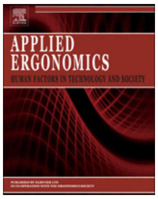
Applied Ergonomics 42 (2010) 114–121

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo



Estimation of the cortical functional connectivity by directed transfer function during mental fatigue

Jian-Ping Liu [a], Chong Zhang [b,*], Chong-Xun Zheng [b]

[a] *Department of Communication Engineering, The Engineering College of the Armed Police Force, 710086 Xi'an, PR China*
[b] *Key Laboratory of Biomedical Information Engineering of Education Ministry, Xi'an Jiaotong University, 710049 Xi'an, PR China*

ARTICLE INFO

Article history:
Received 29 March 2008
Accepted 20 May 2010

Keywords:
Mental fatigue
Electroencephalogram (EEG)
Directed transfer function (DTF)

ABSTRACT

In this paper, the directed transfer function (DTF) method is used to characterize changes in the functional coupling of EEG rhythms in different brain cortical areas due to the mental fatigue caused by long-term cognitive tasks. There is a parietal-to-frontal functional coupling of the total (0.5–30 Hz) EEG frequency band in the right and middle brain cortical areas during the pre-task period, and an inversion of that direction, even a significant prevalence of the frontal-to-parietal direction, after the completion of the task. When mental fatigue levels increase, the parietal-to-frontal functional coupling of the alpha (8–12 Hz) frequency band is weakened, and the beta (13–30 Hz) frequency band changes from a balanced directionality of the functional cortical coupling to frontal-to-parietal functional coupling, whereas the frontal-to-center functional coupling of the total frequency band is enhanced in the right hemisphere, and the frontal-to-center functional coupling of the beta frequency band is heightened in the left hemisphere. Meanwhile, in the central cortical area, the middle-to-left functional coupling of the total, beta and alpha frequency bands increases significantly and the middle-to-right functional coupling of the total and beta frequency bands increases significantly after the task as compared to the pre-task period. These findings suggest that the functional coupling of the frontal, central and parietal brain cortical areas is strongly correlated with a change in mental fatigue levels in the wake–fatigue transition. The experimental results indicate that the DTF method can effectively explore the change of the direction and strength of the information flow underlying cortical-to-cortical functional coupling when mental fatigue is increased by long-term cognitive work. The DTF method may open a promising way to study mental fatigue.

1. Introduction

Mental fatigue usually refers to the effects that people may experience after or during prolonged periods of cognitive activity (Boksem et al., 2005). In this study we define mental fatigue as a change in psychophysiological state due to sustained performance (Desmond and Hancock, 2001; Job and Dalziel, 2001). It is usually accompanied by a sense of weariness, reduced alertness and reduced mental performance, which may lead to accidents, decreased productivity, and even adverse health effects. When people become fatigued, they usually experience difficulties maintaining task performance at an adequate level (Boksem et al., 2005). Mental fatigue is a common physiological phenomenon which may be inevitable for office workers in general and affects different aspects of an individual's quality of life. In industry, many incidents and accidents are related to mental fatigue as the result of sustained performance (Baker et al., 1994). Therefore, the management of fatigue is very important not only for enhancing productivity, but also for protecting occupational health.

To date, many methods have been proposed to estimate mental fatigue. A large number of previous studies use behavioural indices or subjective measures such as reaction time, error ratio or subjective scales (Ku and Smith, 2010). A recent tendency in ergonomic research is to choose more objective measures to assess the mental fatigue state (Hockey et al., 2009; Miyake et al., 2009). These approaches focus on measuring physiological changes of people, such as the electrooculogram (EOG), respiratory signals, heart beat rate, skin electric potential, and particularly electroencephalographic (EEG) activities as a means of detecting mental fatigue states (Egelund, 1982; Li et al., 2003). Although numerous physiological indicators are available to describe an individual's mental fatigue state, the EEG signals may be the most promising, predictive and reliable one (Lal and Craig, 2001). The EEG is widely

---

[*] Corresponding author. Tel.: +86 29 82669055; fax: +86 29 83237910.
E-mail addresses: xlyu.czhang@gmail.com, yuxiaolinzhang@gmail.com (C. Zhang), cxzheng@mail.xjtu.edu.cn (C.-X. Zheng).

0003-6870/$ – see front matter Crown Copyright © 2010 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.apergo.2010.05.008

regarded as the physiological “gold standard” for the assessment of mental fatigue. There have been several EEG studies related to mental fatigue in the past. Some studies investigated the change of EEG activity with the decline of alertness level based on amplitudes or spectral power in given frequency bands (Klimesch, 1999; Eoh et al., 2005). Other studies explored the links between fatigue and changes in event-related potential (ERP) components (Boksem et al., 2005; Murata et al., 2005). Shen et al. tested an EEG-based mental–fatigue monitoring system using a probabilistic-based support vector-machines method (Shen et al., 2008). Moreover, they presented two feature selection approaches for multilevel mental fatigue electroencephalogram (EEG) classification, in which random forest is combined with the heuristic initial feature ranking scheme or the recursive feature elimination scheme (Shen et al., 2007). While these methods represent the spatial distribution of EEG activity, they do not make full use of the information available in the multivariate data structure. Specifically, they neglect information on cross-channel covariance. This information is essential for understanding the mutual relationships between brain sites when conditions change. Investigation of the cortical network's mutual relationships is usually carried out by correlation and coherence measures (Bressler and Kelso, 2001) or phase synchronization measures (Varela et al., 2001) of the EEG data. These measures describe the strengths of interactions between neurons. But these measures cannot reflect the direction of the information flow within the functional coupling of EEG rhythms at paired brain sites. In order to overcome the limits of these approaches, a multivariate spectral measurement called directed transfer function (DTF) was proposed by Kaminski and Blinowska (1991) and used to determine the directional influences between any given pair of channels in a multivariate data set. This is an estimator characterizing at the same time direction and spectral properties of the brain signals, and requires only one multivariate autoregressive (Mvar) model which is estimated from all the EEG channel recordings.

The brain, as a highly complex system, can be considered at various hierarchical levels. In this study, the direction of information flux within EEG functional coupling at electrode pairs between hemispheres and between anterior and posterior cortical areas is assessed by the DTF method during the mental fatigue process, when levels of mental fatigue are heightened by long-term cognitive work. Compared with previous studies, the research presented in this study provides a thorough exploration of the organization and the interaction of several cortical areas during the mental fatigue process.

2. Materials and methods

2.1. Participants

Fifty male graduate students, between 20 and 27 years old ($M = 23.0$ years, SD = 1.6), participated in this study. Personal data (handedness, past medical history, medical family history, etc.) were acquired with a standardized interview before EEG recordings. All participants were in good health. None of them reported on any cardiovascular disease or neurological disorders in the past or had taken any drugs known to affect the EEG. Participants did not work night shifts and had normal sleep time. All of them were accustomed to using the computer mouse and agreed to join the study.

2.2. Experiment and data acquisition

The experimental tasks were three types of simple cognitive tasks. The first type of task was a vigilance task. Three random numbers were displayed at the same time on the CRT screen and changed randomly once every second. The participants were asked to click the right mouse button promptly, as three different odd numbers, such as 1, 7, 9, appeared. Sixteen participants participated in this experiment. The second type of task was the addition and subtraction arithmetic calculation of four one-digit numbers. They were continuously displayed on a computer monitor until the participant responded. The participants solved the problems first, and then decided whether the result was less than, equal to, or greater than the target sum provided. Sixteen participants took part in this experiment. The third type of task was a simple switch task. A white square, subdivided into four subsquares, was displayed at the screen center. Stimulus images were presented in turn, and the image started from the upper left subsquare and moved clockwise. The stimulus images were numbered from zero to nine randomly. The stimulus images were randomly numbered from zero to nine. The color of the stimulus images was randomly red or blue. The subjects were to push the left or right mouse button, respectively related to the image color, when the stimulus image appeared in either of two upper subsquares, or related to the odd or even number identity if the stimulus appeared in either of two lower subsquares. Eighteen participants took part in this experiment. All subjects performed the cognitive task until they either stopped due to exhaustion or 2 h elapsed. The response time and the number of error trials, if any, were recorded.

Participants were required to abstain from alcohol and caffeine-containing substances 24 h before the experiment. Participants were told the study was aimed at investigating the neural correlates of cognitive control; they were unaware the study was about mental fatigue. To avoid the influence of circadian fluctuations on participants, experimental sessions were scheduled at the same time each day. The experimental session started about 8:00 a.m., and no clock or watches were permitted in the laboratory. Subjects had no knowledge about experimental duration. Participants were seated in a dimly lit, sound-attenuated, electrically shielded room. Before starting the experiment, the participants completed a brief demographic questionnaire (age, handedness, hours of sleep, etc.), and ensured that the instructions were understood. First, the psychological self-report measures of sleepiness and fatigue were conducted. Subjective sleepiness was assessed by means of the Stanford Sleepiness Scale and the Karolinska sleepiness scale, and subjective fatigue was measured with the help of the Samn–Perelli checklist, Li's subjective fatigue scale and Borg's CR-10 scale (Li et al., 2003; Hoddes et al., 1973; Akerstedt and Gillberg, 1990; Samn and Perelli, 1982; Borg, 1998). Subsequently, the subjects were required to simply relax and try to think of nothing in particular, and the EEG was recorded in the eyes-closed resting state for 5 min before starting the experimental session. They then performed the cognitive task either until 2 h elapsed or until volitional exhaustion occurred. Participants were instructed to respond as quickly as possible, maintaining a high level of accuracy. A similar EEG recording was conducted immediately after the completion of the cognitive task. The same psychological rating was also carried out. The measurements were carried out at two epochs: pre-task, that was before task; post-task, that was immediately after task. The difference between psychophysiological index pre- and post-task is analyzed with a paired-samples T test.

EEGs were recorded by a Neuroscan 32 channel system (Neuroscan, El Paso, TX, USA) with international 10–20 lead systems. Fp2, Fp1, F4, F3, A2, A1, C4, C3, P4, P3, Fz, Cz and Pz leads were used with Ag/AgCl electrodes. Recordings were referenced to linked-mastoids. Two additional bipolar pairs of electrodes were placed to record horizontal and vertical EOG. Skin impedance was below 5 kΩ on all electrodes. Physiological signals were filtered by band pass filter with bandwidth from 0.01 to 100 Hz. The signal was sampled at 250 Hz and digitized at 16 bit. Eye movement contamination was removed by adaptive filtering methods.