilled sleep questionnaires about personal information (e.g. age, sex, weight and height), sleep condition the night before (e.g. sleep hours, medication taking and alcohol taking), and healthy condition.

A work-rest schedule including mental calculating task and rest break is designed. The work-rest schedule consists of three sequential sections arranging as follows:

Section 1: Long term calculation task (It lasts for 120 minutes and divides into four stages. Each stage lasts for 30 minutes. They are named as Cal1, Cal2, Cal3 and Cal4 stage, respectively).

Section 2: Rest break with music (It lasts for 15 minutes. The music is Mozart Eine Kleine Nachtmusik).

Section 3: Short term calculation task (It lasts for 30 minutes and is named as Cal5 stage).

2.2 Electroencephalogram (EEG) Signals Recording

Electroencephalogram (EEG) signals are recorded simultaneously throughout the experiment. The electrical impedance is under 10 kOhms for all electrodes. Electrodes are placed according to the international 10–20 system and put at the following areas: Fp1, Fp2, F3, F4, Fz, Cz, O1, and O2 against ipsilateral earlobe electrode (A1 or A2). EEG signals are amplified by a digital EEG machine (Nihon-Koden EEG 2110) with the sampling frequency of 200 Hz, a low-frequency cut-off of 0.5Hz, and a high-frequency cut-off of 25Hz. The record data are stored by segments. Each segment contains 1000 samples (5sec).

*This work is supported by Fundamental Research Funds for the Central Universities WH1114028.
Fig. 1 and Fig. 2 show EEG segments at relaxation and calculation states respectively.

3 Methods

3.1 EEG Spectrum Estimation

The digital data of EEG time segments are transformed into the Fourier components by the fast Fourier transform (FFT) algorithm. The periodogram of each segment is obtained as the squares of the magnitude of the Fourier components divided by the data length for each resolving frequency of 0.2 Hz. The features of EEG records at each electrode can be expressed by the periodogram components. EEG central frequency (CenF) is the weighted sum of periodogram components, divided by the summation of periodogram components within total frequency band of $T (0.5-25 \text{ Hz})$ shown in (1).

$$F_{C}(c) = \sum_{f=0}^{25} p(f(c)) \times f, \quad (1)$$

where $p(f(c))$ is periodogram component on the frequency of $f$ at the electrode $c$. Central frequency (CenF) gives a global estimation of periodogram components. The previous study on driver’s mental fatigue shows that central frequency (CenF) becomes smaller when driver’s alertness level drops [5].

3.2 Recurrence Plots (RPs) and Recurrence Quantification Analysis (RQA)

The RQA is a method of nonlinear data analysis for the investigation of dynamical systems. This method, developed by Charles Webber and Joseph Zbilut [6], aims to quantify differently appearing recurrence plots (RPs) based on the small-scale structures. Recurrence plots are graphical tools which visualize the recurrence behaviour of the phase space trajectory of dynamical systems. Recurrence plots are briefly defined in (2).

$$R_{i,j} = \Theta(e - \|x_i - x_j\|), \quad i,j = 1,...,N, \quad (2)$$

where $\|\|$ is the norm (in this research, Min norm is adopted) and $\Theta(\cdot)$ is the Heaviside function. This means if the distance between $x_i$ and $x_j$ is less than $e$, then $R_{i,j} = 1$ and a dot is placed at $(i, j)$ in the RP. The scale $e$ is a cutoff distance defining a sphere centered at $x_i$.

Although several measures have been introduced in RQA in the recent past [7], this research mainly focuses on a fundamental measure i.e. determinism (\%DET) as originally introduced by Webber and Zbilut [6]. Determinism (\%DET), which is the ratio of recurrence points on the diagonal structures to all recurrence points. \%DET is related with the determinism of the system. \%DET is calculated by (3).

$$\%\text{DET} = \sum_{i=1}^{N} P(l) / \sum_{i,j} R_{i,j}, \quad (3)$$

where $P(l)$ is the frequency distribution of the lengths of the diagonal structures in the RP. $l_{\text{min}}$ is the threshold, which excludes the diagonal lines formed by the tangential motion of a phase space trajectory, in this research $l_{\text{min}}=2$.

4 Results

In this research, RQA is applied to discover hidden dynamics of fatigue EEG data, including the structure and the quantification analysis of the recurrence plots (RPs). The purpose is to reveal the dynamical characteristics across the progressive fatigue state.

4.1 Structure of Recurrence Plots (RPs)

The recurrence plots for sine signal and human EEG signal are illustrated in Fig.3 (a) and (b) respectively. The RP of sine signal (Fig.3 (a)) is characterized by a large number of small diamonds, which indicates the determinism of the system. EEGs (Fig.3 (b)) are non-stationary and evolving fluctuant. The RP of human EEGs at mental calculation state (Fig.3 (b)) is characterized by many isolated recurrence points, which demonstrates the complex characteristics of human brain system.

The measures based on diagonal lines, vertical and horizontal structures make it possible to identify and quantify the dynamics of distinct states. Thus in the following section quantification measure of RPs is calculated.

4.2 Recurrence Quantification Analysis (RQA)

A fundamental RQA measure i.e. \%DET of each segment is calculated with a dimension of $m=1$, a delay of $\tau=1$, and a radius of $e=0.2$. To discover the dynamic changes over time,
RQA method is applied to two subjects’ EEG data at O1 electrode. Five minutes data at the end of each calculation state (Cal1 to Cal5) are analyzed. From the observation of %DET (Fig.4 (b) and Fig.5 (b)) over the EEG recordings, it is found that %DET can track the complexity changes of brain electrical activity over time and it is sensitive to the change of vigilance level. %DET reveals a progressive increase from Cal1 to Cal4 stages. High %DET represents high probabilities of the occurrence of the same state at the different time. The higher %DET indicates that the brain electrical activity share a similar underlying dynamic in this period. Besides, it is found that %DET decrease after relaxation, which indicates the decrease of recurrence complexity under an easy state. In the case of subject 1, the mean value of %DET for the Cal1 to Cal5 stages are 5.05, 6.85, 7.89, 9.11 and 4.16 respectively. Meanwhile, EEG central frequency (CenF) maintains some level across the experiment as shown in Fig.4 (c) and Fig.5 (c), which reflects this spectrum estimator is not so sensitive to the change of fatigue and vigilance level.

![Figure 3: The recurrence plots for two signals](image)

![Figure 4: The EEG recordings of subject 1 with RQA and spectral estimators](image)

**Fig.3:** The recurrence plots for two signals (a) a sine signal epoch (b) a human EEG epoch at mental calculation state. RQA parameters: a dimension of \(m=1\), a delay of \(\tau=1\), and a radius of \(\epsilon=0.2\), NORM=min norm. The most obvious feature of RP in Fig.3 (a) is a large number of small diamonds structure. The recurrence plot in Fig.3 (b) has fine structure characterized by many isolated points.

**Fig.4:** The EEG recordings of subject 1 with RQA and spectral estimators. The X-axis represents distinct calculation stage. Cal1 to Cal 4 are four stages before music relaxation. Cal5 is a stage after relaxation. Visual inspections of the signals (a) show larger amplitude from Cal2 to Cal4. %DET (b) clearly show the progressive increase from Cal1 to Cal4 stages and significant decrease at Cal 5 stage. EEG central frequency (CenF) (c) maintains low level across the stages.
Fig. 5: The EEG recordings of subject 2 with RQA and spectral estimators. The X-axis represents distinct calculation stage. Cal1 to Cal 4 are four stages before music relaxation. Cal5 is a stage after relaxation. Visual inspections of the signals (a) show stable medium amplitude over the time. %DET (b) show the progressive increase from Cal2 to Cal4 states and a decrease at Cal 5 stage. EEG central frequency (CenF) (c) maintains moderate level across the stages.

5 Discussions

While numerous physiological indicators are available to measure level of fatigue, EEG signals may be one of the most predictive and reliable [1]. EEGs especially the signals at the occipital region are sensitive to workload and vigilance level. Traditional methods such as time serials visual inspection and spectral analysis [2, 3] are based on the principle that EEGs are generated from random processes. Only stationary and noiseless EEG signals are suitable for these methods. Actually, human’s EEG contains a lot of transient process and is easy to be contaminated by noise. Therefore, these methods fail to detect the embedded dynamics of EEGs. To overcome the drawbacks of traditional methods, this research applied recurrence quantification analysis (RQA) method, which can deal with non-stationary and noisy EEGs. In this study, both RQA measure and spectrum estimator are computed for EEGs record at long-term fatigue experiments. The test results show RQA measure is more sensitive to the change of fatigue level while spectrum estimator fails to track the accumulation of fatigue over the time. Therefore, RQA measure can be applied to evaluate and predict human’s mental fatigue.

6 Conclusions

This research applied recurrence quantification analysis (RQA) method to evaluate the progressive accumulation of mental fatigue during sustained mental work. The results indicate that RQA measure can track the change of fatigue level while spectrum estimator fails. Therefore, RQA measure can be applied to evaluate and predict human’s mental fatigue.

References