ENHANCING NUCLEAR POWER PLANT SAFETY VIA *ON-SITE* MENTAL FATIGUE MANAGEMENT

by

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Nuclear incidents and accidents have occurred at various nuclear power plants. Since some of these incidents and accidents caused by human errors might be preventable, numerous researchers argue that fatigue management for *on-site* workers is the key, especially for mental fatigue. Thus, this study proposes an approach consisting of two mechanisms. A fatigue monitor could identify the mentally fatigued workers by detecting their brain wave rhythms through a brain-computer interface. For such workers, a fatigue alert would awaken them. If the status of the mentally fatigued workers becomes worse, based on a positioning technique (i.e., wireless networks), this mechanism would alert the nearby workers and managers to deal with this condition. The test results indicate that the proposed approach enhanced the capacity to examine the mentally fatigued workers, ensured the accuracy in locating these workers, and avoided possible nuclear incidents. This study is a useful reference for similar applications in the nuclear industry.

Key words: brain-computer interface, electroencephalogram, fatigue, nuclear power plant safety, human error

INTRODUCTION

For decades, nuclear incidents and accidents have occurred at nuclear power plants (NPP) in numerous countries. Two examples are the 1986 Chernobyl (Ukraine) nuclear accident caused by the exploded nuclear reactor, and the 2011 Fukushima Daiichi (Japan) nuclear accident caused by core meltdowns because of an earthquake and the associated with tsunamis [1]. Depending on the International Nuclear Event Scale [2] classification, both accidents reached the worst level (*i. e.*, Level 7). Also, several nuclear incidents and accidents included the 1979 Three Mile Island (United States) nuclear accident, the 1997 and 1999 Tokaimura nuclear accidents (Japan), and the 2003 Paks nuclear incident (Hungry) [3]. Whether these incidents and accidents were caused by natural hazards or human-made factors (*e. g.*, incorrect decision making), ensuring the safety of NPP is important.

In contrast to natural hazards, human-made factors for nuclear incidents could be prevented although NPP are complicated socio-technological systems. Based on various studies, more than 50 % of nuclear incidents are caused by personnel mistakes [4]. These mistakes result from combinations of many causal and situational factors such as workplace conditions (*e. g.* dark, narrow), human physical conditions (*e. g.* fatigued, inattentive), plant situation, and human interface [5]. Moray (1988) argued that optimizing the mental workload allocation could reduce human errors, improve system safety, and increase user satisfaction [6]. In other words, mental fatigue management for on-site workers is a key to the safety of NPP.

To avoid nuclear incidents caused by mentally fatigued workers, this study proposes an approach including two mechanisms. Associated with the brain-control interface (BCI), a fatigue monitor mechanism is used to detect the brain wave rhythms of on-site workers. When this mechanism identifies the workers suffering from mental fatigue, a fatigue alert mechanism is triggered to awaken the workers. Meantime, based on a positioning technique (*i. e.*, wireless networks), the alert mechanism could deliver the alarms and the details (*e. g.*, names, areas, phone numbers) of these fatigued workers to the nearby workers and managers. Those workers and managers, then, could move to the mentally fatigued workers and deal with the situation (*e. g.*, asking the mentally fatigued workers to take a rest). The safety of NPP would be enhanced, while the on-site mental fatigue risks could be managed. This study could serve as a useful reference for mental fatigue management in the nuclear industry.

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LITERATURE REVIEW AND PROBLEM STATEMENT

Shiftwork is common at NPP. *On-site* workers must maintain high efficiency and reliability of their professional performance at any time of day or night [4]. However, for these workers, the consequences of the sleep disorders lead to physical (defined as a painful phenomenon associated with overstressed muscles) and mental (defined as a sensation of weariness) fatigue, lapses of attention, loss of concentration, compromised quality of life, and accidents at work [7, 8]. Also, some researchers described that human errors are exacerbated in the night shifts, especially during the period from AM 3:00 to 6:00 [9]. Since mental fatigue affects physical fatigue in humans, to examine the mentally fatigued workers, two approaches are available: objective and subjective measurements [10].

For objective measurements, through the quantitated physiologic signals of the workers, the state of workers' mental fatigue could be recognized. For example, when a human suffers from mental fatigue, eye blinking becomes slow. Various measurements include the electroencephalogram (EEG), which is a record of voltage difference between various points on the head surface; electrocardiography (ECG), which determines the electrical activity within a heart; electrodermal activity (EDA), which measures electrical phenomena on the skin; electrooculography (EOG), which identifies the movement of the eyeballs; and electromyography (EMG), which is a diagnostic procedure to assess the health of muscles and the nerve cells that control them [11].

Subjective measurements mainly depend on questionnaires that evaluate personal experience regarding the mental fatigue, based on self-feelings. For instance, Smith *et al*. [12], investigating the health of 609 shift workers via a questionnaire, reported that the workers perceived that physiological fatigue, stress level, and general health influenced their tolerance for shift work. The available methods include Cumulative Fatigue Syndrome Index (CFSI), Fatigue Assessment Inventory (FAI), Fatigue Index Score (FIS), Multidimensional Fatigue Scale (MFS), Multiple Resource Questionnaire (MRQ), NASA Task Load Index (NASATLX), Swedish Occupational Fatigue Inventory (SOFI), Visual, Auditory, Cognitive, Psychomotor (VACP), and Workload Index (W/Index) [10, 11].

In contrast to subjective measurements, objective measurements may offer more reliable data [10]. Whether applying objective or subjective measurements, the results help NPP managers to establish various strategies for *on-site* mental fatigue management. These strategies include planning shift schedules, auditing working performance, offering team assistance, forming organizational safety beliefs, holding regular training, and developing pre-alarm mechanisms [13].

Recently, the fitness for duty (FFD) program has been used to audit performance impairment due to alcohol, drugs, fatigue, and illness at NPP [14]. Regarding fatigue risks, several studies also investigated the relationship between the causes and safety management. However, these studies performed the measurements as the participants were before or after their working time. Very few focused on managing mental fatigue of *on-site* workers during work time. More importantly, in contrast to physical fatigue, detecting mental fatigue of *on-site* workers is more difficult. To address this problem, constructing an information system to prevent nuclear incidents caused by mentally fatigued NPP workers in real time, has become more and more important.

APPROACH

To comprehend who and where the mentally fatigued workers are, this study develops two mechanisms: a fatigue monitor and a fatigue alert.

The brain is the foundation of human cognition. By comparing the voltage fluctuations resulting from ionic current flows within the neurons of a brain, four types of brain wave rhythms could be specified: delta (*i. e*., during sleep), theta (*i. e*., accompanied with a variety of psychological states, such as hypnologic imagery), alpha (*i. e*., an alert and relaxed state), and beta (*i. e*., during the reaction-time motor tasks) [15]. The working frequencies of the four rhythms are 1-4, 4-8, 8-13, and 13-30 Hz, respectively. Prior studies revealed that the occurrence of the alpha rhythm gradually increases, especially the lower alpha rhythm (8-10 Hz), when a person becomes mentally fatigued [16]. To inspect such physiological appearances of on-site workers, this study uses a portable headset BCI device [17] (fig. 1) in the proposed approach. Given the international ten-twenty electrode system in EEG [18], this device retrieves the brain wave rhythms from the left side of the forehead (defined as the FP1 electrode) of a worker, which has the best discrimination for the captured results of the alpha rhythm. Thus, the fatigue monitor would process the information exchange with the BCI device.

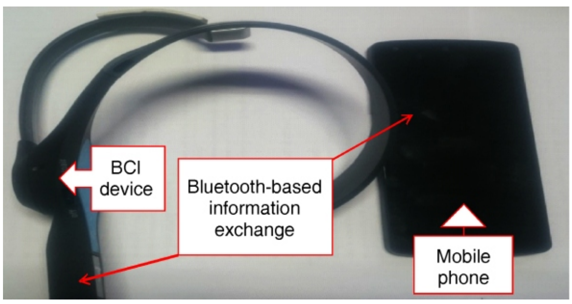

Figure 1. Devices used in the proposed approach

After the mentally fatigued workers could be identified, the fatigue alert mechanism should attempt to change the mental status of such workers, such as generating sounds to notify them. Meantime, this mechanism must learn the locations of these workers. The available positioning techniques include global positioning systems (GPS), ultra wide band (UWB), radio frequency identification (RFID), and wireless networks [19]. In contrast to the GPS used at outdoor environments, UWB needing additional equipment for information communication, and RFID (similar to UWB), wireless networks-based positioning technique, is more appropriate for the proposed approach, since *on-site* workers stay at indoor offices associated with the configured wireless networks. Considering that carrying heavy devices is inconvenient for the workers, this study develops the fatigue monitor mechanism and the fatigue alert mechanism in Google Android-based mobile phones (fig. 1).

Figure 2 shows the flowchart when the two mechanisms are applied at NPP. Since *on-site* workers wear the BCI devices, their brain wave rhythms are acquired. As fig. 3 shows, because of the fatigue monitor mechanism, the mobile phones would wirelessly receive the data from the BCI devices through Bluetooth transmission and immediately analyze the data. For a worker, when the amount of the occurred lower alpha rhythm reaches 120 times in three minutes, the fatigue alert mechanism is triggered. To awaken the mentally fatigued worker, this mechanism shocks the mobile phones and plays warning sounds. If the status regarding mental fatigue of this worker continues (*i. e.*, the amount of the occurred lower alpha rhythm reaches 200 times within five minutes), the fatigue alert mechanism transfers alarms to the nearby workers and managers. Accompanying the Google Maps, the delivered alarms detail the name, location, phone number, and emergency contact person of the mentally fatigued worker (fig. 4). These workers and managers, then, are able to respond to the worker suffering mental fatigue.

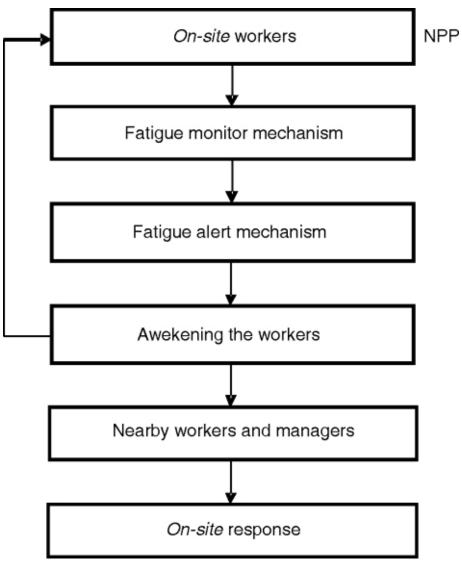

Figure 2. Flowchart for the proposed approach

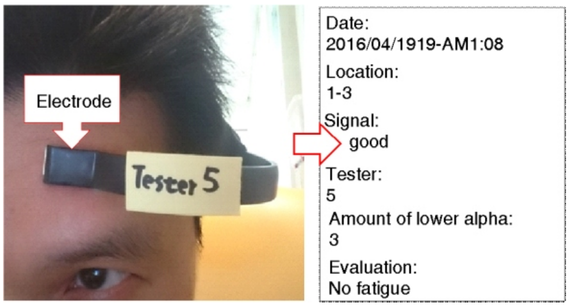

Figure 3. Analyzing brain wave rhythms in real time

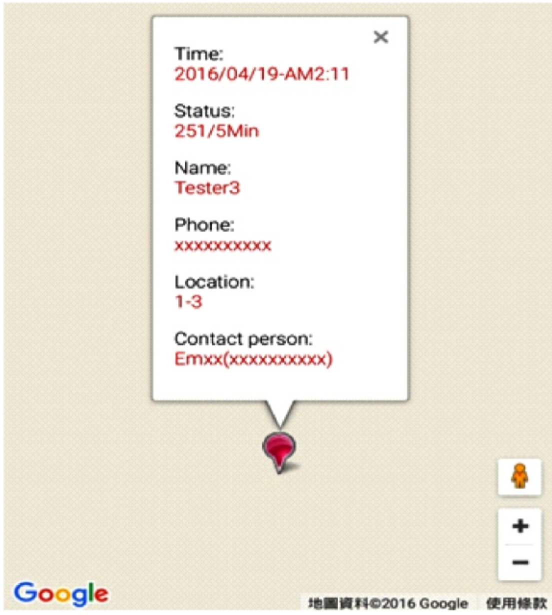

Figure 4. Identifying the *on-site* mentally fatigued worker

TESTS

To understand the efficiency of the proposed approach, this study performed several tests. During a one-month period of the night shift from a. m. 0:00 to 8:00, ten participants working in the NPP control rooms tested two measurements: the visual observation and the proposed approach. For the visual observation, every worker inspected whether the nearby workers suffered from mental fatigue. The two measurements were executed every two weeks. Table 1 shows the results.

– Identified mental fatigue: In the visual observation, 3 and 3 cases regarding mental fatigue were identified in the first and second weeks. For the proposed approach, two phases were defined. In Phase 1, the fatigue alert mechanism merely awakened the mentally fatigued workers recognized by the fatigue monitor mechanism. During Phase 2, for the identical workers, since their mental fatigue had become worse, the nearby workers and managers received alarms. According to tab. 1, the total amount of the mental fatigue in the Phase 1 was 397 cases (*i. e.*, 185 and 212 cases in the third and fourth weeks, respectively) and in Phase 2, 203 cases (*i. e.*, 91 and 112 cases in the

Table 1. Results of the test

Identification and checking	Visual observation		Proposed approach			
	1st week	2nd week	3rd week		4th week	
			Phase 1	Phase 2	Phase 1	Phase 2
Identification and checking	3	3	185	91	212	112
Identified mentol fatigue	2	1	–	60	–	87
Checked ongoing activities	0	1	–	3	–	2

third and fourth weeks, respectively). Obviously, the proposed approach detected more cases than did the visual observation approach. Such results indicated that the visual observation might be inappropriate for *on-site* mental fatigue management; and the cases of mental fatigue could be decreased when the alert mechanism notified the fatigued workers.

– Investigated subjective feelings: To understand the difference between the test results and the subjective feelings, this study interviewed the mentally fatigued workers identified in the visual observation and the proposed approach. For the visual observation, three cases regarding the mental fatigue were verified (*i. e.*, two and one cases in the first and second weeks, respectively). In Phase 1 of the proposed approach, this study did not inspect the subjective feelings. Regarding Phase 2, the alarms transferred by the fatigue alert mechanism correctly illustrated the locations of the mentally fatigued. Meantime in this phase, the workers agreed with the 147 cases regarding the mental fatigue (*i. e.*, 60 of 91 cases regarding the mental fatigue identified by the approach in the third week, and 87 of 112 cases in the fourth week). Thus, in contrast to the visual observation, the proposed approach was more accurate in identifying mental fatigue.
– Checked ongoing activities: When the aforementioned mentally fatigued workers were confirmed, this study audited the activities that these workers were performing so as to examine the potential of nuclear incidents. Regarding the visual observation and Phase 2 of the proposed approach, one case (*i. e.*, in the second week) and five cases (*i. e.*, three in the third week and two in the fourth week) might have led to nuclear incidents. The main condition was that the mentally fatigued workers missed some records when filling in required reports based on standard operating procedures. Since the proposed approach than visual observation identified more cases, than visual observation, regarding the mental fatigue, possible nuclear incidents could be avoided.

DISCUSSION

Results of the tests clearly indicate that the proposed approach succeed in identifying the mentally fatigued workers and their locations. More importantly, this approach was able to monitor various workers synchronously and objectively. However, four main limitations still need advanced improvement:

– Measured specification for the mentally fatigued workers: Since this study examined the potential of applying BCI in detecting workers suffering from mental fatigue in real time, the appropriately triggered values for the fatigue monitor and the fatigue alert mechanisms were not investigated. Such values would affect the sensitivity of the proposed approach, which should be defined in the further studies.
– Comparison of various brain wave rhythms: After reviewing 17 studies, Craig *et al*. [20] argued that the changes of the delta, theta, alpha, or beta rhythms contribute to mental fatigue in humans. Since most of the 17 studies displayed a significant relationship between increased alpha rhythms and detected mental fatigue, this study focused on this particular indicator. To increase the efficiency of the proposed approach for on-site mental fatigue management, comparing the relationship between the different brain wave rhythms and the mentally fatigued workers, would be beneficial.
– Usage of the BCI device adopted in the proposed approach: During this study, numerous factors interrupted the information transmission between the BCI devices and the mobile phones, such as excessively shaking heads, insufficient power supplies, and suddenly popping up messages with numerous applications in the mobile phones. Moreover, some participants in this study claimed that wearing the BCI devices was uncomfortable. If participants carelessly adjust those devices so that the electrodes are not in the correct place on their foreheads, the accuracy of the proposed approach would be affected. These conditions could be revised in the future.
– Distribution of delivered alarms: Because of the wireless networks-based positioning technique, the fatigue alert was able to deliver alarms to the workers and managers nearby the mentally fatigued workers. However, several workers and managers may synchronously receive the identical alarms. If all of the workers and managers move to assist the same mentally fatigued workers, time and resources may be abused. That requires further modification.

CONCLUSIONS

Unlike studies investigating the relationships of causes, mentally fatigued workers, and nuclear incidents, this study focuses on identifying the workers suffering from mental fatigue in real time before nuclear incidents occur. In the proposed approach, two mechanisms were developed to detect who and where the mentally fatigued workers were. A fatigue monitor mechanism acquired the brain wave rhythms of *on-site* workers to evaluate their mental fatigue. When such workers were identified, a fatigue alert mechanism automatically awakened them. If the targeted mental fatigue continued, this mechanism delivered the details of the mentally fatigued workers to nearby workers and managers. Results of the tests confirmed that the proposed approach was able to detect the workers suffering mental fatigue, address their locations, and decrease the potential of nuclear incidents. In sum, this study demonstrated an approach to help *on-site* mental fatigue management at NPP worldwide.

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УНАПРЕЂЕЊЕ СИГУРНОСТИ НУКЛЕАРНЕ ЕЛЕКТРАНЕ ПОМОЋУ УПРАВЉАЊА МЕНТАЛНИМ ЗАМОРОМ НА РАДНОМ МЕСТУ

Нуклеарни инциденти и акциденти дешавају се на разним нуклеарним електранама. Пошто се неки од тих инцидената и акцидената који су изазвани људским грешкама могу спречити, бројни истраживачи тврде да је кључно управљање замором радника на радним местима, посебно менталне исцрпљености. Стога, ова анализа предлже приступ који се састоји од два механизма. Монитор замора може идентификовати ментално заморене раднике откривањем ритмова њихових можданих таласа преко мождано-рачунарског посредника. Такве раднике упозорење на замор може пробудити. Ако се стање ментално уморних радника погоршава, овај механизам заснован на техници позиционирања (то јест, бежичној мрежи), упозориће околне раднике и руководиоце да разреше овакво стање. Резултати теста показују да предложени приступ побољшава могућности да се провере ментално заморени радници, обезбеђује течност у проналажењу ових радника и избегну могући нуклеарни инциденти. Ова студија је корисна референца за сличне примене у нуклеарној индустрији.

Кључне речи: мождано-рачунарски посредник, електроенцефалограм, замор, сигурност нуклеарне електране, људска грешка