A multicomponent and neurophysiological intervention for the emotional and mental states of high-altitude construction workers

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Published in:
Automation in Construction

DOI:
10.1016/j.autcon.2019.102836

Recommended citation(APA):
Xing, X., Li, H., Li, J., Zhong, B., Luo, H., & Skitmore, M. (2019). A multicomponent and neurophysiological intervention for the emotional and mental states of high-altitude construction workers. *Automation in Construction*, *105*, Article 102836. https://doi.org/10.1016/j.autcon.2019.102836

A multicomponent and neurophysiological intervention for the emotional and mental states of high-altitude construction workers

Abstract

The emotional and mental states of high-altitude construction workers (e.g., emotions and mental fatigue) are one of the critical factors affecting work performance (e.g., safety, health, construction quality, and productivity). To prevent undesired results from adverse emotional and mental states, active interventions for workers are important. Taking scaffolders on site as specific objects, a multicomponent (with two intervention sessions) and neurophysiological intervention during working intervals is proposed in this research. A sample of 10 participants is randomly assigned to either an intervention group or control group. Emotional and mental inducement is conducted in advance to simulate the states of scaffolders in normal working conditions. Then a simple, rapid, and active intervention, consisting of a progressive muscle relaxation session and a trigeminal nerve stimulation session, is applied to the experimental group in a lounge environment for 13 min. For the control group, a normal resting mode (i.e. sitting still) is adopted instead. During the experiment, a wearable electroencephalogram sensor is used to collect electrical signals from related brain regions of a subject. Based on corresponding indices, the emotional and mental states of subjects are indicated by electroencephalogram signals. The combined effects of the progressive muscle relaxation and trigeminal nerve stimulation sessions in adjusting adverse emotional and mental states of high-altitude construction workers are determined by statistical analysis.

Keywords:

High-altitude construction workers
Emotional and mental state
Multicomponent and neurophysiological intervention
Electroencephalogram

1. Introduction

High-altitude operation (i.e. working at heights more than 2-meters above the ground) is one of the most common construction activities in construction industry, which is prone to such safety risks as falling from height and object strikes. According to statistics from the Ministry of Housing and Urban-Rural Development of China, 331 fall-from-height accidents occurred in 2017 (accounting for 47.83% of the total number of accidents), which has been identified as the accident type with the highest number of casualties. 82 object-strike accidents occurred, accounting for 11.85%. Considering the specific characteristics of highaltitude construction operations, several initiatives focusing on workers have been proposed to improve the safety of construction work on site and reduce involved risks. For example, based on regulations for the management of special operations personnel in construction, a highaltitude operation worker should receive formal occupational training and pass an examination to obtain the compliance certificate needed. Before starting work, a physical examination should be conducted to detect any disease or physical impediment. Moreover, other regulatory requirements also apply (e.g., wearing a safety belt and antiskid shoes, and learning from accident reports) [1].

In addition to above requirements proposed to high-altitude construction workers, emotional and mental states of workers are one of the critical factors in safety management without comprehensive and clear management regulations. During the construction activities, emotional and mental state of a worker can closely affect his cognitive process and decision-making ability [2,3]. Further, the poor awareness, attitude, and risk perception may lead to unsafe behaviors (e.g., adopting improper working equipment or being reluctance to wear personal protective equipment (PPE)), which consequently has an important impact on worker's safety and work performance on site [4–6]. This is a particular problem for high-altitude operations, where workers on site tend to experience such adverse emotional and mental states as fear, anxiety, stress, and mental fatigue, which can ultimately lead an increased risk of occupational accidents [7]. To some extent, workers can deal with such adverse states flexibly through work breaks. However, an accumulation of inappropriate adjustments can result in chronic mental and physical health issues [8,9]. Many high-altitude construction workers cannot obtain effective remission by self-regulation during working intervals.

As such, to prevent the undesired results from adverse emotional and mental states, active interventions are particularly important. However, existing supervision and corresponding interventions are weak and untargeted. This research aims to present a simple, rapid, and active intervention method to high-altitude workers during working intervals. In order to ensure its pertinence and effectiveness, the timelimited intervention method must have a specific and well-defined focus [10]. Scaffolders, as typical high-altitude workers on site, are taken as the specific focus of attention in this paper.

Based on the research background illustrated above, a multicomponent and neurophysiological intervention method for the scaffolders on site, consisting of a progressive muscle relaxation (PMR) session and a trigeminal nerve stimulation (TNS) session, is proposed. For examining the effectiveness of the intervention sessions, a sample of ten volunteers were tested. First, the ten participants were randomly divided into either an intervention group with seven subjects or a control group with three subjects. An emotional and mental inducement was conducted on ten subjects to simulate the scaffolders into an adverse emotional and mental fatigue state in a normal working situation. Then, the active intervention lasting for 13 min was applied to the experimental group in a lounge environment, while the control group subjects were required to sit still without any other intervention. During the entire experimental process, electrical signals from relevant brain areas of each subject were collected by a wearable electroencephalogram (EEG) sensor. Through the statistical analysis of EEG indices, combined effects and availability of PMR and TNS sessions in adjusting adverse emotional and mental statuses of high-altitude workers are proved.

2. Background

2.1. Emotion-regulation strategy

People not only experience their emotions (positive and negative) passively, but can also modify them actively [11]. The effects of emotion regulation are closely related to mental and physical health issues, relationship satisfaction, and work performance [8]. A suitable emotion regulation can help people cope with their emotions, and react flexibly to their surrounding environment with appropriate behaviors [12]. Chronic deficits in emotion regulation (i.e. the accumulation of inappropriate emotion adjustments) can contribute to psychological malfunctioning and other forms of psychopathological illnesses [13]. As one of the key topics of contemporary psychology, emotion regulation has spanned over multiple discipline fields (e.g., developmental psychology, cognitive psychology, social psychology, personality psychology, clinical psychology, cognitive neurosciences, affective neurosciences, and psychophysiology) [8].

Nowadays, there has been a growing amount of research focusing on emotion regulation, with different emotion-regulation strategies and research individuals. Based on the classification dimensions of targets (i.e. attention, knowledge, and body) and functions (i.e. need-oriented, goal-oriented, and person-oriented), emotion-regulation strategies can be divided into nine categories [8]. By analyzing the emotion-regulation strategies of these nine categories, they can be divided into two major types: internally spontaneous regulation (e.g., attentional avoidance [14], cognitive reappraisal [15], and mindfulness training [16]) and externally guided regulation (venting [17], controlled breathing [18], and progressive muscle relaxation [19]). That is, emotion regulation can be guided by inside regulatory goals which are implicit, or outside interventions which are explicit and accessible to awareness [20].

Sometimes, the inside emotion regulation process can initiate strategically, beyond control without a person's knowledge or intention [21]. However, there are individual differences in the ability to regulate emotion automatically [22]. For example, individual responses to stressful situations vary with such different factors as the demand, personal characteristics, coping resources, personal or environmental restrictions, and outside support [23]. Moreover, the cognitive biases of an individual make it difficult to appraise the situation consciously, which then leads to inappropriate emotion regulation [24]. In particular, employing strategies that do not fit the situation can lead to individual differences in emotion regulation [25].

This paper focuses on the emotion regulation of scaffolders during working intervals. Considering the group characteristics of scaffolders and the operational features of scaffolding on site, the selected emotion regulation strategy needs to be simple, rapid, and effective. Judging from the above illustrations about emotion regulation strategy categories and individual differences in emotion regulation, a regulation strategy of outside intervention, which is more controlled, is required.

Progressive muscle relaxation is a kind of non-pharmacological intervention, which can achieve emotion regulation through a guided deep muscle relaxation process. That is, both physical and emotional conditions can be improved after the outside intervention of PMR. Moreover, as a kind of person-oriented emotion regulation strategy, PMR can maintain the integrity of the overall personality system and access to long-term benefits of attention, knowledge, or body [8]. Thus, PMR is adopted here as an intervention session to regulate workers' adverse emotional states.

2.2. Mental fatigue intervention

Mental fatigue is a universal phenomenon experienced by people who have been involved in a prolonged period of demanding mental effort (e.g., cognitive activity), which can be subjectively described as feeling tired or inactive [26]. In particular, mental fatigue has been identified as a key factor various working groups, leading to low work efficiency and even life threatening issues [27]. According to the 2008 annual summary of the National Sleep Foundation (NSF), around 20% aircraft pilots, 18% train drivers, and 14% truck drivers nearly made operational mistakes under the impact of mental fatigue [28].

Some current studies concentrated on reducing mental fatigue using different intervention methods. Dababneh et al. [29], for example, studied the effect of rest breaks in meat-processing works, and suggest having hourly breaks of 9-min to reduce work fatigue [29]; Smith and Hale [30] summarized the effectiveness of different non-pharmacological interventions (e.g., (1) exercise intervention, such as aerobic exercise, resistance exercise, and energy conservation; and (2) complementary and alternative medicine (CAM) intervention, such as acupuncture, Yoga, and Tai Chi) in reducing fatigue in different chronic illness conditions [30]; Fillion et al. [31] proposed a fatigue-relieving intervention involving stress management and physical activity, which tends to reduce the fatigue of breast cancer survivors [31]; Mizuno et al. [32] studied the effect of mild-stream bathing on alleviating mental fatigue [32]; Lerman et al. [33] summarized fatigue risk factors and made suggestions for the fatigue risk management of working groups, including addressing staffing issues, shift and duty scheduling, employee training and education, sleep disorder management, work environment design, and individual risk assessment and mitigation [33]; Tummers et al. [34] implemented a method of cognitive behavior therapy (CBT) for chronic fatigue syndrome (CFS), as a minimal intervention guided self-instruction without trained therapists [34]; Merat and Jamson [35] proposed three road-based measures as engineering treatments to alleviate the fatigue symptoms of drivers [35]; Montgomery et al. [36] illustrated the effectiveness of cognitivebehavioral therapy combined hypnosis in controlling fatigue in breast cancer patients [36]; and Duc [28] explored the possibility and feasibility of trigeminal nerve stimulation in suppressing the fatigue effects from unintentional sleep [28].

The literature review indicates that existing research into mental fatigue intervention mainly focuses on chronically ill working and patient groups. Little research has focused on construction worker groups or construction sites. According to research [37], an ideal mental health intervention needs to satisfy nine fundamental features: (1) the operation process is well defined, and is conducted based on (2) client goals and (3) societal goals; the intervention method is (4) effective and (5) easy to implement, with (6) minimum side effects; (7) positive longterm outcomes and (8) reasonable costs; (9) the intervention is universally applicable to various communities. Considering the research objects (scaffolders on site) and the specific implementing circumstances (during working intervals), a brief, time-limited, and practical mental fatigue intervention is required, complying with above fundamental features.

Trigeminal nerve stimulation (TNS) is a direct and rapid stimulation of trigeminal nerve branches, through sending adaptable electrical signals to provoke relevant brain activities. Currently, the TNS has been studied in some research of mental health, such as major depressive disorder [38], epilepsy [39], and mental fatigue [28]. Based on the research objective of this research, TNS is adopted as a non-invasive intervention session to reduce the mental fatigue of the scaffolder subjects. Specifically, trigeminal nerve branches go through the thalamus and anterior cingulate cortex, which are functional areas related to emotion, attention, and other cognitive activities [40]. Thus, along with PMR, the combined effects of TNS on emotional state and mental fatigue are studied in this research.

2.3. EEG applied in emotional and mental state detection

Recent research examined the neural mechanisms of the brain in terms of emotional and mental states. For example, Ochsner et al. [43] established a synthetic review and evolving model of functional imaging in the cognitive control of emotion [20]; Kohn et al. [41] examined the central and integrative brain area in cognitive emotion regulation [41]; and Ishii et al. [42] proposed a conceptual model of a dual regulation system to investigate the neural mechanisms of mental fatigue under cognitive tasks [42]. Existing studies also indicated that the nature of emotion and mental interventions can be unveiled by functional imaging [20]. For example, when an emotion regulation is conducted, the prefrontal cortex regions and brain areas related to emotion modulation can become clearly active [43]. Thus, based on the neural mechanisms in the emotional and mental states, adaptable interventions can be conducted under a substantial theoretical foundation, instead of solely empirical support and behavioral data.

EEG is a quantitative reflection of medical imaging to detect the electrical activity of the brain, through which the subjective bias from traditional survey-based assessment of the emotional and mental states can be overcome [2]. EEG can be measured by two major technologies: the electrocorigram and the electrogram [44]. As the former technology can collect the EEG directly and noninvasively based on voltage fluctuations from neurons at the cortical surface, it has been commonly applied to research of diverse fields [45].

There is a growing interest in the role of EEG in the detection and regulation of emotional and mental states for different groups. For example, Li et al. [46] proposed an EEG processing method to evaluate the fatigue effect of drivers [46]; Moseley and DeGiorgio [47] utilized the EEG to reveal the intervention effect of external trigeminal nerve stimulation on refractory status epilepticus [47]; Duc [28] utilized functional magnetic resonance imaging (fMRI) and EEG to investigate the mechanics of mental fatigue regulation in brain areas [28]; Yin and Zhang [48] presented a mental fatigue classification method by different EEG feature distributions through various mental tasks [48]; Acharya et al. [49] proposed a depression diagnosis approach through EEG-based screening, utilizing a deep convolutional neural network [49]. Specifically, in the construction industry, some current research has focused on workers' emotional and mental states on site. For example, Chen et al. [50] proposed a novel measurement approach using neural time–frequency analysis to monitoring construction worker's mental condition to evaluate hazards [50]. Aryal et al. [51] studied the real time physical fatigue monitoring based on the EEG data, the heart rate data, and the infrared temperature data from wearable sensors [51]. Wang et al. [52] proposed a wireless and wearable system based on EEG signals to assess construction workers' attention level [52]. Hwang et al. [2] applied EEG to measuring the emotional states of workers undertaking construction tasks [2]; and Jebelli et al. [53] proposed an approach to recognize construction workers' stress by analyzing EEG signals utilizing the Gaussian Support Vector Machine [53].

However, to the authors' best knowledge, no effort concentrating on the emotional and mental state management of high-altitude construction workers exists. In this research, the EEG technology (non-invasive) is applied to detect the underlying processes of multicomponent and neurophysiological interventions proposed for regulating the emotional and mental states of high-altitude construction workers.

3. Methods

In total, 10 healthy participants aged 18–40, who had basic construction engineering knowledge and working experience on construction sites, were recruited from the Hong Kong Polytechnic University. In this research, all participants were randomly assigned to one of two conditions: (a) an experimental (intervention) group with 7 subjects, and (b) a control group with 3 subjects. Before the contrast experiment, the entire experimental procedure was explained to all subject of two groups. As shown in Fig. 1, all the subjects were induced into emotional and mental states simulating scaffolders in normal working conditions. Then, a multicomponent and neurophysiological intervention, consisting a PMR session and a TNS session, was applied to the experimental group in a lounge environment, while the control group instead sat still without any other intervention. Especially, in order to simulate scaffolders in practical construction sites to induce desired emotional and mental states, some requirements and preparation work were made for the participants as experimental protocol: 1) According to the physical demands for scaffolders, all participants should be in good health, without any disease or physical impediment (e.g., acrophobia and hypertension) influencing the experimental effects; 2) Construction site videos of scaffolding activities were shown to participants, including typical construction scenes such as walking on the high-altitude pipe racks of scaffolding. In the meantime, related basic construction and regulatory requirements were explained to the participants; 3) Further, each participant was asked to keep a normal daily routine to stay in a good physical and mental state before the experiment.

For the preliminary design of experiment steps and setting a set of adaptable parameters involved in the intervention sessions, a preliminary experiment involving three participants was conducted in advance. In the preliminary experiment, subjects were arranged to conduct different simple trials with one of the two intervention sessions respectively. For this research aims to explore a simple intervention method within a limited time, the duration of each session is designed to ensure the desirable intervention effects in the shortest time possible. Through the preliminary experiment, it was shown that the stimulations on the trigeminal nerve had more obvious and rapid effects on subjects subjectively than the PMR process. Based on prior research on relaxation trainings and their practical applications, the duration of the PMR session was set to be 10 min and the TNS was 3 min. Specifically, subjects reported that they felt relaxed, calm, but a little sleepy through the PMR intervention with the background music. Thus, for the practical application purpose, the TNS was set as the following session of the PMR to make subjects keep wide-awake after the stimulation.

During the entire experiment, the EEG was used to record the emotional and mental states of subjects. A wearable EEG device (EMOTIV EPOC+ 14 Channel Mobile EEG), which has 14 electrode channels corresponding to different locations of the scalp, was used to collect EEG data (Fig. 2). The sampling frequency is kept at 128 Hz. Raw EEG data can be transferred in real-time via a wireless receiver. As shown in Fig. 1, for statistically analyzing the effectiveness of the intervention sessions, EEG data from four experimental stages of each trial of two groups were collected, each of which recorded a 2 min experimental segment. The 2 min EEG data from stage 1, collected in a resting state before the intervention, was identified as the baseline for validating the later intervention effects. According to the research objective and practical application purpose, these four EEG data collection periods are enough to account for the effectiveness of each intervention session. Besides, the variation tendency of workers' emotional and mental states in the entire intervention process can be expressed. What's more, it should be noted that the EEG signals are easily affected by external signal interferences. While, the conductions of two intervention sessions (i.e. PMR and TNS) can be along with strong signal effects from body movement or pulse generator. Thus, EEG signals from the entire intervention periods, but above four stages, have been avoided for accurate results.

3.1. Simulation of the emotional and mental states of scaffolders

Typifying the specific characteristics of high-altitude construction operations, scaffolders on site tend to generate adverse emotions (e.g., fear, anxiety, and frustration) and mental fatigue, which are a negative state affecting the work performance. This, in particular, contributes to such safety risks as falls-from-height and object-strikes. Thus, this adverse emotional and mental state is the focus here. Through cognitive tasks and virtual reality (VR) simulation in the laboratory environment, the emotions and mental fatigue simulating scaffolders were induced on subjects in advance, acting as the baseline for verifying the effectiveness of later interventions.

The stroop task in psychology is a typical cognitive task with visual interference that can contribute to cognitive overload. Based on Cognitive Load Theory, a modified stroop color-word interference task was used to induce mental fatigue in a short time. All subjects were required to complete a computer version stroop task for around 30 min, during which time the effects of mental fatigue induction were demonstrated by the reaction time and accuracy. A VR mission simulating the high-altitude walk site was then selected for inducing certain negative emotions of scaffolders. Subjects were required to walk on two slender steel pipes for approximately 10 min, wearing VR glasses displaying the virtual high-altitude walk scene (Fig. 3).

3.2. Intervention procedure

After the emotional and mental inducement to simulate the states of scaffolders on site, a multicomponent and neurophysiological intervention, consisting of a PMR session and a TNS session, was applied to the intervention group in a lounge environment, while the control group sat still without any other intervention. Details of the intervention process are illustrated as follows.

3.2.1. Progressive muscle relaxation

In the PMR session, each subject of the experimental group was arranged in a lounge environment, sitting on a couch to reach a relaxed state without physical distractions. Then the subject was guided away from having thoughts with eyes closed. Audio-guided with background music for around 10 min, particular muscle groups of the subject's body became relaxed in a top-down sequence. EEG data from two experimental segments of 3–5 min and 8–10 min of the PMR session was collected. By eliminating signal noises from body movements, the subjects were guided to pause actions and do meditation with slow and even breaths instead (Fig. 4).

3.2.2. Trigeminal nerve stimulation

A medical and portable external pulse generator (KWD-808 I, Great Wall, China) was applied in the TNS session (Fig. 5). In the preliminary experiment, different trials were conducted for setting an adaptable pulse signal as the output of this pulse generator for the TNS intervention. Based on existing research into TNS and practical applications in medical treatments, nine types of pulse signal (three pulse waveforms with three different frequencies respectively) were tested in the preliminary experiment (Table 1).

In the preliminary TNS trials, the acceptability and the reducing effects on metal fatigue of self-perception were identified as the selection criteria of an adaptable stimulation pulse. Two oval adhesive rubber electrodes were placed on the forehead of the participant, spaced 5 cm apart bilaterally, to stimulate the ophthalmic branch of the trigeminal nerve (Fig. 6). After sending nine types of pulse signal for 100 s as the TNS, subjects reported that the discontinuous wave of 50 Hz, 3 s on/3 s off, and 600 μs pulse width was more effective in making them alert, along with the acceptable vibration from the pulse generator. Thus, this type of pulse signal was selected as the TNS parameter to be applied in the later intervention. Therefore, in the lounge environment after the PMR session, the subject's TNS session was conducted with this specific pulse signal for 3 min.

3.3. Data processing and statistical analysis

3.3.1. Data preprocessing

As EEG signals propagate and summate in the cortex, they can be captured through the scalp by wearable EEG devices when different brain regions are activated. For the EEG signal in microvolts (μV) is susceptible to frequency noises, numerous frequency noises (e.g., atmospheric thermal noise, respiration noise, heartbeats, and needless power frequency) contained in the collected data should be eliminated. Low-frequency noises (0.5 Hz and lower) and high-frequency noises (40 Hz and higher) are removed through the hamming windowed sinc FIR filter. The frequency noises beyond the spectrum of 0.5 Hz–40 Hz in the raw EEG signals are filtered. Then independent component analysis (ICA) is employed to retain the valid components and remove noise components of intrinsic artifacts (e.g., eye movement and facial muscle activity) (Fig. 7). The electrical activity in the brain, representing postsynaptic cortical neuronal potentials, is defined in terms of frequency bands (e.g., delta (δ) (0.5–4 Hz), theta (θ) (4–8 Hz), alpha (α) (8–13 Hz), beta (β) (13–30 Hz), and gamma (γ) (30–40 Hz)). Considering the interested frequency domains for the research objective, a six-layer wavelet packet decomposition and reconstruction was adopted in this research (Fig. 8). Relevant frequency bands (i.e. theta, alpha, and beta) are filtered out for later analysis.

Through the preprocessing of the raw EEG data, valid band powers of 14 electrode channels are obtained. Based on the EEG indices reflecting the emotional and mental states, effects of the proposed intervention method can be measured. Besides, the combined regulation effects of the PMR and TNS intervention sessions on emotional states and mental fatigue are analyzed and evaluated.

3.3.2. Emotional state regulation

For depicting the variation trends of workers' emotional states effectively and intuitively, a tri-dimensional emotion model, ValenceDominance-Arousal (VDA) model, is applied in this research (Fig. 9) [54,55]. In Fig. 9, the valence dimension refers to the transition from negative to positive; the dominance dimension refers to the transition of emotional states from being controlled to in control; and the arousal dimension refers to the transition from inactive to active emotional states [56–58]. Three coordinate surfaces (i.e. Valence-Dominance plane, Valence-Arousal plane; and Dominance-Arousal plane) divide the space of the VDA model into eight parts (i.e. quadrants of I~VII). The coordinate axes of the three dimensions, as the thresholds for different emotional states, define the central levels of emotional state (i.e. regular arousal, neutral valence, and intermediate dominance). Through comparing the coordinate points in positive or negative coordinates, the change of emotional states can be identified. Besides, the intensity of an emotional state is described by the distance of the coordinate point from the origin O.

Based on EEG frequency band powers through data preprocessing, the dimension indices of valence, dominance, and arousal are calculated to quantify the emotional features [58,59]:

Nine types of pulse signal tested in the preliminary experiment.

$$Valence = \frac{\alpha(F4)}{\beta(F4)} - \frac{\alpha(F3)}{\beta(F3)} \qquad (1)$$

$$Dominance = \frac{\beta(FC6)}{\alpha(FC6)} + \frac{\beta(F8)}{\alpha(F8)} + \frac{\beta(P8)}{\alpha(P8)} \qquad (2)$$

$$Arousal = \frac{\alpha(AF3 + AF4 + F3 + F4)}{\beta(AF3 + AF4 + F3 + F4)} \qquad (3)$$

where α(i) and β(i) refer to the alpha and beta band power respectively, collected from the ith EEG electrode channel.

The average coordinate values (i.e. (valence, dominance, arousal)) of the four EEG collection stages of the experimental and the control groups are summarized in Fig. 10. The emotional state tendencies of the subjects in two groups, through the intervention sessions, are visually presented in the VDA model (Fig. 11).

For illustrating the intervention effects of the PMR and TNS sessions, a standard statistical t-test is selected to examine the differences of the valence, dominance, and arousal indices before and after each intervention session (Table 2). The intensities of corresponding emotional states in different experimental stages are summarized in Table 3, calculated by the distances of the coordinate points from origin O.

In the experimental group, there is a significant increase of valence after the PMR session (average from −1.78 to −1.21) ($p < .05$), and a significant increase after the PMR session (average from −1.21 to −0.93) ($p < .05$). The final result of the combined intervention is a significant increase in valence ($p < .05$). For the dominance index, there is a significant increase after the PMR session (average from 1.01 to 1.10) ($p < .05$), with a non-significant decrease after the TNS session (average from 1.10 to 1.09) ($p > .05$). The final result of the combined intervention is a significant increase in dominance ($p < .05$). For the arousal index, there is a significant decrease after the PMR session (average from 5.78 to 4.42) ($p < .05$), with a significant increase after the TNS session (average from 4.42 to 4.48) ($p < .05$). The final result of the combined intervention is a non-significant difference in arousal ($p > .05$), retained at a high level. From the whole perspective, the intensity of the emotional state of the experimental group declined gradually through the two intervention sessions.

However, in the control group, there is no significant difference in valence ($p > .05$), dominance ($p > .05$), or arousal ($p > .05$) after the time-limited (13 min) relaxation period. Reflecting at the intensity of the emotional status, the deceleration is smaller than the experimental group; i.e., a 13 min relaxation period may be insufficient to produce desired effects in adjusting adverse emotional states of subjects.

3.3.3. Mental fatigue regulation

Mental fatigue is a major adverse mental state affecting the work performance of high-altitude operations. Thus, the effects of the proposed intervention on mental fatigue are specifically focused in this research. A quantitative index of mental fatigue is essential for objectively testing the mental fatigue level of a subject. Currently, EEG has been widely applied as a neurophysiological method of assessing mental fatigue [60]. The correlations between some of the most prominent components of the EEG signal (e.g., theta, alpha, and beta frequency bands) and early stages of mental fatigue have been highlighted in prior research [61]. In this research, a combination of frequency band powers (i.e. theta, alpha, and beta) and $(\theta + \alpha)/\beta$ are applied to detect the mental fatigue level quantitatively.Based on the preprocessed EEG data, the average (θ + α)/β during the four experimental stages of the experimental group is shown in Fig. 12, which indicates the trend of mental fatigue with adjustment. Three involved frequency band powers (i.e. theta, alpha, and beta) are also listed (after the normalization). As shown in the bar graph, there is an evolutionary decrease of the alpha band power during the intervention sessions of PMR and TNS. Moreover, the beta band power gradually increases at the same time, while the theta band power has no obvious statistical trend. Above statistical results are consistent with prior research in the correlations between frequency band powers and mental fatigue [61,62]. Combining the trends of these three frequency band powers, the grand average of (θ + α)/β gradually decreases during the four experimental stages, which indicates a mitigation of mental fatigue.

To illustrate the intervention effects of the PMR and TNS sessions on mental fatigue, a standard statistical t-test is selected to examine the differences in indices of (θ + α)/β after the intervention (Table 4). In the experimental group, there is a significant decrease in (θ + α)/β after the PMR session (average from 7.95 to 6.43) ($p < .05$), and a significant decrease after the PMR session (average from 6.43 to 2.90) ($p < .05$). Ultimately, the intervention with combined sessions corresponds with a significant decrease in (θ + α)/β ($p < .05$). However, in the control group, there is no significant difference in (θ + α)/β ($p > .05$) after the time-limited (13 min) relaxation period.

Above analysis is based on the average results considering four different regions of interest (i.e. the frontal cortex, the temporal cortex, the parietal cortex, and the occipital cortex), which are generally utilized for reflecting mental fatigue. According to clinical practice and prior research, aided indices are used in this research for illustrating the intervention effects, utilizing certain channels focusing on different cortex regions. Considering the active brain regions indicating one's mental fatigue [28,63,64], (θ + α)/β concentrating on the frontal cortex and the temporal cortex is calculated in this research. The variation trend of mental fatigue reflected by this index is consistent with above analysis results considering four regions. What's more, the induction and maintenance of arousal, associated with relatively greater activation of the frontal cortex, plays a crucial part in indicating the wake-promoting state [65]. Thus in this research, arousal is specifically selected as another additional index indicating the intervention effects on mental fatigue. The arousal index (see Section 3.3.2) remains at a high level, indirectly indicating a clear mind of the subject after the combined intervention sessions.

4. Discussion

4.1. Effects of the multicomponent intervention on emotional state

After the emotion simulation of Section 3.1, the subjects reported such negative emotions as fear, anxiety, and stress. Based on the EEG data from experimental stage 1, the initial adverse emotional state is identified as the baseline for the later intervention sessions. In this research, a tri-dimensional emotion model (i.e. the VDA model) is applied to evaluate the effects of the proposed multicomponent intervention, combined with the PMR and TNS sessions, on adverse emotional states. After calculating the coordinate values of valence, dominance, and arousal based on preprocessed EEG data, the emotional state in stage 1 belongs to the IV quadrant of the VDA model. That is, the initial adverse emotional state simulating the high-altitude operation is represented by negative and low valence, positive and low dominance, and positive and high arousal. Through calculating and statistically analyzing the dimension indices of the other experimental stages, the independent and combined effects of the PMR and TNS sessions on emotional state adjustment are illustrated. The main discussions are summarized as follows.

- *Valence* is defined as a continuum index ranging between extreme emotions indicating the level of pleasure. In the initial adverse emotional status of experimental stage 1, the valence index is negative at a relatively low level. After the first intervention session (i.e. PMR), the negative *valence* index is significantly increased (a negative value with the absolute value decreasing). In the same way, after the TNS session, the negative valence index is significantly increased (a negative value with the absolute value decreasing). That is, the PMR and TNS sessions play similar roles in *valence* adjustment. The ultimate effect of the combined sessions significant increases the *valence* index, approaching the origin of the coordinate axis *Valence*, which indicates an emotional state of increased happiness, pleasure, and satisfaction.
- *Dominance* is defined as a continuum index ranging between extreme emotions indicating the level of control of one's behavior. In the initial adverse emotional state of experimental stage 1, the *dominance* index is positive at a relatively low level. After the PMR session, the *dominance* index is significantly increased. However, the TNS session corresponds with a non-significant decrease in the dominance index. The ultimate effect of the combined sessions is a significant increase in the dominance index, away from the origin of the coordinate axis *Dominance*, which indicates an emotional state of increased control, influence, and autonomy.
- *Arousal* is defined as a continuum index ranging between extreme emotions indicating the level of excitement. In the initial adverse emotional state of experimental stage 1, the *arousal* index is positive at a relatively high level. After the PMR session, the arousal index is significantly decreased. However, after

the TNS session, the *arousal* index is significantly increased. That is, the PMR and TNS sessions play opposite roles in *arousal* adjustment. Ultimately, the effect of the combined sessions makes a non-significant decrease in arousal index, maintaining a high level, which indicates an emotional state of continuing to be stimulated, excited, and wide-awake.

- The VDA model is applied to recognize emotional states effectively and intuitively. The intensity of an emotional state can be described by the distance of the coordinate point from origin O. The emotional state intensity is gradually declined through the combined intervention sessions of PMR and TNS.
- As for the control group, after the time-limited (13 min) relaxation period, there is no significant difference in *valence*, *dominance*, and *arousal*. Although there is a lessening of emotional state intensity, it is weaker than the experimental group with intervention sessions.

The independent and combined effects of the PMR and TNS sessions in emotional status adjustment are therefore validated. In summary, after this multicomponent and neurophysiological intervention, the adverse emotional state of high-altitude construction workers can be mitigated, and tend to be a relatively pleased, autonomous, and excited level.

4.2. Effects of the multicomponent intervention on mental fatigue

After the mental state simulation of Section 3.1, subjects reported that they felt mentally fatigued. Based on EEG data of experimental stage 1, the initial adverse mental state (mental fatigue) is identified as the baseline of the later intervention sessions. The band power combination of $(\theta + \alpha)/\beta$ is applied to evaluate the PMR and TNS intervention sessions on mental fatigue. Through calculating and statistically analyzing the $(\theta + \alpha)/\beta$ index of the four experimental stages, the independent and combined effects of the PMR and TNS sessions on mental fatigue adjustment are illustrated. The main discussions are summarized as follows.

- In the experimental group, there is a significant decrease in $(\theta + \alpha)/\beta$ index after the PMR session. Similarly, through the TNS session, the $(\theta + \alpha)/\beta$ index is significantly decreased. That is, the PMR and TNS sessions both play important roles in reducing mental fatigue. However, for the control group, there is no significant difference in $(\theta + \alpha)/\beta$ after the time-limited (13 min) relaxation period.
- The variation trends of mental fatigue reflected by another two aided indices are consistent with above statistical analysis, indicating a wide-awake mind of the subject after the combined intervention sessions.

The independent and combined effects of the PMR and TNS sessions on mental fatigue adjustment are therefore demonstrated. In summary, the multicomponent and neurophysiological intervention can help to reduce the mental fatigue of high-altitude construction workers.

4.3. Limitations and future work

First, a limited number of participants are involved in the experiment. Differences between subjects (e.g., in gender, age, and physical fitness) may affect the precision of the results, which can be improved with a larger number of subjects in the future. Second, the research only used PMR and TNS as intervention sessions, and focused on their combined effects. Other kinds of intervention methods and combinations for adjusting emotional and mental states can be explored in the future. Not only the immediate effects of the interventions, but the long-term effects need be studied in the future. Third, indices of more accurate, reflecting the emotional and mental states aimed at the high-altitude construction workers, need to be explored to improve the accuracy of the results. For example, the brain regions with greatest activations in indicating the mental fatigue of workers should be focused to analyze the intervention effects. Moreover, the effects of personal differences for the intervention results, between practical workers on construction sites and the participants involved in this research, should be furtherly considered in the future. In practice, when applying the intervention sessions to actual engineering, it remains to be seen how much the involved parameters (e.g. frequency and duration of the pulse in the TNS session) need to be adjusted for specific workers and intervention environments.

5. Conclusions

Aimed at the major adverse emotional and mental states (e.g. fear, anxiety, stress, and mental fatigue) of high-altitude construction workers, this research proposes a simple and rapid intervention method conducted during working intervals in a lounge environment. This is a multicomponent intervention consisting of a progressive muscle relaxation (PMR) session and a trigeminal nerve stimulation (TNS) session, which are selected and applied based on neurophysiological theories. A contrast experiment were conducted to illustrate the effectiveness of this intervention. The emotional and mental states of the subjects were measured by a wearable EEG sensor during the entire experiment, and EEG data segments indicating four experimental stages of each trial are selected for statistical analysis.

Utilizing different indices, the independent and combined effects of the PMR and TNS sessions in adjusting the adverse emotional and mental states of high-altitude workers are demonstrated. A VAD (*Valence-Arousal-Dominance*) model is applied to quantify the workers' emotional features. According to the trends of indices of valence (significant increase), arousal (retained at a high level), and dominance (significant increase), the proposed intervention is shown to have a significant effect on adjusting emotional state, from negative and passive, to a relatively positive and spiritual level. For measuring and analyzing mental fatigue, a band power combination of $(\theta + \alpha)/\beta$ is applied. This shows that both the PMR and TNS sessions significantly decrease the (θ + α)/β, which indicates that mental fatigue is eliminated. At the same time, the statistical results of the control group show no significant difference in emotional state or mental fatigue.

Although there may be some differences in the results between the practical workers and the involved participants, it should be noted that this research completes the feasibility study of a simple, rapid, and effective intervention approach aimed at scaffolders. It is one of the innovative explorations of the active intervention for high-altitude construction workers, especially in the emotional and mental state field. According to the theories of neural management [66], the research results offer theory supports for the exploration and development of active intervention approaches, aiming the emotions and mental fatigue of high-altitude construction workers. Further, in-depth study in the future can serve as a foundation for providing guidance to the emotional and mental state management on construction sites.

Acknowledgements

This research was partly supported by the General Research Fund (GRF) Grant (BRE/PolyU 152099/18E) entitled “Proactive Monitoring of Work-Related MSD Risk Factors and Fall Risks of Construction Workers Using Wearable Insoles”. Besides, this research was partly supported by “National Natural Science Foundation of China” (No. 51878311, No. 71732001, No. 51678265).

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Figures and Tables

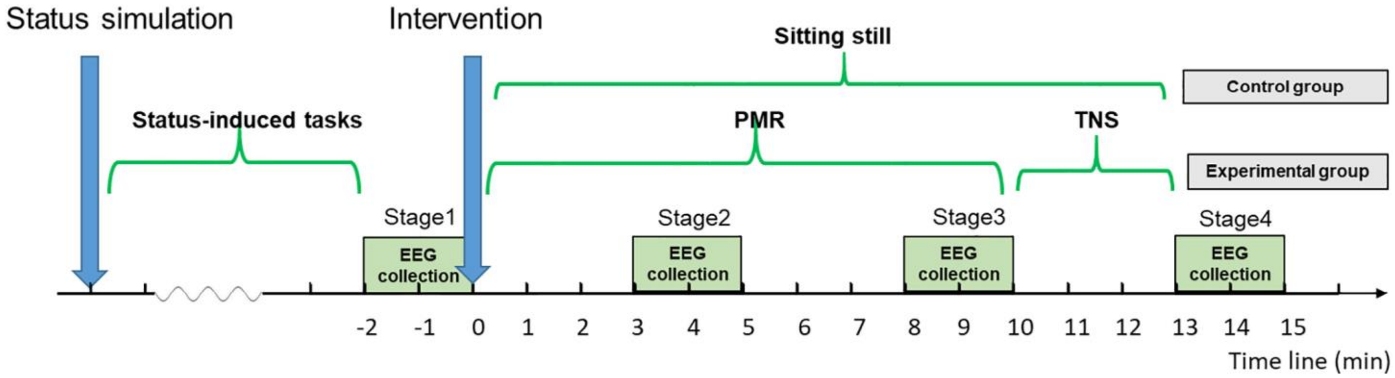


Fig. 1. The entire experiment process, with raw EEG data collection for statistical analysis

Notes: The origin of the time line denotes the starting point of the intervention. The four experimental segments for data collection respectively are: stage 1 (−2–−1 min), stage 2 (3–5 min), stage 3 (8–10 min), and stage 4 (13–15 min)).

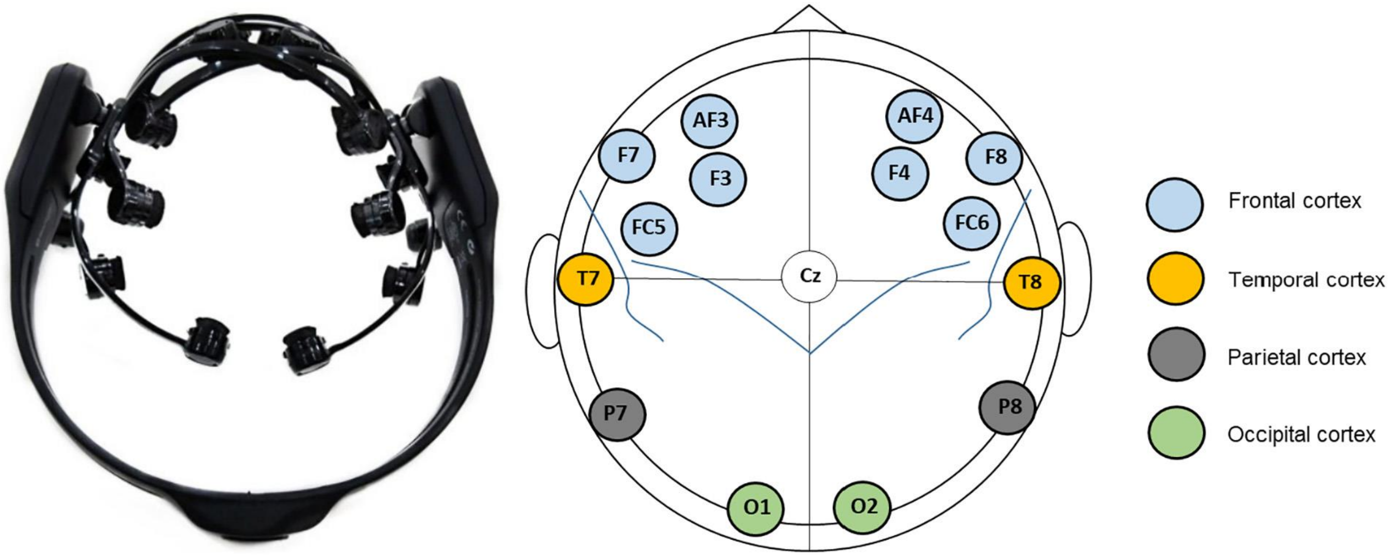


Fig. 2. The wearable EEG device (EMOTIV EPOC+ 14 Channel Mobile EEG) and corresponding 14 electrode channels (i.e. AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4)

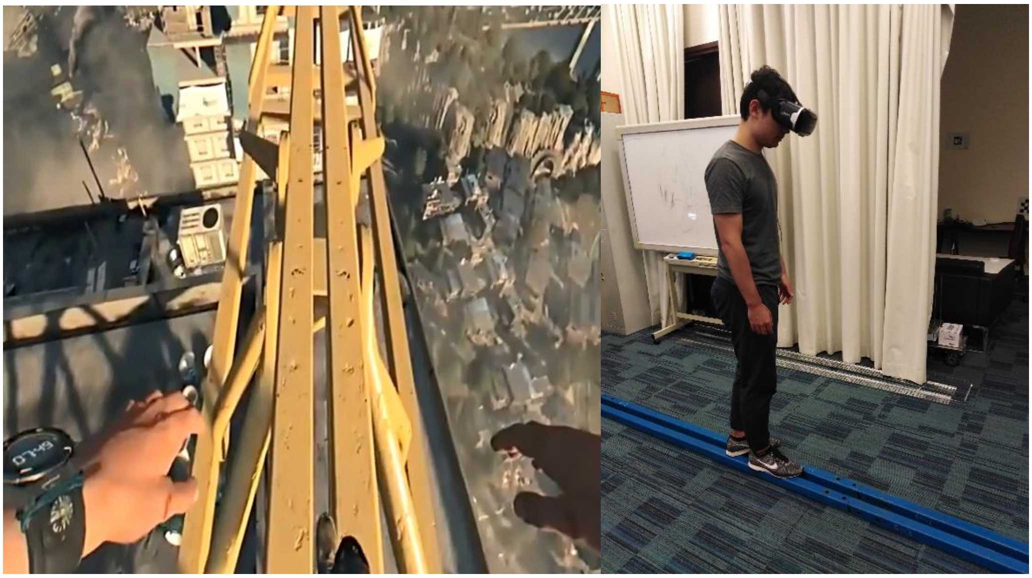
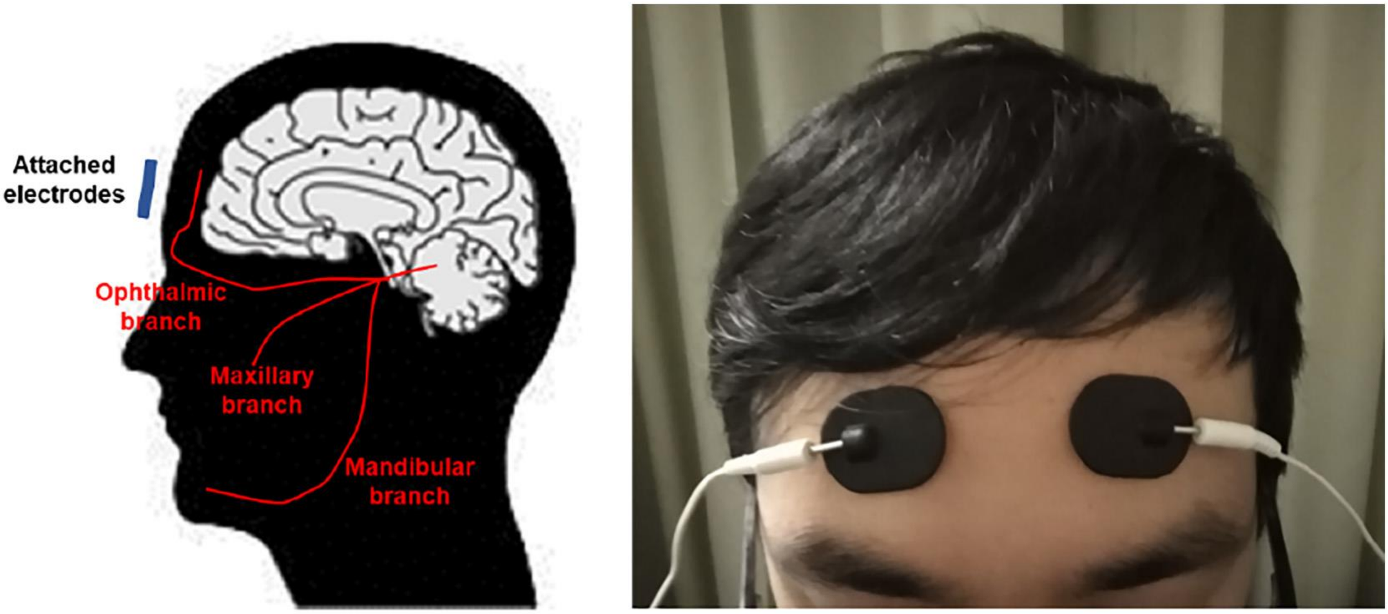


Fig. 3. VR mission simulating the high-altitude walk

Fig. 4. Progressive muscle relaxation in a lounge environment (with a wearable EEG device)

Fig. 5. The medical and portable external pulse generator



(a) (b)

Fig. 6. Two adhesive rubber electrodes placed corresponding to the V1 branches of the trigeminal nerve ((a) schematic of the trigeminal nerve stimulation cited from **Error! Reference source not found.**; and (b) a subject in the practical experiment).

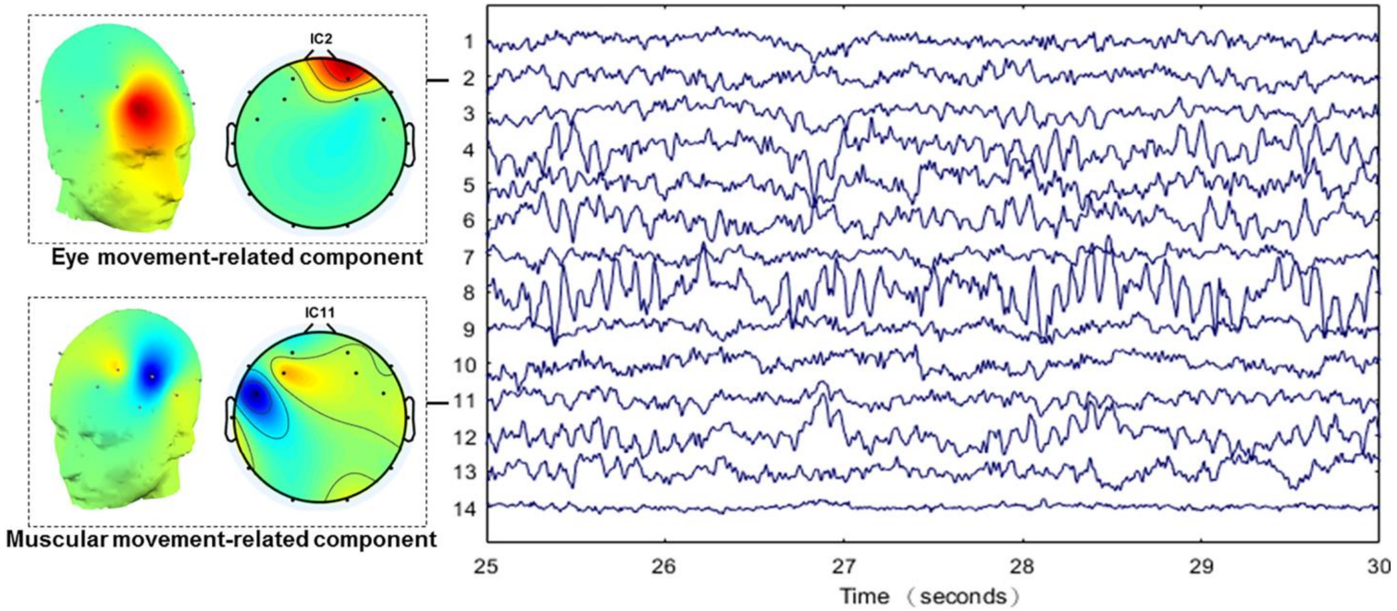


Fig. 7. 14 independent components through ICA and interested noise components of intrinsic artifacts (subject 1).

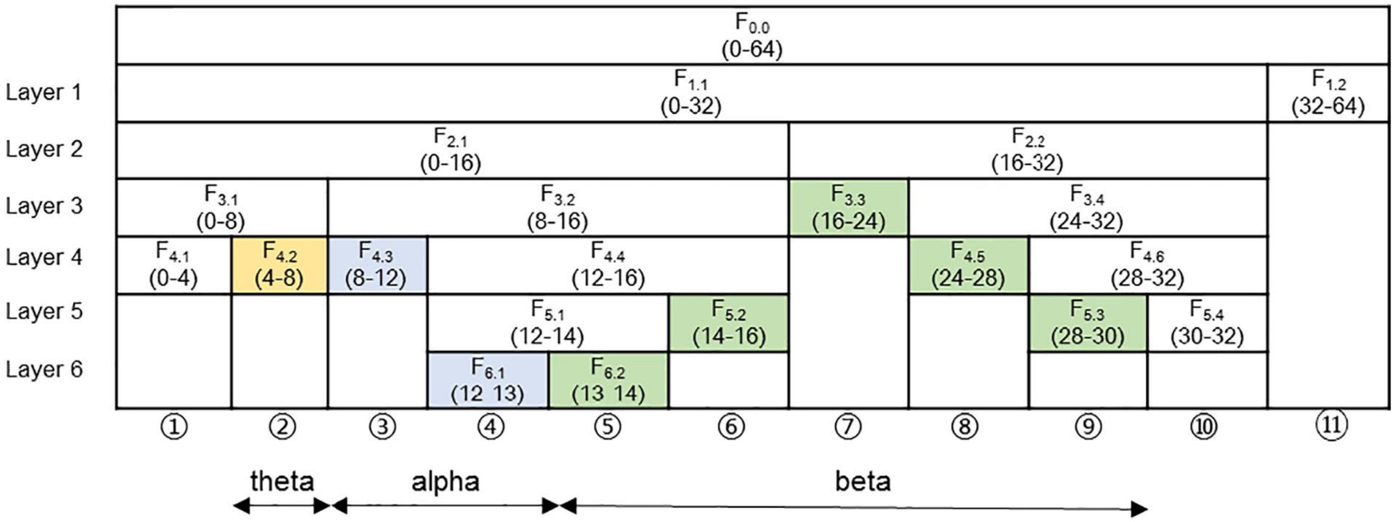


Fig. 8. Structure of the wavelet packet decomposition and reconstruction for valid band powers.

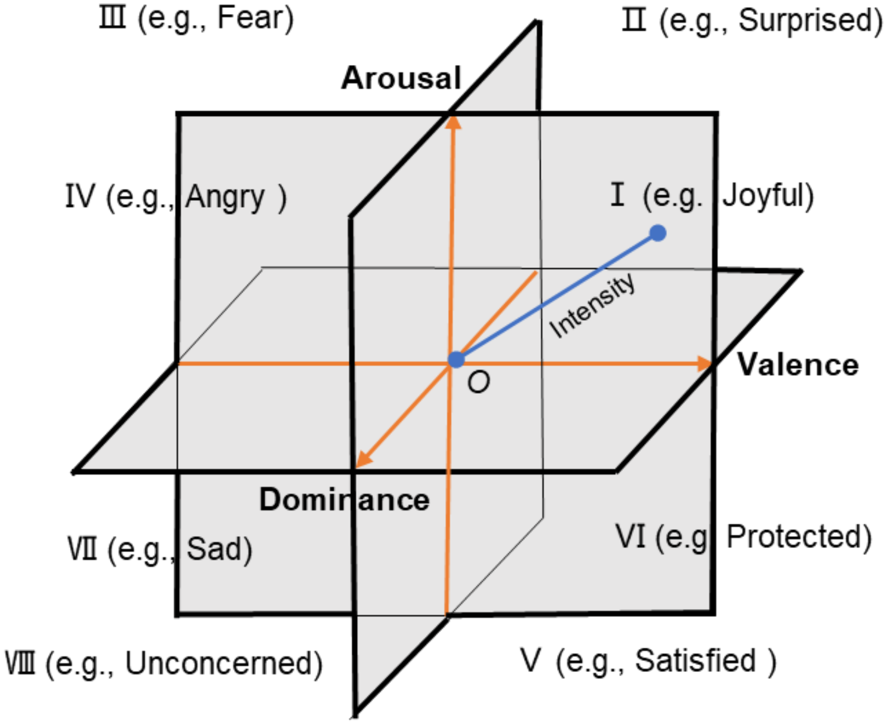


Fig. 9. The VDA model for the recognition of emotional state (typical discrete emotions are mapping to eight quadrants as the examples of specific emotional states).

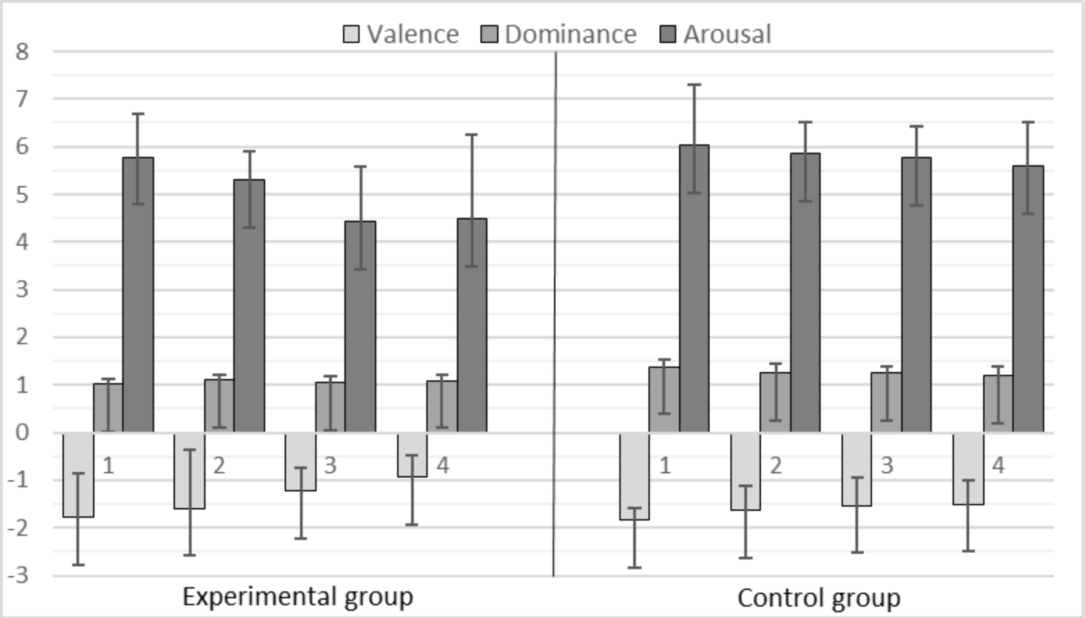


Fig. 10. Average levels of the *valence*, *arousal*, and *dominance* dimension indices in four EEG collection stages of the experimental and control groups

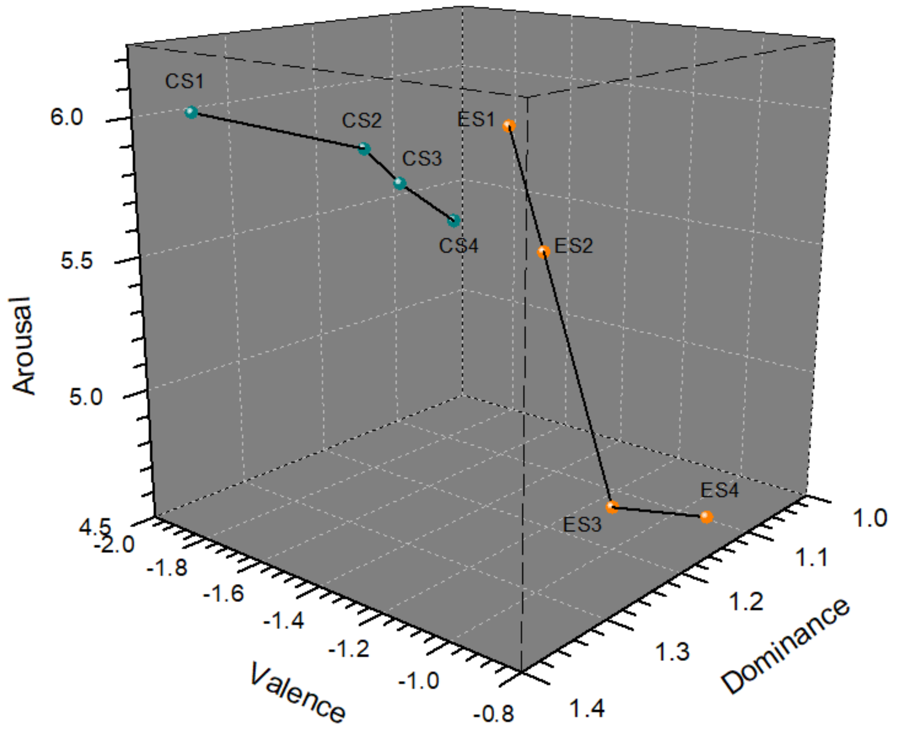


Fig. 11. Average emotional state trends of the experimental and control groups (in this figure, ES*i* represents the *i*th EEG collection stage of the experimental group, and CS*i* represents the *i*th stage of the control group).

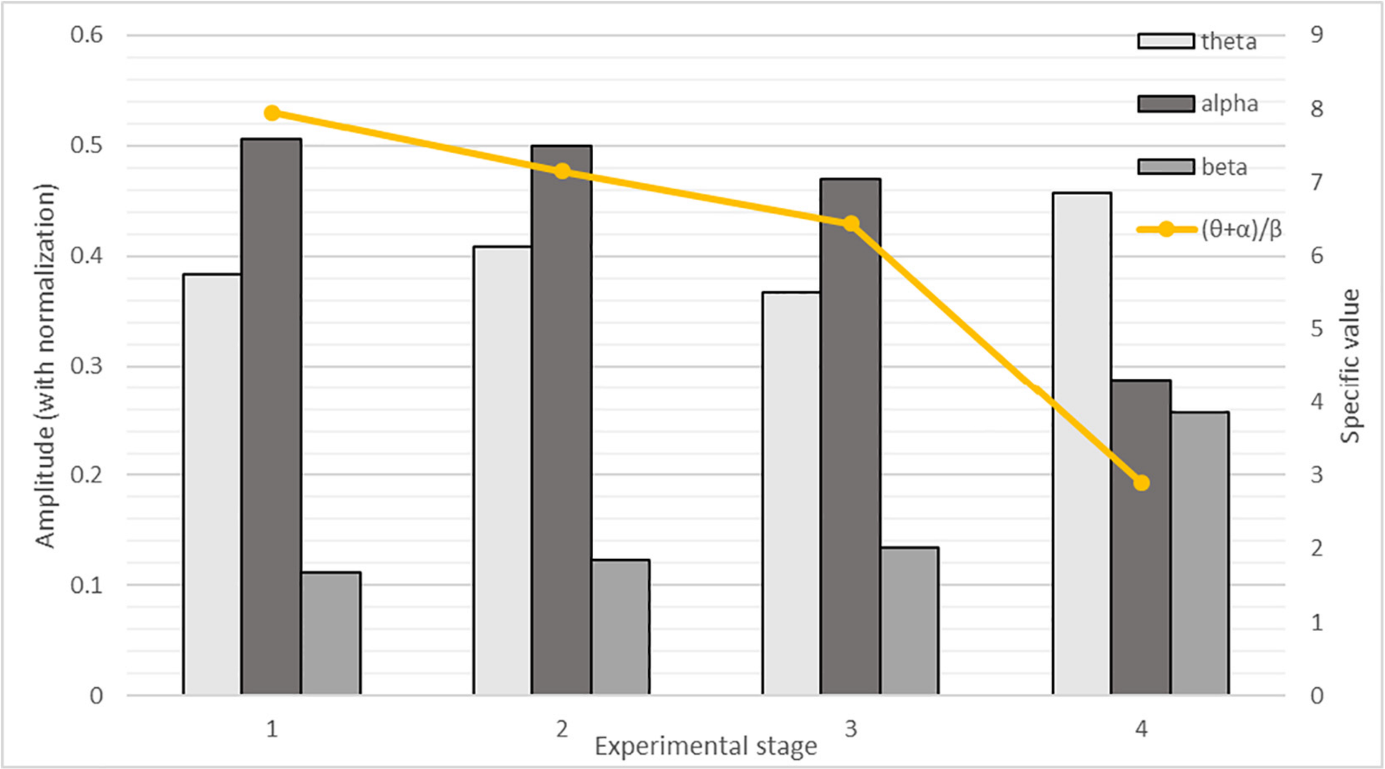


Fig. 12. Trend of mental fatigue adjustment of the experimental group through intervention sessions (bar graph: grand average of frequency band powers of *theta* (θ)(4–8 Hz), *alpha* (α)(8–15 Hz), and *beta* (β)(15–30 Hz) of the four experimental stages (after the normalization). Line graph: grand average of $(\theta+\alpha)/\beta$ of four experimental stages)

Table 1. Nine types of pulse signal tested in the preliminary experiment

Waveform	Frequency1 (Hz)	Frequency2 (Hz)	Frequency3 (Hz)	Note
Continuous wave	10	30	50	-----
Discontinuous wave	10	30	50	3s on/3s off
Disperse-dense wave	10/30	30/40	40/50	2s disperse/4s dense

Table 2. Statistical *t*-test scores for *valence*, *dominance*, and *arousal* after the intervention sessions

Group	Indices		*p*-value	
		PMR	TNS	Ultimate effects
Experimental group	*Valence*	.027 (↑)	.033 (↑)	.013 (↑)
	Dominance	.019 (↑)	.112 (---)	.015 (↑)
	Arousal	.000 (↓)	.048 (↑)	.183 (---)
Control group	*Valence*	/	/	.823 (---)
	Dominance	/	/	.179 (---)
	Arousal	/	/	.234 (---)

Note: The paired-t-test is used in above statistical t-test. The data for the pairedt- test for PMR effects are applied to the EEG data from experimental stage 1 and 3; the data for the TNS effects are from stage 3 and 4; the data for ultimate effects is from experimental stage 1 and 4. The symbols in parentheses represent the impact trends after corresponding intervention sessions: " ↑ " refers to a significant increase of the index; " ↓ " refers to a significant decrease of the index; and "—" refers to a non-significant difference of the index.

Table 3. The intensities of emotional states in different experimental stages

Group	Stage 1	Stage 2	Stage 3	Stage 4
Experimental group	6.136	5.652	4.711	4.703
Control group	6.458	6.221	6.093	5.912

Note: The emotional state of a stage is described by the coordinate value (i.e. (valence, dominance, arousal)). The intensity of emotional state is calculated by the distance of the coordinate point from origin O.

Table 4. Statistical *t*-test scores of *(theta + alpha)/beta* after intervention sessions

Group		*p*-value	
	PMR	TNS	Ultimate effects
Experimental group	.007 (↓)	.022 (↓)	.006 (↓)
Control group	/	/	.422 (---)

Note: the paired-*t* test is used. The data applied for the PMR effects are the EEG data from experimental stages 1 and 3; the data for the TNS effects are from stages 3 and 4; the data for the ultimate effects are from experimental stages 1 and 4. The symbols in parentheses present the impact trends after the corresponding intervention sessions. "↑" refers to a significant increase of the index. "↓"a significant decrease of the index, and "---" refers to a non-significant difference of the index.