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Subjective symptoms and physiological measures of fatigue in air traffic controllers

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ABSTRACT

This study measured the correlation between fatigue and physiological stress symptoms in 102 air traffic controllers (ATCs) in Taiwan. The subjects were asked to complete a fatigue questionnaire and physiological measurement before and after work. The study results showed that nearly 50% of the subjects felt tired and weary after work. However, according to the results of the critical flicker frequency test, all ATCs performed better after work, and the strength of masculine index fingers improved. The systolic and diastolic blood pressure decreased after work. In addition, the levels of urinary 17-hydroxycorticosteroids (17-OHCS) at the pre-shift and post-shift stages were 1.91 ± 1.01 mg/g cr. and 1.50 ± 0.95 mg/g cr., respectively. This study indicated that, while the ATCs' subjective ratings showed possible work-induced fatigue, it did not affect their physiological response. The findings suggested that ATC is a stressful job, and that complaints regarding excess work stress should be taken seriously. Subsequently the study proposed appropriate intervention strategies to address the identified problems.

Relevance to industry: This paper presents the subjective and objective measures of fatigue in ATCs. Recommendations are proposed with respect to potentially viable countermeasures to reduce the impact of fatigue in ATC operations, and achieve a broader understanding of the causal factors for fatigue in ATC.

1. Introduction

Air traffic controllers (ATCs) face serious responsibilities on duty; hence, it is often regarded as one of the most difficult and stressful jobs in the world. The health of ATCs is a subject of concern because of the stress inherent to the job and its potential impact on public safety. The job functions of ATCs involve three main specialties: aerodrome controllers, approach and en-route controllers, and field officers. Aerodrome controllers regulate a specific airport's traffic and use two-way radios to give pilots permission to take off and land. Approach and en-route controllers regulate flights between airports and control their position in the airways between towers using sophisticated radar and computer equipment. Field officers are experts on the terrain, airports, and navigational facilities in their areas. ATCs have many roles in the management of flights. The work is associated with a very high degree of responsibility. While some of these roles involve standing in a control tower with binoculars to control the traffic in the immediate vicinity of an airport, some ATCs handle arrivals and departures at low altitude within the airport environment using a radar screen. Only recently have ergonomic considerations received emphasis on designing work stations and tools for the worker, rather than the task. Furthermore, there are high mental workloads in terms of perception, attention, information processing, problem solving and decision-making (Arvidsson et al., 2006a, 2006b; Imbert et al., 2014; Trapsilawati et al., 2015). It is evident that the cognitive and operational processes of an ATC vary not only according to the number of aircraft under their control, but also with the number and complexity of problems to be solved (Atkinson, 1988; Inoue et al., 2012).

ATCs often experience fatigue on the job due to shift work, heavy workloads, and stress, thus, fatigued subject may be in a microsleep, in which case there will be a missed or tardy response, meaning there can be a general slowing in information-processing speed (Monk and Carrier, 1997). Harrison and Horne (2000) argued that sleep loss results in a loss of cognitive creativity, as indicated by a tendency to use old information processing strategies, even though they are no longer optimal or even practical. A public letter (4/10/2007) from Mark

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Rosenker, the chairman of the U.S. National Transportation Safety Board (NTSB), to Marion Blakely, the Administrator of the Federal Aviation Administration (FAA), and to the Air Traffic Controllers' union, provides useful insights into such real-world examples. The NTSB chairman also expressed concern about one catastrophe and four examples of near misses, all potentially involving fatigued ATCs.

Fatigue is a state of physical and/or mental weakness, and tiredness, which results in reduced mental and/or physical performance (Frone and Tidwell, 2015; Abd-Elfattah et al., 2015). It can decrease a person's alertness and compromise a person's motor skills, reflex ability, judgment and decision-making. In simple terms, fatigue has been generally described as being sleepy, tired or exhausted (Manpower and WSH Council, 2010; Staal, 2004). Fatigue, psychosocial workload and insufficient sleep have been recognized as major consequences of increased work intensity amongst working populations (Åkerstedt, 1995; Härmä et al., 2006). The term fatigue is used in many different senses and to date, there is no single accepted definition. Often, literature distinguishes acute fatigue and chronic fatigue (Mohren et al., 2007); however, fatigue can be further differentiated into: muscular fatigue (Gandevia, 2001); mental fatigue induced by mental or intellectual work (Boksem and Tops, 2008); psychomotor fatigue from overstressing one part of the nervous system or by repetitive work; chronic fatigue associated with post-viral syndromes, such as fibromyalgia (Devanur and Kerr, 2006). The International Civil Aviation Organization defines crewmember fatigue as ‘A physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crewmember's alertness and ability to safely operate an aircraft or perform safety related duties' (International Civil Aviation Organization, 2011). Friedl provides a useful military operational definition as ‘the state of reduced human performance capability due to inability to continue to cope with physiological stressors' (Friedl, 2007). In both instances, it is worthy of note that fatigue is not merely a physiological state to be endured, but rather, by definition, a state of diminished performance and capability. Fatigue is commonly defined as a sensation of exhaustion during or after activities, or a feeling of inadequate energy to begin these activities.

Fatigue among ATCs originates from various stress sources. Great attention has been focused on fatigue caused by shift work, schedules, workload and time on task, and also on factors influencing resistance and vulnerability to fatigue (Luna, 1997; Bisseret, 1971; Brookings et al., 1996; Costa, 1993, 1999). Gander (2001) concluded that rapid backward rotating rosters resulted in significant sleep loss, as do early start times. Since the job functions of ATCs must operate around the clock, shift work is unavoidable. The night shift is obviously an important cause of concern when considering shift work. Many studies have found that ATCs report more sleepiness during the night shift, as compared to day or evening shifts (Cruz and Della, 1995, Cruz et al., 2000; Rhodes et al., 1996). In addition to the problems inherent in night shifts, scheduling the shifts also introduces difficulties. The problem of tired ATCs is exacerbated by scheduling two 8-h shifts within 24 h, a common practice that gives ATCs little chance to get normal sleep.

Workloads are perceived differently from one ATC to another, depending on their experiences, skills, motivation, tiredness, and coping skills (Wickens et al., 1997; Hopkin, 1995). Still, the high workload related to high traffic volume eventually creates fatigue due to the sustained efforts required. The efforts needed to cope with this high workload can only be sustained for a certain period of time. During simulated air traffic control tasks, as time passes, lapses in attention occur more frequently and reaction times increase for complex monitoring tasks, particularly under high task load conditions (Stein, 1991). The performance decrements and fluctuations of alertness, as associated with time on task, are even worse if the ATCs are suffering from sleep loss or sleep disruption (Meyer, 1973).

Fatigue is a factor that cannot be easily assessed after the occurrence of an incident; therefore, no critical incident has been directly attributed to fatigue. However, Roske-Hofstrand (1995) observed that 21% of reported incidents in the Aviation Safety Reporting System (ASRS) mention factors related to fatigue for both pilots and ATCs. Thus, the impairment of ATC performance due to fatigue is thus an important concern for system safety, and requires the development of countermeasures. Understanding the risk factors responsible, as well as the amount of risk, is the first step in mitigating the problem. The assessment of fatigue may be conducted in different ways. In large studies, the most commonly used method is self-reports, as based on questionnaires (Karlqvist et al., 2002; Lassen et al., 2004). This method is a valuable tool for screening symptoms and complaints in different occupational groups, in order to identify high-risk work environments.

While fatigue can be subjectively assessed, it has been shown that such an evaluation does not fully reflect the objective, physiological status of a tired person, mainly because subjective reports are biased by motivation, personal factors, experiences, and training (Morad et al., 2007). Physiological parameters, such as electrocardiogram, electroencephalogram, and rectal temperature, have not been popular in the assessment of fatigue due to their inherent drawbacks, such as the inconvenience of use and difficulties in interpretation of the data (Dussault et al., 2005). Hence, there is an urgent need to find a practicable, non-invasive but objective method, to measure fatigue, particularly in its early stages.

This study was performed with both subjective and objective measures, in order to evaluate fatigue severity and investigate the relationship among fatigue and other associated factors in ATCs; to our knowledge, there have been no studies with such an approach. The objective of this study was to explore the prevalence of fatigue perception and physiological fatigue among ATCs in Taiwan, and identify the risk factors. Based on the results, suggestions are presented for potentially viable countermeasures to reduce the impact of fatigue in ATC operations.

2. Materials and methods

There are 231 ATCs working at 11 work stations for Taiwan Air Navigation and Weather Services. This study was carried out on 102 ATCs (a 44.2% participation rate), including 29 aerodrome controllers, 51 approach and en-route controllers, and 22 field officers. The subjects, including 47 women and 55 men, all participated voluntarily. Their basic information is shown in Table 1. The subjects carried out their routine works, and filled out a questionnaire on the subjective feelings of fatigue during face-to-face interviews, followed by a physiological test, before and after work. The subjects provided general information and assessed subjective syndromes of fatigue prior to the physiological tests, which included the flicker fusion threshold, response stick, near point, thumb/index finger strength, systolic and diastolic pressure, and a 17-OHCS urine test. 17-OHCS is a product of the breakdown of cortisol and other adrenocorticotropic hormones, and cortisol is a glucocorticoid stress hormone important for its anti-inflammatory effects. Glucocorticoids, such as cortisol, are released when the body is in a state of physical or mental exertion. After the glucocorticoids are broken down, the resulting 17-OHCS is removed from the body through the urine. Therefore, the 17-OHCS concentration in urine can be used as an indicator of the level of fatigue. The urine samples of the subjects were taken before and after work for analysis, and the concentrations of the urine samples were confirmed in the effective range. This study collected 102 urine samples before work and 100 urine samples after work. Of these, 180 urine samples belong to 90 ATCs were confirmed as effective, including the urine samples of 50 women and 40 men. By job, the number of urine samples of aerodrome controllers, radar controllers and on-site supervisor were 24, 46, and 20, respectively. A written consent was obtained from the subjects after they were given a clear explanation of the objectives and procedures of

Table 1
Descriptive statistics on subjects (n = 102).

	Aerodrome controllers (n = 29)	Approach and en-route controllers (n = 51)	Field officers(n = 22)	P value[a]
Male	14	18	15	
Female	15	33	7	
Age (yrs)	29.6 ± 4.8	37.5 ± 8.7	50.2 ± 7.4	< 0.01*
Working experience (yrs)	3.0 ± 2.4	11.8 ± 5.1	24.7 ± 7.4	< 0.01*
Shifts (persons)				
Day-shift (07:00–13:00)	23	35	16	0.06
Noon-shift (13:00–19:00)	6	16	4	
Night-shift (19:00–07:00)	0	0	2	
Flight handled (persons)				
< 30 aircrafts	8	6	12	< 0.01*
30-100 aircrafts	12	35	5	
> 100 aircrafts	9	10	5	
Last-night sleeping hours (hrs)	6.78 ± 0.92(4–9)			
Smoker (%)	14.7			
BMI	22.25 ± 3.22(17.67–33.2)			
Alcohol use (%)	3.9			
Commuting time (mins)	26.2 ± 19.3(1–120)			

[a] Significance level by Chi-square test (*$p < 0.05$), or by Fisher's exact test when minimum expected frequency requirements are not met.

the experiment. They were also given the opportunity to ask any question about the study, and had the option to withdraw any time during the experiment. The study was approved by the National Yang-Ming University Institutional Review Board.

2.1. Subjective syndrome of fatigue

The questionnaire of subjective syndrome of fatigue, as proposed by the Research Committee on Industrial Fatigue of Japan's Society for Occupational Health (Research Committee on Industrial Fatigue, 1969), was adopted to determine the prevalence rate and incidence rate of fatigue among the subjects (Sudo and Ohtsuka, 2002; Chang et al., 2009). The questionnaire on the subjective fatigue consisted of three dimensions: Dimension I (drowsiness and dullness), Dimension II (difficulty in concentration), and Dimension III (local physical abnormalities). Each dimension contains 10 items. For each item, the subjects were requested to answer true or false. An index of complaint rate (T) was calculated for each item, according to T = (number of subjects who answered true)/(total subjects investigated). The average complaint rate was computed for each dimension, and the working type was then categorized. Working types were represented by mental type, physical type, or general type, while the value of the average complaint rate T in each dimension appeared as Dimension I > Dimension II > Dimension III, Dimension III > Dimension I > Dimension II, or Dimension I > Dimension III > Dimension II, accordingly.

2.2. Measurements of physiological fatigue

In this study, the frequency at which a completely steady light appeared to be an intermittent light was presented to the subjects and the response time at which a dropping stick could be caught both measured five times each. The averages were treated as the index of fatigue. A digital flicker (Sibata Ltd., Japan) was used to measure the flicker fusion threshold, the bigger the value, the less fatigue, while the subject's response time was obtained using a response stick test (Takei Ltd., Japan), the smaller the value, the less fatigue. The shortest distance at which the subjects could maintain clarity was called 'near point' vision, the smaller the value, the less fatigue, and it was obtained using a Japanese instrument. A force gauge (Sammons Preston Ltd., USA) was used to measure the strength of the thumb and the index finger, the bigger the value, the less fatigue. Three types of pinch were measured: tip pinch, key pinch, and palm pinch. Tip pinch force was measured with only the index finger on top and the other fingers flexed with the thumb below. Key pinch force was measured with the thumb on top and the radial side of the index finger below. Palm pinch force was measured with index and middle finger on top, and thumb below. Heart rate and blood pressure were obtained using a wrist blood pressure meter (Matsushita Ltd., Japan) while the subject was in a sitting position. With the exception of the force gauge, each test was performed five times, and the average value was adopted. Urinary 17-OHCS is a useful indicator of assessing fatigue, and this method has been adopted by many researchers (Miller, 1968; Burton et al., 1977; Heim et al., 2000; Nagata et al., 2006; Mori et al., 2015). The bigger the value of 17-OHCS concentration, the more likely fatigue the subject experienced. Therefore, the amount of 17-OHCS in the subjects' urine was examined by collecting urine from the ATCs before and after work.

2.3. Data analysis

Based on the self-reported questionnaire, descriptive statistics of features of the study subjects were collected. For data analysis, the subjects were divided into aerodrome controllers, approach and en-route controllers, and field officers. The Chi-square test was used to calculate all p values of prevalence and incidences related to subjective fatigue, ocular fatigue, and musculoskeletal fatigue after work among the three groups. The student's *t*-test and Chi-square test were employed to determine if any significant differences in workload, complaint rate and measurements of fatigue were related to age, gender and job group variation. The statistical significance of physiological measurements on males and females were tested using one-way analyses of variance (ANOVA), and multiple comparisons between each physiological measurement were performed using the paired *t*-test. Data from the completed questionnaires were stored in a database and then analyzed using SPSS. Descriptive statistics were performed with regard to the demographic characteristics of the target population and the subjective experienced effect of the treatment.

3. Results

Table 1 shows the descriptive statistics of the subjects' demographic features, based on the self-reported questionnaire data. According to Table 1, there were significant differences in gender, age, experience, and number of aircrafts handled among the three comparison groups. All 102 ATCs were between the ages of 20 and 60 years (M = 36.4, SD = 5.1, median = 37.8), and their overall air traffic control experience ranged from one to more than 30 years (M = 12.4, SD = 2.9).

As shown in Table 2, the most common symptom for ATCs was eye strain (37.3%) before work; however, the degree of discomfort is not statistically significant among the working types. Among all controllers, the symptom of becoming drowsy appeared the most on aerodrome

Table 2
The prevalence and incidence of subjective fatigue symptoms before and after work.

	Prevalence[a] before work	Prevalence after work	Incidence[b] after work
Dimension I (Drowsiness and dullness)	**14.3**	**26.9**	**19.1**
Head feel heavy	9.8	22.6	19.5
Whole body feel tired	2.9	10.8	11.4
Legs feel tired	3.9	12.8	10.1
Yawning	28.4	42.2	29.6
Head feel hot or muddled	5.9	12.8	10.4
Become drowsy	28.4	49	36.8
Feel eye strain	37.3	66.7	34.2
Become rigid or clumsy in motion	6.9	9.8	6.5
Feel unsteady while standing	2	2	1.3
Want to lie down	17.7	40.2	30.7
Dimension II (Difficulty in concentrating)	**8.2**	**14.1**	**14**
Feel difficult in thinking	2	5.9	5
Become weary while talking	9.8	25.5	22.1
Become nervous	5.9	9.8	6.5
Unable to concentrate	9.8	26.5	21.5
Disinterested	11.8	25.5	20.8
Become forgetful	8.8	17.7	13.2
Lack of self-confidence	2.9	11.8	12.8
Anxiety	13.7	22.6	13.3
Unable to straighten up	4.9	10.8	10.4
Lack patience	12.8	23.5	14.5
Dimension III (Local Physical abnormality)	**11.1**	**13.9**	**7.1**
Have a headache	8.8	13.7	7.8
Feel shoulder stiffness	19.6	27.5	13.3
Feel pain in the back	10.8	18.6	7.5
Breathing feel constrained	*	1	1.3
Feel thirsty	28.4	42.2	20
Have a husky voice	12.8	15.7	7.9
Have dizziness	4.9	9.8	6.4
Have a spasm on the eyelids	5.9	2.9	1.3
Have a tremor in the limbs	1	0	0
Feel ill	7.8	7.8	5.3
Feel tired now	**24.5**	**64.7**	**46.1**

[a] Prevalence is the rate of subjects with the symptoms.
[b] Incidence is the rate of subjects without the symptom before work but with the symptom after work.

Table 3
Mean percentage of subjective fatigue symptoms, and fatigue type.

	Aerodrome controllers	Approach and en-route controllers	Field officers	Total	P value
Fatigue complaints before work					
Dimension I	15.5	17.3	5.9	14.3	0.04
Dimension II	6.6	12.2	1.4	8.2	0.03
Dimension III	8.1	15.5	5.1	11.1	0.03
Feel tired now	34.5	27.5	4.6	24.5	0.61
Fatigue complaints after work					
Dimension I	25.5	28.3	19.1	26.9	0.35
Dimension II	1.4	23.2	10	14.1	0.08
Dimension III	10.7	16.9	11.4	13.9	0.63
feel tired now	65.5	70.6	50	64.7	0.80
Incidence					
Dimension I	15.5	18.8	15	19.1	0.10
Dimension II	11	14.9	9.5	14	0.36
Dimension III	5.5	7.5	6.8	7.1	0.70
Feel tired now	41.4	45.1	45.5	46.1	0.10
Fatigue type (after work)	General type	Mental work	General type	Mental work	

controllers (41.4%). However, the discomfort is not statistically significant in working types, while the symptom of feeling thirsty appeared the most on approach and en-route controllers (45.1%), which showed a significant difference ($p < 0.05$). After work, the most frequent symptoms included eye strain (66.7%) and feeling tired (64.7%); however, the two items are not statistically significant in working types. Eye strain was the most common symptom, at 69.0%, 68.6%, and 59.1%, for aerodrome controllers, approach and en-route controllers, and field officers, respectively, while the item of feeling tired was the most common symptom for approach and en-route controllers (70.6%). Nearly 50% of the ATCs had the symptom of feeling tired and weary, while over 40% had the symptoms of feeling thirsty, yawning, and wanting to lie down. Comparing aerodrome controllers with approach and en-route controllers, the prevalence of feeling thirsty was 41.4% and 51.0%, yawning was 41.4% and 49.0%, and wanting to lie down was 41.4% and 45.1%, respectively. Although the previous items are the symptoms of discomfort that appear the most, they are not statistically significant in working types. Approach and en-route controllers (41.2%) were more unlikely to concentrate than aerodrome controllers and field officer did significantly ($p < 0.01$). Table 2 shows that almost all subjective fatigue symptoms increase after work. The incidence of subjective syndrome in ATCs, showing the probability indicated that this symptom will not occur before work and may occur after work. The incidences of feeling tired now, becoming drowsy, feeling eye strain, and wanting to lie down are all above 30%, indicating that these fatigue symptoms are the most common for ATCs. The incidence of subjective fatigue in the three working types does not show statistically significant differences in each symptom. Only the item of husky voice, approach and en-route controllers has a higher incidence rate than the other controllers ($p = 0.083$). Table 3 shows the incidence rate of subjective fatigue symptoms after work, indicating the possibility of symptoms due to daily operation. The symptom of feeling tired had the highest incidence rate, at 41.4%, 45.1%, and 45.5%, among the aerodrome controllers, approach and en-route controllers, and field officers, respectively; however, it is not statistically significant in working types.

In this study, the subjects were mental workers based on the total complaint rate of the pattern of [I > II > III] after work, for aerodrome controllers and flight officers the pattern of [I > III > II] was also shown, but for approach and en-route controllers the pattern of [I > II > III] was found, as shown in Table 3. The numbers of aircraft handled by aerodrome controllers and by approach and en-route controllers were 98 ± 93 and 82 ± 55 on the day of investigation, but there was no statistical difference. However, relating the number of aircraft handled to the prevalence of subjective fatigue after work, the score of local physical abnormalities for subjects who handled more than 100 aircraft was statistically larger than for those who handled fewer aircraft, as shown in Table 4. Therefore, the higher workload of ATCs was prone to causing physical discomfort. The field officers were divided into two groups based on a cutting point of age of 45 for comparison. Table 4 indicates that the effect of age on fatigue was prominent, and it was the highest for local physical abnormalities ($p = 0.07$) among field officers.

Table 5 summarizes the changes between the pre-work and post-work measurements. It was found that the flicker fusion threshold of the controllers was better after work, especially for male controllers, for whom there was statistical significance ($p < 0.01$). While the average near-point measurements were worse after work for all male and female controllers, there was no statistical difference. According to the results of the response stick test, while all controllers performed better after work, no significant differences were shown. Masculine index finger strength became better ($p < 0.01$), while feminine thumb strength became worse ($p = 0.02$), and the index/middle finger became significantly better ($p < 0.01$). In addition, cardiovascular parameters,

Table 4
Numbers of aircraft handled, age and the prevalence of local physical abnormality.

	Aircraft handled		Age		
	≦100	> 100	≦45	> 45	P value[la]
Aerodrome controllers	0.17 ± 2.62	2.30 ± 2.44			0.04
Approach and en-route controllers	0.19 ± 2.62	2.35 ± 1.80			0.02
Field officers			0	3.80 ± 3.80	0.07

[a] Student *t*-test.

i.e. heart rate, systolic and diastolic pressure, were reduced after work.

The results of the urinary 17-OHCS concentration test, as shown in Table 6, suggested that the average concentration before work was 1.91 ± 1.01 mg/g cr. The average 17-OHCS concentration of the male subjects' urine samples was 1.69 ± 0.93 mg/g cr., while the average 17-OHCS concentration of the female subjects' urine samples was 2.10 ± 1.01 mg/g cr. By job, the average urinary 17-OHCS concentrations before work for the aerodrome controllers, approach controllers and field officers were 1.69 ± 1.01 mg/g cr., 1.99 ± 1.05 mg/g cr. and 2.02 ± 0.94 mg/g cr., respectively. The urinary 17-OHCS concentration of the urine samples after work was 1.50 ± 0.95 mg/g cr. The average urinary 17-OHCS concentration of the male subjects' urine samples was 1.47 ± 1.00 mg/g cr., while the average urinary 17-OHCS concentration of the female subjects’ urine samples was 1.53 ± 0.91 mg/g cr. By job, the average urinary 17-OHCS concentrations for the aerodrome controllers, approach controllers, and field officers were 1.41 ± 1.14 mg/g cr., 1.63 ± 0.89 mg/g cr. and 1.34 ± 0.83 mg/g cr., respectively.

This study collects 102 urine samples before work and 100 samples after work. With the exception of those taking medicine, 90 tested urine samples show valid urinary concentration, including 50 females and 40 males. The results of the urinary 17-OHCS concentration test, as shown in Table 6, suggested that the average concentration before and after work was 1.91 ± 1.01 mg/g cr. and 1.50 ± 0.95 mg/g cr., respectively. In addition, regarding the urinary 17-OHCS concentration of different variables before and after work, this study adopts one-way ANOVA to explore the effects of different variables on urinary17-OHCS concentration, including gender, age, working type, working year, working shift, and sleeping hours.

3.1. Gender

Regarding the data of descriptive statistics, for males and females, 17-OHCS concentration before work was higher than after work. Females showed higher 17-OHCS concentration than males in urine

Table 6
Concentration of 17-OHCS in urine before and after work.

Gender/Job groups	Subjects	Before work	After work	P value[a]
Male	40	1.69 ± 0.93	1.47 ± 1.02	0.161
Female	50	2.10 ± 1.01	1.53 ± 0.91	< 0.01*
Total	90	1.91 ± 1.01	1.50 ± 0.95	< 0.01*
P value[b]		0.056	0.763	
Aerodrome controllers	24	1.69 ± 1.01	1.41 ± 1.14	0.081
Approach and en-route controllers	46	1.99 ± 1.05	1.63 ± 0.89	< 0.01*
Field officers	20	2.02 ± 0.93	1.34 ± 0.83	< 0.01*
P value[c]		0.437	0.386	
< 30 years (age)	7	1.56 ± 1.00	1.02 ± 0.39	0.195
30–39	50	1.99 ± 1.09	1.65 ± 1.09	< 0.01*
40–49	17	1.87 ± 0.87	1.39 ± 0.72	0.061
≧50	16	1.80 ± 0.96	1.37 ± 0.84	0.085
P value[c]		0.766	0.334	
< 5 years (working year)	21	1.64 ± 1.01	1.41 ± 1.18	0.212
5–9	31	2.13 ± 1.16	1.66 ± 1.10	< 0.01*
10–19	18	1.91 ± 0.77	1.46 ± 0.58	0.025*
≧20	20	1.87 ± 0.97	1.36 ± 0.88	0.062
P value[c]		0.408	0.684	
< 6 h (sleeping)	7	2.02 ± 0.93	1.32 ± 0.74	0.155
6–6.9	32	1.77 ± 0.90	1.34 ± 0.76	< 0.01*
7–7.9	30	1.93 ± 1.12	1.56 ± 1.14	0.063
≧8	21	2.07 ± 1.12	1.72 ± 0.99	0.039*
P value[c]		0.762	0.489	
Day-shift (07:00–13:00)	65	2.01 ± 1.00	1.52 ± 0.98	< 0.01*
Noon-shift (13:00–19:00)	23	1.70 ± 1.05	1.52 ± 0.90	0.271
Night-shift (19:00–07:00)	2	1.36 ± 0.93	0.52 ± 0.11	0.460
P value[c]		0.341	0.344	

[a] Paired *t*-test, * < 0.05.
[b] Student t-test.
[c] One-way ANOVA.

Table 5
Changes of physiological measurement before and after work.

Measurement items	Female[a]	P value[b]	Male[a]	P value[b]	P value[c]
Critical flicker fusion (Hz)	0.48 ± 2.58	0.17	1.53 ± 2.94	< 0.01*	0.06
Near point (cm)	0.05 ± 2.69	0.89	0.42 ± 4.12	0.49	0.59
Dropping stick (ms)	−4.13 ± 27.84	0.27	−0.66 ± 22.31	0.84	0.47
Strength of the thumb (N)	−4.45 ± 8.90	0.02*	−4.45 ± 13.35	0.09	0.94
Strength of the Index finger (N)	4.45 ± 8.90	< 0.01*	4.45 ± 13.35	< 0.01*	0.03*
Strength of the index and middle finger (N)	4.45 ± 8.90	< 0.01*	4.45 ± 13.35	0.14	0.95
Heart rate (b/m)	−2.6 ± 12.93	0.14	−0.4 ± 11.05	0.80	0.36
Systolic pressure (mmHg)	−0.6 ± 8.44	0.60	−2.43 ± 11.04	0.14	0.14
Diastolic pressure (mmHg)	−0.89 ± 7.04	0.35	−0.43 ± 9.76	0.77	0.62
Subjects	55		47		

[a]Change = after work - before work.
[b]Paired *t*-test.
[c]Student *t*-test.
[d] *P < 0.05.
[e] Critical flicker fusion: - (worse), + (better); Near point: + (worse), -(better); Dropping stick: + (worse), -(better); Strength of the fingers: -(worse), + (better); Heart rate: + (faster), -(slower); Blood pressure: + (higher), -(lower).

samples before and after work. Before work, gender difference was not statistically significant ($F_{1,88} = 3.755$, $P > 0.05$); after work, it was not statistically significant ($F_{1,88} = 0.092$, $P > 0.05$). However, females' difference of urinary 17-OHCS concentration before and after work was statistically significant ($P < 0.01$).

3.2. Working type

17-OHCS concentration before work was higher than after work. Regarding approach controllers, in urine samples before and after work, the 17-OHCS concentration was higher than aerodrome controllers'. The differences of working types before work were not statistically significant ($F_{2,87} = 0.437$, $P > 0.05$); and after work was not significant ($F_{2,87} = 0.386$, $P > 0.05$). Regarding approach controllers and field officers, the difference of the urinary 17-OHCS concentration before and after work was statistically significant ($P < 0.01$).

3.3. Age

The 17-OHCS concentration before work was higher than after work. Regarding the group aged 30–39, in urine samples before and after work, 17-OHCS concentration was higher than the other groups. Before work, age difference was not statistically significant ($F_{3,86} = 0.766$, $P > 0.05$); after work, it was not significant ($F_{3,86} = 0.334$, $P > 0.05$). However, regarding the group aged 30–39, before and after work, the difference of the urinary 17-OHCS concentration was statistically significant ($P < 0.01$).

3.4. Working year

The 17-OHCS concentration before work was higher than after work. Regarding the group of 5–9 working years, in urine samples before and after work, 17-OHCS concentration was higher than the other groups. Before work, the difference of working years was not statistically significant ($F_{3,86} = 0.408$, $P > 0.05$); after work, it was not significant ($F_{3,86} = 0.684$, $P > 0.05$). However, regarding the groups of working years of 5–9 and 10–19 years, before and after work, their difference of urinary 17-OHCS concentration was statistically significant ($P < 0.01$ and $P = 0.025$).

3.5. Sleeping hours

The 17-OHCS concentration before work was higher than after work. Regarding the group of $\geqq 8$ sleeping hours, in urine samples before and after work, 17-OHCS concentration was higher than the other groups. The difference of sleeping hours before work was not statistically significant ($F_{3,86} = 0.762$, $P > 0.05$); after work, it was not significant ($F_{3,86} = 0.489$, $P > 0.05$). Regarding the groups of sleeping hours of 6–6.9 and more than 8 h, the difference of urinary 17-OHCS concentration before and after work was statistically significant ($P < 0.01$ and $P = 0.039$).

3.6. Working shift

The 17-OHCS concentration before work was higher than after work. Regarding the subjects of the day shift, in urine samples before and after work, 17-OHCS concentration was higher than those of the other shifts. The difference of working type before work was not statistically significant ($F_{2,87} = 0.341$, $P > 0.05$); after work, it was insignificant ($F_{2,87} = 0.344$, $P > 0.05$). However, Day-shift (0700–1300) subjects' difference of the urinary 17-OHCS concentration before and after work was statistically significant ($P < 0.05$).

4. Discussion

Subjective fatigue symptoms before work may indicate cumulative chronic job stress with effects that do not disappear even after a period of rest. The most common symptom, with the highest prevalence and incidence rates of subjective fatigue both before and after work, was eye strain. According to the study results, the ATCs experienced eye fatigue and chronic fatigue induced by ocular overloading. Therefore, eye relaxation exercises during work breaks might help to relax the eyes and reduce eye fatigue. It is recommended to avoid hobbies requiring high visual intensity after work, such as web browsing, watching TV, and reading newspapers or magazines. Besides eye strain, feeling tired was the dominant fatigue perception response listed in the questionnaire by all ATCs, while being unable to concentrate was selected by the approach and en-route controllers more than the other ATCs. Having a husky voice also had a high percentage. The approach and en-route controllers face higher mental workload than that experienced by the other ATCs, thus, the operators are suggested to engage in physical activity during their time off for both muscular and mental relaxation.

This study found that the approach and en-route controllers complained about feeling thirsty before work more than the other controllers, and a high percentage became weary while talking and had eyelid spasms as well. It seems that the symptoms appeared as a result of prolonged focus on tracking aircraft movements, consulting, watching the radar, and not drinking water.

The workload-induced fatigue symptom with the highest incidence was feeling tired for all ATCs after work, and feeling thirsty, yawning, and wanting to lie down were also common symptoms. The subjective fatigue symptoms all gave rise to a positive sign after work, and it was supposed that post-work fatigue occurred among the ATCs. Self-reports of degree of liking the music and effectiveness in stress reduction indicate a positive report of music in reducing work stress for air traffic controllers (Lesiuk, 2008). It contributed to the development of a model that aspires to elucidate music and workplace interactions; as well, it had implications for music therapy practice in organizations.

An increase in the critical flicker fusion value and a decrease in the dropping stick time for both female and male subjects demonstrated a better response after work. This indicated that the spirits of the ATCs were still sharp at the end of the work day. Compared with the other tasks, the ATCs most often exercised their concentration to perform tasks during work. This study also found that, in addition to personality-related factors, education was suspected to influence the perception of fatigue. Several research results have implied that higher education levels are associated with higher fatigue levels (Beurskens et al., 2000; Ziino and Ponsford, 2005). Relative to other jobs, an ATC position requires a higher education level. The subjects in this study have either an undergraduate (93%) or postgraduate (7%) degree. Narayan and Krosnick (1996) suggested that highly educated respondents are less likely to satisfice than those with less education, which could help to explain why the outcome of the questionnaire was not consistent with the results of the physiological measurements.

In this study, regarding urine samples before and after work, the average 17-OHCS concentrations were 1.91 ± 1.01 mg/g.cr and 1.50 ± 0.95 mg/g.cr. In urine samples before work, the average 17-OHCS concentration was higher than after work, and was statistically significant ($P < 0.01$). The reason could be in that, urine samples were collected before work at 7–8 o'clock in the morning and 17-OHCS excretion was the top in one day; while collection time after work was one o'clock in the afternoon or seven o'clock in the evening. The results showed that 17-OHCS excretion was reduced, and fatigue caused by work did not increase the 17-OHCS concentration. Regarding the 17-OHCS concentration of urine samples before work, according to different genders, ages, working types, working years, shifts, and sleeping hours, the difference of the urinary 17-OHCS concentrations were not statistically significant; after work, they were not significant. Regarding the age group of 30–39, the urinary 17-OHCS concentration before work was higher than after work, and was statistically significant ($P < 0.01$); according to result of groups of working years, regarding the groups of working years of 5–9 and 10–19, the urinary 17-OHCS concentrations before work were higher than after work, and was statistically significant (P = 0.006 and P = 0.025). Subjects aged 30–39 mostly have 5–9 working years; therefore, the concentration difference is statistically significant. Subjects aged < 30 with working years < 5 might still be at the stages of learning and adaptation, thus, the difference of the urinary 17-OHCS concentration before and after work is insignificant. In addition, groups aged 40–49 and > 50 mostly have working years > 20, meaning they are considerably familiar with their work, thus, the difference of the urinary 17-OHCS concentration before and after work was not statistically significant. According to working types, approach and en-route controllers and field officers had higher urinary 17-OHCS concentrations before work than after work, and the difference was statistically significant. In addition, according to sleeping hours and shifts, although the urinary 17-OHCS concentrations of some groups were statistically significant, it was higher before work than after work, which demonstrated that current ATCs' work model (combination of work stress and rest) might not cause the increase of urinary 17-OHCS concentration, thus, it seemed that fatigue was insignificant.

According to Shiu et al. (1997), who studied the fatigue and the urinary 17-OHCS of bus drivers in metropolitan Taipei, the average urinary 17-OHCS concentrations of the morning shift bus drivers before and after work were 4.36 ± 2.22 mg/g cr. and 5.30 ± 3.10 mg/g cr., respectively., while the average urinary 17-OHCS concentrations of the noon shift bus drivers before and after work were 5.43 ± 2.25 mg/g cr. and 3.15 ± 1.45 mg/g cr., respectively. The urinary 17-OHCS concentrations of the general security guards for company before and after work were 3.48 ± 1.06 mg/g cr. and 1.60 ± 0.66 mg/g cr., respectively. The urinary 17-OHCS concentrations of the ATCs in this study before and after work were 1.91 ± 1.01 mg/g cr. and 1.50 ± 0.95 mg/g cr., respectively. These values were much lower compared to those of other occupations.

It is necessary to understand the physiological characteristics of fatigue in order to measure or evaluate fatigue; however, it is impossible to measure fatigue directly. The consequences of fatigue may be able to point out the symptoms of fatigue, or at least to measure physiological as well as psychological indicators relevant to these symptoms of fatigue. There are a number of indicators that are generally applied in fatigue research, such as cerebral cortical activity level as measured by an EEG, some indicators of vegetative functions, biochemical variables relevant to metabolic changes or endocrine regulation, and channel capacity or perceptual thresholds such as the flicker fusion frequency. However, it remains difficult to draw a generalized conclusion as to the method of selecting the most appropriate test for a given workload.

This study aimed to identify the fatigue experienced by ATCs, thus attempted to capture the ATCs' own perceptions of fatigue by using a two part methodology, including a questionnaire of subjective feelings of fatigue, followed by a series of objective measurements of physiological fatigue. Both methodologies were conducted before and after work to evaluate how fatigue affected and contributed to the cumulative and present workload. The results of this study were discussed in light of their ramifications in the context of future ATC management. This study concluded that the ATCs' subjective ratings showed the possibility of the existence of work-induced fatigue, but the results did not quite correspond to their physiological responses. The ATCs had a relatively higher educational level and were more sensitive to the subjective perception of fatigue than the average workers. Therefore, the fatigue strength was more apparent as suggested by the questionnaire results. Although the ATCs were under a certain level of work pressure due to being responsible for flight safety, their daily working time was shorter (only 6 h) and they could relax for 30 min in the lounge after every 2 h of working. Although sleep taken at work is likely to be short and of poor quality, it still results in an improvement in objective measures of alertness and performance (Signal et al., 2009), Generally they worked only on two shifts (the daytime shift and afternoon shift) and they rarely needed to work at night (there are no fights taking off or landing from 1 to 6 o'clock in the morning). As the subjects of this study were properly rested, it seemed that they avoided the fatigue caused by other factors, such as shift rotation and workload. The comfort level of the working environment and frequency of breaks could effectively reduce the accumulation of work stress. Moreover, the remuneration of the ATCs was two times higher than that of the average job. For the above reasons, the fatigue perception sensitivity, environmental comfort and rest, and even work remuneration were likely to promote the differences between the subjective perceptions and objective measurement results. The subjectively perceived fatigue could only reflect fatigue at the moment of finishing work, and the fatigue accumulated throughout the working day would not be excessive.

5. Conclusions

This study demonstrated that air traffic control is a stressful job, and that complaints regarding excess work stress should be taken seriously. However, it might not be the most stressful occupation in Taiwan as compared with other jobs, such as driving a bus or working as a security guard. A short time of relaxation after ardent stress during work hours is conducive to reduce the stress level and physiological responses. The effect of the number of aircraft handled and the effect of age on fatigue was significant. The findings of this study are expected to improve the awareness of the work and health conditions of ATCs, and contribute to create a healthier workforce. A lower prevalence of fatigued ATCs may lead to lower risks of air traffic accidents, decreased economic loss, increased productivity, and safer aviation for all. Although their managers and supervisors have a supporting role to play, ultimately it is the responsibility of the controller to be aware of fatigue, and to prevent fatigue from affecting their operational performance.

Declarations of interest

None.

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Appendix A. Supplementary data

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References

Abd-Elfattah, H.M., Abdelazeim, F.H., Elshennawy, S., 2015. Physical and cognitive consequences of fatigue: a review. J. Adv. Res. 6 (3), 351–358.
Åkerstedt, T., 1995. Work hours, sleepiness and accidents - introduction and summary. J. Sleep Res. 4, 1–3.
Arvidsson, I., Arvidsson, M., Axmon, A., Hansson, G.A., Johansson, C.R., Skerfving, S., 2006a. Musculoskeletal disorders among female and male air traffic controllers performing identical and demanding computer work. Ergonomics 49, 1052–1067.
Arvidsson, I., Hansson, G.Å., Mathiassen, S.E., Skerfving, S., 2006b. Changes in physical workload with implementation of mouse-based information technology in air traffic control. Int. J. Ind. Ergon. 36, 613–622.
Atkinson, J.M., 1988. Analysis of mental processes involved in air traffic control. Ergonomics 14, 565–570.
Beurskens, A., Bültmann, U., Kant, I., Vercoulen, J.H., Bleijenberg, G., Swaen, G.M., 2000. Fatigue among working people: validity of a questionnaire measure. Occup. Environ. Med. 57, 353–357.
Bisseret, A., 1971. Analysis of mental processes involved in air traffic control. Ergonomics 14, 565–570.
Boksem, M.A., Tops, M., 2008. Mental fatigue: costs and benefits. Brain Res. Rev. 59 (1), 125–139.
Brookings, J.B., Wilson, O.F., Swain, C.R., 1996. Psycho-physiological responses to

changes in workload during simulated air traffic control. Biol. Psychol. 42, 361–377.
Burton, R.R., Storm, W.F., Johnson, L.W., Leverett, S.D., 1977. Stress responses off pilots flying high-performance aircraft during aerial combat maneuvers. Aviat. Space Environ. Med. 48 (4), 301–307.
Chang, F.L., Sun, Y.M., Chuang, K.H., Hsu, D.J., 2009. Work fatigue and physiological symptoms in different occupations of high-elevation construction workers. Appl. Ergon. 40, 591–596.
Costa, G., 1993. Evaluation of workload in air traffic controllers. Ergonomics 36, 1111–1120.
Costa, G., 1999. Fatigue and biological rhythms. In: Garland, D.J., Wise, J.A., VD Hopkin, V.D. (Eds.), Handbook of Aviation Human Factors, pp. 235–255 Mahwah, New Jersey.
Cruz, C., Della, R.P., 1995. Sleep Patterns in Air Traffic Controllers Working Rapidly Rotating Shifts: a Field Study. Final Report DOT/FAA/AM-95/12, Office of Aviation Medicine, Federal Aviation Administration. U.S. Department of Transportation, Washington, D.C.
Cruz, C., Della, R.P., Hackworth, C., 2000. Effects of quick rotating shift schedules on the health and adjustment of air traffic controllers. Aviat. Space Environ. Med. 71, 400–407.
Devanur, L.D., Kerr, J.R., 2006. Chronic fatigue syndrome. J. Clin. Virol. 37, 139–150.
Dussault, C., Jouanin, J.C., Philippe, M., et al., 2005. EEG and ECG changes during simulator operation reflect mental workload and vigilance. Aviat. Space Environ. Med. 76, 344–351.
Friedl, K.E., 2007. What Is behind the Fatigue Concept? NATO Research and Technology Organization, Human Factors and Medicine Panel, RTOMP-HFM-151.
Frone, M.R., Tidwell, M.C.O., 2015. The meaning and measurement of work fatigue: development and evaluation of the three-dimensional work fatigue inventory. J. Occup. Health Psychol. 20 (3), 273–288.
Gander, P., 2001. Fatigue management in air traffic control: the New Zealand approach. Nat. Acad. Sci. Eng. Med. Transport. Res. F Traffic Psychol. Behav.. 4 (1), 49–62.
Gandevia, S.C., 2001. Spinal and supraspinal factors in human muscle fatigue. Physiol. Rev. 81 (4), 1725–1789.
Härmä, M., Kompier, M., Vahtera, J., 2006. Work-related stress and health—risks, mechanisms and countermeasures. Scand. J. Work. Environ. Health 32, 413–419.
Harrison, Y., Horne, J.A., 2000. The impact of sleep deprivation on decision making: a review. J. Exp. Psychol. Appl. 6 (3), 236–249.
Heim, C., Ehlert, U., Hellhammer, D., 2000. The potential role of hypocortisolism in the pathophysiology of stress-related bodily disorders. Psychoneuroendocrinology 25, 1–35.
Hopkin, V.D., 1995. Human Factors in Air Traffic Control. Taylor & Francis, London.
Imbert, J.P., Hodgetts, H.M., Parise, R., et al., 2014. Attentional costs and failures in air traffic control notifications. Ergonomics 57 (12), 1817–1832.
Inoue, S., Furuta, K., Nakata, K., et al., 2012. Cognitive process modelling of controllers in en route air traffic control. Ergonomics 55 (4), 450–464.
International Civil Aviation Organization (ICAO), 2011. Fatigue risk management systems: implementation guide for operators. http://www.icao.int, Accessed date: 11 January 2015.
Karlqvist, L., Tornqvist, E.W., Hagberg, M., Hagman, M., Toomingas, A., 2002. Self-reported working conditions of VDU operators and association with musculoskeletal symptoms: a cross-sectional study focusing on gender differences. Int. J. Ind. Ergon. 30, 277–294.
Lassen, F.C., Mikkelsen, S., Kryger, A.I., Brandt, L.P., Overgaard, E., Thomsen, J.F., Vilstrup, I., Andersen, J.H., 2004. Elbow and wrist/hand symptoms among 6943 computer operators: a 1-year follow-up study (the NUDATA Study). Am. J. Ind. Med. 46, 521–533.
Lesiuk, T., 2008. The effect of preferred music listening on stress levels of air traffic controllers. Arts Psychother. 35 (1), 1–10.
Luna, T.D., 1997. Air traffic controller shiftwork: what are the implications for aviation safety? A review. Aviat. Space Environ. Med. 68 (1), 69–79.
Workplace safety and health guidelines – fatigue management. Ministry of Manpower and WSH Council, 2010. Available from https://www.wshc [Accessed January 30, 2015].
Meyer, R.E., 1973. Stress and the air traffic controller. Revue de Médecine Aéronautique et Spatiale 49, 97–106.
Miller, R.G., 1968. Secretion of 17-OHCS in military aviators as an index of responses to stress: a review. Aero. Med. 39 (5), 498–501.
Mohren, D., Jansen, N., van Amelsvoort, L., Kandt, I., 2007. An Epidemiological Approach of Fatigue and Work. Experiences from the Maastricht Cohort Study. Programma Epidemiologie van Arbeid en Gezondheim, Amersfoort.
Monk, T.H., Carrier, J., 1997. Speed of mental processing in the middle of the night. Sleep 20, 399–401.
Morad, Y., Azaria, B., Avni, I., et al., 2007. Posturography as an indicator of fatigue due to sleep deprivation. Aviat. Space Environ. Med. 78 (9), 859–863.
Mori, E., Maehara, K., Iwata, H., et al., 2015. Comparing older and younger Japanese primiparae: fatigue, depression and biomarkers of stress. Int. J. Nurs. Pract. 21 (1), 10–20.
Nagata, A., Tajima, T., Uchida, M., 2006. Supplemental anti-fatigue effects of cordyceps sinensis (tochu-kaso) extract powder during three stepwise exercise of human. Jpn. J. Phys. Fit. Sports Med. 55 (Suppl. ment), 145–152.
Narayan, S., Krosnick, J.A., 1996. Education moderates some response effects in attitude measurement. Publ. Opin. Q. 60 (1), 58–88.
Reasearch Committee on Industrial Fatigue, 1969. Fatigue Scale by Research Committee on Industrial Fatigue of Japan Society for Occupational Health. Japan Society for Occupational Health, Tokyo (in Japanese).
Rhodes, W., Heslegrave, R., Ujimoto, K., et al., 1996. Impact of Shiftwork and Overtime on Air Traffic Controllers—Phase II: Analysis of Shift Schedule Effects on Sleep, Performance, Physiology and Social Activities (Tech. Rep. No. TP 12816E). Transportation Development Center, Montreal, Canada.
Roske-Hofstrand, R.J., 1995. Raising awareness for fatigue among air traffic controllers. Proc. 8th Int. Symp. Aviat. Psychol. 2, 985–991.
Shiu, H.K., Mao, I.F., Chen, M.L., 1997. Study on Working Fatigue and Urinary 17-hydroxycorticosteroids of City Bus Drivers. Master thesis. National Yang Ming University, Taiwan, ROC.
Signal, T.L., Gander, P.H., Anderson, H., Brash, S., 2009. Scheduled napping as a countermeasure to sleepiness in air traffic controllers. J. Sleep Res. 18 (1), 11–19.
Staal, M.A., 2004. Stress, Cognition, and Human Performance: a literature review and conceptual framework. Nat. Aeronaut. Space Adm NASA/TM-2004-212824.
Stein, E.S., 1991. Evaluating air traffic controllers workload: using real-time person in the loop stimulation. J. Air Traffic Contr. 33, 55–58.
Sudo, N., Ohtsuka, R., 2002. Fatigue complaints among female shift workers in a computer factory of Japan. J. Hum. Ergol. 31, 41–51.
Trapsilawati, F., Qu, X., Wickens, C.D., et al., 2015. Human factors assessment of conflict resolution aid reliability and time pressure in future air traffic control. Ergonomics 58 (6), 897–908.
Wickens, C.D., Mavor, A.S., McGee, J.P., 1997. Flight to the Future. Human Factors in Air Traffic Control. National Academy Press, Washington.
Ziino, C., Ponsford, J., 2005. Measurement and prediction of subjective fatigue following traumatic brain injury. J. Int. Neuropsychol. Soc. 11 (4), 416–425.