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Evaluating the impact of mental fatigue on construction equipment operators' ability to detect hazards using wearable eye-tracking technology

Abstract

Construction equipment related accidents, such as collisions between equipment and pedestrian workers, pose a major challenge to occupational safety at construction sites. Decrement of operators' hazard detection ability resulting from attention failure is a leading cause of these accidents. Although mental fatigue induced by prolonged and monotonous operating tasks is known as the primary cause of this type of failure, little is revealed on how mental fatigue influences operators' ability to detect hazardous situations and associated visual attention features. To address this issue, this study uses wearable eye-tracking technology to evaluate the impact of mental fatigue on operators' ability in hazard detection and the corresponding patterns of visual attention allocation. Twelve healthy participants performed a simulated excavator operating task in a laboratory experiment. Subjective mental fatigue assessment, hazard detection task performance, and eye movement metrics were recorded and analyzed. In the experiment, mental fatigue was effectively induced and manipulated by a Time-On-Operating (TOO) procedure. Results revealed that operators' hazard detection ability decreased with the increase in subjective mental fatigue level, reflected by significant increases in reaction time for hazards and the number of misdetections. Attention allocation-related data were further analyzed to explain the specific manifestations of hazard detection failure in visual attention. The results indicated that the decrease of operators' hazard detection ability is associated with the changes of the distributions of fixation and gaze point while mental fatigue level increases. Consequently, clear observation of surrounding hazards and related details becomes difficult for operators. The findings demonstrate the effectiveness of wearable eye-tracking technology in measuring and quantifying operators' mental fatigue and hazard detection ability. More importantly, the findings offer insights into the impairing effect of mental fatigue on operators' hazard detection ability from a visual attention perspective. Such insights provide a solid basis for developing effective safety interventions and attentional guidance-based safety training methods to mitigate relevant site accidents.

Keywords: construction equipment operator; mental fatigue; hazard detection; wearable eye-tracking technology; attention; collision accident

1. Introduction

Construction equipment (e.g., excavator, loader, crane, and truck) is widely used in construction sites. However, one of the most common construction accidents are related to construction equipment operation, and these accidents range from workplace injuries to deaths [1-3]. The fatality rate of such accidents is high [4,5], and 50% of fatal accidents are related to construction equipment operation [6]. The contact collision between pedestrian workers and equipment accounts for a large portion of this type of accident [1,7], and the situation has not been improved in recent years [2,7].

It has been emphasized that the failure of construction equipment operators to detect hazards is one of the leading causes of construction equipment operation-related accidents [8-10]. This failure is often attributed to attention failure [11], which has become a crucial safety concern in the construction industry. Construction equipment operators are often required to allocate their visual attention to multiple areas (e.g., the construction site in the front, control panel, surrounding workers, and equipment) to complete their regular operation task and remain vigilant for potential hazards around construction equipment for a long time [12]. During the task, mental fatigue caused by continuous operating and monitoring activities has become the main cause of operators' hazard detection failure [13-16]. Previous research has emphasized that mental fatigue can lead to change blindness, inattention, vigilance lapse, and other hazard detection-related problems in the construction industry [8,10,17]. As contact collision accidents can bring serious safety problems, the effect of mental fatigue on operators' hazard detection ability and the corresponding visual attentional features should be analyzed. The findings can be meaningful in reducing the risk of collision between construction equipment and workers.

The relationship between mental fatigue and hazard detection has been investigated in various industries that involve tasks with human–machine interaction, such as the road transportation [18], aviation [19], and nuclear power industries [20]. However, few studies have attempted to empirically investigate this issue in the construction industry, especially from a visual attention perspective. Although the importance of operators' hazard detection ability for construction safety has been realized [11,21-24], most of these studies drew conclusions through qualitative methods or analyzed workers' hazard detection ability from other perspectives, for example, the relationship between hazard detection and safety knowledge [25]. Little is revealed on how mental fatigue influences operators' ability to detect hazardous situations. Specifically, the changes in operators' hazard detection performance and the corresponding patterns of visual attention allocation in the accumulation of mental fatigue remain unknown in the construction industry. Further exploration of the relationship is urgently needed to provide construction practitioners with insights that can guide them in proposing proper safety management strategy for improving construction equipment operation safety.

To fill the research gap, this study evaluates the impact of mental fatigue on construction equipment operators' hazard detection ability and the corresponding visual attention pattern using wearable eye-tracking technology. Operators were required to perform a monotonous and prolonged excavator operation experiment task, involving a regular excavating task and a hazard detection task. Considering the experiment safety and control for other influences on attention (e.g., illumination and team communication) or mental fatigue (e.g., vibration and temperature), a construction equipment operation simulation system was introduced to support the laboratory-based experiment. A Time-On-Operating (TOO) experimental procedure was adopted to manipulate the mental fatigue and capture the corresponding development of operators' task performance. Several fixation/gaze point metrics were proposed to describe and quantify the visual attention-related manifestation of the decrement of operators' hazard detection ability. During the experiment, operators' mental fatigue subjective assessment, hazard detection performance, and the corresponding patterns of visual attention allocation were measured. The changes of operators' hazard detection performance at different levels of mental fatigue were recorded and analyzed, and the corresponding manifestations of operators' visual attention allocation were revealed. The study demonstrates the effectiveness of wearable eye-tracking technology in evaluating and quantifying construction equipment operators' mental fatigue and hazard detection ability. Moreover, the findings can provide insights into the association between mental fatigue and operators' hazard detection failure from a visual attention perspective, which can help to develop effective safety interventions and safety training methods to mitigate the risk of the collision caused by operators' hazard detection failure.

2. Literature review

2.1 Mental fatigue and hazard detection

From a psychological perspective, mental fatigue results from prolonged periods of cognitive activity and leads to a decline in cognitive and behavioral performance [14,15,26]. In the construction industry, compared with construction workers who perform physical activities, construction equipment operators become mentally fatigued easier because of prolonged cognitive-related operating and monitoring tasks. When people are in a state of mental fatigue, they usually experience difficulties in concentrating and focusing their attention on the tasks they are required to perform [14], which can reduce their engagement and motivation for an effortful task and impair their hazard detection performance [27,28]. The ability to detect hazards and perceive and assess potential risk is an important skill for maintaining construction safety [22]. Decrement in hazard detection ability is a critical factor that can affect construction equipment operators' performance and construction safety [11,23,29]. Hence, understanding the relationship between operators' mental fatigue and hazard detection ability is crucial for proposing effective safety interventions for construction equipment operation safety.

Research focusing on the association between mental fatigue and hazard detection has become an important issue in several occupations involving human–machine interaction, such as car drivers [18,30], aircraft pilots [19,31], and nuclear power plant control room operators [20]. These studies have revealed that mental fatigue exerts adverse effects on individual hazard detection performance, which should be a crucial safety concern for accident prevention. However, the effects are distinct because of the differences among task types and environments. In the construction industry, several studies have discussed that mental fatigue can lead to change blindness, inattentiveness, hazard miss, and other attention-related problems in construction sites [8,10,17]. However, in-depth quantitative research that focuses on measuring and evaluating the influence of mental fatigue on construction workers' hazard detection is lacking in the construction industry, especially regarding the visual attention of construction equipment operators. Knowledge about how mental fatigue influences construction equipment operators' hazard detection performance is scant. To address this research gap, we first need to find an effective way to measure operators' mental fatigue level while measuring their hazard detection behaviors during a task. In doing so, we can analyze and explain the relationship between mental fatigue and hazard detection.

2.2 Mental fatigue measurement and eye-tracking technology

According to Aryal, et al. [32], the two methods for measuring mental fatigue are subjective assessment and instrument measurement. The subjective assessment method that was applied earlier was mainly to score the subjective feelings of mental fatigue by answering fixed questions related to individual mental state. (e.g., task engagement, sleepiness, perceived task demand). Several studies have applied various subjective assessment scales to evaluate the level of mental fatigue of construction workers, such as Fatigue Assessment Scale for Construction Workers (FASCW) [33] and NASA Task Load Index (NASA-TLX) [34]. Despite its wide application, the subjective assessment method bears inherent flaws, such as expected deviations when a person's feelings and thoughts about mental fatigue is measured. [35].

With the application of innovative technical devices, instrument measurement method is proposed to monitor a series of individual physiological features that objectively reflect the level of mental fatigue [32], such as electroencephalogram (EEG) [14], electrocardiograph (ECG) [36], and electrooculogram (EOG) [37]. These physiological features greatly improve the reliability and accuracy of mental fatigue measurement, as actively controlling their physiological states is often difficult for people, thus providing objective evidence for mental fatigue assessment [38,39]. However, these devices are invasive in nature and require skin preparation for sensor adherence, which may instigate irritation in construction site. In recent years, eye-tracking technology has become an effective and non-invasive method to measure mental fatigue. Compared with mental fatigue measurement methods based on electrophysiological signal monitoring (e.g., EEG, ECG, etc.), eye-tracking technology is not susceptible to interference from electromagnetic, temperature, and vibration in construction site. Several early warning methods for monitoring mental fatigue and drowsiness in car drivers have been developed based on eye-tracking technology [40,41]. With its low invasiveness and strong anti-interference, eye-tracking technology can be applied to measure operators' mental fatigue.

2.3 Hazard detection, visual attention, and eye-tracking technology

Detecting hazards involves complex cognitive phases [42,43], and the main cognitive phase is visual attention with which people observe or monitor the surrounding situation to gather information about the existence of potential hazards. However, people have finite attention resources and cannot attend to multiple places in their surroundings simultaneously [27]. Workers' error of detecting potential hazards and the corresponding unsafe behaviors in hazardous situations are mainly caused by their visual-attentional failure to perceive the hazard [11].

To shift their vision to their area of interest, people must continuously move their eyes and observe the surrounding environment using fixation or gaze. Their attention is usually focused on the point they are looking at with their eyes. Many studies demonstrated a close mapping between eye movement and visual attention [44-47]. Seeing that visual cues directly affect people's attention distribution, especially in the first phase of perceiving the outside world, a scientific method of investigating attention is to detect eye movement [25]. Eye-tracking technology has been widely used in safety-related research issues of various domains, including the road transportation [13], aviation [42], process [48], and healthcare industry [49].

Recently, eye-tracking technology has been used in the construction industry. This technology can identify, analyze, and assess the various aspects of workers' attention related to their safety performance [11,21,25,50-52]. These studies indicate that the application of eye tracking technology can capture several attention-related safety behavioral characteristics of workers in a hazardous situation in a construction site. Various factors influencing workers' hazard detection and attention are discussed in these studies, such as skill/experience [11,53,54] and safety knowledge [25]. However, as construction equipment operation is distinct from manual construction work, little is known about construction equipment operators' hazard detection and the corresponding patterns of attention allocation as the level of mental fatigue increases. At the same time, what type of eye movement metrics can be used to describe and quantify operators' attention distribution remain unidentified. Considering the reliability and wide range of uses of eye-tracking technology, we applied wearable eye-tracking technology to directly measure operators' mental fatigue and visual attention in this study.

3. Method

To collect relevant data for evaluating the impact of mental fatigue on operators' hazard detection ability, we conducted a controlled excavator operating experiment. A laboratory experiment was designed for experiment control and safety reasons. First, various uncertainties in a construction site, such as illumination, noise, temperature, and communication between workers, are difficult for us to control. Second, we must assess operators' hazard detection performance under the state of mental fatigue during the experiment, and conducting such an experiment in a construction site is dangerous. Therefore, we conducted the lab experiment based on an excavator operating simulation system.

In the experiment, participants must utilize a wearable eye tracker to complete an excavation task in the simulation system. The experiment induced mental fatigue by manipulating the duration of the task. The level of mental fatigue was measured through subjective assessment and eye movement behaviors. At the same time, the hazard detection ability was quantitatively analyzed by the hazard detection task performance and operators' attention distribution pattern. Finally, the impact of mental fatigue on operators' ability to detect hazard was analyzed and evaluated. The details are as follows.

3.1 Participants

Twelve participants (males) between the age of 24 and 35 (*Mean* 27.92 years, *SD* 3.20 years) participated. The participants were excavator operators with on-site construction experience recruited from two private construction contractors. All participants were well rested and in good health as indicated in their self-report. They reported to have slept seven or more hours and were asked to abstain from alcohol or caffeine beverages 24 hours before the experiment. All participants had normal or corrected to normal vision and did not know any information about the aims and expected results of the experiment. Written informed consent was obtained before the experiment.

3.2 Apparatus and measurement

3.2.1 Wearable eye-tracker

The eye movement metrics of the participants were measured using wearable eye-tracking technology [55], as shown in Fig. 1. The Pupil Labs eye tracker has strong and flexible hardware, open source software, and affordable price. These characteristics determine the suitability of this product for research and application in the construction industry. The eye tracker consists of three cameras; one is the world camera, and the other two are eye cameras. The world camera is a 100° diagonal camera directed toward the scene in front of a participant with a sampling frequency of 60 Hz (resolution of 1280 × 720). The eye camera is an IR camera with IR illumination. Two eye cameras can detect and record the participant's gaze point, blink, and pupil behaviors at a sampling frequency of 200 Hz. Pupil eye tracker is lightweight, and it can be adjusted to suit different participants' facial layout, thus reducing interference with participants and increases data reliability.

Fig. 1. Pupil Labs wearable eye tracker and its components [55].

3.2.2 Excavator operating simulation system

An excavator operating simulation system was built on the basis of a construction equipment operating simulation software [56]. As shown in Fig. 2, the simulation system consists of three displays (resolution of 1680 × 1050 pixels), two joysticks with force feedback, and an adjustable seat. The display in the middle presents the scene in front of the excavator cockpit. The left and right displays depict the key scenes in the rearview mirrors on both sides of the excavator as well as other surrounding scenes. The distance between a participant's eye point and the displays is roughly 120 cm. To test the hazard detection performance of participants, two rearview mirrors were placed respectively at the left and right displays (see Fig. 2). The positions of the rearview mirrors in the displays on both sides were set according to the measured position of the rearview mirrors of a real excavator cab. The system can support data acquisition with software that records the simulated task process, thereby ensuring that the collection of relevant parameters reflect participants' task performance.

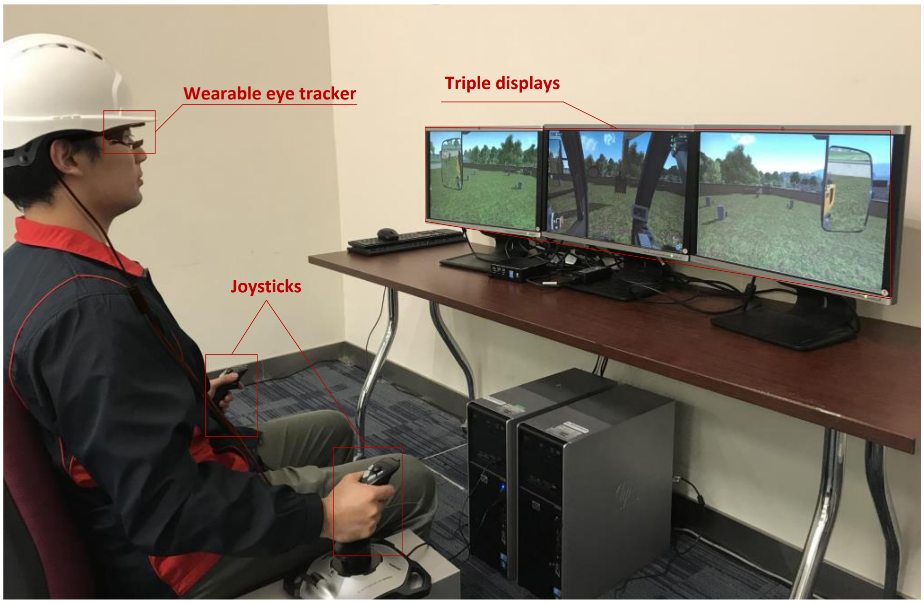

Fig. 2. Excavator operating simulation system.

3.2.3 Subjective assessment scales

The NASA-TLX and Stanford Sleepiness Scale (SSS) were used to assess individual subjective feeling of mental fatigue. The NASA-TLX is intended to measure operators' perceived workload in six dimensions: mental demand, physical demand, effort, own performance, temporal demand, and frustration. Since its development, the NASA-TLX has been used in various studies and research fields, and its reliability and sensitivity have been tested in a steady number of independent evaluations [57]. The SSS provides a global measure of how alert one is feeling, and it contains seven statements ranging from "Feeling active, vital, alert, or wide awake" (level 1) to "No longer fighting sleep, sleep onset soon, having dream-like thoughts" (level 7) [58].

3.3 Experimental design

Two important aspects were considered in the experimental design. First, the experimental task settings must take into account the characteristics of the actual operational task situation and corresponding risks. We combined the common experiment paradigm in the fields of experimental psychology [14,26,27], road transportation safety

[18,30,59], and aviation safety [31] to design an excavator operation experimental task, which consists of primary and secondary tasks.

(1) The primary task is an "excavate-discharge" task, which may be the most common form of excavator operation in earthworks. In this study, a monotonous and prolonged excavate-discharge on a polygonal construction site was designed for excavator operating (see Fig. 3 (a)). Participants must drive the excavator into the excavation area before operating the excavator to excavate the earthwork and finally load the excavated earth to the truck. This cyclical operation process requires participants to continually operate the excavator. All participants should excavate as much as possible and discharge the soil into the truck on the right.

(2) The secondary task is a hazard detection task (HDT). HDT requires participants' simple manual responses to visual stimuli, which can be used to measure their hazard detection performance [30,60]. During excavator operating, the surrounding potential hazards may come from moving pedestrian workers or other equipment. Operators' detection of surrounding hazards is heavily dependent on the rearview mirrors. Whether the operators observe the excavator rearview mirrors and whether they respond correctly to the different situations reflected in the rearview mirrors are critical for construction safety, as emphasized in research and practice [51,61,62]. Therefore, this experiment focuses mainly on operators' hazard detection for the situations reflected in the rearview mirrors. In this experiment, all the situations that may be reflected in the rearview mirrors can be divided into two main types. One is that a pedestrian worker appears (an event) and the other is that no pedestrian worker appears (a non-event). Here, an event is defined as "there are pedestrian workers reflected in the rearview mirrors." That is, whether or not the workers walk into a hazardous area, as long as they are reflected in the rearview mirrors, it is considered an event. An event can be further classified into two types: a signal event is when the worker reflected in the rearview mirror enters the hazardous area, and a non-signal event is when the worker in the rearview mirror does not enter the hazardous area. The classification of the different situations mentioned above is explained in Fig. 3 (b), and the corresponding typical situations are illustrated in Fig. 3 (c). In the experiment, the frequency of all events is set to 4 times/min, and the signal events account for 15% of the total events, which is a moderate lower frequency aiming to reflect the characteristics of a real construction site and the HDT situation [63]. The appearance of different types of events is random for all participants. Once the signal event appears, all participants must do their best to respond quickly and slow down the rotating speed of the excavator or temporarily stop the operation to avoid collisions.

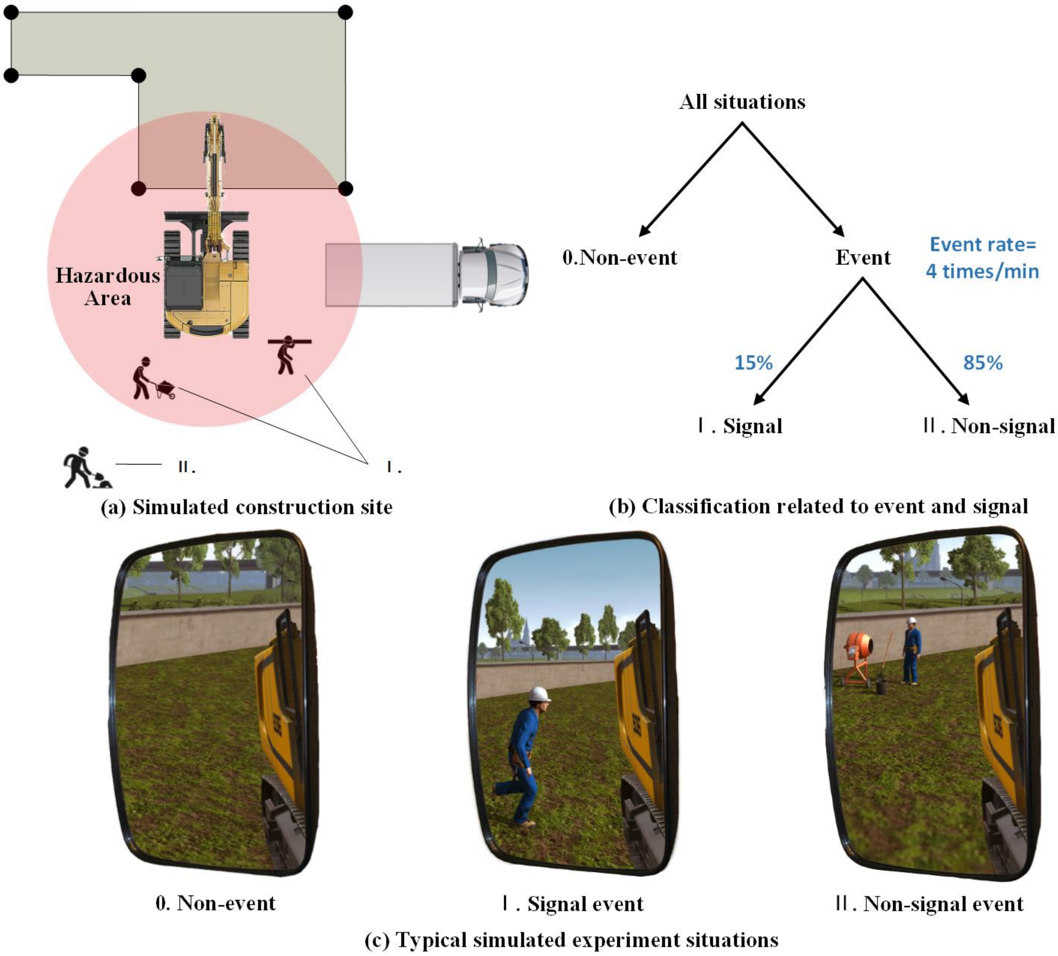

Fig. 3. Experimental task design: (a) Simulated construction site, (b) Classification related to event and signal, (c) Typical simulated experiment situations.

Second, a Time-On-Task procedure is considered to effectively induce mental fatigue. Time-On-Task is the length of time spent actively involved in a task. The Time-On-Task procedure is a common experimental design paradigm used to induce mental fatigue [14,26,28]. In this study, participants must complete a prolonged and monotonous experimental operating task, including the excavation task and HDT. Accordingly, we adopted a Time-On-Operating (TOO) experimental procedure in the experimental task.

Based on the two aforementioned requirements, the study followed a within-subjects design with the TOO as the independent variable [30,64]. In this within-subject design experiment, all participants were treated with the same independent variable. Each experimental session consisted of five 12 min long TOO phases (TOO1: 0–12 min, TOO 2: 12–24 min, TOO 3: 24–36 min, TOO 4: 36–48 min, and TOO 5: 48–60 min). Participants should perform the excavation task and HDT simultaneously during each phase. As dependent variables, we considered several eye movement metrics, HDT performance, and subjective mental fatigue assessment.

3.4 Experiment procedure

Participants were instructed to perform the TOO procedure using the simulation system in a temperature-controlled laboratory. The lighting conditions in the laboratory were stable, and the simulated scenario involved bright daylight conditions. The experiment was conducted at 9:00–11:00 AM or 3:00–5:00 PM because this is the time for normal daily work [36]. The entire experiment lasted approximately 100 min, including a practice task, a rest break and five TOO phases, as shown in Fig. 4. Before the formal experiment, we explained the experimental precautions to the participants and collected their anonymous information (sex, age, mental illness history, and other illnesses). A 20 min long practice to use the integrated simulation system was carried out in advance. Participants needed to wear the eye tracker before the practice begins. The seat height was adjusted to ensure that all participants' sights were at the same height and that the eye tracker was calibrated during the practice phase. The participants then took a 10 min long rest to prevent mental fatigue. After the rest, we informed participants to operate the excavator according to the operation procedure and inform them to do their best to comply with basic construction safety rules and task requirements mentioned previously. To avoid an end-spurt effect reactivation that occurs when participants know they are approaching the end of an experiment session, participants were uninformed about the experiment duration [59].

To collect participants' eye movement data, they were required to wear the eye tracker during the entire experiment. Participants' primary task and HDT performance were recorded in real time. To effectively collect HDT performance data, the simulation system provides a button on each of the two joysticks. When a signal event appears in the left rearview mirror, then the participant needs to press the left button as fast as possible and press the right button when a signal event appears in the right rearview mirror (see Fig. 2). To evaluate the effectiveness of the fatigue-inducing manipulation, participants were asked to complete the NASA-TLX and the SSS to assess their subjective feelings of mental fatigue before and after each TOO phase (see Fig. 4).

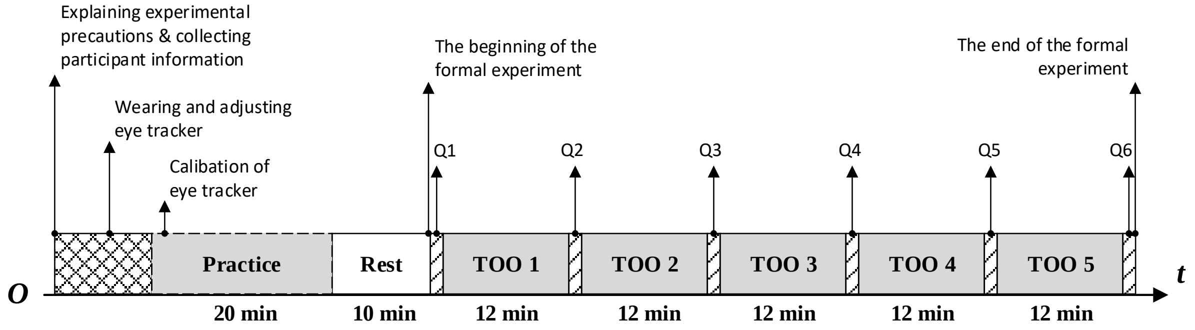

Fig. 4. Experimental procedure.

Note: Q1, Q2, …, Q6 refer to subjective assessment of the mental fatigue between each TOO phase.

3.5 Data analysis

The data analysis is mainly divided into three steps, and the specific steps and methods taken are explained in detail below.

Step 1. Data preprocessing

We first used exploratory data analysis methods to check for erroneous data. Possible erroneous data include abnormal value, noisy data, and participants deviating from the experimental protocol. Erroneous data sets found were eliminated. We then synchronized the sensor data and removed all observations that were not captured in the formal experiment (five TOO phases).

Step 2. Defining metrics

In the study, most of the variables can be obtained directly from the preprocessed data, including blink-related metrics (blink rate and blink duration) and pupil-related metrics (pupil diameter and percent change in pupil diameter (PCPD)) However, to achieve the research objectives, the metrics must be defined and calculated to better describe the hazard detection performance and the corresponding visual attention allocation and provide available dependent variables for statistical analysis.

(1) Hazard detection performance metrics

Participants' hazard detection performance was evaluated in terms of reaction time, hazard miss rate, and false alarm rate. Responses were considered correct if the correct button was pressed between 150 ms and 1800 ms after signal onset. This threshold is set to measure operators' response speed to potential stimuli (i.e., hazards) [14,26,27], which is important for safety operation. If the wrong button was pressed, the response was considered a false alarm. All other responses were considered a "hazard miss."

(2) Visual attention allocation metrics

To describe participants' visual attention allocation patterns, several fixation- and gaze-related metrics are defined. A visual fixation is an aggregation of gaze points on a single location (see Fig. 5). Fixation duration and fixation count are often used to describe how much attention resources a person has allocated to an object. The fixation duration is the dwell time of one fixation within a radius. Fixation count indicates the number of times the participant looks at a certain area. In the study, the average fixation duration was used to describe the dwell time of the fixation within an area of interest (AOI). The percentage of the count of the fixation allocated to each AOI was used to describe the allocation of participants' attentional resources. Accordingly, three AOIs were determined, which are the left (AOI_{left}), front (AOI_{front}), and right (AOI_{right}) display of the simulation system (see Fig.3 (b)). The percentage of the count of the fixation allocated within each AOI in a given time interval is calculated as Eq. (1).

$$percentage\ of\ fixation\ count(i) = \frac{fixation\ count\ (i)}{TC} \tag{1}$$

where i ={*left, front, right*}. *TC* is the total count of fixation within three AOIs in a given time interval.

To describe and reveal the spatial distribution characteristics of operators' visual attention throughout the task, this study focuses on the distribution of operators' gaze points. To be able to quantitatively describe and analyze the distribution of gaze points, each AOI (display) is assigned a normalized coordinate system, in which the origin is at the bottom left and $(1,1)$ at the top right of the AOI. In the normalized coordinate system, each gaze point can be given a standardized coordinate value (see Fig. 5). The horizontal distances from the gaze points on AOI_{left} and AOI_{right} to AOI_{front} in each TOO phase are used to directly describe the change in the spatial distribution of operators' visual attention. Fig. 5 shows that $d_{l\to f}$ is the horizontal distance from the gaze points on AOI_{left} to AOI_{front}, which can be calculated with $1 - x_l$. $d_{r\to f}$ is the horizontal distance from the gaze points on AOI_{right} to AOI_{front}, which can be calculated with x_r. It should be noted that x_l and x_r are the abscissa values of gaze points in the normalized coordinate system of AOI_{left} and AOI_{right}, respectively. The 10th, 50th, and 90th percentile of $d_{l\to f}$ and $d_{r\to f}$ of corresponding gaze points were calculated as the representative data collected for the study. The 50th percentile is used as an indicator of the average value of the dependent variable for statistical analysis, whereas the difference between the 10th and 90th percentiles is a measure of the distribution of gaze points in each TOO phase.

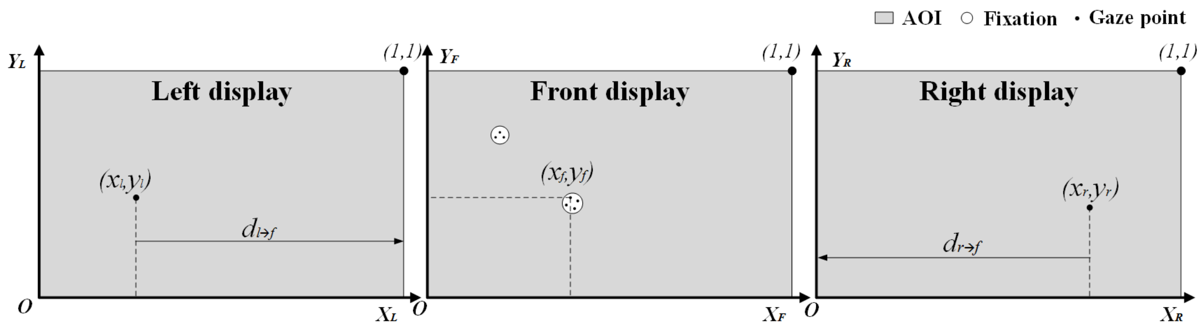

Fig. 5. Normalized coordinate systems of three AOIs.

Through data preparation, we obtained independent and dependent variables that can be used for statistical analysis. The independent variable is TOO. Dependent variables include eye movement metrics, HDT performance metrics, and subjective assessment of mental fatigue. Table 1 lists the detailed dependent variables.

Table 1. List of dependent variables in the study.

Main data categories	Dependent variables
Eye movement metrics	Blink-related: blink count/rate, blink duration
	Pupil-related: pupil diameter, percent change in pupil diameter (PCPD)

	Fixation-related: fixation duration, fixation count
	Gaze-related: gaze point position ($d_{l \to f}$ and $d_{r \to f}$)
HDT performance metrics	Reaction time, hazard miss rate, false alarm rate
Subjective assessment	NASA-TLX score, SSS score

Step 3. Statistical analysis

Demonstrating first that the experiment effectively induces mental fatigue is necessary. Referring to previous studies, we collected multiple types of dependent variables from subjective assessments and relevant eye movement metrics to support the assessment of mental fatigue. Statistical analyses of the assessment score of subjective mental fatigue, mean blink count, mean pupil diameter, and mean PCPD were performed using one-way repeated measures ANOVA with the independent variable time-on-task procedure. To analyze the effect of mental fatigue, we performed one-way repeated measures ANOVA on HDT performance and attention-allocation-related dependent variables with TOO as the repeated-measures factor. When the sphericity assumption was violated, a Greenhouse Geisser correction was applied. We used the Bonferroni adjustment to correct for post hoc pairwise comparisons. To deeply analyze the visual attention allocation features as hazard detection performance decrease, Spearman correlation analysis was used to investigate the correlations between hazard detection performance metrics and attention allocation metrics in each TOO phase. Significance level was set at $\alpha \leq 0.05$. IBM SPSS Statistics 25 [65] was used for all statistical analyses.

4. Results

In the study, all 12 participants successfully completed the experiment. Therefore, data from all participants were used for statistical analysis.

4.1 Mental fatigue inducing and assessment

To demonstrate that the experiment has successfully induced mental fatigue, relevant mental fatigue indices must be identified and analyzed by examining the effectiveness of TOO manipulation [14,26,28]. Subjective assessment that reflects participants' increased unwillingness (i.e., sleepiness, boredom, stress) to continue the task with time-on-task procedure is a common method to measure mental fatigue [14,26-28,64]. Eye movement metrics, such as blink rate [66], blink duration [67], and pupil diameter [28,67] have been proven to be effective measures of mental fatigue. As objective measurements, these metrics are effective evidence for the inducement of mental fatigue. Therefore, we analyzed changes in pupil diameter, blink duration, and blink count depending on the TOO, and in the NASA-TLX and SSS scores before and after each TOO phase. Table 2 provides the mean values for these dependent variables.

Table 2. Means and standard deviations of mental fatigue metrics in five TOO phases.

Metrics		Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Subjective assessment	NASA-TLX (0-100)	18.90 (3.59)	26.94 (7.56)	42.94 (6.54)	55.60 (4.40)	63.06 (3.73)
	SSS (0-10)	1.18 (0.41)	2.27 (0.65)	3.45 (0.52)	4.36 (0.67)	5.55 (0.93)
Eye movement	Blink count	98.67 (17.99)	116.08 (14.64.)	155.33 (14.28)	177.08 (17.74)	186.33 (12.86)
	Blink duration (s)	0.293 (0.01)	0.305 (0.02)	0.331 (0.04)	0.352 (0.04)	0.369 (0.05)
	Pupil diameter (px)	55.61 (6.76)	53.59 (6.69)	52.26 (7.09)	51.79 (6.94)	51.39 (7.04)
	PCPD (%)	4.63 (5.55)	4.11 (3.09)	4.66 (6.90)	3.67 (4.50)	4.48 (6.07)

4.1.1 Subjective assessment

Subjective mental fatigue measured by the NASA-TLX showed a significant increase from 18.90 (SD = 3.59) before the first TOO phase to 63.06 (SD = 3.73) after the last TOO phase ($F(2.14,23.50) = 226.13, p < 0.01, \eta_p^2 = 0.95$). Similarly, SSS scores increased with time on task ($F(2.80,27.96) = 130.33, p < 0.01, \eta_p^2 = 0.93$). Post hoc comparisons indicated notable differences in the assessment scores of subjective mental fatigue for each of the five TOO phases. These results indicate that participants felt increasing levels of mental fatigue as the experiment progressed (see Fig. 6).

4.1.2 Mental fatigue-related eye movement metrics

Blink count and *Blink duration.* Considerable main effects of time on task on blink count ($F(2.34,25.77) = 131.01, p < 0.01, \eta_p^2 = 0.92$) and blink duration ($F(1.66,18.28) = 28.44, p < 0.01, \eta_p^2 = 0.72$) were found. Subsequent pairwise comparisons showed notable differences in blink count for each of the five TOO phases. Pairwise comparisons also indicated that blink duration in Phase 1 was significantly shorter than those in Phases 3, 4, and 5. Blink duration in Phases 2 and 3 were considerably shorter than those in Phases 4 and 5. All other pairwise comparisons were not significant. The results of blink count are in line with earlier findings that blink rate will increase under time-on-task fatigue effects [66]. Increases in participants' blink duration are related to increased mental fatigue according to Hopstaken, et al. [28]. All changes of blink behaviors indicate the effectiveness of time on task in inducing mental fatigue (see Fig. 6).

Pupil diameter and *PCPD*. We found that pupil diameter significantly decreased from TOO 1 to TOO 5 ($F(1.54,16.95) = 22.87, p < 0.01, \eta_p^2 = 0.68$). Post hoc comparisons revealed that pupil diameter in the Phase 1 was considerably smaller than that in all other phases (see Fig. 6), except that no statistically significant difference was noted in other pairwise comparisons. The average PCPD showed that the pupil diameter of participants continued to decrease in all TOO phases. However, no notable effects of time on task on PCPD were observed, indicating that the rate of pupil diameter reduction was relatively stable. The findings are consistent with the conclusion that pupil size becomes smaller when people experience mental fatigue [28,67].

Taken together, the results of the subjective assessment and eye movement measures indicate that participants experienced increased mental fatigue after engaging in the five TOO phases. These validation metrics provide evidence of our successful manipulation of TOO for inducing mental fatigue. Participants experienced higher levels of mental fatigue as the experiment progressed. Therefore, we can analyze the effect of mental fatigue on operators' hazard detection and explore the underlying manifestations of visual attention allocation by basing on the relevant variables of five TOO phases.

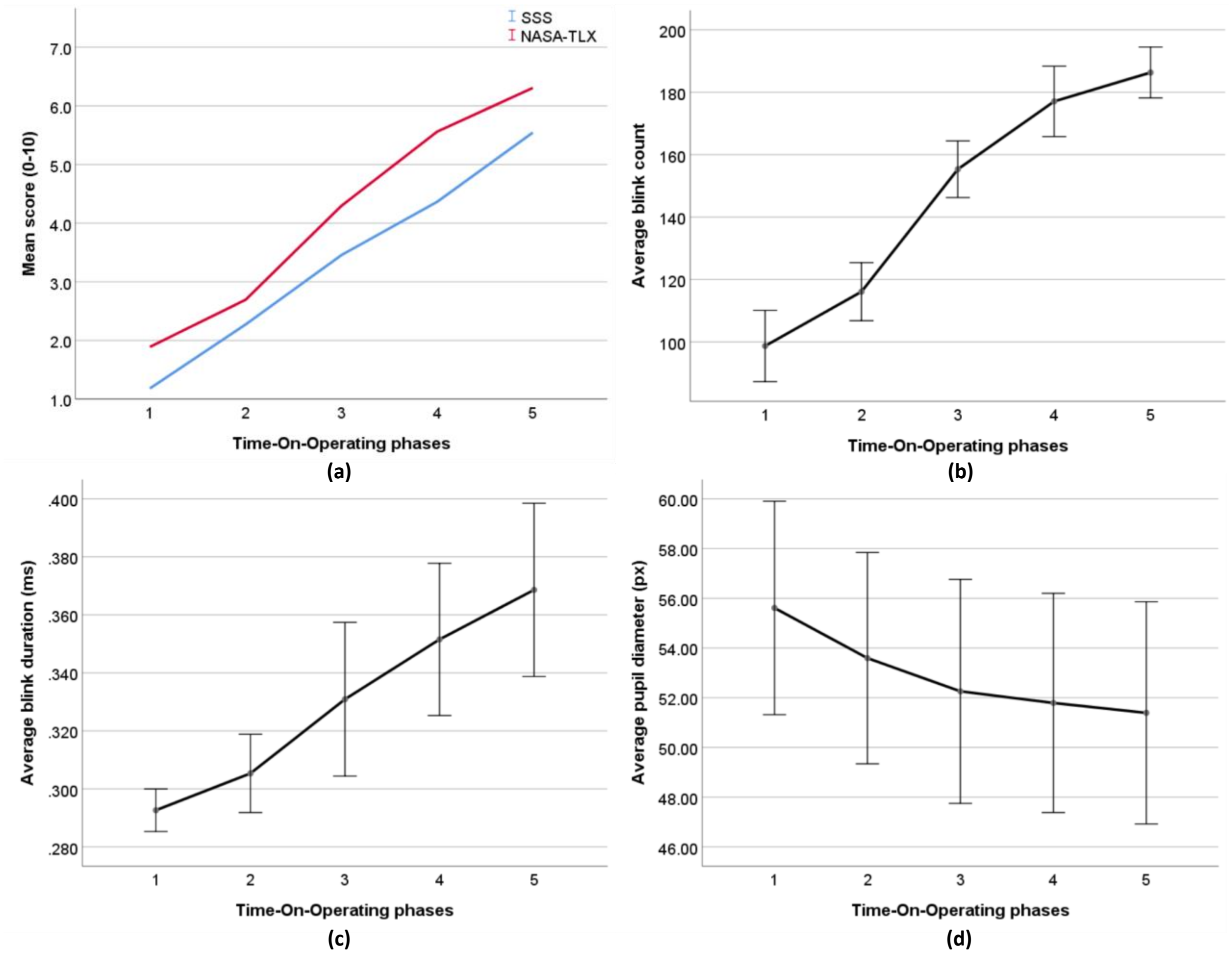

Fig. 6. Mental fatigue metrics with increasing TOO phases, (a) Mean score of subjective assessment; (b) Average blink count; (c) Average blink duration; (d) Average pupil diameter.

4.2 Hazard detection task performance

Reaction time. On the average, participants slowed down with increasing time on task ($F(2.59,28.54) = 156.50, p < 0.05, \eta_p^2 = 0.93$) (see Fig. 7). Post hoc comparisons indicated notable differences in reaction time for each of the five TOO phases, which mean that participants' response to hazard slows down as mental fatigue increases.

Hazard miss rate and *False alarm rate.* Participants increasingly missed hazards and made false alarms with increasing time on task ($F(4,44) = 39.00, p < 0.05, \eta_p^2 = 0.78$ and $F(3.36,36.92) = 28.24, p < 0.01, \eta_p^2 = 0.72$, respectively) (see Fig. 7). According to the post hoc pairwise comparisons, the hazard miss rate in Phase 1 was notably less than that in Phases 3, 4, and 5. The hazard miss rate in Phase 2 was notably less than that in Phases 4 and 5. The hazard miss rate in Phase 3 was notably less than that in Phase 5. The false alarm rate in Phase 1 was notably higher than that in Phase 2–5. The false alarm rate in Phase 2 was notably higher than those in Phases 3, 4, and 5. No other statistically significant difference was noted in pairwise comparisons.

Taken together, the results showed that participants need a considerable amount of time to identify hazards. They increasingly missed hazards and made considerable false identification of non-hazards as mental fatigue increased. These findings on hazard detection performance are in line with the results of the subjective measures, which indicate a relationship between mental fatigue and task performance.

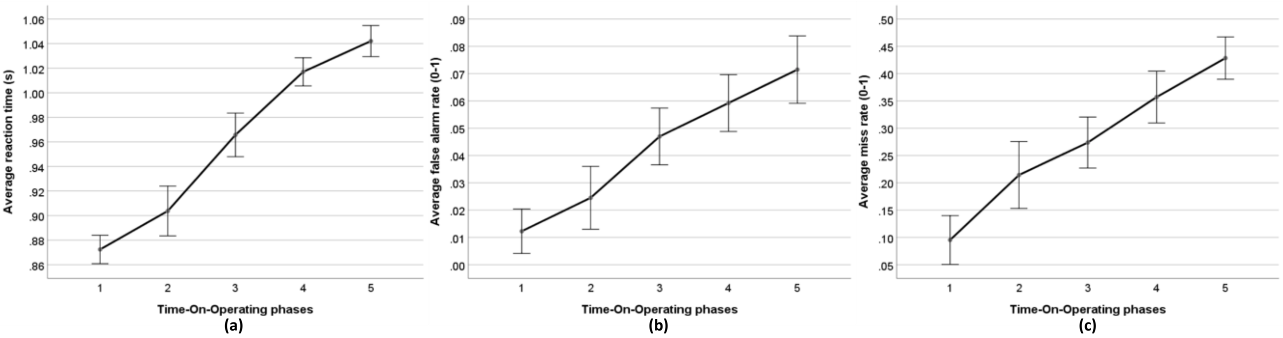

Fig. 7. Hazard detection performance with increasing TOO, (a) Average reaction time; (b) Average false alarm rate; (c) Average miss rate.

4.3 Spatial distribution characteristics of operators' visual attention

Fixation duration. No significant effects of time on task on fixation duration were observed. Fig. 8 shows that the operator has no considerable change in average fixation duration within each AOI over time. The fixation duration maintained at a steady level as mental fatigue increased. However, operators spent a long time observing AOI_{front}, as seen from the considerable difference in the average fixation duration between AOI_{front} and AOI_{left}/AOI_{right}.

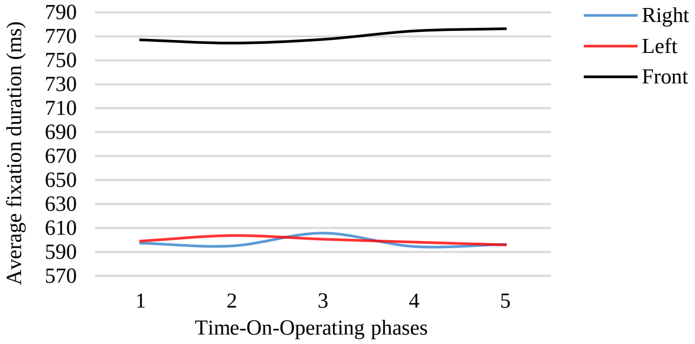

Fig. 8. Average fixation duration within each AOI with increasing TOO.

Fixation count. Time on task had a notable main effect on fixation count within AOI_{left} and AOI_{right} ($F(4,44) = 5.64, p < 0.01, \eta_p^2 = 0.34$ and $F(2.11,23.25) = 13.05, p < 0.01, \eta_p^2 = 0.54$, respectively). No notable results were obtained in the analysis of fixation count within AOI_{front}. Further post hoc pairwise comparisons showed that the fixation count within AOI_{left} in Phase 1 was considerably more than those in Phases 2, 3, and 5. In AOI_{right}, the fixation count in Phase 1 was considerably more than those in Phases 3, 4, and 5. The fixation count in Phase 2 was considerably more than that in Phase 5. All other pairwise comparisons were not notable. Fig. 9 illustrates that as the task progressed, that is, as mental fatigue increased, the count of fixation distributed in AOI_{left} and AOI_{right} decreased, and the percentage of the count of the fixation allocated within AOI_{left} and AOI_{right} decreased.

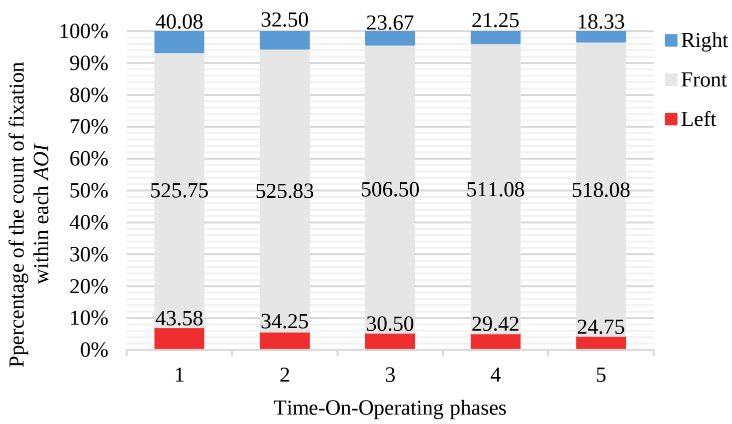

Fig. 9. Percentage of the count of the fixation allocated within each AOI with increasing TOO.

Note: The data labels refer to the average fixation count.

Gaze point position. Table 3 reports the average values for the 10th, 50th, and 90th percentile of $d_{l \to f}$ and $d_{r \to f}$ of the corresponding gaze points in the normalized coordinate system of AOI_{left} and AOI_{right}. As participants' mental fatigue increased, the average $d_{l \to f}$ of gaze points in AOI_{left} ($F(2.72,32.61) = 17.08, p < 0.01, \eta_p^2 = 0.59$), and the average $d_{r \to f}$ of gaze points in AOI_{right} considerably decreased ($F(3.23,38.84) = 7.57, p <$

$0.01, \eta_p^2 = 0.39$). Subsequent post hoc comparisons indicated that the average $d_{l\to f}$ of gaze points within AOI_{left} of Phase 1 was considerably larger than those in Phase 3, 4, and 5. The average $d_{l\to f}$ of gaze points in AOI_{left} of Phase 5 was considerably smaller than those in Phase 1–4. In AOI_{right}, the post hoc comparison indicated that the average $d_{r\to f}$ of gaze points of Phase 1 was considerably larger than that of Phase 5. All other pairwise comparisons were not notable. In Fig. 10, when participants experienced mental fatigue, the position of their gaze point distributed in AOI_{left} and AOI_{right} gradually approached the front of the excavator cockpit (AOI_{front}).

Table 3. Mean value and standard deviation of 10th, 50th, and 90th percentile of $d_{l\to f}$ and $d_{r\to f}$ of corresponding gaze points.

TOO	AOI_{left}			AOI_{right}		
	10th	50th	90th	10th	50th	90th
Phase 1	0.15 (0.05)	0.63 (0.12)	0.86 (0.05)	0.12 (0.08)	0.57 (0.05)	0.84 (0.05)
Phase 2	0.10 (0.05)	0.54 (0.12)	0.83 (0.10)	0.15 (0.07)	0.53 (0.09)	0.83 (0.06)
Phase 3	0.09 (0.04)	0.47 (0.12)	0.85 (0.07)	0.13 (0.07)	0.51 (0.11)	0.83 (0.07)
Phase 4	0.11 (0.05)	0.46 (0.12)	0.78 (0.07)	0.10 (0.06)	0.47 (0.13)	0.81 (0.07)
Phase 5	0.09 (0.03)	0.35 (0.08)	0.67 (0.14)	0.06 (0.05)	0.41 (0.10)	0.81 (0.09)

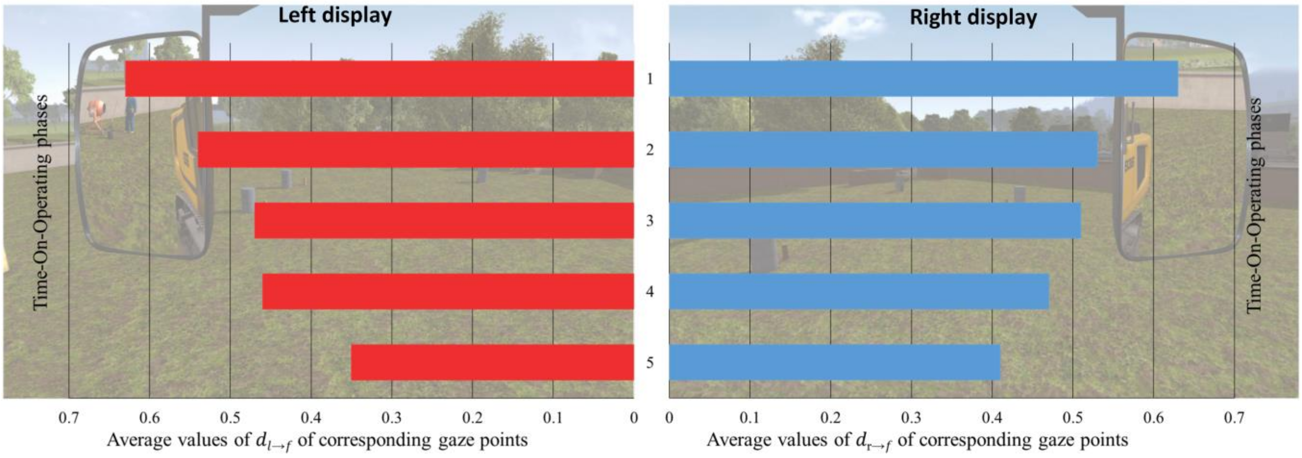

Fig. 10. 50th percentile of $d_{l\to f}$ and $d_{r\to f}$ of corresponding gaze points with increasing TOO.

To intuitively show changes in the distribution of operators' gaze point position with increased mental fatigue, heat maps were made to represent the gaze distribution in each of the five TOO phases (see Fig. 11). Fig. 11 shows that when participants were in a low mental fatigue state (Phase 1), the gaze points were in the area where the signal changed, and they directly observed the key targets around the excavator (i.e., rearview mirrors). The gaze point distribution in Phase 3 showed signs of deviation from the signal change area (rearview mirrors) as mental fatigue increased. When the participant was in a state of extreme mental fatigue, his gaze points were gathered toward the front, and the key targets around the excavator were hardly observed directly.

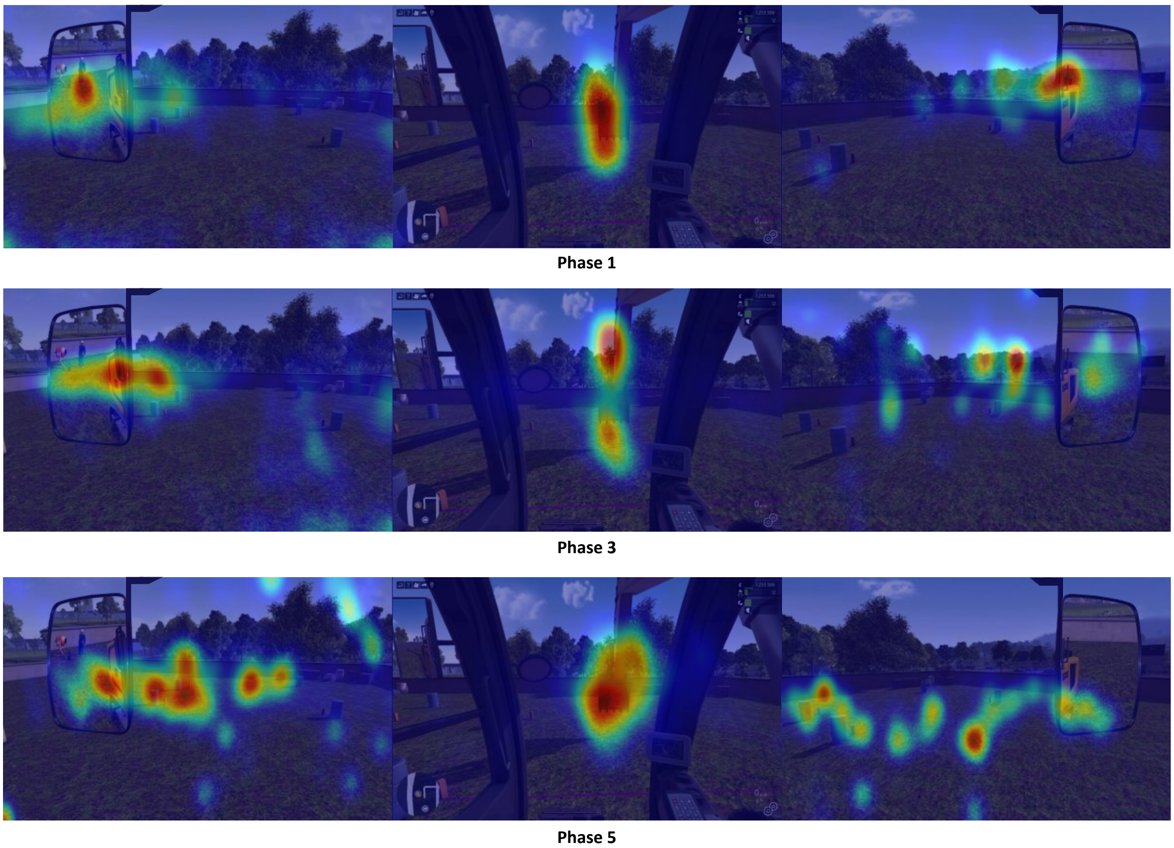

Fig. 11. Heat map of gaze point distribution.

Based on the above analysis of hazard detection performance and the spatial distribution characteristics of visual attention, the decrease in operators' hazard detection performance can be caused by the change in visual attention allocation as mental fatigue increases. We conducted a Spearman correlation analysis between operators' hazard detection performance (reaction time, hazard miss rate, and false alarm rate) and visual attention allocation features (fixation count and gaze point position). The findings directly support the relatedness of these measures. We found strong correlations between all hazard detection performance metrics and their corresponding visual attention allocation metrics. This finding statistically confirms a decrement in hazard detection performance as time on task was associated with a specific pattern of visual attention allocation. The results revealed several key findings. Negative correlations between reaction time and fixation count within AOI_{left} and AOI_{right} were found ($p < 0.01$). Reaction time, hazard miss rate, and false alarm rate were significantly correlated with gaze point position ($p < 0.01$). As mental fatigue increased, participants' fixation allocated to AOI_{left} and AOI_{right} decreased and the gaze points gradually closed to AOI_{front}. This finding means that participants did not directly observe the potential hazards through the rearview mirror, thereby making it difficult for them to identify changes in the surroundings. The influence was manifested by the decline of participants' hazard detection ability. Specifically, participants' reaction time for hazards increased, and the correct response rate of hazard identification decreased. This effect can easily lead to serious construction safety problems, such as collision and rolling accidents.

5. **Discussion**

5.1 Impairing effects of mental fatigue on operators' hazard detection ability and their visual attention allocation

Hazard detection decrement and the associated attention failure caused by mental fatigue among construction equipment operators cause dangers in the construction industry. This study focuses on construction equipment operators who are responsible for prolonged excavation and discharging tasks while they detect and respond to hazards that may cause potential collisions. In the study, we first applied wearable eye-tracking technology to measure blink and pupil behaviors. The use of these measures were combined with the subjective assessment of mental fatigue to validate the ability to induce mental fatigue by using TOO procedure. Results indicated that operators experienced higher levels of mental fatigue as TOO progressed. Increases in hazard miss rate, false alarm rate, and reaction time show that participants' rate of missing peripheral hazards increases by over 40% after a continuous 60 min experimental task. The findings showed that mental fatigue can heavily impair construction equipment operators' ability to detect hazards even in early phases of excavation tasks (nearly 30% of hazard miss rate for the 36 min task). The reaction time measured in this study included the time needed to detect the hazard but did not include the time needed to avoid the hazard. Hence, hazards can be worse in actual construction sites because the reaction time may be underestimated compared with real operation tasks. Previous studies have demonstrated that increased hazard miss rate and slow reaction speeds are typical features of vigilance lapse [30,42], which means that operators are prone to hazard detection failures (i.e., missing potential hazards) and lead to a high risk of collision or rolling accidents.

To intensively discuss how operators' hazard detection ability decreases under mental fatigue, we measured and quantified spatial distribution characteristics of participants' attention through wearable eye-tracking technology. We also analyzed the relationship between mental fatigue and hazard detection from the perspective of visual attention allocation. The findings indicate that the decrement of operators' hazard detection ability results from the changes in his visual attention allocation with increasing mental fatigue. Operators' fixation allocated to both sides of the excavator (the rearview mirrors) decreased and the position of his gaze point gradually approached the front of his sight because of mental fatigue.

According to applied attention theory, people need to exert mental and physical efforts when they allocate their limited attention resources for accessing information [68]. The information access effort is often associated with several features of the physical layout of visual space, including the viewing angle separating two information sources, the extent to which the information lies on different depth planes, and the amount of clutter that requires to be examined before the goal of the observation is achieved [42,68]. Such phenomenon is known as the “edge effect,” in which these factors can impair the allocation of visual attention from one information source to another, especially when the spatial locations of the two information sources are far apart [69]. In this study, all counts of fixation allocated within each AOI and the corresponding average fixation duration in each of the five TOO phases revealed that the operators may focus their observation heavily toward the center of the display and are less likely to scan to the rearview mirrors, which requires a wide range of head movements. This behavior is typical of edge effect. Edge effect became increasingly evident due to the accumulation of mental fatigue, especially when operators identified and judged the distance between the worker and the excavator, which required them to exert more cognitive resources. The number of visual fixations on rearview mirrors of the equipment became less and the distribution of the gaze point gradually approached the central display as mental fatigue increased. According to previous studies [14,70], the critical effect of mental fatigue is an aversion to a further investing effort in maintaining task performance. During the operating process, the increase in operators’ mental fatigue makes them reluctant to pay more attention to the edges far from the visual center, which greatly impairs the distribution of visual attention on the surroundings of the equipment. As a consequence, detecting potential peripheral hazards in a timely manner becomes difficult for operators.

Mental fatigue generally reduces the subjective willingness of the operators to exert effort to observe the surroundings of the construction equipment, which means less attentional resources are allocated to surrounding hazards. When the operators experience mental fatigue, they are inclined to quickly glance at the surroundings, rather than to directly observe the hazards surrounding the equipment. This behavior can lead to missing hazards and decreased speed in responding to risks of collision or rolling. This result is consistent with previous research [14,27]. Therefore, the pattern of operators’ attention allocation can be extremely unsafe in actual construction sites with complex and uncertain situations. Clear observation of the surrounding hazards and specific details is difficult for operators. These findings can help construction practitioners gain a deep understanding of operators’ mental fatigue so as to propose better safety strategies that can reduce relevant risks and prevent collision accidents.

5.2 Implications

Given that mental fatigue impairs operators' ability to detect hazards, we emphasize the importance of effective strategies for mitigating the impairing effect of mental fatigue and improving hazard detection performance. As has been mentioned above, participants' hazard detection rate decreased to 70% of the initial performance after 36 min of operating and to 60% after a 60 min task. Their reaction times have also considerably increased as the task progressed. These discoveries can be used as a theoretical basis for improving construction working shifts. Construction managers should strengthen their supervision after each 30–40 min operation task. They can set a break for operators to allow them to recover from mental fatigue. Alternatively, they can introduce other safety interventions to improve operators' hazard detection performance during the course of the task, such as auditory attentional cueing [42], analog highlighting and instruction projection [71], and neuropsychological recovery method [72]. In addition, they can consider the difference in the accumulation speed of mental fatigue caused by the complexity of the construction task (i.e., the surrounding environment and the difficulty of task operation) to carry out a precise adjustment and formulation of work shifts.

Hazard detection is a vigilance task, which is a typical application paradigm for signal detection theory (SDT) [42]. Hence, we can explore solutions to improve operators' hazard detection performance based on the principle of SDT. SDT explains that operators' hazard detection performance is determined by his response criterion and sensitivity to hazards. Response criterion is a standard used by a person to perceive whether a signal (i.e., hazard) has occurred or not, whereas sensitivity indicates the difficulty or ease to detect if a target signal is present from background events. If a person is in a state of mental fatigue, then his response criterion and sensitivities will undergo changes. Based on SDT, researchers have tried to use the specific pattern of response criterion and sensitivity of car drivers with high safety performance for the training on safe driving of novices [73]. This idea can be used in safety trainings of construction equipment operators. In addition, the usage of a wearable eye tracker can help capture hazard detection or other visual behavior strategies of operators under various scenarios of equipment operation. By doing so, attentional-guidance-based operation safety training methods can be proposed to enhance operators' hazard detection ability and mitigate the impact of mental fatigue. In the construction industry, several researchers have applied eye-tracking technology as an auxiliary tool to provide a basis to confirm the effectiveness of training programs in enhancing manual workers' hazard detection ability and improving their visual search strategies [11,50,52,74]. Using eye-tracking technology to capture and learn the visual behavior of operators with high safety performance for the evaluation and training of novices is an effective way to improve the safety in construction equipment operation. This direction will be one of our future works.

This study demonstrates the effectiveness of eye-tracking technology to monitor construction equipment operators' mental fatigue and hazard detection ability decrement. Our results suggest that blink and pupil behaviors are feasible indicators of construction equipment operators' mental fatigue. The wearable eye tracker can monitor operators' gaze point position changes in real time in the most direct way. It can also be used for early warning of hazard detection ability decrement or vigilance lapse. Wearable eye-tracking technology has low intrusiveness and has broad application prospects in construction equipment operation tasks or other construction tasks.

5.3 Limitation and future works

The laboratory experiment conducted in the study tried to simulate the real operation experience as much as possible. However, capturing the real-operating environment through simulation is difficult. The complexity and uncertainty of an actual construction site are difficult to replicate in a laboratory experiment. For example, although the location and form of the stimuli in the laboratory experiment have been reasonably designed, they are still different from the randomness of the on-site environment, especially in a vigilance-related experiment [42,75]. In a real construction equipment operation task, the rate of accumulation of mental fatigue may be higher, and operators' hazard detection ability may decrease quickly. The operator needs to exert multiple cognitive resources to identify various hazards in the construction site. Future research can further demonstrate the validity of the research results and the availability of eye-tracking technology through a field experiment.

6. Conclusions

With the development of construction automation, safety in construction equipment operation has become an important concern for construction practitioners. The failure of construction equipment operators in detecting surrounding hazard are often associated with collisions between construction equipment and pedestrian workers, causing severe injuries and fatal accidents. Mental fatigue is one of the leading causes of operators' hazard detection failure. Previous studies mentioned that mental fatigue can cause inattention, vigilance lapse, and other hazard detection failures on the construction site. Thus, this paper aims to evaluate the influences of mental fatigue on operators' hazard detection and the corresponding visual attention through the application of wearable eye-tracking technology. Participants were recruited to perform simulated excavator operating task in a laboratory experiment. The research results showed that operators' hazard detection performance decreased when they experienced mental fatigue. Further analysis of the spatial distribution characteristics of their visual attention suggested that they were likely to quickly scan a narrow area to perceive the surrounding situation, rather than directly inspecting the hazards around the excavator. This behavior can lead to missed hazards and declined speed in responding to collision risks.

The research findings are useful for research and practice. The feasibility of eye-tracking technology applied to monitor and quantify construction equipment operators' mental fatigue and hazard detection decrement was demonstrated. The impairing effect of mental fatigue on operators' hazard detection ability and the corresponding change pattern of visual attention pattern were found. Consequently, effective safety interventions and visual-based safety training methods can be proposed for reducing operators' hazard detection failures and enhancing their hazard detection ability. However, the laboratory experiment has inherent deficiencies compared with the file experiment. Future work can focus on improving the experiment design and further verify the reliability of the research and the practicality of eye-tracking technology in construction sites.

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