Estimating Mental Fatigue Based on Multichannel Linear Descriptors Analysis

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Abstract. In this paper, two different mental fatigue experiments, sleep deprivation and prolonged time of work, were designed to investigate their effect on mental fatigue respectively. Three parameters of multichannel linear descriptors i.e. Ω, Φ and Σ are used to measure the level of mental fatigue for the first time. When mental fatigue level increases, the brain neurons are restrained, this results in the increase of synchrony degree between the distributed electroencephalogram (EEG). Therefore, spatial complexity Ω, field strength Σ and field changes Φ of regional brain region would reduce. The experimental results also show that the average values of Ω, Φ and Σ of EEG decrease with the prolonging of sleep deprivation and working time, and then also decrease with the increase of mental fatigue level. The average values of Ω, Φ and Σ of EEG strongly correlate with mental fatigue. The multichannel linear descriptors of EEG are expected to serve as the indexes to evaluate mental fatigue level objectively.

Keywords: mental fatigue, Electroencephalogram (EEG), multichannel linear descriptors.

1 Introduction

Mental fatigue is a term to cover the deterioration of mental performance due to the preceding exercise of mental or physical activities [1]. D. van der Linden et al defined mental fatigue as a change in psychophysiological state due to sustained performance [2]. This change in psychophysiological state has subjective and objective manifestation, which include an increased resistance against further effort, an increased propensity towards less analytic information processing, and changes in mood. Sustained performance, in this definition, does not necessarily involve the same task but can extend over different tasks that require mental effort, such as fatigue because of a day in the office. Fatigue, especially mental fatigue, is inevitable for office workers and in life in general. Working on cognitive demanding tasks for a considerable time often leads to mental fatigue, which can impact behavior of mental task. Mental fatigue is usually related to a loss of efficiency and disinclination to effort. In industry, many incidents and accidents have been related to mental fatigue.

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It is important to manage and cope with mental fatigue so that the workers do not damage their health cases. Therefore, the management of mental fatigue is important from the viewpoint of occupational risk management, productivity, and occupational health.

One of the interesting questions in mental fatigue research is in what way cognitive control of behavior changes under mental fatigue. Lorist et al used behavioural and EEG-data to study the effects of time-on-task (i.e., mental fatigue) on planning and task switching [3]. The EEG-data of their study showed that with increasing time-on-task there was a reduced involvement of those brain areas that are associated with the exertion of executive control (the frontal lobes). It is hypothesized that mental fatigue is indicated by the degradation of the ability to sustain an adequate performance in mental tasks, due to the exertion of mental and physical activities during preceding work times [1]. It was reported that subjects protected their performance by spending more effort in the unfavorable conditions: after several hours of work and after continuous work without short rest breaks [1]. The most important change in performance reported by many authors in relation to fatigue is the deterioration of the organization of behavior [4,5]. But the ways of evaluating mental fatigue now are based on a subjective sensation rather than on an objective assessment of changes in psychophysiological state, and it does not allow for a clear discrimination between different levels of mental fatigue. Moreover, there is a poor association between physiological and more subjective measures of fatigue. Recent years, a variety of psychophysiological parameters have been used as indicators of mental fatigue, with EEG perhaps being the most promising [6]. It can reflect the electrical activity of the central neural system (CNS). Therefore, monitoring EEG may be a promising variable for use in fatigue countermeasure devices.

2 Material and Method

This study is conducted to provide some additional insights into mental fatigue and its underlying processes, tries to use a new approach of multichannel linear descriptors to analyze mental fatigue induced by sleep deprivation and prolonged time of work, and aims to investigate the relationship between different mental fatigue state and multichannel linear descriptors of EEG. Five subjects performed two different experiments. First, three subjects were chosen for 24-hour sleep-deprived mental fatigue experiment respectively to explore the relationship between different mental state and the corresponding average values of Ω, Φ and Σ, which can also be used to test whether the circadian rhythm and sleep affect the average values of Ω, Φ and Σ. Then three subjects participated in two mental fatigue states experiment to explore how the average values of Ω, Φ and Σ in related the prolonged time of work.

2.1 Experiments and Data

Five subjects were chosen for mental fatigue experiments. They were both male and right-handed college students. The work time periods of the college are a.m. 9:00~12:00 and p.m. 1:00~5:00. The electrodes were placed at Fp1, Fp2 and Fz reference to the 10-20 system. The impedances of all electrodes were kept below

5KΩ. The reference electrode was pasted to the skin just above the tuber of the clavicle at the right bottom of the Adam's apple. The experimental environment kept quiet and the temperature was around 20 °C. Subjects were seated in a comfortable chair throughout the experiment. They were asked to simply relax and try to think of nothing in particular. The data were recorded using a PL-EEG Wavepoint system and were sampled at about 6 ms' interval. In order to investigate the relationship between three multichannel linear descriptors and mental fatigue, two mental fatigue experiments were designed as follows:

Experiment 1: Mental Fatigue Experiment under 24-hour Sleep-deprived States. This experiment was carried out by two subjects. The light was on during the experiment. Subjects were sleep deprived from a.m. 11:00 to next day for 24 hours. The first EEG data segment was recorded at a.m. 11:00 while subjects felt wide wake and alert which was denoted state 1-1. The second EEG data segment was recorded at a.m. 11:00 of the next day while subjects felt a little sleepy and fatigue which was denoted state 1-2. The recording duration of each state was about 5 minutes and the subjects' eyes were closed.

Experiment 2: Two Mental Fatigue States Experiment. To explore the relationship between the mental fatigue and three multichannel linear descriptors of EEG and to avoid the physiological accommodation of the circadian rhythm and the sleep influences on mental fatigue, two mental fatigue states experiment was designed. In this experiment, all three subjects were concentrating on reading for a whole afternoon and were required to take notes while reading. The first EEG data segment was recorded at p.m. 4:00 for five minutes while subjects felt a little tired which was denoted state 2-1. The second EEG data segment was recorded at p.m. 5:00 for five minutes while subjects felt very tired which was denoted state 2-2. The light was off and subjects' eyes were closed when EEG data were recorded.

2.2 Multichannel Linear Descriptors

Wackermann proposed a $\sum - \phi - \Omega$ system for describing the comprehensive global brain macrostate [7,8]. Let us consider N EEG samples in the observed time window at K electrodes to construct the voltage vectors $\{u_1, \cdots u_N\}$, where each $u_i (i = 1, \cdots N)$ corresponds to the state vector representing the spatial distribution of EEG voltage over the scalp at the ith sample. The data are assumed to have been already centered to zero mean and transformed to the average reference. Then Ω, Φ and Σ can be calculated as follows [7,8,9]:

$$m_0 = \frac{1}{N} \sum_i \|u_i\|^2 . \tag{1}$$

$$m_1 = \frac{1}{N} \sum_i \left\| \frac{\Delta u_i}{\Delta t} \right\|^2 , where\, \Delta u_i = u_i - u_{i-1} . \tag{2}$$

$$\Sigma = \sqrt{m_0 / K} \tag{3}$$

$$\phi = \frac{1}{2\pi}\sqrt{\frac{m_1}{m_0}} \tag{4}$$

The covariance matrix is constructed as:

$$C = \frac{1}{N}\sum_n u_n u_n^T \ . \tag{5}$$

The eigenvalues $\lambda_1 \cdots \lambda_K$ of matrix C is calculated, then Ω complexity can be obtained:

$$\log\Omega = -\sum_i \lambda_i^{'} \log \lambda_i^{'} \ . \tag{6}$$

where $\lambda_i^{'}$ is the normalized eigenvalue.

In the $\Sigma - \phi - \Omega$ system, K-dimensional voltage vectors constructed from the simultaneous EEG measurements over K electrodes with time varying are regarded as the trajectories in the K-dimensional state space. By the three linear descriptors, the physical properties of the EEG trajectory and then the brain macrostates are characterized. Φ reflects mean frequency of the corresponding field changes; Ω measures the spatial complexity of the regional brain region, which decomposes the multichannel EEG data into spatial principal components and then quantifies the degree of synchrony between the distributed EEG by the extension along the principal axes;. Larger value of Ω corresponds to the low synchrony. It can be seen that by EEG over the K electrodes the three linear descriptors describe the different brain macorstate features of the interested brain regions.

2.2 Analysis of the Mental Fatigue EEG

In order to get the data of spontaneous EEG signals, a FIR filter with bandpass 0.5-30 Hz was used. And the three-channel EEG data over Fp1, Fp2 and Fz were centered to zero mean value and transformed to the average reference. To eliminate the effect of EEG signal power on Ω complexity, the data were normalized by mean power of each channel before calculating Ω complexity. Then Ω, Φ and Σ were calculated separately for electrode arrays (Fp1, Fz) and (Fp2, Fz). Ω complexity quantifies the amount of spatial synchrony so that it reflects the degree of synchronization of two spatially distributed brain processes over the contralateral, ipsilateral and mid-central regions respectively; Σ reflects the corresponding regional field power; Φ characterize the speed of regional field changes of the contralateral, ipsilateral and mid-central regions respectively.

One minute EEG data of each trial in different mental fatigue state are selected to be analyzed. To obtain the time courses of Ω, Φ and Σ, the first 1000 sample segment is chosen as basic data segment and 17 samples (0.1s) as step length. By shifting the

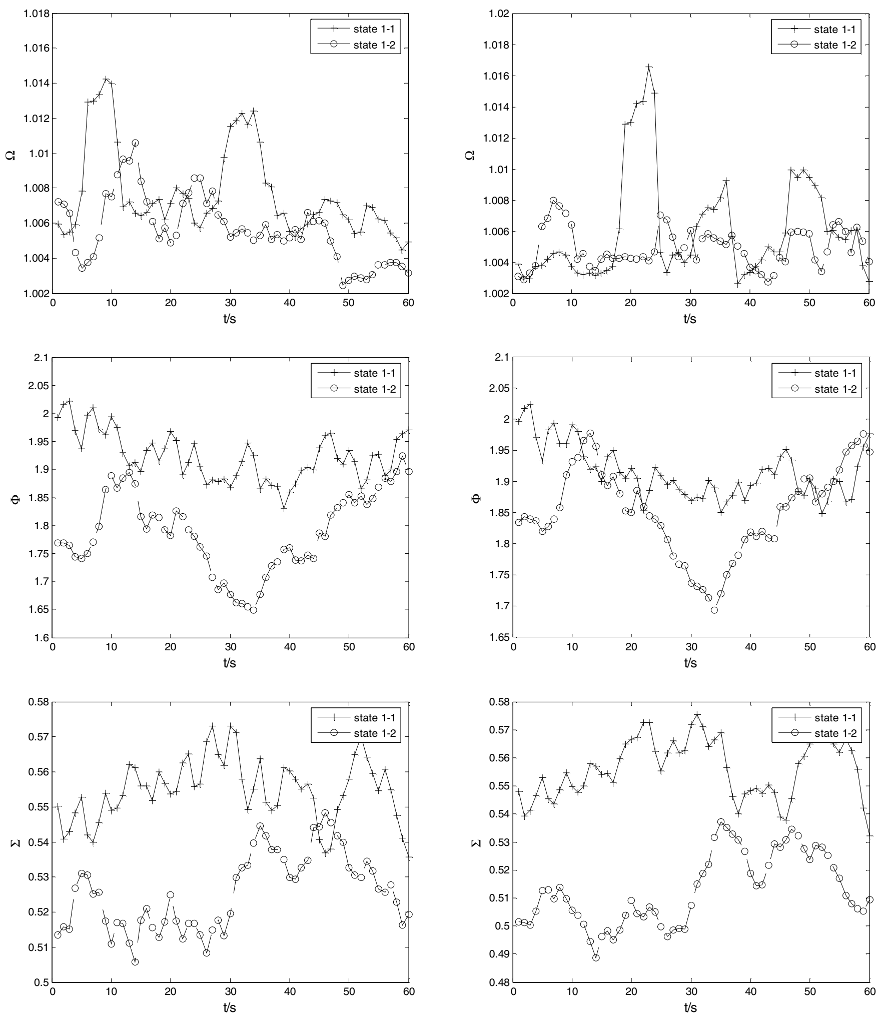

Fig. 1. The time courses of Ω, Φ and Σ between Fp1 and Fz, Fp2 and Fz under 24-hours sleep-deprived states (Experiment 1), the first EEG data segment was recorded at a.m. 11:00 while subjects felt wide wake and alert which was denoted state 1-1, and the second EEG data segment was recorded at a.m. 11:00 of the next day while subjects felt a little sleepy and fatigue which was denoted state 1-2.

basic data segment with step length from the start to the end of the trial, calculating Ω, Φ and Σ across all the trials for each segment. To eliminate the influences of Ω, Φ and Σ's fluctuation, the mean value within a second is calculated. So the time courses of Ω, Φ and Σ are obtained.

Alterations in the person's state of mind are associated with physiological alterations at the neuronal level and sometimes also at the regional brain level [10]. Functionally, central neural system circuitry is complex, consisting of a number of afferent connections, efferent connections and loop ('feedback') connections [11].

Two distinct loops, a motor loop and an association or complex loop, connect basal ganglia with neocortex [12]. The association or complex loop connected caudate with inputs from the cortical association areas and the final output from basal ganglia is projected to the prefrontal cortex. Recent findings have provided considerable evidence that cortex, basal ganglia and thalamus are all linked by the re-entrant circuits [13]. So prefrontal cortex has close connection with mental fatigue, and Ω, Φ and Σ calculated from EEG data of prefrontal cortex in different mental fatigue states can yield information which reveals short time changes due to mental fatigue.

3 Results

For each mental fatigue state of subject 1, the continuous mean values of Ω, Φ and Σ between Fp1 and Fz, Fp2 and Fz for one minute EEG data are calculated. The analysis results of 24-hour sleep-deprived states are given in figure 1. For subject 2, the time courses of Ω, Φ and Σ are similar to those of subject 1.

The independent-samples t test is used to analyze the mean values of Ω, Φ and Σ which achieved in state 1-1 and state 1-2. The results of statistical analysis suggest that the average values of Ω, Φ and Σ for every subject under two different sleep-deprived states have significant differences in general. The results of mean comparison after 24-hour sleep deprivation are shown in table 1.

Table 1. T test of mean comparison under 24-hour sleep-deprived states (mean ± s.d., $n = 60$)

			Ω	Φ	Σ
subject 1	(Fp1, Fz)	state 1-1	1.0077±.0026	1.9237±.0437	.5547±.0090
		state 1-2	1.0057±.0019**	1.7879±.0709**	.5257±.0109**
	(Fp2, Fz)	state 1-1	1.0061±.0034	1.9167±.0425	.5561±.0106
		state 1-2	1.0049±.0013*	1.8519±.0718**	.01274±.0016**
subject 2	(Fp1, Fz)	state 1-1	1.0319±.0401	1.7501±.0770	.5333±.0362
		state 1-2	1.0060±.0023**	1.4679±.2011**	.4732±.0135**
	(Fp2, Fz)	state 1-1	1.0342±.0503	1.7248±.0934	.5404±.0402
		state 1-2	1.0058±.0018**	1.4213±.2041**	.4764±.0182**

We calculated respectively how significantly the average of differences between the mean values of Ω, Φ and Σ for every subject under two different sleep-deprived states using the t-test. The significance measures are shown in boxes. *P<0.05, **P<0.01, significantly different from the value at state 1-1.

From figure 1 and table 1, it can also be seen that there is a large decrease in the average values of Ω, Φ and Σ under state 1-2 (a.m. 11:00—a.m. 11:05 in the first day) compared to that under state 1-1 (a.m. 11:00—a.m. 11:05 in the next day) not only between Fp1 and Fz but also between Fp2 and Fz. It may means that the influence of sleep loss on mental fatigue is very important and the average values of Ω, Φ and Σ decrease with the prolonging of sleep-deprived time.

For each different mental fatigue state of three subjects under experiment 2, the continuous mean values of Ω, Φ and Σ between Fp1 and Fz, Fp2 and Fz for one

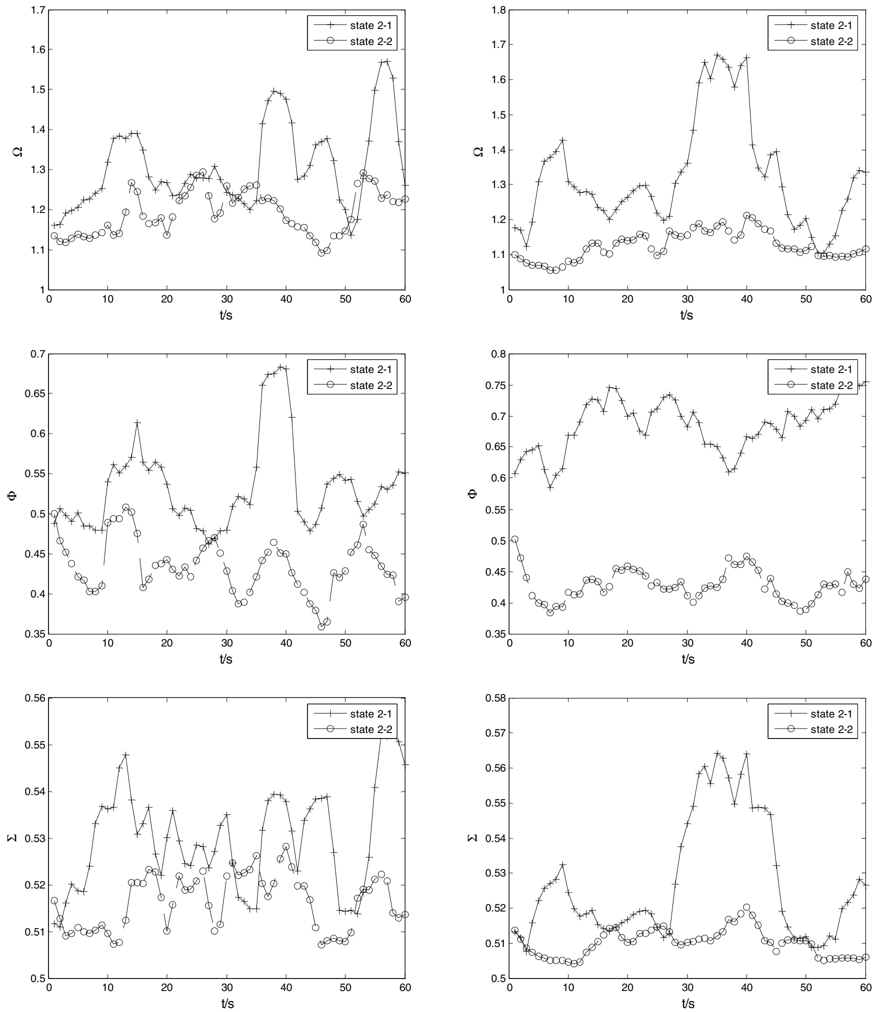

Fig. 2. The time courses of Ω, Φ and Σ between Fp1 and Fz, Fp2 and Fz under two mental fatigue experiment (Experiment 2), the first EEG data segment was recorded at p.m. 4:00 while subjects felt a little tired which was denoted as state 2-1, and the second EEG data segment was recorded at p.m. 5:00 while subjects felt very tired which was denoted as state 2-2.

minute EEG data are calculated. The analysis results are given in figure 2. The time courses of Ω, Φ and Σ for the other two subjects are similar to those of subject 3.

The independent-samples t test is used to analyze the mean values of Ω, Φ and Σ which achieved in state 2-1 and state 2-2. The results of statistical analysis suggest that Ω, Φ and Σ of every subject under two mental fatigue states have significant differences. The results of mean comparison under two mental fatigue states are shown in table 2.

Table 2. T test of mean comparison under two mental fatigue states（ mean ± s.d., $n = 60$ ）

			Ω	Φ	Σ
subject 3	(Fp1, Fz)	state 2-1	1.3090±.1054	.5329±.0548	.5300±.0111
		state 2-2	1.1913±.0554**	.4345±.0342**	.5163±.0059**
	(Fp2, Fz)	state 2-1	1.3221±.1544	.6853±.0431	.5273±.0172
		state 2-2	1.1247±.0399**	.4279±.0248**	.5101±.0039**
subject 4	(Fp1, Fz)	state 2-1	1.2702±.0975	.8993±.0761	.5281±.0106
		state 2-2	1.1975±.1002**	.4307±.0471**	.5144±.0086**
	(Fp2, Fz)	state 2-1	1.2120±.0781	.9201±.0877	.5202±.0096
		state 2-2	1.1029±.0864**	.2915±.0425**	.5160±.0082*
subject 5	(Fp1, Fz)	state 2-1	1.2945±.1095	.9580±.3892	.5379±.0114
		state 2-2	1.2563±.0814*	.4181±.0353**	.5239±.0104**
	(Fp2, Fz)	state 2-1	1.2970±.0948	.8661±.3281	.5436±.0093
		state 2-2	1.1898±.0444**	.3594±.0232**	.5291±.0113**

We calculated respectively how significantly the average of differences between the mean values of Ω, Φ and Σ for every subject under two mental fatigue states using the t-test. The significance measures are shown in boxes. *P<0.05, **P<0.01, significantly different from the value at state 2-1.

From figure 2 and table 2, it can be seen that there are obvious differences for the values of Ω, Φ and Σ between state 2-1(p.m. 4:00—p.m. 4:05) and state 2-2(p.m. 5:00—p.m. 5:05).That is, the values of Ω, Φ and Σ and the mental fatigue state are correlative. Furthermore, the values of Ω, Φ and Σ under state 2-1(p.m. 4:00—p.m. 4:05) are larger than that under state 2-2(p.m. 5:00—p.m. 5:05). It indicates that the values of Ω, Φ and Σ increase with work time prolonging. The average values of Ω, Φ and Σ between Fp1 and Fz, Fp2 and Fz, strongly correlated with the level of mental fatigue.

4 Discussion

Ω complexity measures the spatial complexity of regional brain region and indicates the degree of synchronization between functional processes spatially distributed over different brain regions; Φ reflects mean frequency of the corresponding field changes; Σ describes the field strength of the regional brain region. When mental fatigue level increases, the brain neurons are restrained, this results in the increase of synchrony between the distributed EEG. Meanwhile, the frequency of the corresponding field changes and field strength of the regional brain region reduce.

In all current experiments, the average values of Ω, Φ and Σ between two channels Fp1 and Fz, Fp2 and Fz, are correlated with the mental fatigue state. The experiments show that the average values of Ω, Φ and Σ of EEG decrease with the prolonging of sleep-deprived time or work time. Moreover, the prolonged time of work and sleep deprivation have a greater effect on mental fatigue, and they induce the state of mental fatigue. So the average values of Ω, Φ and Σ between two channels FP1 and Fz, Fp2 and Fz, increase with the intensifying of mental fatigue level in two mental fatigue experiments. This fact may suggest that there are stronger independent, parallel, functional processes active between the two regions, which is just strongly correlative with the level of mental fatigue. This result is also consistent with the findings of Szelenberger et al (Szelenberger, 1996) which found highly significant overall effect, with Ω complexity progressively decreasing in the sequence of sleep stages [8,14].

In sum, mental fatigue is likely to be an integrated phenomenon with complex interaction among central and peripheral factors, physiological and psychological factors, and so on. All factors appear to mutually influence each other. In two mental fatigue experiments it is proved that the multichannel linear descriptors of EEG are strongly correlative with the mental fatigue state. This method may be useful in further research and is able to evaluate mental fatigue level objectively.

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