An experimental method to study the effect of fatigue on construction workers' safety performance

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Abstract
Fatigue is believed to have a negative effect on workers' safety performance. The current fatigue studies in construction have relied on questionnaire or interview survey, and due to certain limitations of such research method, the changing patterns of errors and the types of errors associated with different levels of fatigue are not well understood. By viewing an unsafe behavior as a cognitive failure, this research proposes an experimental method to study the effect of fatigue on construction workers' safety performance. First, the research designed a typical manual handling task to simulate the actual construction work. The participant's fatigue level could be measured by a Fatigue Assessment Scale for Construction Workers (FASCW), and the participant's safety performance could be measured by monitoring the participant's errors when performing the tasks. Second, a pilot study was conducted to show that the experimental tasks could induce fatigue effectively, and workers made more errors in a fatigue state. Third, the formal study found that the fatigue level of 20 was a critical point from where the effect of fatigue began to emerge. When a worker's fatigue level exceeded 20, there was a linear relationship between fatigue levels and error rates. In terms of error types, when at a relatively low fatigue level above 20, a worker's errors were mainly due to the failure of hazard perception. But as fatigue accumulated, its impact on the worker's capacity of motor control became significant. Relevant implications derived from the experimental findings for safety management are also discussed.

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1. Introduction

Construction workers are prone to fatigue as the construction work is typically characterized by heavy workload (Hartmann and Fleischer, 2005), awkward work postures (Mattila et al., 1993), and prolonged work hours (Dong, 2005). Fatigue at work may be associated with decreased motivation, vigilance, work capability and performance (De Vries et al., 2003), which could possibly result in accidents and injuries (Swaen et al., 2003). The impact of fatigue is likely to be more serious under the construction environment, which is usually regarded as dynamic and risky (Pinto et al., 2011; Ringen et al., 1995).

A number of literature have attempted to study the relationship between fatigue and safety outcomes. Dong (2005) examined the connection between work hours and safety outcomes among construction workers by analyzing the data collected from the National Longitudinal Survey of Youth. The results provided evidence that the fatiguing factors (i.e. overtime and irregular work scheduling) had an adverse effect on worker safety. Powell and Copping (2010) conducted a field study on a sample of construction workers to measure the sleep deprivation and its consequence. They found that fatigue caused by inadequate sleep might results in decrements in performance and a higher risk of accident. Chan (2011) evaluated the major risks contributed to accidents in oil and gas construction through questionnaire and interview surveys and found that, all of the stakeholders unanimously ranked fatigue as the most critical risk. A similar study was also conducted by Adane et al. (2013), who investigated the causes of work-related injuries among building construction workers and found that overexertion was one of the leading causes.

Regarding the mechanisms of fatigue effect, most research focus on the factors related to "energy" such as resources and efforts (Matthews and Desmond, 2002). According to cognitive psychology, resources refer to the reservoirs of "fuel" or "energy" for information processing (Matthews et al., 2000). The proper resource allocation is essential for the accomplishment of various tasks (Hollands and Wickens, 1999). And the process of resource...
allocation can be distinguished by active control and non-active control (Robert and Hockey, 1997). Non-active control happens when dealing with low demanding tasks, and active control happens when dealing with high demanding tasks. The activities of active control are dependent on a person’s effort regulation (Matthews and Desmond, 2002; Robert and Hockey, 1997).

The research focusing on “resource availability” emphasize the limitation of resources. When a person is in a fatigue state, the physiological energies will be attenuated, which means the decline of resource availability (Matthews and Desmond, 2002). And when resources are not adequate for the accomplishment of tasks, the task performance will be impaired (Desmond and Matthews, 1996). See et al. (1995)'s study supported the view of resource availability, and found that task performance was sensitive to task difficulty.

Meanwhile, the research focusing on “effort regulation” believe that fatigue can affect the effort to allocate resources to meet the task demands (Hancock, 1989). So, the decline of effort level, rather than the availability of resources, is the reason for task performance impairment caused by fatigue. Some research found that even in a fatigue state, a stable task performance was still able to be maintained (Desmond and Hoyes, 1996). Contrasting to the resource theory, the effort regulation theory believes that the impact of fatigue is more significant under low demanding tasks. In Matthews and Desmond (2002)'s study, drivers performed a simulated driving task, in which task demands were manipulated by varying road curvature. The study found that the effect of fatigue would appear only under “underload” conditions, and when stimulated by a motivational manipulation, task performance was improved instantly.

Therefore, fatigue may affect task performance through different mechanisms, and the corresponding strategies to manage the effects caused by fatigue must also be differentiated. The current fatigue studies in construction have largely relied on the research method of questionnaire or interview survey (Hsu et al., 2008). A recent study by Azevedo et al. (2014) evaluated the possibility of falls while performing tasks by simulating manual handling tasks on a 4-m treadmill, and Tixier et al. (2014) analyzed the relationship between emotions and risk perception through a controlled experiment.

However, few of the current studies have tried to address the effect of fatigue on safety more quantitatively through experiments. Compared to experiment, a questionnaire or interview survey may have certain limitations. First, it is hard to quantitatively define a causal relationship between fatigue and safety due to various distractions of confounders on the construction sites. Second, it is difficult to assess how safety is affected by fatigue, as well as the effectiveness of a potential fatigue countermeasure. Therefore, though it is clear that fatigue will generally affect safety performance, it is specifically unclear on (1) the changing patterns of errors while the level of fatigue grows; (2) the types of errors associated with different levels of fatigue.

In fact, the method of experiment has been widely used to study the effect of fatigue on task performance in a wide range of areas such as driving (Matthews and Desmond, 2002), manufacturing (Moore and colin, 1996) and sports (Moore et al., 2012). Aiming at a better understanding of the effect of fatigue on construction workers’ safety performance, this research proposes an experimental design including the design of experimental tasks and the design of a supporting platform. The experimental design is expected to enable a simultaneous measure of both fatigue and safety performance. A pilot study was conducted, with the purpose of assessing the feasibility of the proposed experimental design in studying fatigue and safety, and determining the settings of task difficulty. In the formal study, the effect of fatigue on safety performance was analyzed.

2. Experimental design

2.1. Theoretical basis

On the one hand, a reason that hinders the studies on fatigue and safety in construction is the mismatch of measurement between the two variables. Fatigue can be measured in either an objective or a subjective way. Objective measures of fatigue focus on the physiological processes (e.g. Electromyography (Petrofsky et al., 1982), Electrocardiography (Egelund, 1982) and Electroencephalography (Lal and Craig, 2001)) and subjective measures usually refer to fatigue assessment scales (Dittner et al., 2004). No matter which type of measure is used, the fatigue level may fluctuate even in a single work shift. However, safety performance measured by indicators of injuries, incidents, or unsafe behaviors is relatively stable in short term and has a low sensitivity to the change of fatigue.

On the other hand, the selections of safety strategies are largely related to the research paradigm of construction safety. As stated by Mitropoulos et al. (2009), most of the current safety studies and practices in the construction sector are grounded on the normative paradigm, which generally define safety as obeying a series of normative behaviors (e.g. safety rules) and then regard an actual behavior as unsafe if it has some extent of deviation from the normative behaviors (Rasmussen, 1997). Safety strategies guided by the normative paradigm emphasize management commitment and policies to prevent unsafe conditions, and focus on workers’ training and motivation to prevent unsafe behaviors (Mitropoulos et al., 2009). However, these strategies ignore the influence of production system, team processes and human factors (e.g. fatigue) on behaviors as well as the occurrence of errors and accidents (Mitropoulos et al., 2009).

Recognizing the limitations of current strategies, Mitropoulos et al. (2009) proposed a Cognitive Model of Construction Safety, which has provided a theoretical framework connecting fatigue and safety. According to the model, an “error” is defined no longer as a deviation from a prescribed procedure, but as a failure of the applied capability to match task demands. Fatigue is identified as an influencing factor to applied capability (e.g., fatigue may reduce the overall capability, so as to increase the probability of errors). By viewing an unsafe behavior as a cognitive failure, the model suggests a feasible way to measure fatigue and safety performance in a laboratory setting. Specifically, certain cognitive tasks can be designed to simulate the actual construction work, and the errors when performing the tasks are also able to be captured.

2.2. Experimental tasks and the supporting platform

2.2.1. Experimental tasks

The desired experimental tasks are required to not only represent the characteristics of the actual construction work, but also allow a practical measurement of both fatigue and safety performance. This research designs a typical manual handling task to simulate the actual construction work, and measures safety performance by monitoring the participant’s errors when performing the task.

The manual handling task is a short-distance manual transport of heavy materials, which requires a squatting posture when lifting up and laying down the materials. Manual handling is a common activity of workers on construction sites (Buchholz et al., 1996). It has addressed two critical features of the actual construction work on safety and health: (1) lifting/handling of heavy materials/tools (Holmström et al., 1992); (2) awkward postures such as squatting, kneeling and climbing (Paquet et al., 2001).

The designs for the experimental tasks include the distance of manual handling, the weight and materials of manual handling, and the required manner for manual handling.
Based on the discussions with site managers, safety officers and workers, and considering that long distance handling is usually dependent on machines such as cranes and trucks, the distance of manual handling in the experimental task is set at 10 m, which is relatively common on construction sites.

According to a survey among 217 construction workers (Zhang, 2014), 71% of the workers were handling objects around 15 kg over one hour during a typical workday. Therefore, the weight of manual handling is reasonably set at 15 kg. And since a sand bag would be much less harmful when unexpectedly dropped down, it is selected as the materials of manual handling for the protection of participants.

In addition, a participant should conduct the manual handling task back and forth in a required manner. Specifically, a participant begins a task by squatting and lifting up the materials, implements the task by carrying and walking to the destination location, and ends the task by squatting and laying down the materials.

**Fig. 1** presents the general design of the experimental task.

**2.2.2. The supporting platform**

The manual handling task should be performed in a “risky” area manipulated by an electronic controlled device. As shown in Fig. 1, the “risky” area in the middle of the pathway consists of four strips (1–2–3–4). Each strip is attached with a warning light in yellow color. The “risky” area is a simulation of the dynamic and hazardous environment which requires workers to maintain vigilance and act safely (Fang et al., 2004). Specifically, a worker will sequentially pass through two steps when performing the task. The first step is “perception”, which refers to the visual discrimination of different light signals. The signals are indicators of either safe or hazardous. The second step is “motor control”, which requires to avoid the areas with “hazardous” signals while walking through. The task is designed to test whether a participant is able to identify and correctly respond to the potential hazards when performing a physically demanding activity. From the perspective of human factor, this kind of task represents a typical pattern of the interaction between individuals and the external system. During this interaction, an impairment of individuals’ perceptual and motor functions may lead to errors, which have been widely accepted as a major cause to occupational accidents (Celik and Cebi, 2009; Leplat and Rasmussen, 1984; Salminen and Tallberg, 1996; Wiegmann and Shappell, 2012).

A trial is defined as a completion of work either from material storage Location A to Location B or inverse. In each trial (e.g., from Location A to Location B), when a participant goes across the infrared sensing line L1 and approaches to the “risky” area, the warning lights will indicate the potential “hazards” by flashing. Specifically, there are two types of flashes, a long flash and a short flash, indicating “HAZARDOUS” and “SAFE” respectively. As for the whole “risky” area, three HAZARDOUS–SAFE patterns with an adjustable probability of occurrence are set: (1) strips “1–3” HAZARDOUS and “2–4” SAFE; (2) strips “1–3” SAFE and “2–4” HAZARDOUS; and (3) strips “1–2–3–4” all SAFE. In this research, the “all SAFE” pattern is eliminated, and an equal probability of 0.5 is set for the first and second patterns. The participant needs to detect the warning lights’ signals, identify the potential HAZARDOUS strips and then, completely avoid them when passing through the “risky” area. Situation remains the same when the participant is conducting manual handling from Location B to Location A.

The designs for the supporting platform include the width of each strip and the distance from the infrared sensing line to the “risky” area.

Each strip should be set an appropriate width according to the requirement that both having enough room to hold a participant’s foot and letting the participant be convenient to step over. Considering that the average length of Chinese adults’ shoes is around 0.3 m and the average stride length is around 0.75 m (Zhang, 2014), the width of each strip (1–2–3–4) is set at 0.4 m.

The distance from the infrared sensing line to the “risky” area is set at 1.5 m. Under such circumstance, since an adult’s general walking speed is around 1.5 m/s, the participant will approximately have one second to detect the signal, understand the signal and perceive responses. On one hand, the time is enough for simple visual discrimination (Vanrullen and Thorpe, 2001); on the other hand, the design ensures a certain level of task difficulty, which requires the participant’s concentration.

**Fig. 2** illustrates the full view and key components of the supporting platform. **Fig. 3** shows the platform’s digital connections and working principles.

Moreover, the task difficulty is primarily determined by the durations of the long and short flash. The more distinct the two durations are, the easier the task will be. In principle, the settings should be neither too difficult nor too easy. Difficult settings may result in a high sensitivity of task performance not only to the target variable (i.e., fatigue) but also to the potential confounders. If many of these extraneous variables are uncontrolled or uncontrollable, the data obtained will be noisy (Thorne, 2006). Conversely, easy settings may help to eliminate the interference of potential confounders, but makes the task performance insensitive to fatigue. As common to many experimental studies, sensitivity and variability are usually inseparable (Thorne, 2006). So it is critical for the study to determine a reasonable level of task difficulty with acceptable sensitivity and variability. The issue of task difficulty will be determined in the pilot study.

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1 For interpretation of color in **Fig. 1**, the reader is referred to the web version of this article.
2.3. Performance measurement

This research measures safety performance by monitoring the participant’s errors when performing the tasks. The supporting platform enables the detection of errors by a laser-based component. As shown in Fig. 4, laser tubes are installed at the side boundaries and the central line of each strip. An error will be detected when any part of the participant’s foot stepping into the hazardous strip.

Fig. 5 presents the criteria of error detection. Only two strips are shown as an example. R1–R1′, R3–R3′ and R5–R5′ are three laser tubes at the side boundaries of the two strips. R2–R2′ and R4–R4′ are two laser tubes at the central lines of the two strips. Basically, there are two types of errors (Error I and Error II) that can be distinguished. Error I refers to the situation that the only central laser ray R2–R2′ is blocked, which means a whole foot steps into the hazardous strip. This type of error may occur mostly when a participant misjudges the hazardous strip as safe, but still has a precise foot control. Error II refers to the situation that both the boundary ray R3–R3′ and the central ray R4–R4′ are blocked, which implies that a participant actually knows which strip is safe, but is not able to act precisely. When only the central ray R4–R4′ is blocked, it implies a safe pass. The two types of errors are consistent with the twofold role of fatigue in the etiology of accidents: first, fatigue may decrease the ability to process information about a hazardous
situation; and second, fatigue may decrease the ability to adequately respond to a hazardous situation (Swaen et al., 2003). In an actual experiment, errors may be in the form of Error I or Error II, or both. Information regarding the error type may help to understand the types of errors associated with different levels of fatigue.

3. A pilot study

The primary goal of the pilot study is to assess the feasibility of the proposed experimental design in studying fatigue and safety. Specifically, the designed experiment is expected to realize that: (1) the participant’s fatigue level will increase along with the number of trials performed; (2) the error rate in a fatigue state will be significantly higher than that in a non-fatigue state. Besides, the pilot study also aims to determine an appropriate level of task difficulty.

3.1. Participants and materials

A total of 20 male rebar workers were recruited as paid participants. Working at a nearby construction site, the workers were performing the same job task (rebar cutting, bending and fixing) during the whole experimental period (four weeks). Typically they started their work at 7 am and went off duty at 5:30 pm, with a lunch break from 11:30 am to 12:30 pm. To be consistent, all the twenty workers were invited to participate in the experiment after their lunch break (around 12:30 pm). Table 1 describes the demographic characteristics of all participants.

3.2. Experiment

The experiment was conducted in an indoor laboratory. Twenty participants were randomly divided into two groups (Group A and B). Both groups were required to perform the manual handling task as described above. The only difference was the task difficulty. For Group A, a higher level of task difficulty was provided: the durations of long and short flash were 0.2 s and 0.1 s respectively. For Group B, the durations of long and short flash were 0.4 s and 0.2 s respectively. Each participant completed 200 trials with a 3-min break after every 50 trials. Considering the potential learning effect, a practice section with at least 20 trials was mandatory at the beginning of the experiment. Participants were not allowed to formally start their trials until they reported a familiarity with the tasks and the supporting platform. Task performance (i.e., safe or error) was automatically measured by the supporting platform throughout the experiment and the error rate was calculated after every 50 trials. The fatigue level of a participant was recorded before, during and after the tasks (at every break time). Three sets of analyses were run: (1) the first set tested the change of fatigue level with the number of trials performed; (2) the second set compared the task performance in different fatigue levels; (3) the third set compared the task performance under different settings of task difficulty.

An interview was conducted with each participant after the experiment, to investigate their perceptions about the feasibility of the experimental design in simulating the actual construction work.

3.3. Measures

The fatigue level of a participant was measured by a Fatigue Assessment Scale for Construction Workers (FASCW). The FASCW, developed by one of the authors (Zhang, 2014), captures the critical fatigue symptoms among construction workers. The development of FASCW, which contains the development of an English version scale and a Chinese version scale, is introduced in Table 2. The Chinese version FASCW, a three-dimension scale, was used in the experiment. The first dimension “physical inactiveness”, contains three items such as “I have less strength in muscles”, “Legs feel tired/heavy”, “My body movement slows down”. The second dimension “mental fatigue”, contains three items such as “My thoughts easily wander”, “Lacking in energy”, “Eyes feel strained”. The third dimension “discomfort”, contains four items such as “Arms/legs feel numb”, “Shoulders feel stiff/pain”, “My joints feel achy”, “I feel cramps in muscles”. For each item, the participant should indicate the degree to which they felt on a 5-point scale.

Table 1
Demographic characteristics of participants in the pilot study.

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Mean (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>23.0–35.0</td>
<td>27.2 (3.3)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>165.0–175.0</td>
<td>169.6 (3.9)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>55.0–77.5</td>
<td>63.8 (5.7)</td>
</tr>
<tr>
<td>Years in industry</td>
<td>1.0–9.0</td>
<td>4.9 (2.0)</td>
</tr>
<tr>
<td>Years as rebar workers</td>
<td>1.0–9.0</td>
<td>4.1 (2.0)</td>
</tr>
</tbody>
</table>

Fig. 5. Criteria of error detection. The letter “H” stands for “HAZARDOUS” and “S” stands for “SAFE”. 5–1 and 5–2 will be detected as Error I and Error II respectively. Only 5–3 will be regarded as safe because no part of the foot steps into the hazardous strip.
The development of FASCW.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Approach</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>The English version</td>
<td>1. Preliminary scale development</td>
<td>Literature review/Delphi consensus technique/focus group sessions</td>
</tr>
<tr>
<td></td>
<td>2. Factor analysis and scale validity</td>
<td>Survey (sample size: 144)/data analysis</td>
</tr>
<tr>
<td>The Chinese version</td>
<td>3. Item translation from the English version</td>
<td>Translation and back-translation</td>
</tr>
<tr>
<td></td>
<td>4. Item revision</td>
<td>Interview on Chinese workers</td>
</tr>
<tr>
<td></td>
<td>5. Factor analysis and scale validity</td>
<td>Survey (sample size: 217)/data analysis</td>
</tr>
</tbody>
</table>

(1 = not at all; 2 = a little bit; 3 = somewhat; 4 = much; 5 = extremely). The results of the scale validation work have indicated satisfactory internal consistency, test–retest reliability, concurrent validity, convergent validity and divergent validity.

3.4. Procedures

Table 3 presents the sequences of activities during the experiment. After their arrival at the laboratory, participants were first given an introduction to the goal and procedures of the experiment, as well as the manner to perform the tasks. They were also instructed to try their best to avoid potential errors during the tasks. Second, participants completed the practice section and had a 3-min break after the practice. Third, the initial fatigue state was measured and recorded by the completion of FASCW #1 as a baseline. Thereafter, participants performed the main tasks including 4 sections with 50 trials each, as well as a completion of the FASCW at every break time. Finally, when the tasks completed, participants completed a face to face interview. The whole process lasted approximately 90 min for each participant.

3.5. Results

Table 4 shows the fatigue level changes of the participants before, during and after the tasks. The average fatigue level before the experiment was 12.4, which increased to 23.8 when four sections of tasks completed.

As shown in Table 5, for each participant, the fatigue level and the number of errors in the last section of tasks were significantly higher. In this experiment, the participant in the first section of tasks could be regarded as in a non-fatigue state, and in the last section of tasks could be regarded as in a fatigue state. Therefore, contrasting to the non-fatigue state, participants tended to make more errors in the fatigue state. The experimental result quantitatively indicated that safety performance was negatively affected by fatigue.

Table 3
The experiment’s procedures.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Introduction to the experiment</td>
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<tr>
<td>2</td>
<td>Practice (at least 20 trials)</td>
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<tr>
<td>3</td>
<td>Break</td>
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<tr>
<td>4</td>
<td>Main tasks</td>
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<tr>
<td>5</td>
<td>Break</td>
</tr>
<tr>
<td>6</td>
<td>Interview</td>
</tr>
</tbody>
</table>

As discussed in the above section, it is critical for the study to determine a reasonable level of task difficulty. Table 6 shows the task performance under two scenarios. The tasks in Group A were more difficult, and meanwhile the average number of errors in Group A was more. So a higher sensitivity to fatigue was shown in Group A. However, the standard deviation of the average number was also larger. On the contrary, Group B’s task difficulty was lower, and the average number of errors was less and with a smaller standard deviation. So a lower sensitivity to fatigue was shown in Group B.

In terms of task difficulty, the settings of “0.4 s long flash and 0.2 s short flash” are better. As discussed in the above section, a reasonable level of task difficulty should be with acceptable sensitivity and variability. Workers in Group A generally thought the settings of “0.2 s long flash and 0.1 s short flash” were a little difficult to distinguish even when they were not fatigue. The result also showed that worker 6 made more errors when he was not fatigue. In the actual construction work, a worker’s vigilance, reaction capability and physical coordination are regarded as the most important factors to avoid hazards. The settings of “0.2 s long flash and 0.1 s short flash” may require skills more than such factors to be successfully identified, so to some extent they are not suitable for the simulation of actual construction work. On the contrary, workers in Group B generally thought the settings of “0.4 s long flash and 0.2 s short flash” were appropriate. Most of the workers could distinguish between long flash and short flash when they were not fatigue, and errors happened when their attentions were not focused.

But when compared with the actual construction work, the settings of “0.4 s long flash and 0.2 s short flash” is still higher. Most hazards are static on site, so that workers can stop to check when they are not sure. However, for the purpose of observing the effect of fatigue in a laboratory setting, the suitable task difficulty should be a balance between sensitivity and variability.

4. The effect of fatigue on task performance

The pilot study has demonstrated the feasibility of the proposed experimental design in studying fatigue and safety. The fatigue level of workers can be measured by the FASCW, and the safety performance can be measured by the experimental task performance. Therefore, by applying the level of task difficulty determined in the pilot study, the effect of fatigue on task performance was analyzed in the formal study. As introduced in Section
2.3, the study further distinguished two types of errors into Error I and Error II, to analyze the effect of fatigue on both types of errors.

Ten rebar workers on a nearby construction site were recruited for the formal study. The demographic characteristics of the workers are shown in Table 7. In order to test the workers’ performance under a wide range of possible fatigue levels, they were required to complete the experiment twice on two separate days (i.e., one time after a half-day’s normal work on site, and another time after a whole-day’s normal work on site), to simulate the actual construction work when working in the afternoon and when overtime working in the evening respectively. The experimental procedures were the same as in the pilot study. Fig. 6 shows a number of pictures taken when a worker was on the experiment.

4.1. The relationship between fatigue and error rate

After every 50 trials, each worker was required to fill in the FAS-CW, and the worker’s error rate was calculated. Hence, the fatigue level of the worker and the corresponding error rate could be used as one pair of “fatigue-error” data. For a 200-trial experiment, 4 pairs of data were expected to be obtained. During the experiment, each worker completed 200 trials, except that: (1) worker 1 only completed 150 trials and discontinued due to discomfort; (2) worker 2 voluntarily completed 300 trials when participating in the experiment after a half-day normal work; and (3) worker 5 and worker 6 voluntarily completed 250 trials each when participating in the experiment after a whole-day’s normal work. Therefore, 83 pairs of “fatigue-error” data were finally obtained.

According to the data, the fatigue levels varied between 12 and 38, and the error rates varied between 4% and 38%. Table 8 shows the t-test results for the average error rates under different fatigue levels. When the fatigue level was lower than 20, the differences between error rates were not significant ($P = 0.18 > 0.05$). And when the fatigue level was higher than 20, the differences between error rates were becoming significant. Therefore, the fatigue level 20 was determined as a critical point where the effect of fatigue began to emerge. Fig. 7 shows the overall relationship between the assessed fatigue levels and the recorded error rates.

By analyzing the sample data when fatigue levels were higher than 20, a linear regression model shows the best goodness of fitting ($R^2 = 0.8251$), as shown in Formula (1). The value of 1.44% was the slope of the linear function, meaning that when the fatigue

<table>
<thead>
<tr>
<th>Table 5</th>
<th>The fatigue level and the number of errors during the first and last sections of tasks.</th>
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<tbody>
<tr>
<td>Fatigue level</td>
<td>First section of tasks</td>
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<tr>
<td>Average</td>
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<tr>
<td>Standard deviation</td>
<td>2.9</td>
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<table>
<thead>
<tr>
<th>Table 6</th>
<th>Task performance under two scenarios.</th>
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<tbody>
<tr>
<td>Number of errors</td>
<td>First section of tasks (non-fatigue state)</td>
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<td>------------</td>
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<tr>
<td>Group A</td>
<td>Worker 1</td>
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<td></td>
<td>Average</td>
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<td></td>
<td>Standard deviation</td>
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<td>Worker 11</td>
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</tr>
<tr>
<td></td>
<td>Worker 18</td>
</tr>
<tr>
<td></td>
<td>Worker 19</td>
</tr>
<tr>
<td></td>
<td>Worker 20</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Standard deviation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Demographic characteristics of workers in the formal study.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Height (cm)</td>
</tr>
<tr>
<td>Range</td>
<td>23.0–29.0</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>26.1 (2.1)</td>
</tr>
</tbody>
</table>
level was higher than 20, each unit increase of the fatigue level would cause a value of 1.44% increase in the error rate on average. The value of \(\frac{1}{C_0}\) was the intercept of the linear function. The range of fatigue levels was from 21 to 38.

Error rate = 1.44% * Fatigue level – 19.08\% \hspace{1cm} (1)

When applied individually to each of the ten workers, Fig. 8 shows that except for worker 7, all other workers’ error rates increased significantly when fatigue levels were approximately higher than 20. And when fatigue levels were lower than 20, the change of error rates were not significant. The analysis shows the fitness of the linear regression model in depicting the relationship between fatigue levels and error rates.

Table 8
The t-test results for the average error rates under different fatigue levels.

<table>
<thead>
<tr>
<th>Fatigue level</th>
<th>Sample size</th>
<th>Average error rate (%)</th>
<th>P (t-test)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–15</td>
<td>22</td>
<td>7.5</td>
<td>0.180</td>
</tr>
<tr>
<td>16–20</td>
<td>22</td>
<td>8.5</td>
<td>0.000</td>
</tr>
<tr>
<td>21–25</td>
<td>22</td>
<td>13.4</td>
<td>0.000</td>
</tr>
<tr>
<td>26–30</td>
<td>11</td>
<td>20.5</td>
<td>0.006</td>
</tr>
<tr>
<td>31–40</td>
<td>6</td>
<td>28.0</td>
<td></td>
</tr>
</tbody>
</table>

Y = 0.0144X – 0.1908
\(R^2 = 0.8251\)

A site survey was conducted to validate the findings of the experiment. 217 respondents participated in the survey. The survey asked workers’ feelings about the most tired period during a workday, and let them recall the specific time of occurring of all the accidents and near misses they had encountered in the past month. The result (Fig. 9) showed that the two most tired periods were “16:00–18:00” and “10:00–12:00”, and both periods were the two-hour periods before workers went off duty in the morning and in the afternoon respectively. Meanwhile, such periods were associated with the most accidents and near misses recalled by the workers. The survey result shows consistency with the findings of the experiment. In addition, the statistic studies on occupational accidents in construction industry also showed that more accidents happened at such time of the day (Camino López et al., 2011; Ling et al., 2009).

4.2. Error I or Error II?

As introduced in Section 2.3, errors may be in the form of Error I or Error II, or both. Information regarding the error type may help to understand the types of errors associated with different levels of fatigue. Table 9 shows that, when the effect of fatigue began to emerge (i.e., fatigue level from 21 to 25), Error I was the main type of errors (62.9%). In such periods, workers' errors were mainly due to the hazards' perception failure. This reflected the mechanism that fatigue might decrease the ability to process the hazardous information. However, when fatigue accumulated, the percentage of Error I decreased, and the percentage of Error II increased. This reflected the other mechanism that fatigue might decrease the ability to adequately respond to a hazardous situation. In this situation, even when a worker could perceive the hazardous information, an error might happen due to the reduction of the capacity of motor control.

In order to investigate the two types of errors in the actual construction work, the 10 workers participating the experiment were interviewed on their past accident experiences, and they were also requested to recall the causes of the accidents. As a result, a list of 14 accidents was collected. 8 of the 14 accidents could be categorized as results of perception failure. An example of such accidents was as follow (in the form of the worker’s narrative):

“When I was working on the steel bar binding, I didn’t notice the gap in between, and tumbled forward over it.”
The other 6 of the 14 accidents could be categorized as results of motor control failure. An example of such accidents was as follows (in the form of the worker’s narrative):

“I have completed a whole day’s work. And just when I was on my way back to the dorm, although I saw a hole ahead, I still couldn’t adjust my foot step to avoid falling into it.”

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Fig. 8. The relationship between fatigue levels and error rates on individuals.
5. Discussion

5.1. The feasibility of the experimental design

Referring to the interviews conducted on participants after the experiment, the major concerns on the feasibility of the experimental design in studying fatigue and safety are discussed.

(1) The experimental tasks can effectively induce fatigue. Referring to the fatigue level measured by FASCW, Table 4 has shown that the fatigue level increases significantly with the number of trials performed by the participants. The interviews on the participants also showed that all the participants believed that the experimental tasks deepened their levels of fatigue, and their first feelings after the experiment were “tired” or “quite tired”. This is qualitatively consistent with the FASCW’s measurement.

(2) The fatigue induced by the experimental tasks shows similarities with the real work fatigue. Such similarities were reported by the participants, including that “waist and knees felt achy”, “body movement slowed down”, and “difficult to straighten up after bending or squatting”. The differences also exist. Participants thought that in the actual construction work, the workload was less intensive and the accumulation of fatigue was slower. But in order to observe the effect of fatigue in a laboratory setting, it is necessary to enforce more intensive tasks and accelerate the process of fatigue accumulation.

(3) The experimental tasks can simulate typical tasks in the actual construction work. The participants were all rebar workers, and 75% of them raised the example of “walking on the steel grid” in the actual construction work as a situation similar to the designed experimental task. The steel grid refers to the orthogonal overlapping grids when binding the steel of the foundation slab or floor panel (Fig. 10). When walking on the steel grid, workers have to be careful to avoid stepping into the spaces between steels. 60% of the participants raised the example of “stepping on nails”. Nails are common on site. If not dealt with properly, nails would hurt workers easily (Fig. 11).

5.2. Implications for safety management

The study quantitatively explores the relationship between fatigue and experimental task performance. The results are insightful to the management on workers’ fatigue.

(1) The study has measured the relationship between the fatigue level and the worker’s error rate in the experiment, and the changing patterns of errors while the level of fatigue grows have been identified.

The fatigue level of 20 is identified as a critical point from where the effect of fatigue begins to emerge. When a worker’s fatigue level is lower than 20, the effect of fatigue on safety performance is not significant. When a worker’s fatigue level exceeds 20, there is a linear relationship between fatigue levels and error rates. Specifically, each unit increase of the fatigue level would cause a value of 1.44% increase in the error rate on average.

The fatigue level 20 means that the average score of each item of the 10-item FASCW reaches 2, which indicates that each symptom reaches “a little bit” fatigue. According to a survey of 10 workers on a real site, the worker’s fatigue level reached 20 on average at around 15:30 in the afternoon, which indicates that the effect of fatigue may be emerged when there are still approximately two hours before workers can go off duty in the afternoon. And the survey also showed that when workers needed to work overtime in the evening, the workers’ fatigue levels were nearly all above 20, which indicates that the effect of fatigue should be specially paid attention to when working overtime in the evening.

The result of the experiment provides an important reference for safety management to relieve the effect of fatigue on safety performance. Management can use the developed FASCW to measure the fatigue states of different types of workers while they are at work, and their patterns of fatigue can be estimated. Therefore, when a worker’s fatigue level is approaching 20, management can either emphasize on hazard identification and warning to increase the worker’s ability to process the hazardous information, or enforce targeted fatigue relief plans to increase the worker’s capacity of motor control.

(2) The study has found that the types of errors associated with different levels of fatigue were different.

When the fatigue level is low, workers’ errors are mainly due to the hazards’ perception failure, which indicates that fatigue may decrease the ability to process the hazardous information. However, when the fatigue level is high, the percentage of motor control failures increases, which indicates that fatigue may decrease the ability to adequately respond to a hazardous situation.

It is indicated that when the fatigue level is from 21 to 25, workers’ errors are mainly due to the failure of the perception of...
hazards. And under such circumstances, emphasizing on hazard identification and warning can actually help workers identify the hazards and act correspondingly. Hence, the effect of fatigue can be mitigated.

But as fatigue accumulates, fatigue’s impact on a worker’s capacity of motor control may be more and more significant. And in this situation, merely by emphasizing on hazard identification and warning may not be as effective as when the fatigue level is relatively low. Under such circumstances, management should consider targeted fatigue relief plans such as adjusting the work schedule and enforcing breaks between work tasks to relieve the worker’s fatigue and increase the worker’s capacity of motor control.

5.3. An experimental tool

The traditional measurement of construction workers’ safety performance includes accident statistics and analysis, site survey, behavior observation, etc. Such approaches have played an important role on the construction safety research, but certain limitations still exist due to high uncertainty, low sensitivity and data availability. The experimental method can realize a simultaneous measure of both fatigue and safety performance by simulating the actual construction work in a laboratory setting. Through the pilot study, the feasibility of the proposed experimental design in studying fatigue and safety is demonstrated. The formal study has attempted to quantitatively define a causal relationship between fatigue and safety. The types of errors associated with different levels of fatigue, as well as the effectiveness of fatigue countermeasures are also among discussion. The experiments conducted have offered researchers a new way to look at the research on fatigue and safety.

In future studies, the designed experiment can be used as a tool to further explore the causal relationship between fatigue and safety. For instance, regarding Matthews and Desmond (2002)’s result in the domain of driving safety, in the construction environment, whether the effect of fatigue is more significant under “underload” conditions needs further evidence. Based on the experiment, researchers can design different probabilities of hazards occurrence by adjusting the frequency of the warning light flash on the supporting platform, and by recruiting workers to participate in the experiment, evidence supporting whether “resource availability” theory or “effort regulation” theory in the interpretation of fatigue effect can be obtained, and a better understanding of the effect of fatigue on construction workers’ safety performance can be achieved.

The supporting platform also allows a detailed time measurement during the tasks. Time information of each critical action can be collected in every single trial including: lifting up the materials, going across the sensing lines, stepping into the strips and, laying down the materials. A complete trial cycle is the interval from the time when a participant lifts up the materials to the time when the participant lifts up the materials again. The information of the cycle time indicates how fast a participant is performing the tasks, which may be used to measure the productivity related performance and to further discuss the relationship between safety and productivity.

5.4. Limitations

Construction activities are of dynamics and complexity, and there exists substantial differences among different construction work. It is very difficult for the researchers to have a comprehensive simulation on the actual construction work. As a start point, this research selected a typical manual handling task to simulate the actual construction work, and had a positive application of the experimental method on construction safety research. Indeed, a single task’s design is far from a comprehensive depiction of construction workers’ performance. In future studies, it is expected that more typical tasks can be integrated into the experiment, so as to have a better simulation on the actual construction work.

Another limitation is the insufficient number of workers participating in the experiment. Due to time and budget constraint, only 20 workers were involved in the pilot study and only 10 in the formal study. In order to minimize the disruption of individual differences to the experimental results, this research intentionally chose participants with similar features such as work type, age, height, weight and years in construction industry. The chosen participants were performing the same regular job task during the experimental period. They were also invited to participate in the experiment at a same time on separate workdays. In future studies, workers with different backgrounds can be chosen, to study the impact of individual differences on fatigue and safety.

6. Conclusion

This research proposes an experimental method to study the effect of fatigue on construction workers’ safety performance. Manual handling was selected as the typical task for the experiment, and a supporting platform was built. During the experiment, the fatigue level of a participant was measured by a subjective assessment scale before, during and after the tasks. The safety performance was measured by monitoring the participants’ errors when performing the tasks.

The research shows that the experiment is feasible in simulating fatigue and safety in the actual construction work: (1) The experimental tasks can induce fatigue effectively, and the induced fatigue shows similarities with the real work fatigue; (2) Workers tend to make more errors in a fatigue state; (3) The designed manual handling task can simulate the actual construction work. Two examples are “walking on the steel grid” and “stepping on nails”.

The research measures the relationship between fatigue and safety performance, and the changing patterns of errors while the level of fatigue grows have been identified. The fatigue level of 20 is identified as a critical point from where the effect of fatigue begins to emerge. When a worker’s fatigue level is lower than 20, the effect of fatigue on safety performance is not significant. When a worker’s fatigue level exceeds 20, there is a linear relationship between fatigue levels and error rates. By distinguishing two types of errors, the research’s result also shows that when at a relatively low fatigue level above 20, workers’ errors are mainly due to the failure of hazard perception. But as fatigue accumulates, its impact on worker’s capacity of motor control becomes significant.

In future studies, the designed experiment can be used as a tool to further explore the causal relationship between fatigue and
safety, and a better understanding of the effect of fatigue on construction workers’ safety performance can be achieved.

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References


