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Mental Fatigue Measurement Using EEG

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1. Introduction

1.1 Background

We live in a highly technological and information-oriented society. The use of computers in modern society is omnipresent. They are used for innumerable applications in various sizes and forms. Over the past 20 years, the personal computer has become widely used, both in the office and at home. People use computers to write documents, maintain databases, manage finances, draw diagrams and graphics, make presentations, compile mailing lists, search computer databases, write application programs, use the Internet, and myriad other tasks. Since such work requires prolonged vigilance and mental activity with sedentary work, fatigue caused from visual display terminal(VDT) tasks frequently occurs in the workplace.

Fatigue is a major, but usually neglected, factor that increases the occurrence of performance errors and lapses. Fatigue, especially mental fatigue, is inevitable for office workers and in life in general. Fatigue is usually related to a loss of efficiency and disinclination to effort. It is also possible that cumulative mental fatigue leads to decreased productivity in the workplace and induces critical errors in the worst cases. Many experimental studies have demonstrated that mental fatigue induces deterioration in cognitive functions. Responses become slower, more variable, and more error prone after mental fatigue (Scheffers et al., 1999; Dorrian et al., 2000; Smith et al., 2002). The importance of adequate fatigue monitoring could be demonstrated by the Exxon Valdez oil tanker accident. The direct cause of this, America's worst oil spill, was a human performance error, which had been observed and cautioned about before; however, the warning had arrived too late in order to remedy the situation because the severely fatigued mate did not immediately respond to the warning (Dement and Vaughan, 1999). Deficits in perceptual processes after extended wakefulness are responsible for performance deficits.

Mental fatigue refers to the effects that people may experience after or during prolonged periods of cognitive activity. In this sense, it is a very common phenomenon in everyday modern life. Therefore, the management of mental fatigue is important from the viewpoint of occupational risk management, productivity, and occupational health.

1.2 Motivation

Until now, very little has been known about the psychophysiological mechanisms underlying mental fatigue. Here, this study was in an attempt to gain more insight in the

mechanisms that are central to mental fatigue and in arousal level and the cognitive functions that are most affected by mental fatigue. The assessment of mental fatigue should be conducted based on physiological evidences using both arousal level from EEG (Okogbaa et al., 1994) and cognitive information processing from ERP (Murata et al., 2005). These measures would provide reliable and effective evaluation of mental fatigue.

1.3 The objectives of this study

This study aimed to assess mental fatigue by using electroencephalographic measures and response tests in visual display terminal (VDT) tasks. The experimental design used by Murata et al. (2005) was adopted herein to evaluate mental fatigue using ERP. The combination of indices based on arousal level (EEG) and cognitive information processing (ERP) were employed to evaluate mental fatigue in this study. The objects of this study were included as following:

1. To explore the arousal level and cognitive function for mental fatigue in VDT tasks by using electroencephalographic measures.
2. To compare the behavior response (RT, ER) and physiological response (EEG, ERP) to mental fatigue in VDT tasks.
3. To examine the recovery state from mental fatigue after 180 min experimental tasks with 60 min period of rest.

2. EEG and ERP

2.1 Cerebrum

The cerebrum is the part of the brain that most people think of when the term brain is mentioned. Anatomically, the brain can be divided into three parts: the forebrain, midbrain, and hindbrain; the forebrain includes the several lobes of the cerebral cortex that control higher functions. The cerebrum has two cerebral hemispheres. A cerebral hemisphere (hemispherium cerebrale) is defined as one of the two regions of the brain that are delineated by the body's median plane. The brain can thus be described as being divided into left and right cerebral hemispheres. The cerebral cortex includes the frontal, temporal, occipital, and parietal lobes and the central sulcus (as depicted in Figure 2.1). The frontal lobes are positioned in front of (anterior to) the parietal lobes. The temporal lobes are located beneath and behind the frontal lobes. The occipital lobes located in the rearmost portion of the skull and behind the parietal lobes are the smallest of four true lobes in the human brain. The central sulcus separates the parietal lobe from the frontal lobe (Seeley et al., 2003).

1. The frontal lobe

The frontal lobe is an area in the brain of mammals located at the front of each cerebral hemisphere. In the human brain, the precentral gyrus and the related cortical tissue that folds into the central sulcus comprise the primary motor cortex, which controls voluntary movements of specific body parts associated with areas of the gyrus. The frontal lobes have been found to play a part in impulse control, judgment, language production, working memory, motor function, problem solving, sexual behavior, socialization, and spontaneity. The frontal lobes assist in planning, coordinating, controlling, and executing behavior. The so-called executive functions of the frontal lobes involve the ability to recognize future consequences resulting from current actions, to choose between good and bad actions (or better and best), override and suppress unacceptable social responses, and determine similarities and differences between things or events.

2. The parietal lobe

The parietal lobe integrates sensory information from different modalities, particularly determining spatial locations of objects. For example, it comprises somatosensory cortex and the

dorsal stream of the visual system. This enables regions of the parietal cortex to map objects perceived visually into body coordinate positions. The parietal lobe plays important roles in integrating sensory information from various parts of the body, knowledge of numbers and their relations, and in the manipulation of objects. Portions of the parietal lobe are involved with visuospatial processing. Much less is known about this lobe than the other three in the cerebrum.

3. The temporal lobes

The temporal lobes are part of the cerebrum. They lie at the sides of the brain, beneath the lateral or Sylvian fissure. The temporal lobes are where the thumbs would be. The temporal lobe is involved in auditory processing and is home to the primary auditory cortex. It is also heavily involved in semantics both in speech and vision. The temporal lobe contains the hippocampus and is therefore involved in memory formation as well. The functions of the left temporal lobe are not limited to low-level perception but extend to comprehension, naming, verbal memory and other language functions.

4. The occipital lobe

The occipital lobe is the visual processing center of the mammalian brain, containing most of the anatomical region of the visual cortex. There are many extrastriate regions, and these are specialized for different visual tasks, such as visuospatial processing, color discrimination and motion perception. Retinal sensors convey stimuli through the optic tracts to the lateral geniculate bodies, where optic radiations continue to the visual cortex. Each visual cortex receives raw sensory information from the outside half of the retina on the same side of the head and from the inside half of the retina on the other side of the head.

5. Central sulcus

The central sulcus is a fold in the cerebral cortex of brains in vertebrates. Also called the central fissure, it was originally called the fissure of Rolando or the Rolandic fissure, after Luigi Rolando. The central sulcus is a prominent landmark of the brain, separating the parietal lobe from the frontal lobe and the primary motor cortex from the primary somatosensory cortex. Also included is the somatomotor system (complex and multifaceted) which controls the skeletal musculature. It interacts with primary sensory systems and the cerebellum, which also has important interactions with the sensory systems.

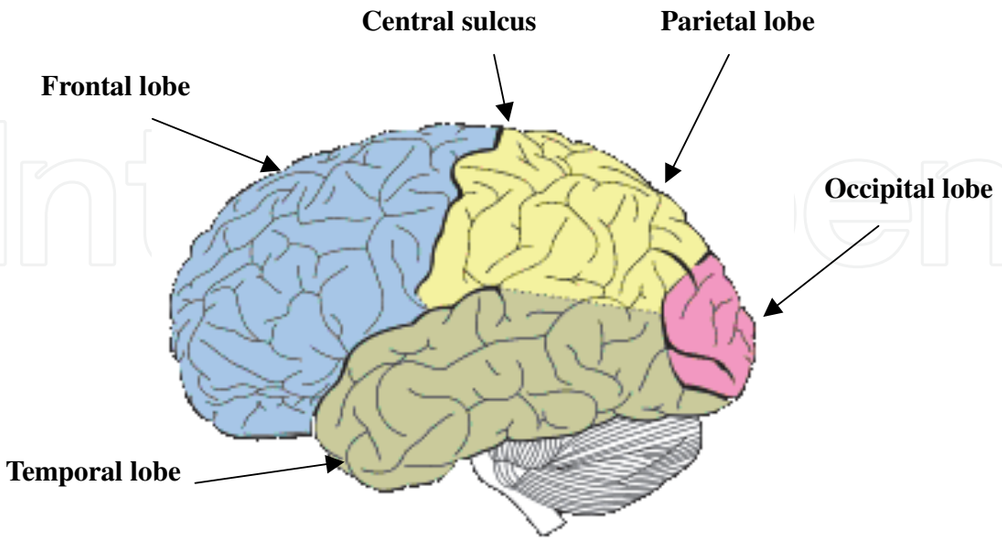


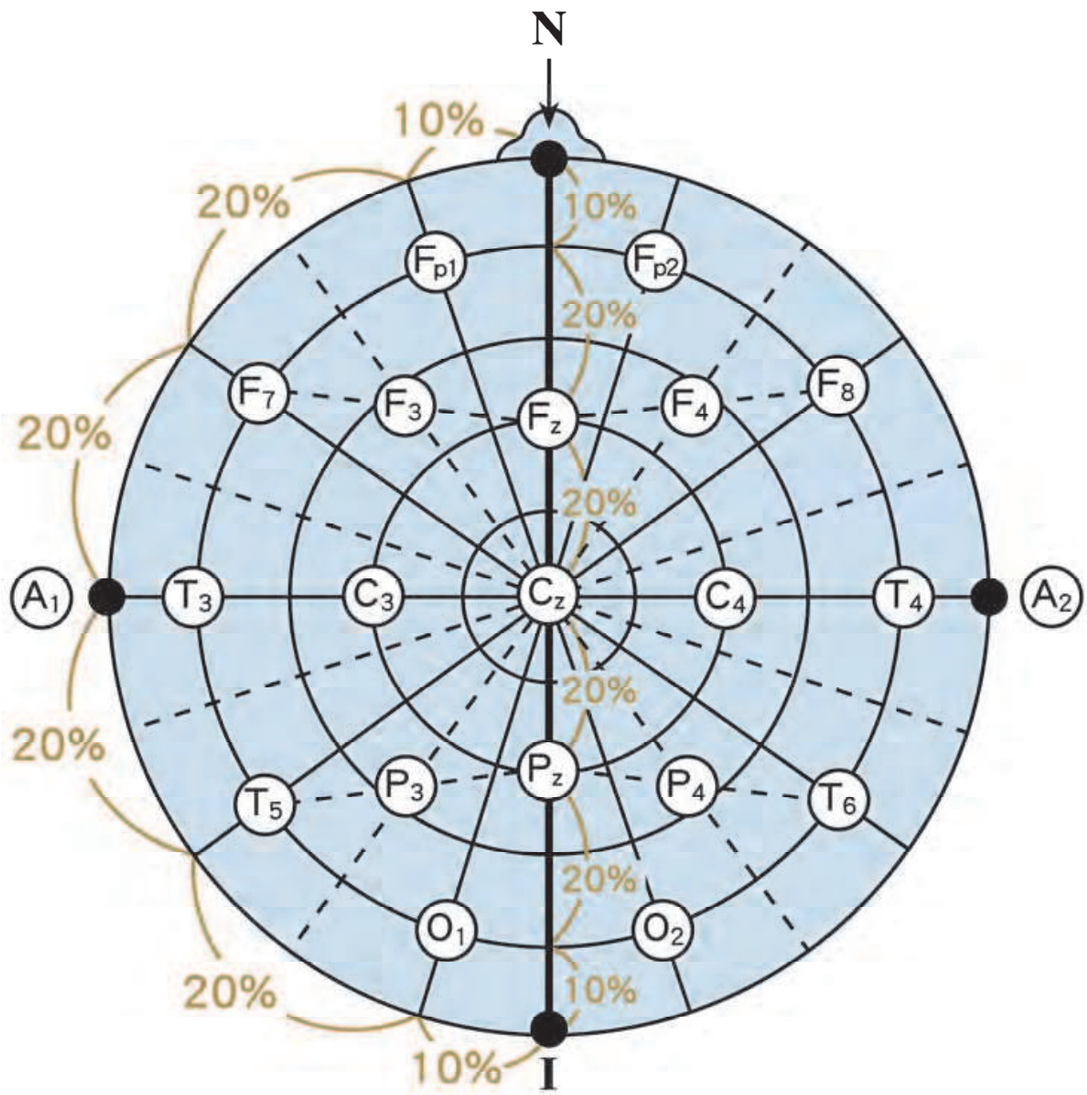
Fig. 2.1. The cerebral cortex include the frontal, temporal, occipital, parietal lobes and central sulcus.

2.2 EEG

Hans Berger (1873~1941), the discoverer of the human EEG, was a neuropsychiatrist. Electroencephalography is the neurophysiologic measurement of the electrical activity of the brain by recording from electrodes placed on the scalp or, in special cases, subdurally or in the cerebral cortex. Electrode placement is accomplished by measuring the scalp. Electrode locations and names are specified by the International 10–20 system, as depicted in Figure 2.2 (Andreassi, 2000). This system ensures a system of placement that is reliable and reproducible. The resulting traces are known as an electroencephalogram (EEG) and represent an electrical signal (postsynaptic potentials) from a large number of neurons. These are sometimes called brainwaves, though this use is discouraged (Cobb, 1983), because the brain does not broadcast electrical waves. The EEG is a brain function test, but in clinical use it is a "gross correlate of brain activity" (Ebersole, 2002). Electrical currents are not measured, but rather voltage differences between different parts of the brain. "EEGs" are frequently used in experimentation because the process is non-invasive to the research subject. The subject does not need to make a decision or behavioral action in order to log data, and it can detect covert responses to stimuli, such as reading. The EEG is capable of detecting changes in electrical activity in the brain on a millisecond-level.

Four major types of continuous rhythmic sinusoidal EEG activity are recognized (alpha, beta, delta and theta), as depicted in Figure 2.3 (Fisch, 1991). There is no precise agreement on the frequency ranges for each type. Delta is the frequency range up to 4 Hz and is often associated with the very young and certain encephalopathies and underlying lesions. It is seen in stage 3 and 4 sleep. Theta is the frequency range from 4 Hz to 8 Hz and is associated with drowsiness, childhood, adolescence and young adulthood. This EEG frequency can sometimes be produced by hyperventilation. Theta waves can be seen during hypnagogic states such as trances, hypnosis, deep day dreams, lucid dreaming and light sleep and the preconscious state just upon waking, and just before falling asleep. Alpha is the frequency range from 8 Hz to 13 Hz. It comes from the occipital (visual) and parietal cortex and is characteristic of a relaxed, alert state of consciousness. For alpha rhythms to arise, usually the eyes need to be closed. Alpha attenuates with extreme sleepiness or with open eyes and increased visual flow. Beta is the frequency range above 13 Hz. Low amplitude beta with multiple and varying frequencies is often associated with active, busy or anxious thinking and active concentration.

When people become fatigued, they usually report difficulties in concentrating and focusing their attention on the tasks they are required to perform (Boksem et al., 2005). Various aspects of EEG, including power distribution and event-related potential (ERP), have been employed to assess specific mental tasks, e.g. arousal level (Eoh et al., 2005; Waard and Brookhuis, 1991) and cognitive depth (Boksem et al., 2005; Murata et al., 2005). One of the common findings of EEG studies on a drop in arousal level is that the EEG shifts from fast and low amplitude waves to slow and high amplitude ones (Klimesch, 1999; Lafrance and Dumont, 2000). More specifically, under decreased alertness, there is a progressive increase in low-frequency alpha and theta activity (Klimesch, 1999; Lafrance and Dumont, 2000; Oken and Salinsky, 1992), probably reflecting a decrease in cortical activation (Cook et al., 1998; Laufs et al., 2003). Therefore, the amount of alpha and theta power provides an adequate index of the level of fatigue that subjects experience (Boksem et al., 2005).



F_p1, F_p2 : prefrontal
F3, F4 : frontal
C3, C4 : central
P3, P4 : parietal
O1, O2 : occipital
F7, F8 : anterior temporal
N : Nasion
I : Inion

T3, T4 : mid-temporal
T5, T6 : posterior temporal
A1, A2 : ear (or mastoid)
Fz : frontal midline
Cz : central vertex
Pz : parietal midline
(note: z = zero)

Fig. 2.2. International 10–20 system, electrode positions are determined by measurements from landmarks on the head.

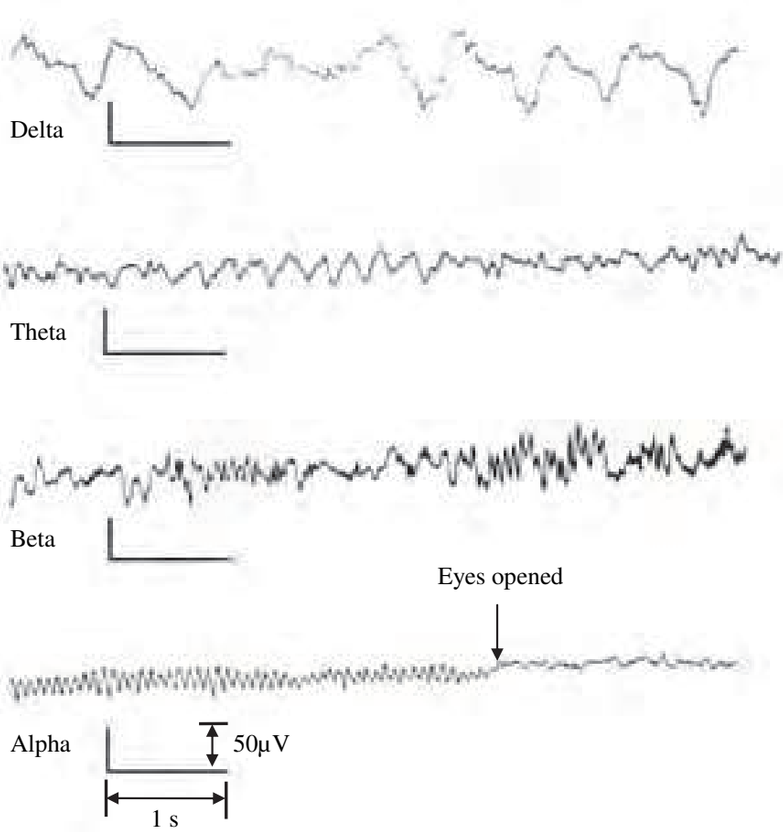


Fig. 2.3. Basic EEG waveform. First row: delta rhythm frequency at 0.5–4 Hz; second row: theta rhythm frequency at 4–8 Hz; third row: beta rhythm frequency at 13–20 Hz; fourth row: alpha rhythm frequency at 8–13 Hz.

2.3 ERP

The event-related potential (ERP) is a transient series of voltage oscillations in the brain recorded from scalp EEG following a discrete event. An ERP is a stereotyped electrophysiological response to an internal or external stimulus. More simply, it is a measured brain response as a result of a thought or perception. ERPs can be reliably measured using electroencephalography (EEG), a measure of brain electrical activity from the skull and scalp. As the EEG reflects thousands of simultaneously ongoing brain processes, the brain response to a specific stimulus or event of interest is usually masked with direct EEG measurement. One of the most robust features of the ERP response is a response to unpredictable stimuli. In actual recording situations, it is difficult to see an ERP after the presentation of a single stimulus. Rather, the ERPs become visible, when many dozens or hundreds of individual presentations are averaged together (as depicted in Figure 2.4). This technique cancels out noise in the data, and only the voltage response in relation to the stimulus is mathematically enhanced. While evoked potentials reflect the processing of the physical stimulus, event-related potentials are caused by the higher processes, that might involve memory, expectation, attention, or changes in the mental state, among others. Description of the scalp or surface cortical ERP distribution is the starting point for identifying the ERP generators, involving the topographic mapping of the ERP waveform

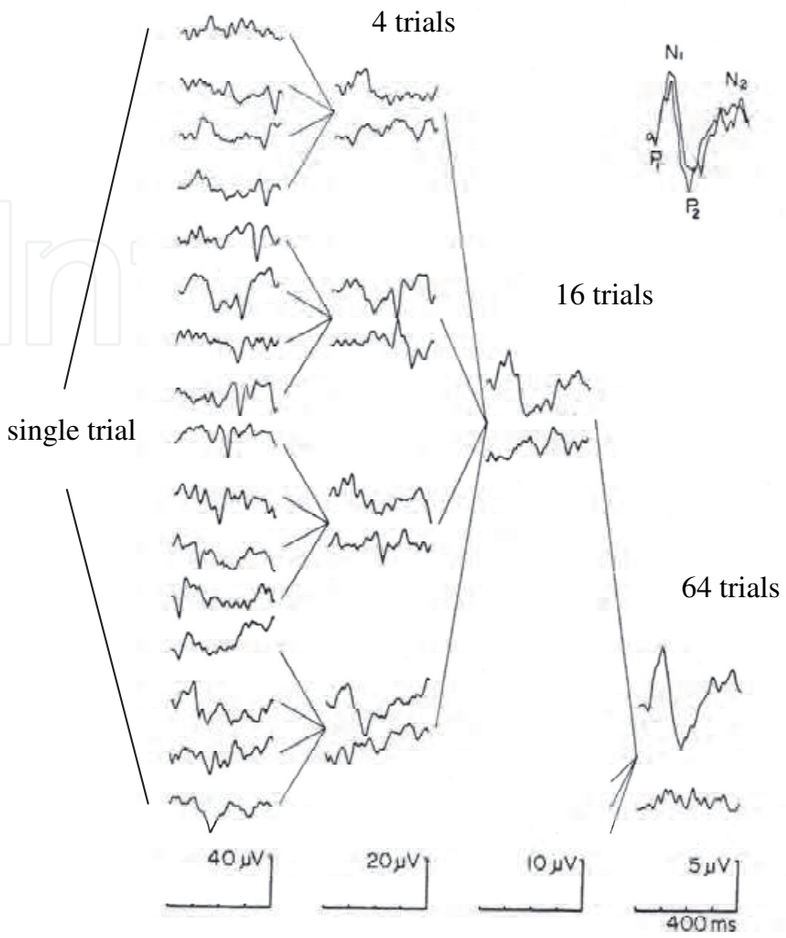


Fig. 2.4. Averaged waveform of ERP. Leftmost column: 16 single trial ERPs. Second column from left: average ERPs computed across 4 trials (upper waveform of each pair) and an estimate of the noise residual (lower waveform of each pair). Second column from right: average ERP computed across 16 trials (upper waveform) and noise residual (lower waveform). Rightmost column: average ERP computed across 64 trials and noise residual. (From Picton, 1980)

over time according to the International 10-20 system (Figure 2.2). It is often convenient as a first approximation to identify ERP peaks and troughs as positive or negative "components," as is the standard practice in the analysis of human scalp-recorded ERP (Picton, 1988; Niedermeyer et al., 1993). The ERP has been traditionally partitioned into a number of separate components. The most consistent finding is a modulation of the posterior P100 (peaking between 100 and 160 ms after stimulus presentation) and N100 (160–210 ms) components by attention (Eason, 1981; Rugg et al., 1987; Wijers et al., 1989a, b). When a particular location is attended, the exogenous P100 and N100 waves elicited by stimuli at that location are enlarged (Hillyard and Münte, 1984; Mangun and Hillyard, 1988, 1990), an effect that has been interpreted as a sign of attentional modulation of sensory processing in the visual pathways (Mangun et al., 1993). This has been viewed as a representation of a "sensory gain" mechanism (Hillyard et al., 1990): as a result of biasing

the information processing system, the responsivity to stimuli presented at attended locations is amplified, and further processing of these stimuli will therefore be enhanced. A later component, starting at approximately 200–250 ms post stimulus, consisting of negativity at central electrodes, with a maximum at Cz, has been labeled the N200 component. This ERP component has been found to reflect the further processing of relevant information (i.e. stimuli that require a response) (Lange et al., 1998; Okita et al., 1985; Wijers et al, 1989a, b). In the stimulus-locked ERP, the P300 was defined as the most positive peak in a window between 200 and 500 milliseconds. The latency of each ERP component was defined as the time between the onset of the arrow array and the time when the peak value appeared for stimulus-locked ERP. (Ullsperger et al., 1986, 1988). The P300 component is useful to identify the depth of cognitive information processing. It has been reported that the P300 amplitude elicited by mental task loading decreases with the increase in the perceptual/cognitive difficulty of the task (Donchin, 1979; Isreal et al., 1980a, b; Kramer et al., 1983, 1985; Mangun and Hillyard, 1987; Ullsperger et al., 1986, 1988). Thus, the P300 amplitude mainly reflects the depth or degree of cognitively processing the stimulus. In other words, it is highly related to the level of attention. In addition to magnitude aspect, the P300 latency was prolonged when the stimulus was cognitively difficult to process (Murata et al., 2005). Uetake and Murata (2000) reported that the P300 amplitude and latency could be employed to assess mental fatigue induced during a VDT task. They indicated that the P300 latency was prolonged and the P300 amplitude decreased with cumulative mental fatigue.

3. Methods

3.1 Subjects

Twenty-three university male students with a mean age 22.0 ± 1.3 years participated as volunteer subjects. They had normal hearing and normal or corrected-to-normal vision (via medical tests). Each participant met all the inclusion criteria: no medical, psychiatric, or head injury, and not using any medications or drugs. However, three participants were terminated by the experimenter due to excessive movement artifacts in the EEG during the test. Thus, complete data sets were collected from twenty participants who were right handed by self-report. An informed written consent form was obtained from all the participants after the procedure of the study was explained and the laboratory facilities were introduced to them. They were paid for their participation in the study.

3.2 Experimental procedures

The participants were instructed to avoid alcohol and caffeine in the 24 hours before the test. On the test day, the experimental task started at 8 AM. Participants performed the task alone in a dimly lit, sound-attenuated, electrically shielded test room. The experiment task was clearly explained first, and participants were allowed to practice until they felt familiar with it. The subject was required to record the EEG and measure the ERPs before starting the experimental session. The EEG was measured at rest condition for five min, and then a modified Eriksen flanker task was performed (Eriksen and Eriksen, 1974) under the experimenter's instruction.

After the measurement of the ERPs was finished, the subject conducted an experimental task for 180 min. The experimental task was to mentally add two three-digit numbers that were displayed on the LCD and enter the answer using a keyboard for 30 min. There was no time constraint for the mental addition trial and the task was self-paced. The task was

programmed on a personal computer using C language. The illumination on the LCD was about 300 lx. The viewing distance was about 80 cm. The response time and the error trial, if any, were recorded on a hard disk data file. After mental arithmetic, the subjects performed data entry for 2 h, and then underwent mental arithmetic for 30 min. The experimental procedure is shown in Figure 3.1.

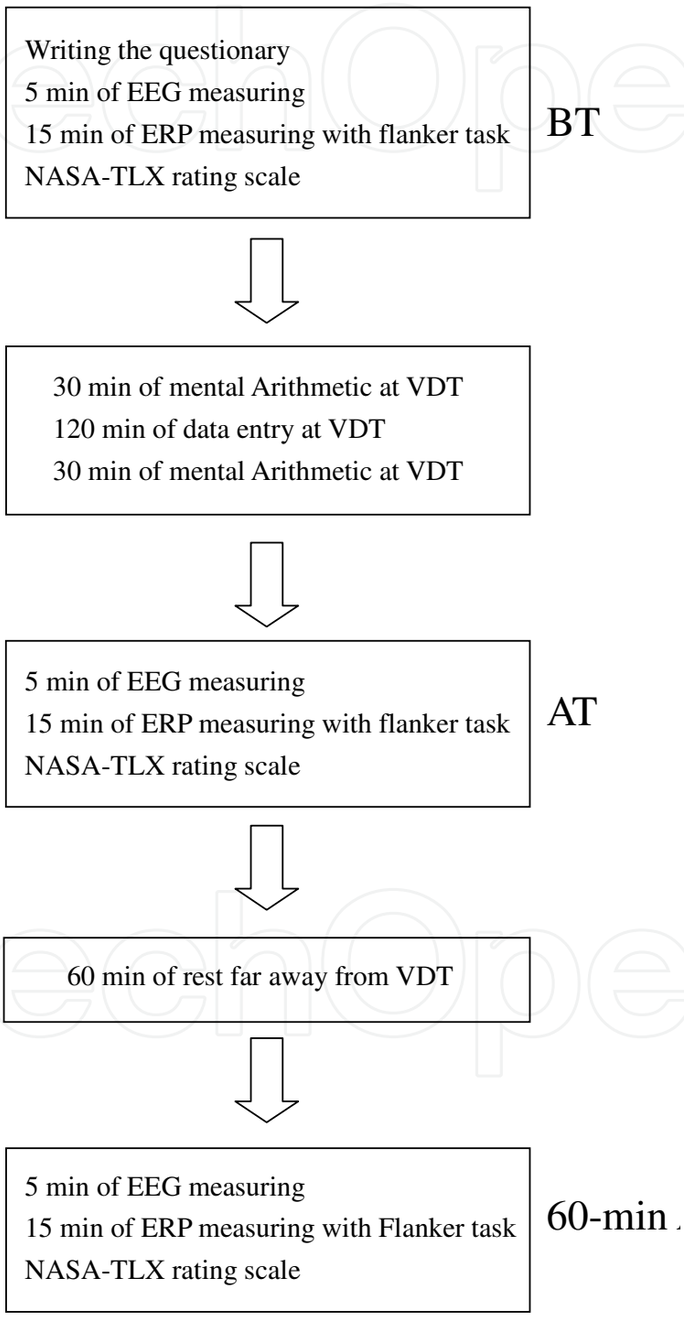


Fig. 3.1. The flow chart of the experimental procedure, including three measuring sessions (BT, AT, and 60-min AT), 120 min of VDT tasks, and 60 min of rest.

Similar EEG recordings were conducted immediately after the completion of the 180-min experimental task. After 60 min rest, the participants repeated the EEG measurement mentioned above, and then finished the whole test. At the end of each EEG measurement, self-report assessments of task loading were obtained by using the NASA-Task Load Index (TLX) rating scale (Hart and Staveland, 1988). The NASA-Task Load Index (NASA-TLX) consists of six component scales. An average of these six scales, weighted to reflect the contribution of each factor to the workload of a specific activity from the perspective of the rater, is proposed as an integrated measure of overall workload (referred to Appendix).

3.3 Behavior response tasks

A modified Eriksen flanker task with word stimuli replaced by arrow stimuli was adopted in this study. The stimuli were presented on a computer screen (15 inches) with a dark background and with a viewing distance of 80 cm (as shown in Figure 3.2(a)). The participants wore an elastic cap and comfortable clothing and sat in front of the computer monitor, as shown in Figure 3.2(b). A participant was required to press a designated button on a control panel (with reference to Adam et al. 1996, as depicted in Figure 3.2(c)) connected with the computer in response to the target stimulus. Designed buttons on the control panel were applied to orient the position between the start and control points of participant's moving finger.

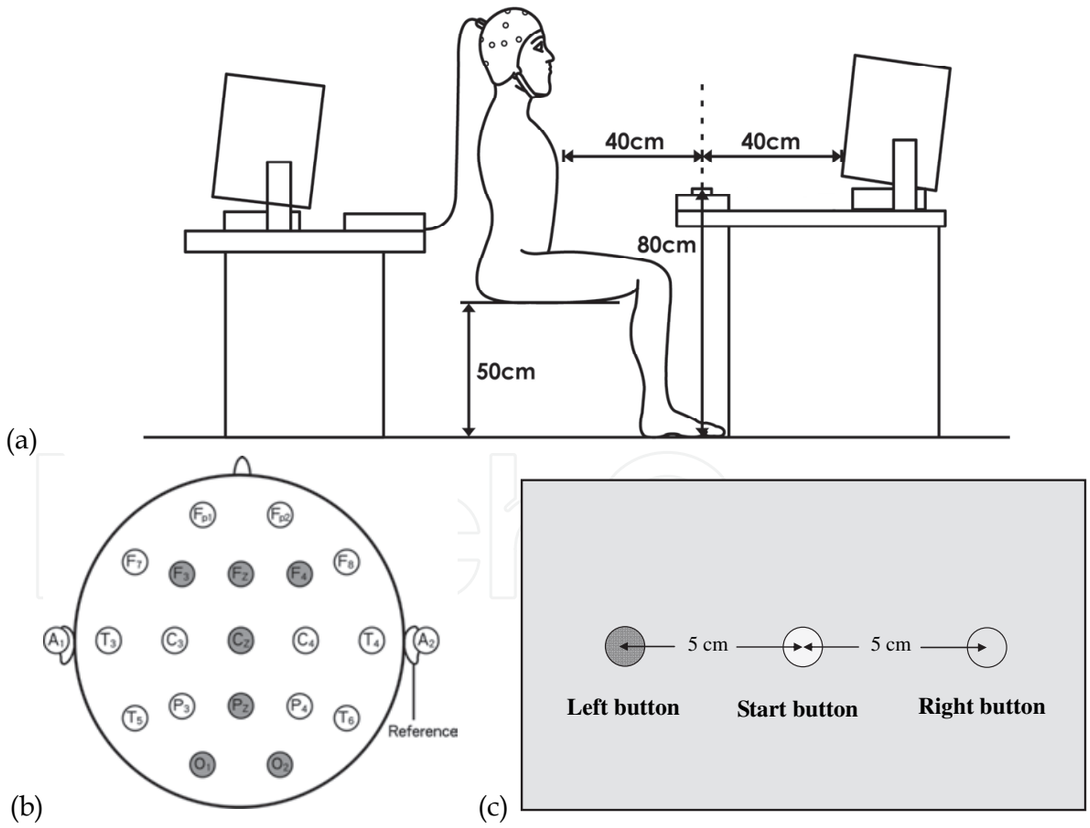


Fig. 3.2. (a) The layout and the position of the test device related to the participant wearing an EEG cap with scalp electrodes in international 10–20 montage. (b) Reference electrode is located on the right earlobe. (c) The self-made panel of control buttons was connected with the test device

Fig. 3.3. A participant wearing an EEG cap with scalp electrodes performed the modified flanker task

A participant was asked to focus on the arrow in the center of a visual array of five arrows on a computer screen, designated as target, and to respond with the right index finger to press the left or right button depending on the direction of the target arrow. The target arrow was flanked by four other arrows, two pointing to the left and two to the right, pointing in the same direction as the target (congruent) or in the opposite direction (incongruent) (as delineated in Figure 3.4). Congruent and incongruent trials were presented with equal probabilities. The left- and right-button responses signaled by target arrows occurred equally as often as well.

When the experimental task started, target arrows appeared at one time for each test trial. As soon as the target arrows were presented, the participant withdrew the right index finger from the start button to press a corresponding button and then returned the finger to the start button and finished a test trial. Trials were presented in pseudorandom order to limit the consecutive number of trials with same arrow arrays below five. Participants pressed the left button in response to a target arrow pointing to the left and the right button to a right-

pointing target. Each trial started with the presentation of a central fixation white cross "+", which lasted for 1 second. The arrow array appeared 200 milliseconds later after the fixation cross disappeared and it lasted for 50 milliseconds. The target arrow was in dark gray. The flanker arrows immediately surrounding the target arrow were in light gray and larger than the target, while the farthest flankers were in white and larger than the adjacent flankers. The inter-trial interval started from 2 seconds (maximum time interval for response) or when a button was pressed within 2 seconds after the presentation of the arrow array and was randomized between 1200 and 2000 milliseconds.

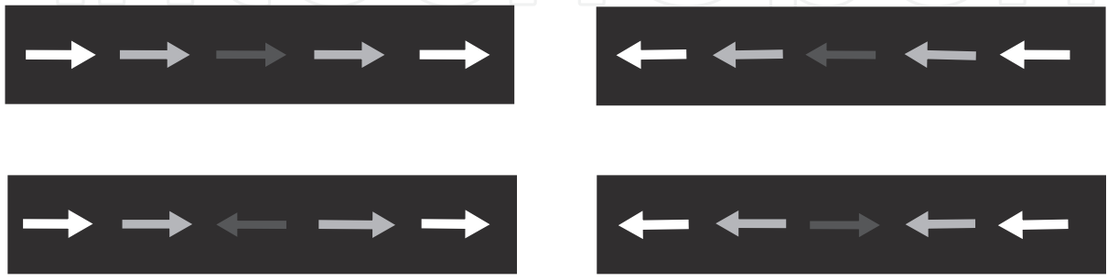


Fig. 3.4. The target arrow was flanked by four other arrows, two left arrows and two right ones, pointing in the same direction as the target (upper rows as congruent) or in the opposite direction (lower rows as incongruent).

Participants were initially trained with 50 trials and without feedback. Subsequently, they completed 3 blocks of 200 trials at the three test sessions (BT, AT, and 60-min AT). One test session took about 15 to 20 minutes. The whole experiment including EEG measures and experimental task lasted about 5 h, including pauses, placement and removal of EEG electrodes.

In this study, RT was measured as the time between the onset of the arrow array and the control button press. Trials with RTs longer or shorter than twice the value of the standard deviation for RT were excluded from calculation for mean RT. ER was calculated as the percentage of miss or erroneous responses.

3.4 EEG recording and data analysis

During the task performance, EEG was recorded by using an electrode cap (Quick-Cap, Compumedics NeuroScan, El Paso, Texas) with Ag/AgCl electrodes placed at F3, Fz, F4, Cz, Pz, O1, and O2 in the International 10–20 montage with an electronically linked mastoids reference as shown in Figure 3.2(b) (Andreassi, 2000). Two Ag/AgCl electrodes were placed 2 cm above and 2 cm below the left eye to record vertical electrooculogram (EOG). Two electrodes were positioned at 1 cm external to the outer canthus of each eye for horizontal EOG recording. A ground electrode was placed on the forehead. Electrode impedances were kept below 10 kΩ. The EEG and EOG were amplified by SYNAMPS amplifiers (Neuroscan, Inc.) and sampled at 500 Hz. The EEG epochs were then corrected by eye movement by using the Ocular Artifact Reduction (Semlitsch et al., 1986) command of SCAN 4.3 (Neuroscan, Inc.) and then underwent movement-artifact detection by using the Artifact Rejection command.

For measuring the background EEG pattern of participant, EEG spectral analysis was performed only for the 5-min rest condition. The recorded EEG during 5-min rest condition was subsequently transformed from time into frequency domains by fast Fourier transform (FFT) using a 5-s Hanning windowing function.
For ERP analysis, the EEG data were further digitally high-pass filtered at 1 Hz (–12 dB/octave) and were then segmented into stimulus-locked EEG epochs from 200 milliseconds before and 800 milliseconds after the onset of displaying the arrow array of flank test. The stimulus-locked EEG signals were baseline corrected between –100 milliseconds before the onset of stimulus. The averaged waveforms (i.e. ERPs) for stimulus-locked EEG epochs were band-pass filtered at 1 to 10 Hz prior to subsequent analyses.The amplitude and latency measures for P300 were derived from the stimulus-locked ERP recorded at F3, Fz, F4, Cz, Pz, O1, and O2 electrodes, respectively. It is noted that the EEG epochs of the trials with omitted responses or with RTs longer or shorter than twice the value of the standard deviation for RT were not included in the stimulus-locked ERP.
We analyzed the relationship between EEG power of θ, α, β, θ/α, β/α and (α+θ)/β indices (Brookhuis and Waard, 1993; Eoh et al., 2005; Ryu and Myung, 2005) as well as the amplitudes and latencies of the P300 component (Murata et al., 2005). The basic index means the relative power of the EEG θ, α and β bands. The δ band was not included in our analysis, since it happens in a deep sleep state and usually overlaps with artifacts. The relative power equation of the θ, α, and β bands are represented respectively as:

$$\text{Relative power of } \theta = (\text{power of } \theta) \;/\; (\text{power of } \theta + \text{ power of } \alpha + \text{ power of } \beta) \quad (1)$$

$$\text{Relative power of } \alpha = (\text{power of } \alpha) \;/\; (\text{power of } \theta + \text{ power of } \alpha + \text{ power of } \beta) \quad (2)$$

$$\text{Relative power of } \beta = (\text{power of } \beta) \;/\; (\text{power of } \theta + \text{ power of } \alpha + \text{ power of } \beta) \quad (3)$$

Since the basic indices have a tendency to "contradict each other", the ratio indices were calculated to amplify the difference. The known ratio indices β/α, θ/α, and (θ+α)/β were analyzed in previous studies (Brookhuis and Waard, 1993; Pyun and Kim, 2000; Ryu and Myung, 2005)
EEG power and ERP measured at recording sites F3, Fz, F4, Cz, Pz, O1, and O2, were analyzed by means of separate repeated-measures analyses of variance (ANOVA) with the within-subjects factors "session" including before (BT), immediately after (AT), and 60 min after (60-min AT) tasks, and "electrode" (F3, Fz, F4, Cz, Pz, O1, and O2). Where appropriate, differences from, sessions, electrodes, or electrode-by-session interactions were further evaluated with Fisher LSD post hoc tests (nominal level of alpha: $P<0.05$). ANOVA test, an inferential statistical procedure, examines the variation and tests whether the between group variance is greater than the within group variance. The larger the F ratio (the larger the variation between the groups) is, the greater the probability (the smaller p value) of rejecting a multiple group situations are the same. A one-way ANOVA ($p<0.05$) is used to determine if there is a difference between the groups.

4. Results

4.1 Performance and psychological evaluation of fatigue

All false responses on a modified Eriksen flanker task were calculated as ER. The mean RTs for each trial and the ERs were obtained at the three test sessions. The RT and ER results are

summarized in Appendix. A one-way (session: BT, AT, and 60-min AT) ANOVA carried out on the RT revealed no significant main effect of the session, whereas a one-way ANOVA conducted on the ER revealed a predominant difference between BT and AT ($F(2,38) = 6.371$, $p < 0.05$), while no significant difference was found between BT and 60-min AT. Figure 4.1 depicts the comparison of RTs on the modified Eriksen flanker task among three sessions (BT, AT, and 60-min AT). The RT tended to be prolonged at the post-task measurement. As a result of a similar one-way ANOVA carried out on the RT, no significant main effect of the measurement epoch was detected. The mean rating scale of mental fatigue tended to increase immediately after the completion of the task. At 60 min after the completion of the experimental task, the rating scale decreased and was nearly equal to the value in the BT session (as shown in Figure 4.2). A one-way ANOVA conducted on the rating scale revealed a pronounced difference between BT and AT ($F(2,38) = 5.23$, $p < 0.05$).

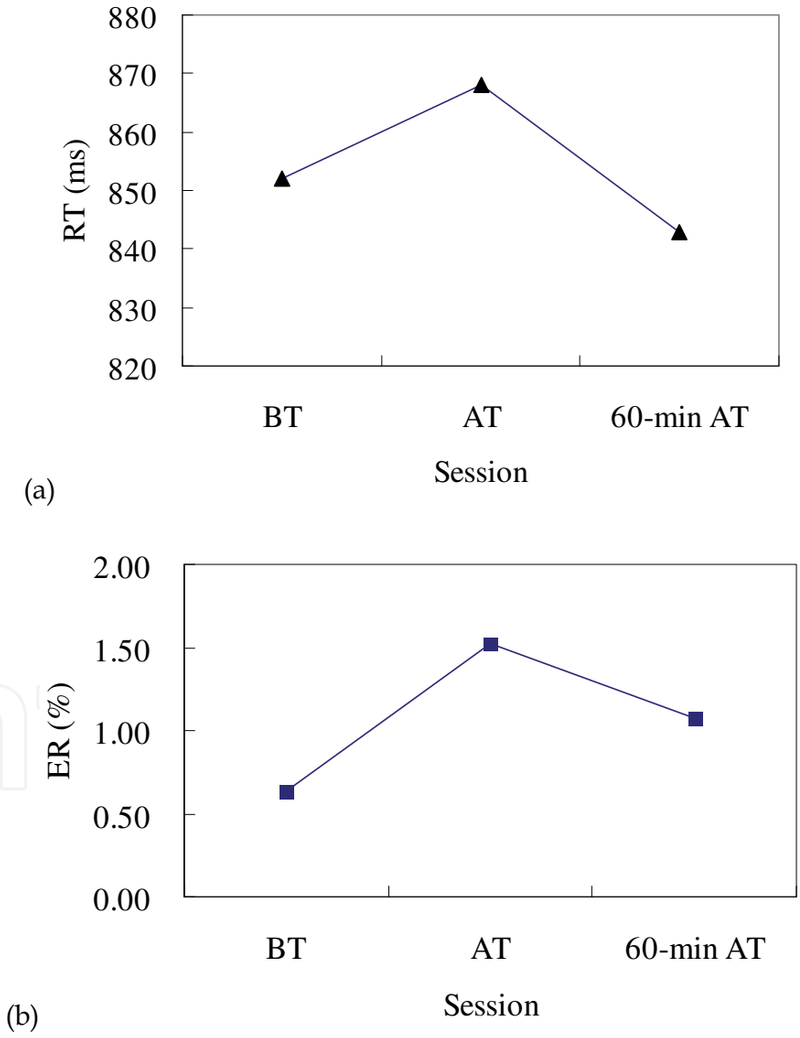


Fig. 4.1. Comparison of (a) RT and (b) ER on modified Eriksen flanker task among three sessions. BT: before task, AT: immediately after task

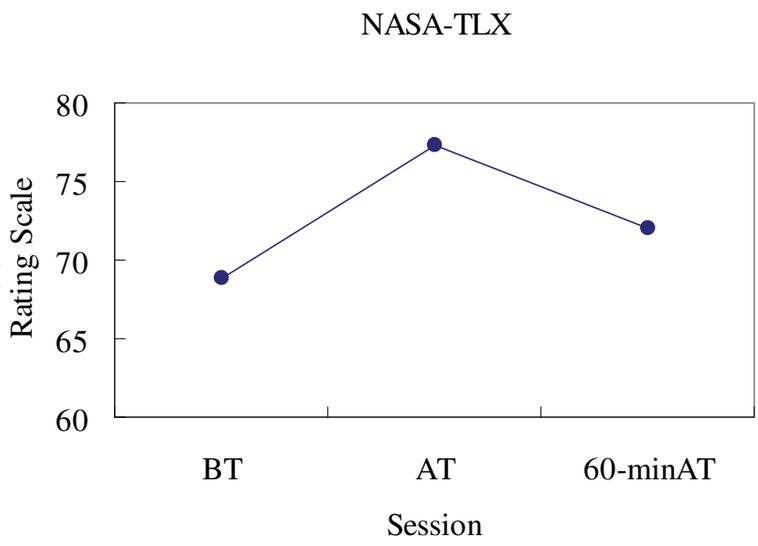


Fig. 4.2. Comparison of NASA-Task Load Index (TLX) rating scale on mental fatigue among three sessions. BT: before task, AT: immediately after task

4.2 EEG power spectra

The EEG indices, classified into two groups—the basic index and the ratio index, were derived from the reorganized data. Since the basic indices have a tendency to "contradict each other", the ratio indices were calculated to amplify the differences. The known ratio indices β/α, θ/α, and $(\theta+\alpha)/\beta$ were analyzed in previous studies (Brookhuis and Waard, 1993; Pyun and Kim, 2000; Ryu and Myung, 2005). The ANOVA results of EEG measured at the three sessions (BT, AT, and 60-min AT) are summarized in Table 1. All indices showed significant differences in location, and all indices except β and β/α showed significant differences in session. (see Table 4.1). Student-Newman-Keuls (SNK) post hoc analysis for the factor of location showed that the frontal (F3, Fz, F4), centro-parietal (Cz, Pz) and occipital (O1, O2) were separated into statistically different groups ($\alpha = 0.05$). In the post hoc analysis for the factor of the session, BT and AT revealed significantly different. No indices showed a significant difference of interaction effect. The ANOVA for 3 basic indices and 3 ratio indices are shown in Table 4.2 ~ 4.7.

Index	Location	Session	Interaction
θ	<0.01**	<0.01**	0.997
α	<0.01**	<0.01**	0.880
β	<0.01**	0.718	0.819
θ/α	<0.01**	<0.01**	0.070
β/α	<0.01**	0.224	0.574
$(\alpha+\theta)/\beta$	<0.01**	<0.01**	0.171

*Significant at $\alpha = 0.05$, **Significant at $\alpha = 0.01$.

Table 4.1. ANOVA summary for EEG measurement.

Electrode	F3	Fz	F4	Cz	Pz	O1	O2
F for (1–2)	8.216	16.038	16.752	13.641	7.391	6.414	5.155
P value for (1–2)	**0.010**	**0.001**	**0.001**	**0.002**	**0.014**	**0.020**	**0.035**
F for (1–3)	2.794	5.846	4.205	3.392	0.982	1.984	1.418
P value for (1–3)	0.111	**0.026**	0.054	0.081	0.334	0.175	0.248

Note: 1 denoted session BT; 2 denoted session AT; 3 denoted session 60-min AT
Table 4.2. ANOVA of basic index θ.

Electrode	F3	Fz	F4	Cz	Pz	O1	O2
F for (1–2)	11.594	13.728	14.935	16.059	4.532	6.962	5.998
P value for (1–2)	**0.003**	**0.002**	**0.001**	**0.001**	**0.047**	**0.016**	**0.024**
F for (1–3)	8.298	8.505	5.442	5.068	0.741	2.381	2.292
P value for (1–3)	**0.010**	**0.009**	**0.031**	**0.036**	0.400	0.139	0.147

Note: 1 denoted session BT; 2 denoted session AT; 3 denoted session 60-min AT
Table 4.3. ANOVA of basic index α.

Electrode	F3	Fz	F4	Cz	Pz	O1	O2
F for (1–2)	0.106	0.138	0.034	0.319	0.584	0.641	0.002
P value for (1–2)	0.748	0.714	0.856	0.579	0.454	0.433	0.965
F for (1–3)	2.419	1.097	2.688	1.139	0.068	0.153	0.021
P value for (1–3)	0.136	0.308	0.118	0.299	0.797	0.700	0.885

Note: 1 denoted session BT; 2 denoted session AT; 3 denoted session 60-min AT
Table 4.4. ANOVA of basic index β.

Electrode	F3	Fz	F4	Cz	Pz	O1	O2
F for (1–2)	0.106	0.138	0.034	0.319	0.584	0.641	0.002
P value for (1–2)	0.748	0.714	0.856	0.579	0.454	0.433	0.965
F for (1–3)	2.419	1.097	2.688	1.139	0.068	0.153	0.021
P value for (1–3)	0.136	0.308	0.118	0.299	0.797	0.700	0.885

Note: 1 denoted session BT; 2 denoted session AT; 3 denoted session 60-min AT
Table 4.5. ANOVA of ratio index β/α.

Electrode	F3	Fz	F4	Cz	Pz	O1	O2
F for (1–2)	11.701	22.309	14.945	14.560	7.245	6.734	4.928
P value for (1–2)	**0.003**	**0.000**	**0.001**	**0.001**	**0.014**	**0.018**	**0.039**
F for (1–3)	4.337	5.299	5.568	4.097	1.996	2.506	1.825
P value for (1–3)	0.051	**0.033**	**0.029**	0.057	0.174	0.130	0.193

Note: 1 denoted session BT; 2 denoted session AT; 3 denoted session 60-min AT
Table 4.6. ANOVA of ratio index θ/α.

Electrode	F3	Fz	F4	Cz	Pz	O1	O2
F for (1–2)	0.905	0.309	0.857	0.164	0.106	4.509	4.416
P value for (1–2)	0.353	0.585	0.366	0.690	0.748	**0.046**	**0.049**
F for (1–3)	5.058	4.519	5.330	3.561	0.456	1.077	0.623
P value for (1–3)	**0.037**	**0.047**	**0.032**	0.075	0.508	0.312	0.440

Note: 1 denoted session BT; 2 denoted session AT; 3 denoted session 60-min AT
Table 4.7. ANOVA of ratio index (α+θ)/β.

The basic indices θ and α at all recording sites tended to increase and decrease respectively, immediately after the completion of an experimental task. At 60 min after the experimental task was completed, the basic indices θ and α decreased and increased respectively, and recovered to the level in the BT session, as depicted in Figure 4.3(a) and 7(b). As shown in Figure 4.3 (e), the ratio indices θ/α revealed significantly increased immediately after the completion of an experimental task than those before the task at all electrode sites. However, (θ+α)/β showed a significant decrease after the completion of an experimental task. Only the value at the occipital increased to the level in the BT session at 60 min after the experimental task was completed, as shown in Figure 4.3 (f).

4.3 P 300 component of ERP

The ANOVA results of P300 component of ERP measured at the three sessions (BT, AT, and 60-min AT) are summarized in Table 4.8. The ANOVA for P300 latency and amplitude are shown in Table 4.9 and 4.10 respectively. The amplitude and latency showed significant differences in location, and the latency showed significant difference in session, while the amplitude revealed no significant differences in session. The P300 latency at Pz tended to decrease immediately after the completion of an experimental task. It increased at 60 min after the experimental task was completed but failed to recover to the level in the BT session, as illustrated in Figure 4.4 (e). A one-way (measurement epoch) ANOVA conducted on the P300 latency revealed a significant main effect at recording site of Pz, $F(2,38) = 5.684$, $p<0.05$. The P300 amplitude, in accordance with this, tended to decrease at the post-task measurement and failed to recover to the pre-task level at 60 min after the completion of the experimental task. A similar ANOVA conducted on the P300 amplitude revealed a significant main effect of the

measurement epoch at recording sites of Pz ((F(2,38) = 4.575, p<0.05), O1 (F(2,38) = 9.182, p<0.01) and O2 (F(2,38) = 4.694, p<0.05) (as illustrated in Figures 4.4 (e) ~ (g)).

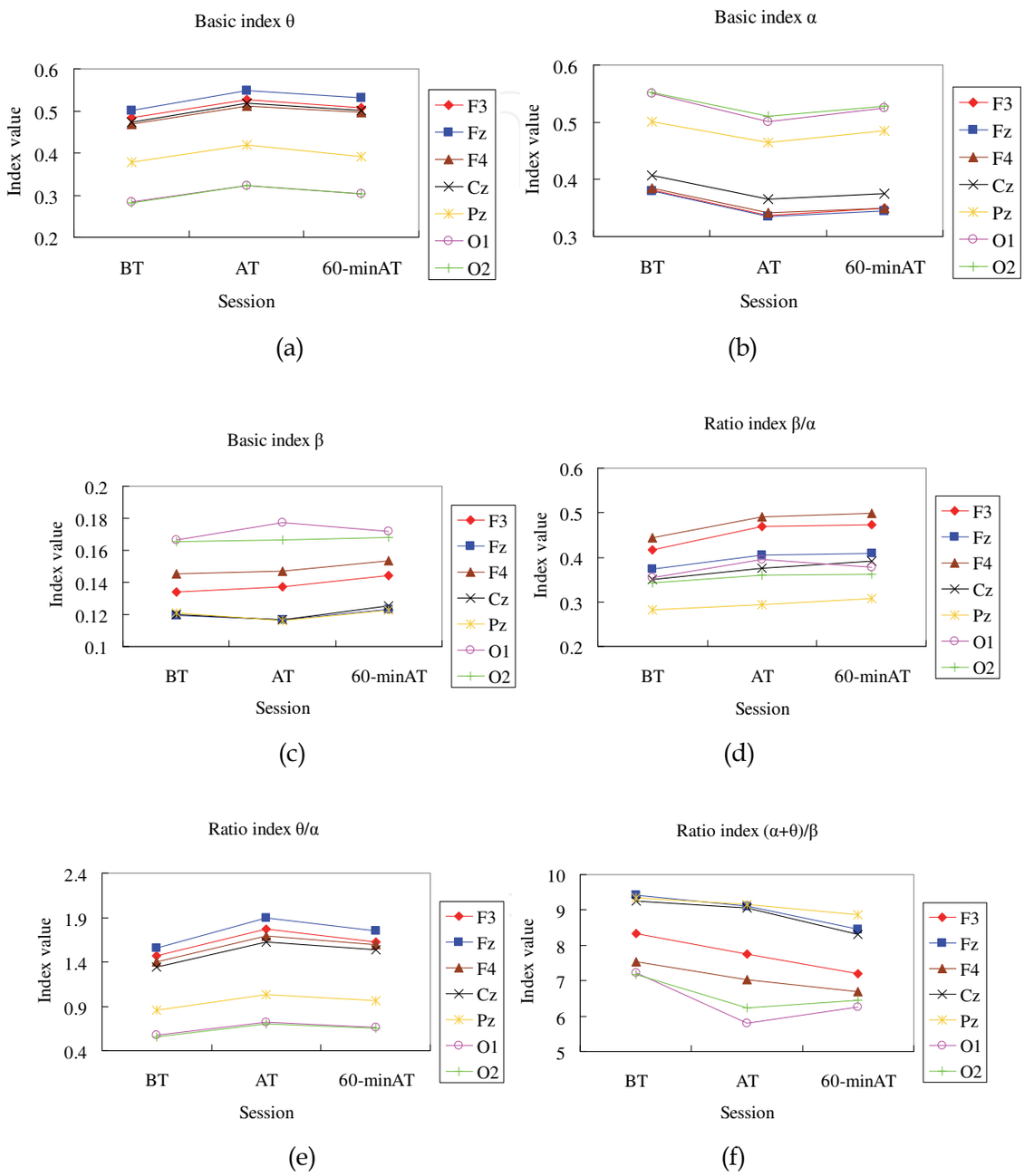


Fig. 4.3. Comparison of EEG indices among three sessions. BT: before task, AT: immediately after task. (a), (b), and (c) are basic indices θ, β, and α. (d), (e), and (f) are ratio indices β/α, θ/α and (θ+α)/β

Component	Location	Session	Interaction
Amplitude	<0.01**	0.077	0.243
Latency	<0.01**	<0.05*	0.286

*Significant at $\alpha = 0.05$, **Significant at $\alpha = 0.01$.
Table 4.8. ANOVA summary for P300 component of ERP measurement.

Electrode	F3	Fz	F4	Cz	Pz	O1	O2
F for (1–2)	0.533	2.152	3.308	0.533	5.684	1.556	0.748
P value for (1–2)	0.137	0.159	0.085	0.474	**0.028**	0.227	0.398
F for (1–3)	2.365	1.752	0.022	0.311	2.967	0.776	3.142
P value for (1–3)	0.141	0.201	0.884	0.584	0.101	0.389	0.092

Note: 1 denoted session BT; 2 denoted session AT; 3 denoted session 60-min AT
Table 4.9. ANOVA of P300 latency.

Electrode	F3	Fz	F4	Cz	Pz	O1	O2
F for (1–2)	2.525	0.757	1.072	0.499	4.575	9.182	4.694
P value for (1–2)	0.129	0.395	0.313	0.488	**0.041**	**0.007**	**0.043**
F for (1–3)	0.043	1.375	1.262	4.404	0.009	2.476	1.823
P value for (1–3)	0.837	0.256	0.275	**0.049**	0.924	0.132	0.193

Note: 1 denoted session BT; 2 denoted session AT; 3 denoted session 60-min AT
Table 4.10. ANOVA of P300 amplitude

5. Discussion and conclusion

5.1 Discussion

Based on the RT and ER on the modified Eriksen flanker task (see Figure 4.1) and the psychological rating scale of fatigue (see Figure 4.2) in the experimental task, it can be judged that the experimental task induced a tendency toward mental fatigue in the subjects. The effects of mental fatigue resulted in the level of attention to decrease (Boksem et al., 2005). The decreased level of attention caused a significant increase in ER and an increased tendency in RT. At 60 min after the completion of the experimental task, the RT and ER on Eriksen flanker task decreased, which indicated that the state of fatigue had improved during the 60-min rest, but did not recover to the original state.

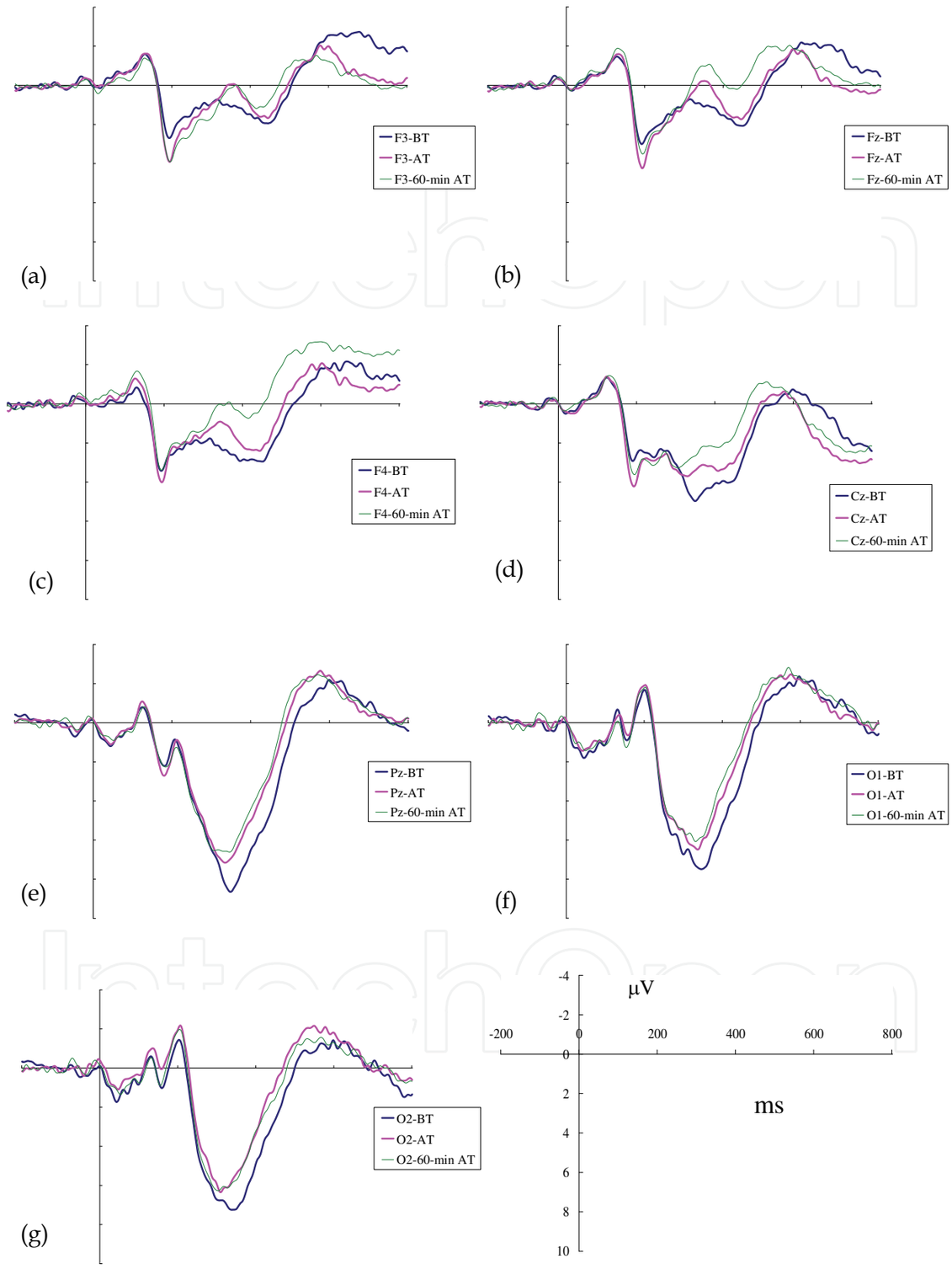


Fig. 4.4. Grand-averaged P300 waveform at seven recording sites F3, Fz, F4, Cz, Pz, O1, and O2 among three sessions. BT: before task, AT: immediately after task.

Research has shown that β waves are associated with increased alertness and arousal, α waves occur during relaxed conditions, at decreased attention levels and in a drowsy but wakeful state, and θ waves mainly occur at sleep state one (Grandjean, 1988; Okogbaa et al., 1994; Rains and Penzien, 2003). Among the EEG power spectra observed in this study, the α and θ waves showed significant changes while completing the experiment task in this study. The changes were consistent with those of previous studies (Åkerstedt et al., 1991; Lal and Craig, 2001). Changes in EEG with vigilance have generally shown that deterioration in performance is associated with increased θ wave and changes in α intensity (Davies, 1965; Morrel, 1966; Gale et al., 1977). Makeig and Jung (1995) also found that changes in α and θ waves were related to reduced performance and fatigue. In this study, we found that the index θ increased and the index α decreased after 3 h of VDT task. The subjects revealed some extent of mental fatigue, but their alertness level was increased after the experimental task. Mental arithmetic was a secondary task in this study. Hitch (1978) argued that working memory plays a major role in the task. On the other hand, it is also recognized that it includes the processes required to recognize numbers in their Arabic form, those required to comprehend verbal representation of numbers, those that assign magnitudes to numerical quantities, those that report a numerical sum, and so forth (Dahaene et al., 1999). Therefore, mental arithmetic seems to engage memory processes in respect to retrieval of arithmetic facts from long-term memory. During the experimental task, the processes required to recognize numbers is also needed. Mental effort that requires memory processes is known to suppress EEG alpha activity (Klimesch, 1997).

Among the ratio indices, index θ/α and index (α+θ)/β were statistically significant in this experiment. Index θ/α of session BT discriminated session AT which no other indices could do and it recovered to closely original state at 60-min AT (see Figure 4.3). Index (α+θ)/β showed different statistical characteristics compared to index θ/α due to the mutual addition effect of α waves and θ waves during the repetitive phase transition between wakefulness and microsleep. Because the changes of basic indices α and θ (increased θ and decreased α) showed different direction, the mutual addition effect of α and θ waves counteracted each other and reduced the index value, while θ/α accelerated the increase of the index valve due to the amplification of division. After the completion of an experimental task, the ratio index (θ+α)/β was decreased significantly at the occipital— visual dominating area. It revealed the main fatigue induced from the VDT task was in the visual area. The index value of (θ+α)/β increased at 60-min AT manifested the fatigue had improved, but did not recover to original state, except for visual sensory, after 60 min of rest. In this study, we found that index θ/α was more available than the other two ratio indices for assessment of mental fatigue in VDT task.

On the other hand, the P300 component of ERP indicated that the mentally and physically fatigued state could be explained by decreased activity of the central nervous system (CNS). This phenomenon revealed a decreased depth of cognitive information processing and a decreased level of attention. It has been pointed out that the increase of P300 latency is related to the temporal aspect due to the difficulty in cognitive information processing (Ullsperger et al., 1986, 1988; Donchin, 1979; Neuman et al., 1986). These findings were applied to the evaluation of mental fatigue. Uetake and Murata (2000) indicated that the appearance of mental fatigue is reflected more strongly in the two P300 components of

amplitude and latency. The delayed cognitive information processing (the prolonged P300 latency) and the decreased activity of cognitive information processing (decrease of the P300 amplitude) were found to be effective measures of mental fatigue. Traditionally, the assessment of mental fatigue is conducted by using the decreased arousal level (EEG). Okogbaa et al. (1994) investigated the relationship between EEG and mental fatigue. Although θ, α, β, and θ/α indexes were calculated to assess mental fatigue, these indices did not necessarily decrease with time and correlate with the appearance of mental fatigue or decrease of performance. The indices based on EEG measurement, in general, show the arousal level in the brain, but do not necessarily reflect the cognitive aspects such as the depth of cognitive information processing and the delay of processing. As clarified in this study, mental fatigue seems to be more strongly related to the declining the depth of cognitive information processing, i.e. the cognitive function. However, we did not find the delay of information processing due to the decrease of P300 latency after the experimental task. The possible reason was the mental arithmetic task improved the information processing capability. It revealed that the amplitude of P300 had better discrimination than latency of P300 for assessment of mental fatigue.

It is impossible to continuously measure ERP, therefore, the assessment of mental fatigue should be conducted with more confidence from the viewpoints of both arousal level (EEG) and cognitive information processing (ERP). The finding that mental fatigue was reflected in the decreased cognitive function such as the P300 component, would be significant and useful to promote the assessment of mental fatigue by means of multiple psychophysiological indices. None of these measures alone was a particularly powerful signal or warning of mental fatigue. Systematically taking these measures into account would lead to an effective evaluation method. The method proposed in this study is potentially applicable to the evaluation of the fatigued state of workers and to the management of mental fatigue from the viewpoints of occupational risk management, productivity, and occupational health.

5.2 Conclusion

The assessment of mental fatigue induced from 3 h of VDT task was undertaken by using indices of EEG bands and P300 component of ERP. In the EEG analysis for the VDT task, basic indices α and θ, ratio indices θ/α and (α+θ)/β were found to be statistically significant. It revealed the main fatigue induced from the VDT task was in the visual area. After 60 min of rest, the participants' fatigue did not diminish to the original state except visual sensory. After the experimental task, the amplitude significantly decreased, and the latency of P300 significantly shortened due to the mental arithmetic task improving the information processing capability. It revealed that index θ/α was more available than the other two ratio indices and the amplitude of P300 had better discrimination than latency of P300 for assessment of mental fatigue in VDT tasks. The P300 component of ERP indicated the possibility that one aspect of the mentally fatigued state could be explained by the decreased activity of CNS. This phenomenon is related to a decreased depth of cognitive information processing and a decreased level of attention. The method proposed in this study is potentially applicable to the evaluation of the fatigued state of workers and to the management of mental fatigue from the viewpoint of occupational risk management.

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