Effects of physical fatigue on the induction of mental fatigue of construction workers: a pilot study based on a neurophysiological approach

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Abstract: Within a dynamic and complex working environment, fatigue statuses (involving physical and mental fatigue) of workers on construction sites tend to have a more serious impact on work performance than general workplaces. To improve safety management on sites, valid fatigue management measures for workers are urgently required. Specifically, there are construction activities requiring both physical and cognitive effort. As a critical premise for putting forward feasible fatigue management measures, correlations between physical and mental fatigue on work performance should be identified. This research explored the effects of physical fatigue on the induction of mental fatigue of construction workers, by adopting a pilot experimental method. Manual handling tasks of different intensities were firstly designed for stimulating certain expected physical fatigue statuses. A cognition-required risk identification task was then arranged for inducing mental fatigue, during which a wearable electroencephalogram (EEG) sensor was utilized for fatigue detection and measurement. Through a comprehensive data analysis method based on EEG rhythms, it was found that the high physical fatigue can significantly accelerate the induction of mental fatigue. Considering the resource allotment, more vigilant and attentional resources were required during the intensive manual handling tasks for the highly controlled limbs and the mind to steps. Thus, additional resources were invested to maintain the same level of cognitive performance in the risk identification tasks, which led to the increased mental fatigue. In practice, the heavy physical task can be regarded as one of the factors affecting the development of mental fatigue status, and therefore impairing cognitive functioning and other mental performances of the brain. The pilot study results provided a reference for fatigue management of construction workers to promote comprehensive safety management on construction sites.

Keywords: Construction activity; Physical fatigue; Mental fatigue; Correlation and influence; Pilot experiment

1 Introduction

Construction is a dynamic and complicated process with unique working conditions. Risk events occur frequently due to various risk factors, which can consequently lead to safety accidents and property loss. According to statistics from the Ministry of Housing and Urban-Rural Development of China, there were 581 safety accidents with 673 fatalities in the Chinese construction industry in the first three quarters of 2018. To reduce potential risks and improve safety on construction sites, initiatives for establishing comprehensive management systems have been encouraged. Regulations on construction worker management have received greater attention. For example, for special operation personnel in the construction industry, formal occupational training, compliance certification, and physical examinations are required prior to commencing work. Further, regulatory compliances aimed at the construction process (e.g., wearing personal protective equipment and following specific construction procedures) are proposed [1]. In addition to above management practices, construction workers require constant alertness and attention on their surrounding dynamic construction site environment to recognize potential risks and prevent accidents and injuries. Resulting from excessive workload, a worker is prone to carry out construction activities under the fatigue status with a poor cognitive condition, such as slowed reaction time, reduced vigilance, reduced decision-making ability, task distraction, and loss of situational awareness [2]. Cognitive failure led by fatigue can lead to unsafe behaviors of workers. Further, the low work quality and productivity and the increased risk occurrence probability can be contributed [3-4]. However, existing efforts on the fatigue management of construction worker, which closely related to several risk-related outcomes, were relatively limited.

Depending on the types of fatigue, the ways it leads to risk-related outcomes can be summarized as two main categories. (1) "physical fatigue -> cognitive failure -> risk-related outcomes": Physically-demanding tasks are typical during the construction phase. Intensive physical work is prone to physical fatigue of workers, along with poor judgment to the dynamic environment and involved hazards. Overexertion in construction activities has become one of the leading causes of occupational injuries among building construction workers [5]. (2) "mental fatigue -> cognitive failure -> risk-related outcomes": In particular, some construction workers (e.g., electricians and scaffolders) also experience intensive cognitive demands in practical construction activities. A clear mental status is required to maximize work performance and ensure construction safety. Due to perpetual cognitive demands within constrained timeframes, incremented cognitive load can easily lead to mental fatigue [6]. Mental fatigue is a critical factor leading to cognitive performance decreasing (e.g., the occurrence of change blindness, inattentiveness, and lapses in vigilance), which consequently weakens workers' ability in recognizing potential risk factors in surrounding construction environments [7-8].

As construction site is more dynamic and riskier than general workplaces, impacts of workers' fatigue on work performance can be more serious. Thus, it is necessary to adopt valid fatigue supervision and management approaches for measuring, mitigating, and managing workers' fatigue, which can help to promote comprehensive safety management on construction sites. As for construction activities executed requiring both physical and cognitive effort, one of the critical premises is identifying interactions between physical fatigue and mental fatigue on work performance. This research focused on the development of mental fatigue in a cognitive task (doesn't involving intensive cognitive load) under different physical fatigue levels. That is, weather physical fatigue has effects on the induction of mental fatigue of construction workers was explored. It was valuable for analyzing and deriving the interaction rules between physical fatigue and mental fatigue and the mechanisms underlying the development of fatigue. Further, targeted recommendations for fatigue management can be proposed to promote comprehensive safety management on construction sites. This was the starting point of this research.

For above research objective, a pilot experiment involving a series of independent trials was conducted in a laboratory setting. During these trials, manual handling tasks of different intensities were firstly arranged for stimulating certain expected physical fatigue statuses. Then, a cognition-required risk identification task was designed to induce mental fatigue statuses. One of the major considerations in the experimental design was how to measure the physical and mental fatigue intuitively and quantitatively. Borg's Rating of Perceived Exertion (RPE) was utilized in this research for detecting the level of physical fatigue [9]. A wearable electroencephalogram (EEG) sensor was utilized to collect the neural information required for the mental fatigue detection and measurement. Through intra-group comparisons between different independent trials, effects of physical fatigue on the induction of mental fatigue were identified from the experiment results. Finally, recommendations for improved fatigue management of construction workers were proposed based on the research results.

2 Related research

2.1 Fatigue management

Fatigue is a common but noteworthy phenomenon in various workplaces, resulting from intensive manual labor or mental exertion. Without a universal definition, fatigue is broadly regarded as a complex and multidimensional outcome from the lassitude/exhaustion of physical or mental strength [10]. The occurrence of fatigue status, along with decreased motivation and vigilance [11], can consequently become an important factor contributing to the increased probability of accidents and injuries [12]. Thus, well-rested physical status and alert mental status are critical for workers in workplaces, to prevent errors and accidents and to maximize work performance.

Fatigue-related studies have been conducted in a wide variety of domains. For example, Antwi-Afari et al. (2017) analyzed work-related musculoskeletal disorders of construction workers and summarized corresponding risk factors in repetitive lifting tasks [13]. Consequently, specific and targeted fatigue management measures have been proposed for improving workforce physical and mental health in practice. Dababneh et al. (2001) studied the effect of rest breaks on meat-processing workers, and suggested hourly breaks of nine minutes for reducing work fatigue [14]; Lerman et al. (2012) highlighted five key defenses against fatigue errors in workplaces (i.e., balance between workload and staffing; shift and duty scheduling; employee training and education and sleep disorder management; work environment design; and individual risk assessment and mitigation) [2]; Merat and Jamson (2013) proposed a series of road-based fatigue management measures, as engineering treatments, to alleviate driver fatigue symptoms [15]. Xing et al. (2019) proposed a multicomponent and neurophysiological intervention approach aiming at the mental fatigue status of high-altitude construction workers [16].

Construction activities involve a series of workload-intensive and risk-sensitive tasks, for which more stringent requirements about physical and mental status of construction workers are needed to manage work performance (e.g., workers' safety and health, construction quality and productivity). Researchers have increasingly focused on the physical/mental statuses of construction workers. Parijat et al. (2008) found that localized muscle fatigue of the quadriceps can increase the risk of slip-induced falls, through a contrast experiment requiring participants to walk across a vinyl floor surface in a fatigued (or non-fatigued) state [17]. Chen et al. (2016) studied the method of monitoring mental conditions of construction workers to evaluate hazards, and validated neural time–frequency analysis as a novel measurement approach [18]. Wang et al. (2017) proposed a quantitative and automatic method to assess construction workers' attention level using a wireless and wearable electroencephalography system [19]. Aryal et al. (2017) developed a physical fatigue monitoring method by utilizing a series of wearable sensors (i.e. an EEG sensor, a heart rate monitor, and infrared temperature sensors). Based on the biological data obtained from these sensors, boosted tree classifiers were trained and utilized for physical fatigue detection [9]. Fang et al. (2015) designed an experiment to test different categories of errors made by workers in a physically fatigued state, and the experimental results illustrated the impact of physical fatigue on construction workers' safety performance [20]. Based on the literature review, it is noted that prior research has mainly focused on fatigue/mental status detection and its effects on work performance or safety outcomes. Few efforts have focused on improving the fatigue management of construction workers. In practice, fatigue management of construction workers is still a relatively weak area in safety management on sites, with a need for comprehensive, differentiated, clear, and feasible management regulations and measures.

2.2 Correlations of physical and mental fatigue

Fatigue has been well-accepted as a concept and was usually described as physical fatigue and/or mental fatigue in existing literature [9]. Physical fatigue is widely described as the reduction in capacity to perform physical work, resulting from activities requiring physical effort [21]. Mental fatigue is a universal phenomenon and results from prolonged periods of task-demanding mental activity (e.g., cognitive tasks), which can be subjectively described as a mental status of feeling tired or inactive [22]. Mental fatigue has been regarded as a key factor impacting work performance, which is closely linked with low work efficiency, increased risk of error, and even chronic and life-threatening issues [23]. Based on the literature review in section 2.1, most of existing fatigue-related studies focused on either physical fatigue or mental fatigue in certain research fields. Taking physical fatigue and mental fatigue as independent variables, different fatigue monitoring indicators were proposed and applied.

The construction site is a workplace that has specific requirements in managing workers' physical and mental fatigue status. Construction workers are often required to perform physically-intensive tasks in challenging environmental conditions, and need to stay focused and alert in recognizing risk factors within surrounding environment to avoid potential risk events. Further, there are many types of construction activities requiring both intensive physical and cognitive effort (e.g., construction activities involving technical tasks and requiring specialist skills). Generally, these construction activities not only require workers to perform physical functions to execute tasks using physical strength, but also perform cognitive functions to plan and complete tasks at the same time [24]. Thus, the association and interaction between physical and mental fatigue should be considered in the management of construction worker fatigue.

Recently, the number of studies on the relationships between physical and mental fatigue/performance has increased in various research domains. For example, focusing on the effects of mental fatigue on physical fatigue/performance, Mehta and Parasuraman (2014) investigated the contribution of mental fatigue on the development of voluntary physical fatigue using a neuroergonomic approach [25]. Zhang et al. (2015) studied the association between fatigue status and performance in physical and cognitive functions by surveying 606 construction workers, suggesting an association between reported fatigue and difficulties with physical and cognitive functions [26]. Van Cutsem et al. (2017) explored the effects of mental fatigue on the endurance performance of athletes in heat conditions through a pilot experiment, and reported that no negative effect of mild mental fatigue was observed on the physiological and perceptional responses to endurance performance

[27]. Pageaux et al. (2015) confirmed the relationships between mental fatigue and the performance of the vastus lateralis muscle during cycling, reflected in the electromyography root mean square value [28]. Van et al. (2017) reviewed existing research on the effects of mental fatigue on physical fatigue/performance in a variety of domains through a systematic review of literature [29]. Focusing on the effects of physical fatigue on mental fatigue/performance, Moore et al. (2012) confirmed the effects of exercise-induced fatigue on cognitive function through a series of tests (i.e. visual perceptual discrimination test, memory-based vigilance test, and visual perceptual discrimination test) [30]. Bullock and Giesbrecht (2014) investigated the influence of physical activity-induced arousal and fatigue on selective attention and cognitive performance in a laboratory environment [31]. Loy and O'Connor (2016) confirmed that histamine, acting on brain H_1 receptors, had a role in reducing mental fatigue induced through exercise [32]. Olson et al. (2016) suggested the divergent effects of aerobic exercise on behavioral performance and cognitive control, by conducting Eriksen flanker task tests while exercising on a cycle ergometer [33]. DiDomenico and Nussbaum (2011) studied the effects of various types of physical activity on mental workload and cognitive performance adopting heart rate variability and visual analog scale [34]. Based on above research, interactions (including the causality) between two kinds of fatigue in certain conditions were explored and proved, and knowledge on the potential mechanisms underlying the development of fatigue was extended.

According to above research review, most research focused on the influences of mental fatigue on physical performance. Targeted fatigue management measures and suggestions have been proposed. For example, mentally-demanding tasks should be avoided before physical tasks that require endurance to optimize performance [35]. In the construction industry, a limited number of studies have paid attention to the effects of physical fatigue on construction workers' safety performance [20]. This includes the study of monitoring methods aimed at the fatigue and mental workload of construction workers (e.g., utilizing physiological measurements) [9][18]. However, it is noted that only a limited number of existing studies focused on the relationships between physical and mental fatigue/performance in the construction industry. Further, few attempts have been made to examine the correlation and influence mechanisms between physical fatigue and mental fatigue of construction workers, considering the specific work characteristics of construction activities. As such, the effects of physical fatigue on the induction of mental fatigue are still unclear, constraining the development of comprehensive and differentiated fatigue management measures on construction sites.

2.3 Physical and mental fatigue recognition

The measure and quantification of fatigue is one of the critical issues in fatigue assessment for improving fatigue management. Questionnaire and interview survey, using assessment scales relied on subjective evaluation, are the most common approaches applied in fatigue related studies [20]. Considering the physiological changes and interactions of some local (e.g., muscular) and central factors (e.g., cardiovascular, metabolic, thermoregulatory changes) of workers during the physically-demanding tasks, physiological measurements have been gradually applied in physical fatigue measurements [9][36]. For example, surface electromyography has been used in some studies for monitoring localized muscular fatigue of different industrial workers, focusing on specific muscle groups [37-38]. Besides, overall physical fatigue has been explored using comprehensive physiological measurements (e.g., heart rate, blood pressure, oxygen uptake, and thermoregulatory changes) [9][39-40]. Combined with environmental conditions, location information, characteristics of specific construction activities, and other related factors, different wearable sensors have been utilized to detect and warn a worker's physical fatigue by collecting physiological data [40-41].

Mental fatigue can be manifested subjectively, behaviorally, and physiologically, which a person can change to some extent, such as a significant increase in subjective fatigue levels (e.g. feelings of tiredness, reduced alertness and motivation) [42], acute changes as a physiological response [43], and the decline in cognitive performance [44]. Many mental fatigue recognition and measurement approaches have been applied in prior research based on these manifestations. For example, Shahid et al. (2011) proposed the Fatigue Severity Scale (FSS) with nine items to assess fatigue, which was regarded as a symptom of chronic conditions and disorders [45]. By investigating the effects of fatigue statuses in different aspects, the degree of fatigue can be assessed using the FSS. More recently, some studies have examined mental fatigue by considering the neural mechanisms of the brain. For example, Ishii et al. (2014) proposed a conceptual model using a dual regulation system to investigate the neural mechanisms of mental fatigue under cognitive tasks [46]. Especially, electroencephalography (EEG) has been used to quantitatively detect and measure the electrical activity of the brain, overcoming the subjective bias from traditional survey-based assessment [47]. There are two general techniques for EEG measurement: the electrocorigram and the electrogram [48]. As the former technique can collect EEG data directly and noninvasively, based on voltage fluctuations from neurons at the cortical surface, it is much more commonly used in current EEG studies [49]. There is a growing interest in the role of EEG in the detection and measurement of mental fatigue. For example, Li et al. (2012) proposed an EEG processing method to evaluate driver fatigue effect [50]; Duc (2014) utilized functional magnetic resonance imaging (fMRI) and EEG to investigate the mechanics of mental fatigue regulation in specific brain areas [51]; Yin and Zhang (2018) presented a mental fatigue classification method by different EEG feature distributions through various mental tasks [52]. As EEG objectively measures the neural mechanisms, the research results on mental fatigue can provide a robust theoretical foundation for practical fatigue management.

3 Methods

A pilot experiment, involving a series independent trials, was designed and conducted to investigate the effects of physical fatigue on the induction of mental fatigue. Expected physical fatigue statuses at different levels were stimulated in an indoor laboratory. Then, corresponding mental statuses were induced through a cognition-required task. In this experimental procedure, EEG was adopted to indicate and measure the mental fatigue statuses of subjects, instead of relying on subjective survey-based self-assessments that have been used in prior research. After data preprocessing, a comprehensive data analysis method using EEG rhythms was applied. Effects of different physical fatigue levels on mental fatigue-related mental statuses were explored through intra-group comparisons of different trials.

3.1 Experiment design

For testing the development of mental fatigue under the influence of physical fatigue at different levels, an experiment consisting of four mutually independent trials (i.e. trial 1~4) was adopted in this research (Fig. 1). Each trial included three major phases: physical fatigue stimulation (respectively with different physical task intensities), mental fatigue inducing, and EEG collection. Four trials of a subject were performed in the same day to reduce interferences of other factors. Adequate breaks were provided between every two trials for recovering from the generated fatigue. Details of the designed experiment process and involved experimental tasks were presented as follows.

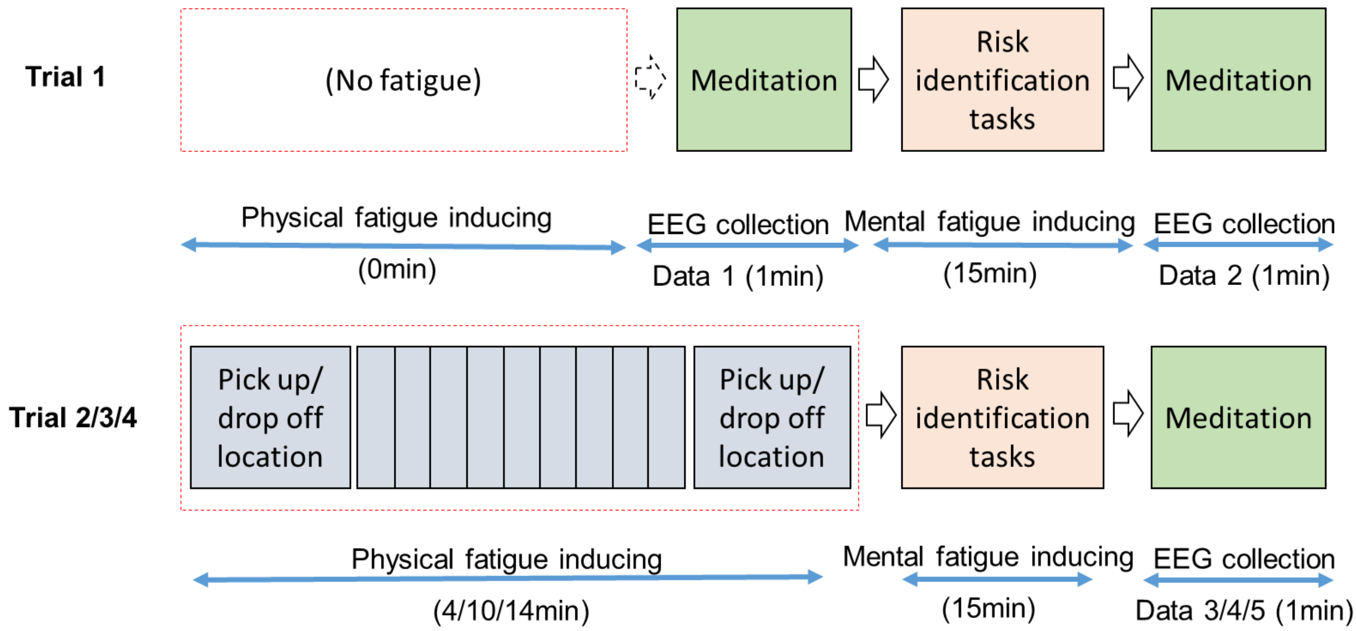


Fig. 1. The entire experiment process designed with four independent trials.

- Physical fatigue stimulation: For stimulating subjects' expected physical fatigue statuses, a manual handling task transporting heavy materials (15 kg), in a squatting posture when lifting up and laying down the materials, is adopted in this research simulating the actual construction work [9][20]. To replicate the dynamic and hazardous environment of construction sites (e.g., uneven ground with material and sundry stacking), subjects are tasked to carry materials up and down stairs, for which vigilance and close attention is required to carefully mind steps [53].
- Mental fatigue inducing: Considering the specific characteristics of the construction workplace, risk perception is important for workers to accurately and rapidly identify hidden risk factors on sites. To test the development of mental fatigue under different physical fatigue levels, a recognition-required risk identification task is adopted in this research. This mental fatigue inducing phase is designed based on a series of pictures of practical construction sites. Twenty percent of the picture sets comprise the targeted pictures (with particular construction scenes involving potential risks). The trial involved different pictures appearing, in turn, on a computer screen at a regular interval (4 seconds). Under these mentally demanding conditions, subjects are required to focus on, identify and judge the targeted pictures from picture sets one by one.
- EEG collection: After the recognition-required risk identification task of each trial, an EEG sensor is used to record the subjects' mental status for one minute. In this research, a wearable EEG device (i.e. the EMOTIV EPOC+ 14 Channel Mobile EEG), which has 14 electrode channels corresponding to different locations of the scalp, is utilized (Fig. 2). Raw EEG data can be transferred in real-time via a wireless receiver, at a 128 Hz sampling frequency. During the EEG collection phase, subjects are required to sit still restricting body movements and be in a meditative state with eyes closed. In this way, the EEG signals can be measured and collected without excessive noise due to external signal interference.

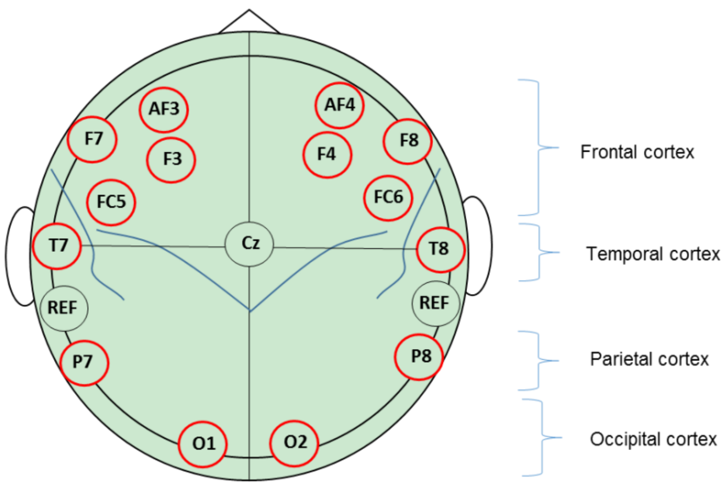


Fig. 2. Objective electrode channels in four cortical regions (i.e. AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4).

3.2 The pilot study and data collection

3.2.1 Protocol and preliminary training

In this research, nine healthy people aged 25-40, were recruited from the Hong Kong Polytechnic University to be subjects in the experiment. To ensure the accuracy and credibility of the experiment results, an experiment protocol was developed in advance with all necessary requirements and preparation instructions. First, the protocol required all subjects to be in good physical health and free from mental illness (i.e. without neural diseases history and medicine uptake that might affect brain functions). Second, subjects should have basic engineering expertise and construction experience on sites (e.g., majoring in civil engineering construction, engineering management, or other related majors; having internship/working experience on construction sites). Through a pre-study interview, subjects reported their own conditions and were determined if meeting all requirements. Considering the learning effects [54-58], all subjects were introduced to a pre-training session before the main experiment. The entire experiment procedure was firstly introduced to subjects. Besides, instructions regarding which were the targeted pictures in the risk identification tasks and how to point out the involved potential risk factors were given. During the pre-training session, another four picture sets of practical construction sites, other than the picture sets used in the main experiment, were presented to each subject. Behavioral performances and self-reports of subjects in the pre-training session were collected for optimizing the experimental procedure.

3.2.2 Experiment procedure

The experiment was arranged in an indoor laboratory at the Hong Kong Polytechnic University. In Trial 1, 1min EEG signal (i.e. data 1) was firstly collected before the risk identification task, acting as the experiment baseline (reflecting a status under no physical or mental fatigue). Then, subjects were requested to conduct the 15min risk identification task using the computer screen (Fig. 3). During this task, subjects were reminded to concentrate on the constantly changing pictures. Once targeted pictures appeared, subjects pointed out and recorded the related potential risk factors (e.g., no protective suit, unqualified edge protection, unqualified scaffolding works). Then, another 1min EEG signal (i.e. data 2) was recorded.

Fig. 3. 15min risk identification task based on picture set.

In Trial 2/3/4, subjects were first required to conduct the manual handling tasks. In this research, the manual handling tasks were designed to stimulate the targeted different fatigue levels through various task intensities. In particular, the physical task intensities (i.e. durations of the manual handling task) of the four trials should be determined in consideration of individual differences. Thus in this research, during the physical fatigue stimulating phase, the Borg's Rating of Perceived Exertion (RPE) was adopted for measuring the perceived fatigue level [9][59]. According to the fatigue descriptions in RPE, exertion levels of "RPE 12~14", "RPE 15~16", and "RPE 17~20" were respectively defined as low fatigue, medium fatigue, and high fatigue. Correspondingly, they can be described by subjects as subjective perceptions, such as "somewhat hard", "hard", and "extremely hard". In the physical fatigue stimulating phase, subjects were arranged to complete the manual handling tasks in a relatively fast, but steady walking pace. For every 2 minutes, they were required to provide verbal feedback on their physical fatigue level. The profile information of each subject and reported fatigue levels in defined periods of time were recorded, as shown in Table 1. Taking individual differences into account, the time thresholds of three fatigue levels of one subject were set as the defined durations of manual handling tasks in corresponding trials. For example, for subject 1, the durations of the manual handling task in trial 2~4 were designed to be 6min, 12min, and 18min (i.e. 2min more than the reported time range), whereby the duration in trial 1 can be regarded as 0 min (i.e. no physical fatigue).

Table 1. Subjects' profile information and reported fatigue levels according to RPE.

				Physical fatigue level		
				Low fatigue	Medium fatigue	High fatigue
Subject	Weight (Kg)	Gender	Age	RPE 12~14	RPE 15~16	RPE 17~20
1	62	Male	28	0~6 min	6~14 min	>16 min
2	60	Male	30	0~6 min	6~12 min	>14 min
3	65	Male	33	0~6 min	6~16 min	>18 min

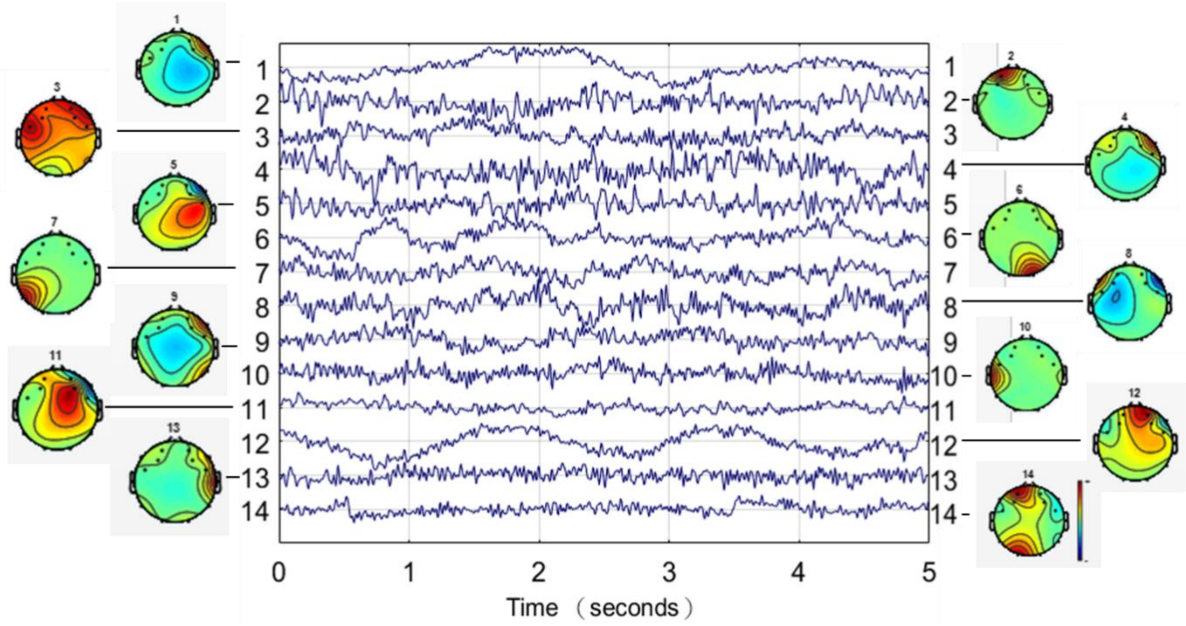
4	65	Male	29	0~4 min	4~16 min	>18 min
5	68	Male	27	0~6 min	6~16 min	>18 min
6	55	Male	25	0~4 min	4~10 min	>12 min
7	65	Male	28	0~4 min	4~12 min	>14 min
8	70	Male	32	0~6 min	6~16 min	>18 min
9	65	Male	28	0~4 min	4~16 min	>18 min

During the physical fatigue stimulating phase, all subjects were required to wear personal protective equipment and shoes, and pay attention to the height differences of stairs to prevent accidental injuries. Then, risk identification tasks were arranged with different picture sets to avoid learning effects. At the end of each trial, 1min EEG signals (i.e. data 3~5) were measured. After the experiment, 36 records of safety performance from the risk identification task and 45 EEG data segments in total were collected from the nine subjects.

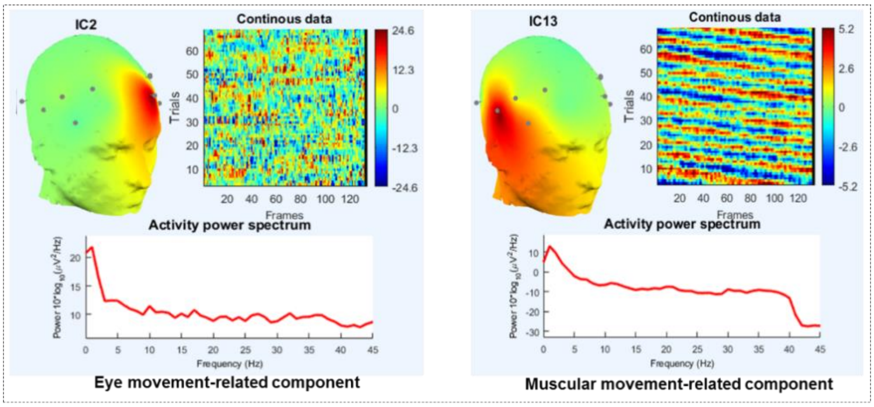
3.3 Data processing and analysis

3.3.1 Data preprocessing

In the EEG collection phase, subjects were asked to take slow and even breaths, with their eyes closed and without physical distractions. In this way, required signals can be measured without excessive intrinsic and extrinsic artifacts. Considering the sensitivity of the EEG signal in microvolts (μV) and the accuracy of later data statistics, data preprocessing through filtering and independent component analysis (ICA) was adopted to further remove frequency noise [47]. In this research, low-frequency noises (0.5Hz and lower) and high-frequency noises (40Hz and higher) were removed through the hamming windowed sinc FIR filter. Frequency noise (e.g., normally line noise or white noise) beyond the objective spectrum were filtered [60]. Then, ICA was employed to retain the valid components and remove the noise components of intrinsic artifacts (e.g., eye movement and facial muscle activity) (Fig. 4). Considering the physiological significances of different frequency band powers (i.e., prominent components of EEG signal), researchers have explored the associations between complex human psychosocial conditions and EEG signals. As supported in prior research [61-66], early stages of mental fatigue were correlated closely with theta (θ) (4–8 Hz), alpha (α) (8–13 Hz), and beta (β) (13–30 Hz) frequency bands. A six-layer wavelet packet decomposition and reconstruction were adopted to filter out these related frequency bands.



(a)



(b)

Fig. 4. ICA for removing noise components of intrinsic artifacts (data 1 of Subject 1): (a) 14 independent components and corresponding scale maps; (b) noise components of intrinsic artifacts after analyzing.

3.3.2 Mental fatigue indication and analysis

In this research, a comprehensive data analysis method using EEG rhythms was applied. First, topographical distributions and evolutions of interested frequency band powers (i.e. theta, alpha, and beta) were observed. Then, their general trends of a subject in different data segments were shown using grand average power spectral density (PSD). Considering the mental fatigue regulation in specific brain areas, the normalized intensities of theta, alpha, and beta in different data segments were analyzed, focusing on the entire brain and the frontal and temporal cortex. Based on the physiological significances of different frequency band powers, (theta+alpha)/beta were adopted in this research for detecting the mental fatigue level quantitatively, which can amplify the differences between single EEG rhythms [61][63-65][67-69].

Taking Subject 5 as example, the grand average distribution and evolution of *theta*, *alpha*, and *beta* power in the four trials is presented in the following topology (Fig. 5). Based on this topographical data, there were intuitive activations and changes of the related powers across the entire brain, throughout the entire experiment.

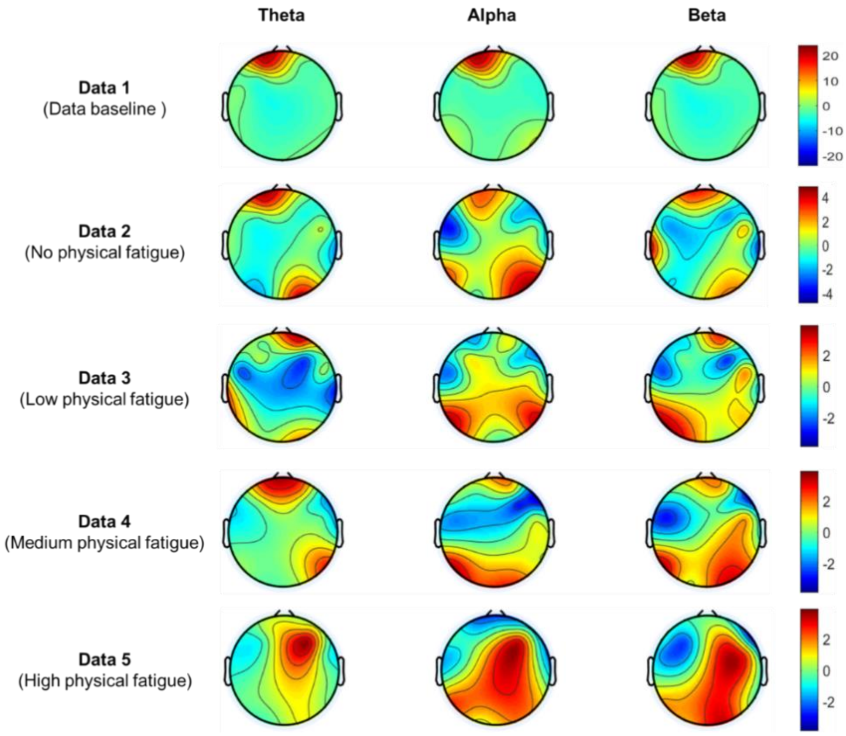


Fig. 5. Topographical distributions and evolutions of *theta*, *alpha*, and *beta* power in grand average of each EEG data segment (Subject 5) (Note: red-shaded areas indicate high activities, and blue-shaded areas indicate low activities).

The grand average power spectral density (PSD) of the nine subjects in five data segments is shown in Fig. 6. As shown in the area marked in red gridlines, compared with the data baseline (i.e. data 1), there was a significant increase of *alpha* power after the recognition-required risk identification task under a high physical fatigue level (i.e. data 5). While other data segments, reflecting mental statuses induced under different physical fatigue levels, didn't have obvious and abrupt changes in the related frequency domains.

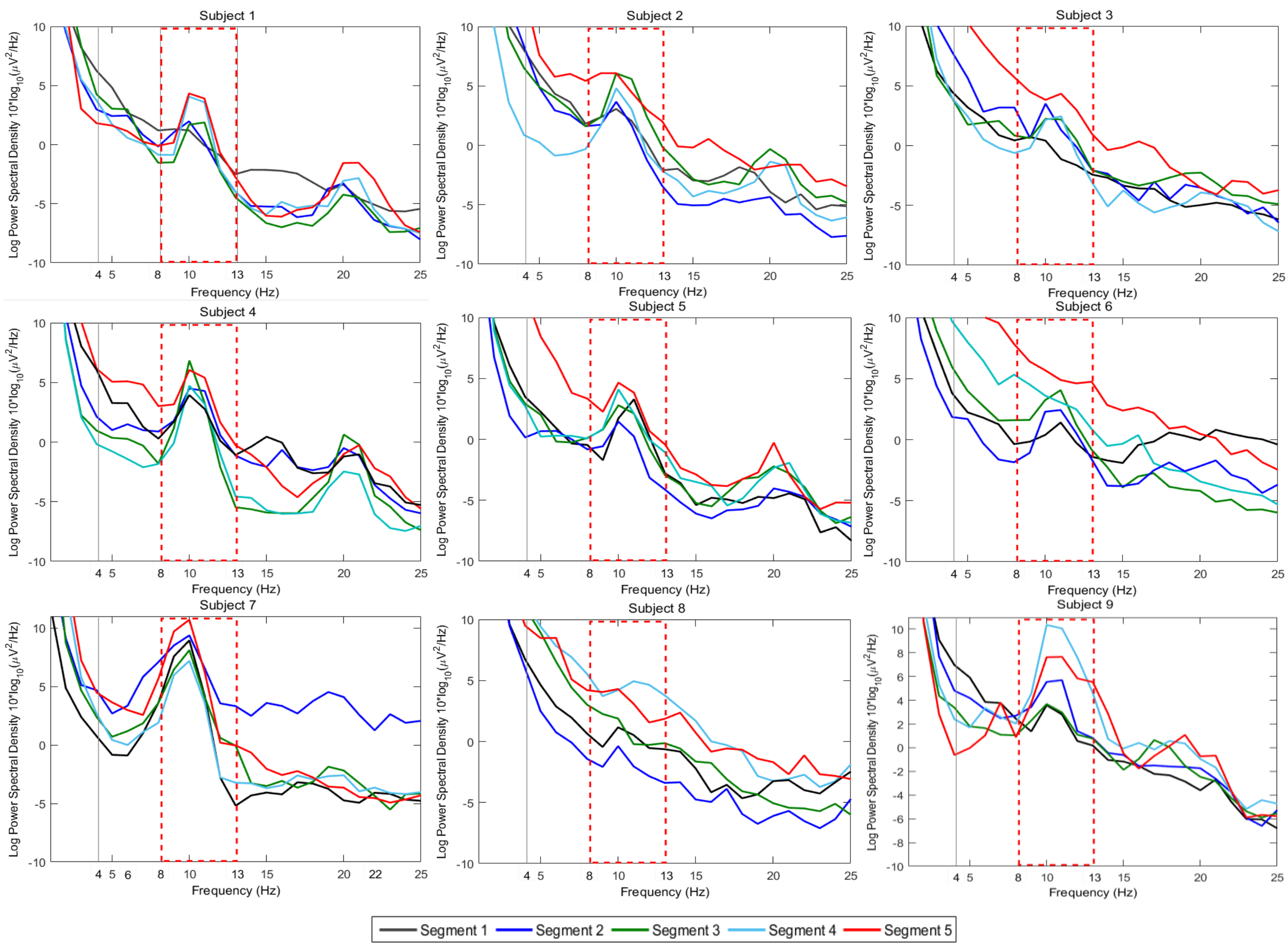


Fig. 6. Grand average PSD of nine subjects in five data segments.

Considering the entire brain and the frontal and temporal cortex, the normalized intensities of *theta*, *alpha*, and *beta* in five data segments are shown in Fig. 7. Besides, adopting analysis of paired-t tests, effects of different physical fatigue levels on the induction of mental fatigue were examine (Table 2). That is, mental fatigue statuses (presented by EEG index and interested frequency bands) of segment 2 ~ 5 were respectively compared to the baseline status of segment 1. It was observed that there was a marked increase of mental fatigue ($(\theta+\alpha)/\beta$) in data segment 5, a mental status induced under high physical fatigue. At the same time, *alpha* power increased significantly across the entire brain. As supported in prior research [61-64], mental statuses in the frontal and temporal cortex were also captured in this research. Data from the frontal and temporal cortex also showed a marked increase of mental fatigue in data segment 5. No other significant changes were observed in the experiment.

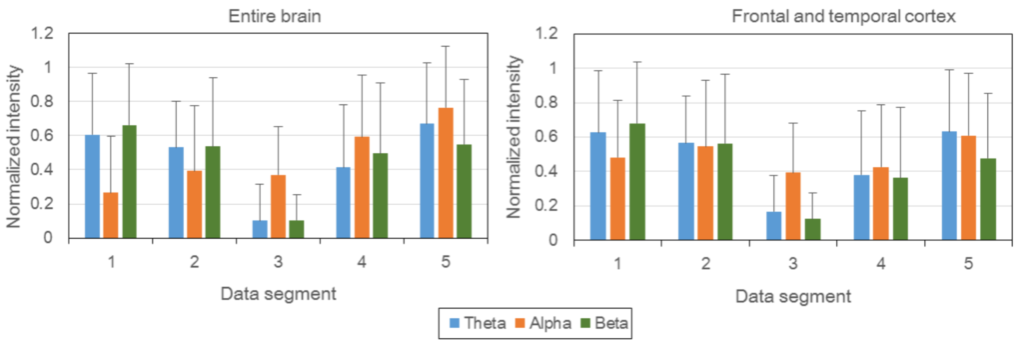


Fig. 7. Normalized intensities of *theta*, *alpha*, and *beta* power in five data segments.

Table 2. Statistical *t*-test of interested frequency bands and mental fatigue (i.e. index of $(\theta+\alpha)/\beta$)

Index	Entire brain				Frontal and temporal cortex			
	Segment 2	Segment 3	Segment 4	Segment 5	Segment 2	Segment 3	Segment 4	Segment 5
θ	----	0.001	----	----	----	----	----	----
α	----	----	----	0.014	----	----	----	----
β	----	0.036	----	----	----	0.010	----	----
$(\theta+\alpha)/\beta$	----	----	----	0.030	----	----	----	0.005

Note: Values involved in Table 2 are *p*-values.

4 Discussion

4.1 Effects of the physical fatigue on the induction of mental fatigue

This research explored the effects of physical fatigue on the induction of mental fatigue through a neurophysiological approach. An experiment consisting of four independent trials was designed in this research. For each trial, three phases (i.e. a manual handling task of particular intensity for stimulating an expected physical fatigue level, a recognition-required risk identification task for inducing mental fatigue, and EEG collection) were conducted. Considering the challenging conditions experienced in a construction work environment, it is important for workers to identify hidden risk factors on sites rapidly and accurately. Thus, in this research, each subject's performance in the risk identification task was recorded and described based on the testing accuracy in each trial (Table 3):

$$\text{Testing accuracy} = \frac{\text{Number of identified pictures involving potential risks}}{\text{Number of targeted pictures involving potential risks}} \times 100\%$$

where the testing accuracy was defined as the recall rate of targeted pictures.

Table 3. Subject's performance in the risk identification task (testing accuracy (%)).

Subject	Trial 1	Trial 2	Trial 3	Trial 4
1	98	92	83	90
2	88	76	78	90
3	89	77	78	83
4	86	79	92	87
5	87	85	88	93
6	89	89	89	94
7	94	95	92	90
8	88	82	91	88
9	73	80	83	96

In this research, data analysis was based on the method of intra-group comparison, reporting the tendency of fatigue status of each subject during the four trials. Through statistical analysis based on Table 3, there was no significant difference in testing accuracy between trial 1 and other trials. These performance results were mainly due to the limited testing time (15min) and being observed with the reminder to stay focused during the task procedure. For revealing the variation tendencies of subjects' mental fatigue under certain physically and mentally-demanding tasks, EEG data of subjects in five specific points in time (i.e. segment 1~5) was collected, and differences between the mental fatigue status of segment 2~5 and the baseline mental status of segment 1 were computed. When comparing EEG data segment 2 to 1, it was noted that the time-limited cognition-required task itself cannot effectively induce mental fatigue. Further, comparing EEG data segment 3/4 to 1, it was noted that there was still no significant effect of the low and medium physical fatigue levels on the induction of mental fatigue. However, under the high fatigue level (i.e. data 5), mental fatigue induction become apparent, even after this relatively simple cognitive task. The significant development can be demonstrated by the index of $(\theta+\alpha)/\beta$, reflecting both the entire brain and the frontal and temporal cortex. As shown in Fig. 8, despite personal differences, it was observed that the cognition-required task under high physical fatigue can clearly lead to an uptrend in mental fatigue.

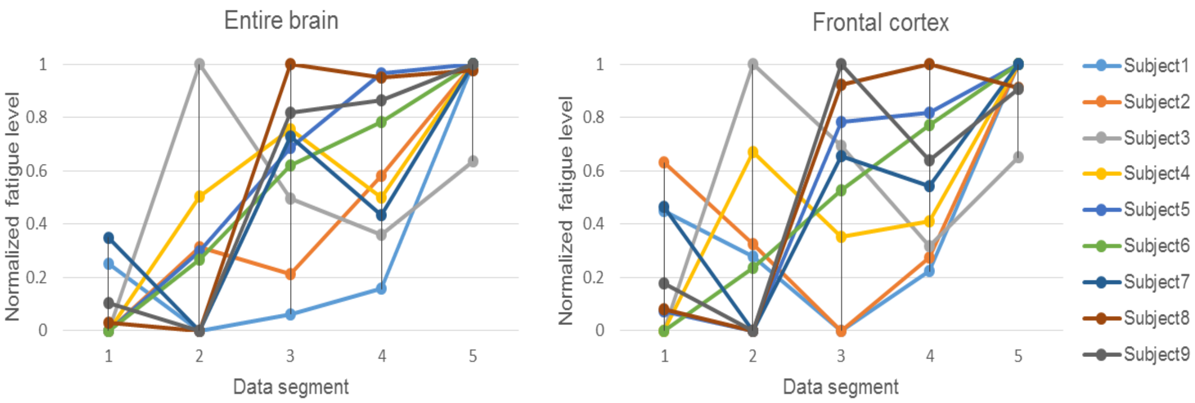


Fig. 8. Mental fatigue under different physical fatigue intensities.

In practice, construction activities requiring both physical and cognitive effort are situations that may require resource allotment [34]. The perception of mental workload of a subject was sensitive to changes in the conditions of the tasks being performed [70]. After evaluating differences between the demand and the performance, additional resources can be invested to meeting demands, which can be reflected in the higher ratings of mental workload [34][71]. During the manual handling tasks of this research, vigilant and attentional resources were required for the highly controlled elbow and knee and the mind to steps. For the later risk identification tasks, with subjects being observed with the reminder to stay focused during the task procedure, there was no significant difference in testing accuracy of four trials. However, additional resources were invested to maintain the same level of performance (especially under high physical fatigue), which can be the reason mental fatigue induced apparently.

4.2 Recommendations on fatigue management based on the pilot study results

As construction work involves physically-intensive and risk-sensitive tasks, it is critical for workers to stay alert with a focused mental state to complete construction activities and achieve high performance. In particular, workers need to pay close attention to their surrounding environment during work activity to identify potential safety risks. In practice, there are construction activities that require both physical and cognitive effort. The pilot study results indicated that high physical fatigue resulting from intensive physical tasks may accelerate the development of mental fatigue. Even the cognitive intensive construction activities can be completed as requested under a focused mind and external management constraints, accumulated mental fatigue can further affect workers' alertness and attention in responding to the dynamic construction site environment and other construction tasks [7-8].

By exploring the effects of physical fatigue on the induction of mental fatigue, the pilot study results provided a reference for the fatigue management of construction workers to further promote safety management on construction sites. For example, compared to mental fatigue, the status of physical fatigue was relatively dominant and quantifiable, which can be managed from the perspective of task intensity and workload. To safely facilitate the completion of certain construction activities, the physical workload and intensity need to be examined and managed with respect to fatigue management. According to the research results, measures proposed for physical fatigue management can play an indirect role in mitigating and managing mental fatigue on sites. In considering the requirements of workers' mental status with certain construction activities, a moderate range of work intensity should be implemented for physically-demanding tasks. Meanwhile, targeted measures for fatigue management should be proposed in the future, based on personal differences.

In addition, when subjects were permitted to practice the risk identification task in the preliminary experiment, the testing performance observed in the later stage was significantly better than that of the initial stage. A higher testing accuracy was achieved when a relatively relaxed status was reported. This preliminary testing result can be mainly attributed to the subjects' familiarity with the cognitive task. In practice, adequate and feasible pre-job training is valuable for construction workers to become familiar with certain tasks and reduce unnecessary mental workload. Additionally, from the perspective of fatigue management, there are also significant positive and practical benefits in conducting site safety training.

4.3 Limitations and future work

There are some limitations in the current research. Firstly, in practice, construction sites experience dynamic and complex working conditions. The indoor experiment designed and adopted in this research only simulated one workplace scene, and was far from capturing all external environmental interference factors. In the future, comprehensive field trials would be useful to validate the research outputs in specific circumstances, across multiple environmental interference factors. Second, through intra-group comparisons, this research only focused on the development trend of mental fatigue statuses, under the influence of different physical task intensities. The thresholds between different mental fatigue levels were not examined in this research. Besides, physical fatigue levels were recognized and recorded based on self-report measures. In future research of interactions between physical and mental fatigue, a comprehensive approach (e.g., a measurement approach utilizing physiological or biomechanical indicators [9][72]) could be explored for the more objective and real-time physical fatigue recognition and measurement. Further, as a pilot study, the number of subjects involved in this research were insufficient to capture the breadth potential personal differences that may be experienced in practice. A larger group of subjects (particularly aiming at specific worker groups) is recommended for future work to improve the validity of the research outputs. In this way, targeted and personalized fatigue management measures can be developed to provide practical benefits in the management of construction safety.

5 Conclusions

This pilot study explored the effects of physical fatigue on the induction of mental fatigue of construction workers. Under various physical task intensities, different mental fatigue statuses were induced through a cognition-required task, and were measured utilizing a wearable EEG sensor. Through intra-group comparisons, the variation tendency of mental fatigue intensity under the effects of physical fatigue was analyzed. The research results showed that high physical fatigue can contribute to the development of mental fatigue, even if the cognitive task itself may not involve intensive cognitive load. Therefore, intensive physical task-induced fatigue can be regarded as one of the factors that impair cognitive functioning and other mental performances. With more field trials to be conducted in future to build upon the pilot study findings, the research results provided a base reference for improving fatigue management of construction workers. As such, targeted recommendations and fatigue countermeasures can be proposed to promote comprehensive safety management on construction sites.

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