Enhancing Workers' Vigilance to Electrical Hazards through a Virtually Simulated Accident

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ABSTRACT

Electrocution is one of the major causes of fatalities in the construction industry. Despite periodic safety training aimed at retaining workers' vigilance (i.e., sustained attention) to electrical hazards, workers tend to fail to maintain vigilance toward frequent encounters with electrical hazards. Providing an effective intervention that restores workers' vigilance is thus critical to reducing electrocution accidents. To this end, this study proposes a Virtual Reality (VR) safety training environment that exposes workers to repeated electrical hazards and simulates an electrocution accident when workers come in contact with the hazards. A pilot experiment was conducted, and participants' vigilance (i.e., eye fixations on the hazard) was measured using eye-tracking sensors. The results reveal the potential effect of experiencing VR-simulated electrocution on enhancing workers' vigilance to electrical hazards. The outcomes of this study will lay the foundation for further studies to employ VR as a safety training environment that allows workers to experience a simulated electrocution, thereby contributing to a potential reduction in fatal electrocutions.

INTRODUCTION

Electrocution is one of the primary causes of fatal accidents in construction sites. The Occupational Safety and Health Administration (OSHA) recognizes electrocution as one of the "construction focus four" hazards (OSHA 2011). Despite periodic safety training aimed at retaining workers' vigilance (i.e., sustained attention) to electrocution risks at workplaces, the number of electrocutions is still high: between 2011 and 2015, 364 fatal electrocutions occurred in the construction industry (CPWR 2018). Previous studies have indicated that a large portion of electrocution accidents are attributed to workers' unsafe behaviors (Baby et al. 2021; Janicak 2008; Koustellis et al. 2013). In particular, workers are apt to stop paying attention when they are routinely exposed to electrical hazards, and this insufficient attention/vigilance can lead to fatal electrocutions (Castillo-Rosa et al. 2017). Therefore, addressing workers' insufficient vigilance to frequently exposed hazards and providing effective interventions are critical to reducing electrocutions (Ke et al. 2021). Because it is difficult to measure worker vigilance in a natural environment, current safety training focuses mainly on refreshing safety knowledge and does not involve behavioral interventions. Consequently, it is not clear that current practices effectively enhance workers' vigilance to electrical hazards that they routinely encounter while at work.

Researchers have started to utilize biosensing technologies (e.g., eye-tracking sensors and an electroencephalograph) and VR to assess workers' responses to workplace hazards (Hasanzadeh et al. 2017; Wang et al. 2019). While these studies demonstrated the feasibility of evaluating individual workers' visual attention patterns or sensitivities to workplace hazards, knowledge gaps still exist regarding how to analyze workers' lowered vigilance to frequently encountered electrocution hazards in a VR environment and how to evaluate the effectiveness of a VR-based intervention. To this end, this study (1) proposes a VR-based behavioral intervention that repeatedly exposes workers to electrocution hazards and provides a simulated electrocution experience, and (2) examines the intervention's usefulness in enhancing workers' vigilance to electrical hazards.

BACKGROUND

Vigilance and Visual Attention

"Vigilance" refers to the degree of attention a worker is allocating to stimuli in a surrounding environment (Deng et al. 2018; Warm 1984). Although sustaining vigilance over time is critical to working close to hazards, it has been demonstrated that workers tend to pay less attention to routinely encountered hazards (Esterman et al. 2016; Hubal et al. 2010). Evidence from previous studies supports the notion that vigilance decreases over time, and that this attentional failure is a major factor contributing to injuries and fatal accidents (Grier et al. 2003; Wang et al. 2019). Since visual attention is essential to perceiving the surrounding environment (Rensink et al. 1997), researchers have focused on monitoring workers' visual attention to workplace hazards using eye-tracking technologies (Hasanzadeh et al. 2017; Jeelani et al. 2018; Kim et al. 2021). However, the association between construction workers' vigilance decrement and frequent exposure to electrical hazards has been rarely investigated in the literature.

Accident Experience and Safe Behaviors

Previous studies have found that the occurrence of negative safety events (i.e., workplace injuries) that result from workers' inattentive behaviors can contribute significantly to enhancing workers' attention to hazards (Oah et al. 2018; Rundmo 1995). Workers who have directly or indirectly engaged in a workplace accident or injury in the past tend to perceive more risk and behave more safely than those who have not (Bohm and Harris 2010; Daalmans and Daalmans 2012). However, for ethical reasons, workers cannot be exposed to a risk of actual injury for the purpose of safety training. Thus, in order to enhance safety at construction sites, researchers have investigated the effects of workers' experience of simulated accidents on safe behaviors. For example, Bhandari and Hallowell (2017) found that watching a simulated injury can provoke a surge of negative emotions that may increase workers' attention to workplace hazards. Given those findings, this study set out to examine how experiencing simulated electrocution affects workers' vigilance to frequently encountered electrical hazards.

Virtual Reality and Construction Safety

Recent efforts in construction safety have begun to exploit VR to understand what affects workers' unsafe behaviors in hazardous situations. The use of VR allows researchers to expose workers to hazardous situations and observe their behaviors without risking actual injury (Kim and Ahn 2020). Previous studies utilized VR to analyze and improve individual workers' hazard recognition skills (Hasanzadeh et al. 2017; Jeelani et al. 2020). Hasanzadeh et al. (2020) also exploited VR to examine the association between roofers' risk-taking behaviors and the installation of safety protection. While these studies demonstrate the feasibility of using VR to identify factors that affect workers' unsafe behaviors, there have been few empirical investigations into how VR-based interventions can address workers' lowered vigilance.

METHODOLOGY

The objectives of this study were achieved through three steps. A virtual electrical tower maintenance work task that continuously exposes participants to electrical hazards was designed and used in a pilot experiment. Participants' vigilance toward the hazards was measured using eye-tracking sensors. A data analysis was then conducted to examine the effect experiencing a virtually simulated electrocution had on participants' vigilance.

Scenario Design and Virtual Environment Modeling

An electrical tower maintenance work environment was selected for the experimental scenario. The designed VR scenario continuously exposes participants to potential electrocution hazards associated with hanging overhead power lines because contact with overhead power lines is the leading cause of fatal electrocutions in the workplace (BLS 2020; Taylor et al. 2002). In the VR environment, participants are tasked with climbing an electrical tower, taking fuses from a toolbox, and placing them in a fuse box. To repeatedly expose participants to electrical hazards, the toolbox and the fuse box are located on opposite corners of the tower, with the path between them obstructed by high-voltage, hanging electrical wires. The virtual electrical tower is comprised of six floors, and the fuse fabrication task is replicated on each floor. To complete the task, a participant needs to pass by hanging wires approximately one hundred times. The scenario was designed to ensure that while the hazard is present, it is easily avoidable. In this way, it was purposefully intended to provoke a decrease in participants' vigilance to the hazards while they are performing the repetitive and monotonous task.

All virtual objects and components used in the study were created using Autodesk Maya. The unity game engine was employed to build an immersive VR environment. The unity game engine enables researchers to finely control experimental variables and document a participant's behavioral/response data in real-time. To build a close-to-reality virtual environment, ambient sounds were carefully designed to be realistic: the sounds made when a virtual fuse falls on the floor, or when virtual tools hit against each other. Furthermore, to mimic electrocution, if a participant touches a hanging wire, visual and haptic feedback is generated. Visual sparks are displayed through a Head-Mounted Display (HMD), and haptic feedback is provided simultaneously via motion controllers.

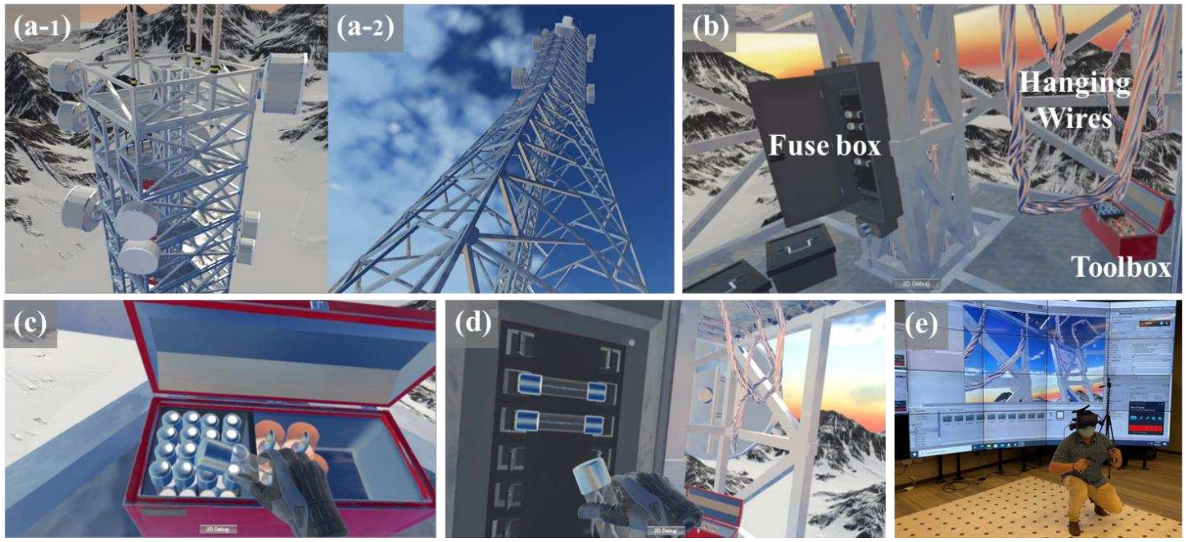

Figure 1. The experimental environment and the task: (a-1 – a-2) overview of the virtual electrical tower; (b) a floor on which the task is located; (c) holding a fuse from the toolbox; (d) placing a fuse into the fuse box; (e) the TAMU BIM-CAVE where the experiment was performed.

Vigilance Measurement

Participants' vigilance to electric hanging wires was measured with 60 Hz of frequency using eye-tracking sensors embedded in the HMD. Visually checking surrounding hazards is an important safety behavior. Thus, the developed VR environment monitors the gaze behavior of a participant and documents the duration of fixation each time when a participant looks at the hanging wires while performing the assigned task. The eye-tracking sensors cast an invisible ray from the origin of a participant's view, and the name of any object hit by the ray is documented, thereby enabling to know when and how long a participant gazes at the electrical hazards. Since the duration of fixation is generally defined as 200–300 milliseconds of motionless gaze (Pan et al. 2004), the system documents the duration of fixations only when a participant gazes at the hanging wires for more than 200 milliseconds.

Simulated Electrocution Accident

To examine the effect of experiencing a simulated electrocution accident on participants' vigilance to the electrical hazards, the module that simulates the virtual electrocution accident is included in the VR environment. The hanging wires on the sixth floor are designed to make it impossible to avoid electrocution. The wires are longer than the wires on the floors below and completely block the path between the fuse box and the toolbox, and move in response to simulated wind. When a participant makes contact with the wire, the electrocution is simulated. To provide a realistic electrocution experience, an electrocution sound effect is presented, the displayed screen is shaken, and strong haptic feedback is provided through motion controllers. Furthermore, to provoke participants' emotional arousal and dramatize the accident scene, a fall accident is integrated with the electrocution accident simulation. A participant is ejected from the tower at the end of the simulated electrocution.

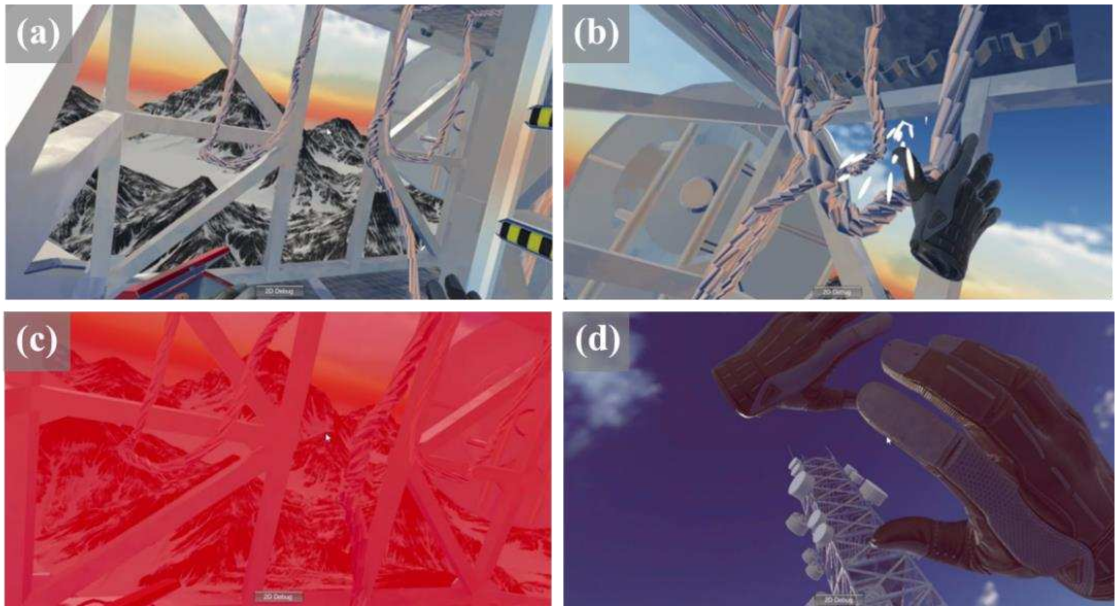

Figure 2. Simulated electrocution accident: (a) hanging wires on the sixth floor that make it impossible to avoid electrocution; (b) – (c) visual, auditory, and haptic effects during the simulated electrocution; (d) falling from the tower

Conditions and Procedures of the Pilot Experiment

A pilot experiment was conducted in the Building Information Modeling-Computer Aided Virtual Environment (BIM-CAVE) at Texas A&M University (TAMU). A total of eight participants (five males and three females; $M_{age} = 25.25$ and $SD_{age} = 3.53$), TAMU graduate students majoring in construction management, participated in the pilot experiment. None of the participants had any prior experience with electrical maintenance work. Before the experiment, all participants watched the safety training video that warns of the risks of electrical hazards at workplaces. Subsequently, a practice session was provided to enable participants to learn how to perform the assigned task in the VR environment. During the practice session, the electrical hazards (i.e., hanging wires) were not presented. In the experiment, the participants were randomly assigned to one of two groups: the accident group (AG) and the no accident group (NAG). The VR environment for NAG did not include the accident simulation module. Therefore, during the experiment, the NAG participants did not experience the accident regardless of unconscious/conscious contacts with the electrical wires. Only participants assigned to the AG group experienced the simulated electrocution. To examine the effect of experiencing the simulated electrocution accident on enhancing vigilance, all participants were asked to participate in the second experiment conducted a week after the first experiment. The second experiment did not include the simulated accident. After the experiment, a follow-up interview was conducted to ask participants to recall and evaluate their behaviors during the experiment. Each experiment took about an hour per participant.

RESULTS AND FINDINGS

Using data obtained from the participants' gaze behaviors, parametric regression analysis was conducted because the association between the repeated exposures to the hazards and the changes in participants' vigilance was assumed as linear. The bivariate linear regression models predicting participants' vigilance (i.e., *duration of fixation*) from a number of exposures to the electrocution hazards (i.e., *floor*) were constructed using the following equation:

$$\widehat{y_i} = B_0 + B_1 X + r \tag{1}$$

where $\widehat{y_i}$ is *duration of fixation* at *floor* X; B_0 is the intercept of the regression line at X = 0; and B_1 is the slope of the regression that indicates the change in *duration of fixation* $\widehat{y_i}$ for each increase in *floor* X. In the first experiment, both groups exhibited similar patterns in a total duration of fixation at each floor. The regression models were significant, R^2= .343, $F(1, 18)$ = 9.404, and p = 0.006 (for AG), R^2= .275, $F(1, 22)$ = 8.331, p = 0.009 (for NAG). The repeated exposures to the hazard (*floor*) negatively predicted *duration of fixation*. The results of both groups indicate that participants' vigilance decreased with the increase in the number of exposures to the hazards (Table 1 and Fig.3 [a]).

Table 1. Regression coefficient indicating the influence of repeated exposures to hazards on the decrease in duration of fixation

Group	Predictors	B_1	S.E.	*p-value*
Accident Group	Floor	- 3.086	1.006	0.006*
No Accident Group	Floor	- 1.596	.553	0.009*

Note: * Significant at the p = .05 level

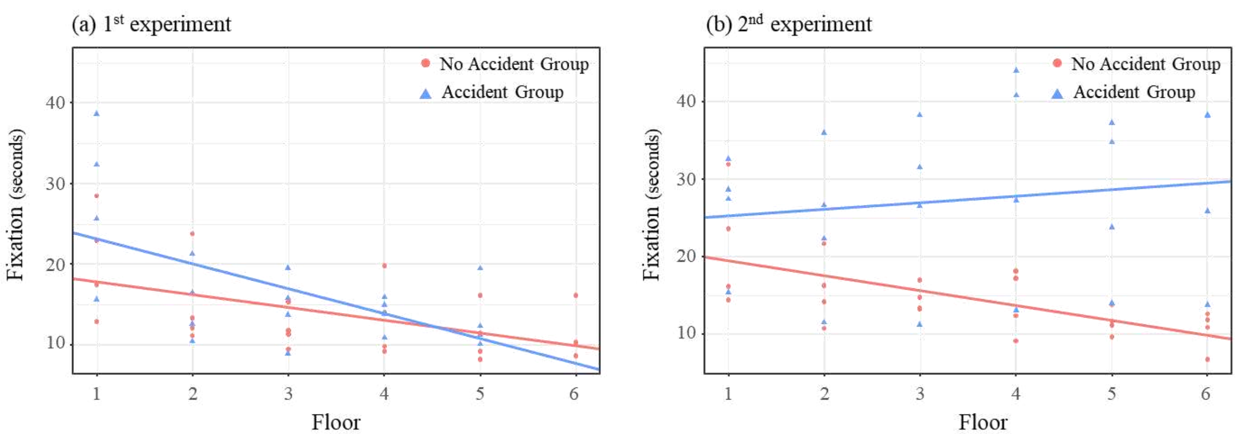

Figure 3. The slopes of the effect of repeated exposures (*floor*) to the hazards on *duration of fixation*: (a) the results of the 1st experiment; (b) the results of the 2nd experiment

A multiple linear regression analysis was performed to examine how experiencing the simulated electrocution accident affected participants' vigilance to the electrical hazards. A participant's experience of the simulated accident in the first experiment was considered as a categorical variable (dummy-coded as 0 for NAG and 1 for AG) in the following regression equation:

$$\hat{y} = B_0 + B_1 X + B_2 A + B_3 XA + r \tag{2}$$

where $\hat{y}$ is the dependent variable (*duration of fixation*) at *floor* X and accident experience A; B_0 is the simple intercept of the regression line in NAG ($A = 0$); B_1 is the change in the regression coefficient for each increase in *floors* X; B_2 is the difference in simple intercepts, comparing AG ($A = 1$) with NAG ($A = 0$); and B_3 is the difference in simple slopes, comparing AG ($A = 1$) with NAG ($A = 0$). The results, R^2 = .457, $F(44)$ = 12.36, p < 0.001 (Table 2), indicate a significant interaction between the simulated electrocution experience in the first experiment and repeated exposures to the electrocution hazard in the second experiment, B_1 = 2.778, p = 0.041. These findings demonstrate that experiencing the simulated accident significantly mitigated the decrement of participants' vigilance to repeatedly exposed electrical hazards (Fig.3 [b]).

Table 2. Regression coefficients indicating the effect of experiencing simulated accident on duration of fixation

Experiment		B_1	**S.E.**	***p-value***
2nd	Floor	- 1.936	.935	0.044**
	Experiencing simulated electrocution accident in the first experiment	3.043	5.148	0.558*
	Floor × Experiencing simulated electrocution accident in the first experiment	2.778	1.322	0.041*

Note: * Significant at the p = .05 level

DISCUSSION

During the follow-up interviews, participants reported that they always looked at the hanging wires when passing by the wires. However, the results of the pilot experiment contradict those recollections. During the experiment, participants' vigilance toward the hanging wires decreased over time. This might suggest that participants unconsciously paid less attention to the hanging wires and instead focused on the assigned task. One of the participants reported, "I started to ignore the hanging wires since the wires stayed in the same place. Subsequently, I got used to passing by it." This interview response supports the findings of the statistical analyses. Furthermore, before the experiment, all participants watched the safety training video and were instructed to be careful around the hanging wires in order to stay safe. However, even when the participants were exposed to safety knowledge about the risks of electrical hazards, a decrement of vigilance was observed. The results of the analysis of the second experiment indicate that experiencing the simulated electrocution can enhance vigilance to frequently exposed electrical hazards. The participants who experienced the simulated electrocution in the first experiment exhibited enhanced vigilance to the electrical hazards. In the follow-up interview, two participants responded that experiencing the accident in the VR environment made them likely to pay more attention to electrical hazards in a real environment.

The study has several limitations. The sample size is small, and all of the participants were students. It is possible that the behavioral responses of students to exposed electrical hazards might differ from experienced workers' responses. Furthermore, since it is unacceptable to expose workers to the actual risk of injuries or accidents, we examined the effect of the simulated accident experience in a VR environment. Future studies will validate its impact on workers' vigilance even in a real environment.

CONCLUSION

This study proposed a VR environment that repeatedly exposes workers to electrical hazards during an assigned task and demonstrates the simulated electrocutions with visual, auditory, and haptic feedback that dramatize the accident experience. The outcomes of the pilot experiment indicate the usefulness of demonstrating a simulated electrocution accident in a virtual environment in enhancing workers' vigilance to frequently encountered electrocution hazards. These findings highlight the positive potential of using VR to observe workers' lowered vigilance to workplace hazards and demonstrate a negative consequence of low vigilance to hazards at workplaces, and offer evidence to support a shift from conventional safety knowledge-focused training to behavioral intervention-focused safety training.

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