Tran-SET

Transportation Consortium of South-Central States

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Preventing Struck-by Hazards: Defying Risk habituation via Virtual Accident Simulation

Project No. 20SATAMU20

Lead University: Texas A&M University

Final Report

August 2021

Disclaimer

Acknowledgements

The PIs would like to acknowledge the contribution of the graduate student assistant, Namgyun Kim, who has been working on this project since it started. Also, we are also grateful for the constructive comments provided by Dr. Brian A. Anderson, the associate professor of Department of Psychological & Brain Sciences at Texas A&M University.

TECHNICAL DOCUMENTATION PAGE

1. Project No. 20SATAMU20	**2. Government Accession No.**	**3. Recipient's Catalog No.**

4. Title and Subtitle Preventing Struck-by Hazards: Defying Risk-habituation via Virtual Accident Simulation	**5. Report Date** Aug. 2021 **6. Performing Organization Code**
7. Author(s) PI: Changbum Ahn https://orcid.org/0000-0002-6733-2216	**8. Performing Organization Report No.**
9. Performing Organization Name and Address Transportation Consortium of South-Central States (Tran-SET) University Transportation Center for Region 6 3319 Patrick F. Taylor Hall, Louisiana State University, Baton Rouge, LA 70803	**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address United States of America Department of Transportation Research and Innovative Technology Administration	**13. Type of Report and Period Covered** Final Research Report Aug. 2020 – Aug. 2021 **14. Sponsoring Agency Code**

15. Supplementary Notes

Report uploaded and accessible at [Tran-SET's website (http://transet.lsu.edu/)](http://transet.lsu.edu/).

16. Abstract

Repeated exposure to struck-by hazards in road work zones generates workers' habituation to risks related to those hazards, a key contributor to accidents in road work zones. Thus, analyzing the development of risk habituation and providing proper intervention are crucial to preventing accidents in road work zones. In this context, this study employs a virtual reality (VR) environment as a behavioral intervention tool to investigate its effect on mitigating a decline in workers' vigilance with habituation to hazards in workplaces. A virtual environment that simulates a road maintenance task was developed and used to repeatedly expose subjects to struck-by hazards in road construction sites. A VR accident was simulated in response to the emergence of habituation to hazards within the virtual environment. The intervention effect was investigated to analyze the frequency and threshold of subjects' vigilant behaviors. The results indicated that the developed VR environment evoked a decline in subjects' attentiveness as a result of risk habituation within a relatively short period of experiment time, and the simulated VR accidents generated a sustained effect in reducing risk habituation. The findings of this study provide the understanding of how workers' risk habituation can be observed using VR and how a behavioral intervention in a VR environment can reduce risk habituation to repeatedly exposed workplace hazards.

17. Key Words Risk Habituation, Virtual Reality, Unsafe Behavior, Safety Training, Eye-tracking	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 26	**22. Price**

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized.**

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AGC	Associated General Contractors of America
BIM-CAVE	Building Information Modeling-Computer Aided Virtual Environment
BLS	Bureau of Labor Statistics
CPWR	The Center for Construction Research and Training
HMD	Head Mounted Display
NPC	Non-Player Character
TAMU	Texas A&M University
VR	Virtual Reality

EXECUTIVE SUMMARY

After repeated exposure to hazards in workplaces, workers are often habituated to risks associated with those hazards, a key factor in workplace accidents. To prevent fatalities in workplaces, it is crucial to understand the development of risk habituation and provide effective intervention. However, since workers cannot be exposed to actual hazardous situations, risk habituation is hard to analyze and prevent in the real world. In this context, this study evaluates the effectiveness of virtual reality (VR) as an intervention tool to tackle a decline in workers' vigilance resulting from habituation to workplace hazards. The virtual road construction environment which enables trainees to engage in repeated hazardous situations is developed. A laboratory experiment was conducted to exploit the validity of the developed VR model. While performing a road maintenance task in the VR environment, subjects who frequently showed unsafe behaviors (e.g., working in close proximity to heavy construction equipment and ignoring warning alarms) were struck by a road construction vehicle. A week after the subjects returned to participate in the same experiment. Pretest-posttest analyses were performed to examine the sustained effect of experiencing the simulated VR accident. The results indicate that the developed VR model effectively elicited a decline in workers' vigilance associated with risk habituation within a relatively short period of training time, and the simulated VR struck-by accidents produced a sustained effect on mitigating workers' risk habituation. The risk habituation tendency of the group exposed to the virtual accident was lower than the group without the virtual accident experience. The outcomes of this research will lay the foundation for further study to employ virtual reality as an intervention tool to reduce workers' risk habituation in road work zones.

1. INTRODUCTION

Workers in road construction and maintenance work are exposed to unique hazards, such as close proximity to construction equipment and high-speed traffic, which can lead to life-threatening accidents (*1*, *2*). Between 2011 and 2015, 609 fatal accidents were reported at road construction sites in the United States (*3*). Reducing fatalities among road construction workers is one of the most critical concerns facing Departments of Transportation (DOTs).

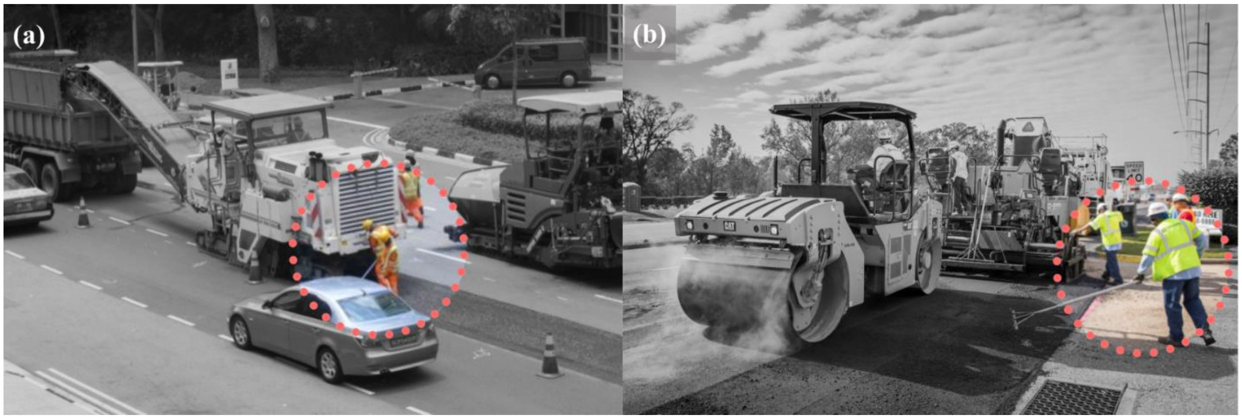

Figure 1. Road construction workers, exposed to multiple struck-by hazards: (a) Workers at an asphalt milling worksite (*4*), (b) Workers at asphalt paving worksite (*5*).

Among those fatalities in road construction work zones, being struck by construction equipment is the most common cause of death (*6*). Specifically, more than 50 percent of all fatalities at road work zones are associated with backovers and runovers by mobile equipment or construction vehicles (*7*). Even though proximity warnings and back-up alarms were presented in many cases and the construction vehicles were moving slowly, workers fail to avoid approaching hazards and engaged in accidents because they did not pay attention to the warning sounds. As demonstrated in these instances, many fatalities in roadway construction work zones are rooted in workers' unsafe behaviors associated with biased/underestimated risk perception.

Previous studies have indicated that repeated exposures to risk may contribute to bias in workers' risk perception. For instance, Majekodunmi and Farrow showed that after regular exposure to lift truck tasks, drivers underestimated the risks of forklift truck driving (*8*). This behavioral phenomenon is regarded as risk habituation (*9*, *10*). Workers habituated to repeatedly exposed hazards in their workplace are apt to underestimate risks and engage in unsafe behaviors (*8*). Evidence from accident reports in road construction work zones has indicated that workers are often habituated to the audible back-up alarms from construction vehicles, fail to pay attention to slowly approaching vehicles, and subsequently get struck by the vehicles (*11*, *12*).

In spite of significant efforts to prevent struck-by vehicle accidents, they remain the main cause of fatalities in road construction work zones. Current safety training relies largely on periodic training to transfer and remind safety knowledge. However, evidence (*13*) reveals that conventional instructor-led classroom training rarely results in palpable benefits due to passive and insufficiently engaging instruction methods (*14*, *15*). Furthermore, such training does not effectively prevent workers' risk habituation and fatalities that result from struck-by equipment.

Therefore, it is critical to developing effective safety training methods that prevent workers' risk habituation.

To reduce these struck-by accidents, previous studies developed warning systems—automated proximity warnings—that use various sensing technologies (*16–18*). Despite these efforts, many struck-by fatalities in road work zones still occur due to workers' unsafe behaviors caused by biased risk perception (*12, 19*).

Although providing personalized safety training based on the analysis of individual workers' risk habituation tendencies could be the most effective strategy to prevent struck-by fatalities at road work zones, analyzing an individual worker's risk habituation is almost impossible in real-world conditions since workers cannot be exposed to actual hazardous situations for the purpose of monitoring unsafe behaviors. To this end, physical response patterns to common and high-risk hazards collected in a virtual environment can be used effectively to provide personalized safety training (i.e., feedback on personal risk habituation tendencies) to workers.

To address the above-mentioned challenges of the current safety training methods, the proposed research will explore the creation of an immersive Virtual Reality (VR) training environment that repeatedly exposes trainees to high-risk hazards in road construction work zones and enables trainees to experience the potential consequence resulting from his/her habituated behaviors. In addition, the proposed VR training environment will enable the identification of workers who are potentially vulnerable to risk habituation, thereby advancing our ability to provide personalized safety training to individual workers. The following four questions will be thoroughly examined with the aim of improving safety and achieving zero fatalities at road construction work zones:

1. How can an immersive VR road construction environment be developed, that provides simulated struck-by accident experiences?
2. How should empirical data from individual workers' responses to common and high-risk hazards at road construction work zones be collected and analyzed?
3. How can workers' risk habituation in hazardous situations be detected?
4. How can workers who are more vulnerable to risk habituation than other workers be identified?

2. OBJECTIVES

This research constructs a Virtual Reality (VR) training system that enables researchers and practitioners to analyze trainees' risk habituation tendencies based on collected behavioral response data (i.e., eye tracking, vigilant behavior in a VR environment), and offers interventions that effectively prevent risk habituation by demonstrating the negative consequences of unsafe behaviors. Past injury simulations using a synthetic hand model were found to be effective in promoting situational interest among construction workers (*20*), so this study utilizes such interventions to impede the development of risk habituation. To this end, the goal of the proposed research is to develop an immersive VR safety training environment that exposes a trainee to repeated hazards in road construction work zones in a VR environment and triggers VR-simulated accidents that result from the trainees' unsafe behaviors while participating in the training

The specific objectives to achieve this goal include:

Objective 1: To develop an immersive VR road construction environment that elicits workers' risk habituation and provides simulated struck-by accident experience;

Objective 2: To collect and analyze empirical data from workers' responses to simulated high-risk hazards in the virtual road construction environment;

Objective 3: To validate the impact of the proposed VR training environment on risk habituation;

Objective 4: To explore individual differences in the rate of risk habituation in order to provide a theoretical foundation for personalized safety training

3. LITERATURE REVIEW

3.1. Fatal Accidents in Road Construction Sites

In road construction and maintenance sites, workers are inevitably exposed to safety risks, such as working near live traffic (*21*). Therefore, despite continuous efforts to improve safety in road construction and maintenance sites, about 100 workers are killed at road construction sites every year in the US alone (*22*). A fatal accident at road construction sites occurs every 15 hours, and an injury at road construction sites occurs every 16 minutes (*23*). Specifically, struck-by heavy construction equipment or dump trucks account for more than 50 percent of all fatal injuries and accidents at road construction sites.

With the approval of the infrastructure bill, the nation's aging highways, bridges, and roads—nearly 280,000 kilometers of America's highways and major roads—will be repaired or rebuilt in the coming years (*24*). The implementation of the infrastructure improvement plan will expose more workers to the abovementioned safety risks. Thus, there is a critical need to improve current safety management strategies in road construction sites.

To address high rates of fatalities at road construction sites, several strategies have been developed and employed in the last decades. For example, truck-mounted attenuators (TMAs) have been widely adopted to protect workers from work zone intrusion crashes. Previous studies investigated and suggested work zone intrusion alert systems (WZIAS) that detect intrusions and alert workers (*25, 26*). Although those efforts have contributed to reducing accidents associated with live traffic, accidents between road construction workers and construction equipment within road construction sites still continuously occur (*1*).

3.2. Risk Habituation and Safety

Approximately 80–90% of all workplace accidents are caused by workers' unsafe behaviors (*27, 28*). Previous studies have demonstrated that an individual's risk perception significantly affects his/her unsafe behaviors at construction sites. Repeated exposure to hazards in the workplace can cause bias in workers' risk perception (*29*). Even if workers properly identify hazards, they may engage in unsafe behaviors due to improper perception and evaluation of risks (*30*). The capability of a stimulus from surrounding hazards to elicit a response diminishes when workers are exposed to those hazards repeatedly, a tendency called risk habituation (Figure 2) (*9, 31*).

In road work zones, workers' vigilance and alertness to approaching surrounding construction equipment are apt to diminish after repeated exposure to struck-by hazards associated with construction vehicles and equipment; Workers tend to ignore the frequent proximity of construction vehicles. This behavioral tendency can be accelerated when there is no appropriate feedback regardless of workers' frequent engagement in habituated unsafe behaviors. For example, the gait patterns of workers changed around workplace hazards they repeatedly face while performing construction tasks (*22*). Another previous study showed that truck drivers' attentiveness to workplace hazards decreased after repeated exposures (*8*). To this end, understanding workers' risk habituation to repeatedly exposed struck-by hazards and providing an intervention are important to reducing fatal accidents at road work zones.

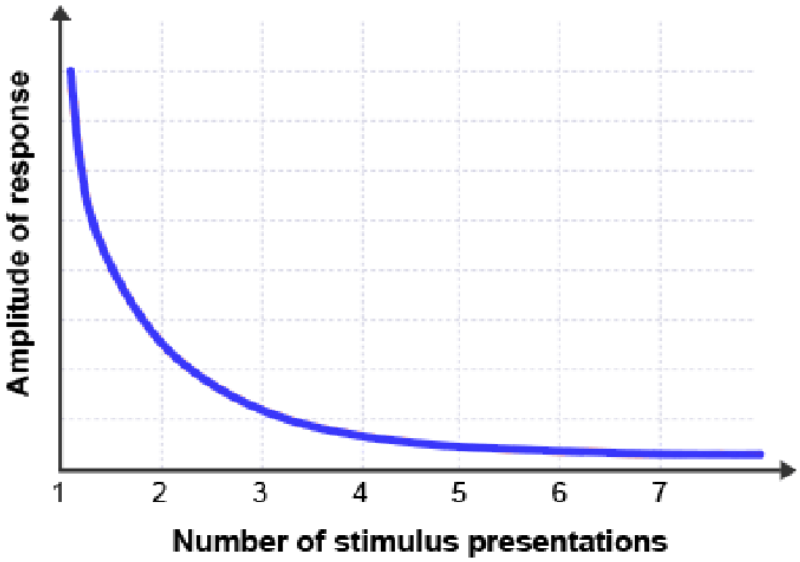

Figure 2. A hypothetical habituation curve in response to repeated stimuli (*31*)

Over many years, risk habituation to repeatedly exposed hazards has been noted as a key causal factor of workers' unsafe behaviors (*19*, *32*). Irizarry and Abraham examined the factors influencing risk perception in ironworkers, and their results indicate that previous working experience at workplaces is correlated with unsafe behaviors caused by bias in workers' risk perception (*33*). Another study indicated that repeated exposure causes workers to become accustomed to the hazards related to their tasks (*8*). While these studies indicate that risk habituation is one of the factors causing unsafe behaviors, a knowledge gap still exists regarding which specific personal and situational factors critically influence the development process of risk habituation and how this development process can be interrupted, due to the methodological limitations of the approaches adopted in the previous studies, which were uniformly retrospective and self-evaluative. Current practices mostly rely on periodic training to educate and refresh safety knowledge. Such trainings do not involve any direct behavioral interventions and therefore do not directly impact workers' risk habituation. Consequently, current practices are questionably effective in reducing workers' risk habituation.

Risk habituation can be observed as reduced attention toward repeatedly exposed workplace hazards (*34*). Risk habituation is a kind of learning. Therefore, risk habituation can be mitigated through a behavioral intervention (*10*). Specifically, providing time-sensitive feedback once risk habituation is observed is a critical step in the implementation of an effective intervention (*35*).

3.3. VR in Safety Training

With the recent development of VR technologies, the creation of an interactive and effective learning environment for hands-on experience has been enabled (*36*, *37*). VR offers various advantages in occupational education and training, including presentation of complex stimuli and precise control of training environment, safe learning environments, and tailored intervention (*38*, *39*). Given such advantages, researchers have adopted VR for safety training. The results of previous studies in construction (*40*, *41*), aviation (*42*), and mining (*43*) have revealed that workers who participated in VR safety training showed better achievement in learning safety knowledge than workers who were trained using conventional instructional methods. In addition to effective safety knowledge transfer, VR-based safety training can also strengthen safety skills by exposing trainees to simulated hazardous situations without the actual risk of injury (*44–46*).

In recent years, construction studies (*41*, *47*) have tried to enhance hazard-recognition skills by presenting various hazards in a VR environment and have demonstrated the effectiveness of such approaches over conventional methods. Recent studies have begun to explore the potential of VR-based safety training as a behavioral intervention tool. These studies demonstrate the consequences of unsafe behaviors during a trainee's simulation exercise of safety/emergency procedures (*20*, *47–49*). Such studies indicated that the measurement of human responses toward exposed hazards in a virtual environment may provide information about workers' unsafe behaviors, there is still no effective strategy that enables researchers and safety managers to understand how workers' risk habituation can be observed and measured in a VR environment.

3.4. Accident Experience and Risk Habituation

Previous studies have shown that workers tend to engage in unsafe behaviors more frequently when there is no negative consequence (i.e., injuries or accidents) to unsafe behaviors in workplaces (*12*, *50*). Although the objective risks of exposed hazards remain unchanged, the level of perceived risk decreases as exposure to hazards increases. Curry et al. found that workers who haven't experienced an injury are apt to become easily habituated to workplace hazards and engage in unsafe behaviors more frequently (*51*). In contrast, individuals who have been injured in the past exhibited a high level of risk perception (*12*, *52*). Such lowered risk sensitivity can be recovered when workers indirectly experience a potential accident associated with their everyday workplace tasks since negative emotion resulting from accident experience is more likely to capture attention and stay in memory longer (*11*, *53*).

Previous studies explored the effectiveness of simulated accident experiences in preventing unsafe behaviors. Bhandari et al. found that a naturalistic injury simulation can arouse negative emotions to workplace hazards and enhance the level of perceived risk (*54*). In another study, simulating equipment breakage in a virtual environment promoted trainees to operate equipment more safely (*48*). The results of previous studies revealed that workers who experienced an equipment breakage in a virtual environment showed improved safe behaviors in a dangerous equipment operation.

Despite VR's potential, research into safety training using VR is still nascent. The evaluation of past studies' effectiveness has relied mostly on indirect measurements (e.g., trainees' perception of the approach's impact) due to the challenges in measuring behavioral outcomes. In this context, efforts to rigorously evaluate the impact of VR safety training will play a critical role in advancing their practical applications. To this end, this study utilizes behavioral and physiological measurements of habituated behaviors to assess the impact of VR safety training in workers' risk habituation, thereby providing a theoretical foundation for personalized safety training that effectively prevents struck-by fatalities in road work zones.

4. METHODOLOGY

This research developed an immersive VR road construction environment that exposes trainees to repeated struck-by hazards and presents simulated accidents. Then, an experiment with human subjects was carefully designed and conducted. In order to examine the effectiveness of the developed VR model on reducing trainees' risk habituation, the experiment results were analyzed using pretest-posttest analyses. The relationship between and an individual's personality traits and risk habituation tendencies was also analyzed. Figure 3 illustrates the methodology of this research.

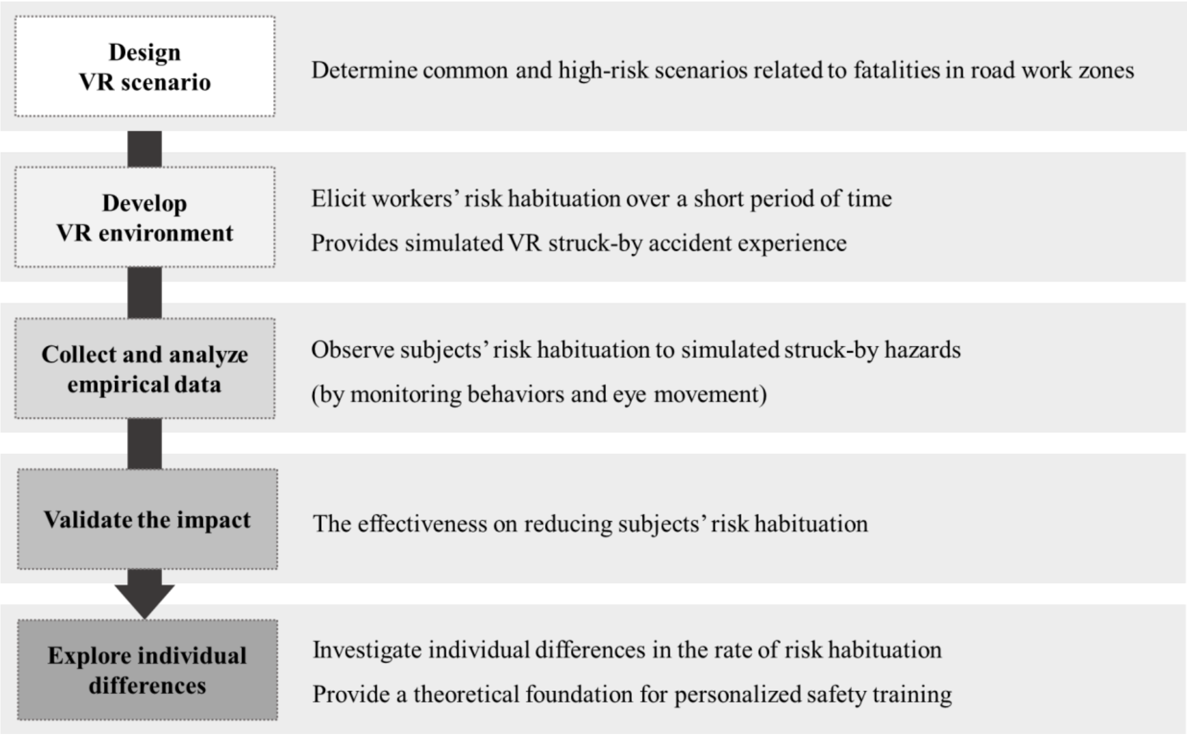

Figure 3. Research methodology.

Task 1. VR scenario design: Determine common and high-risk scenarios related to fatalities in road construction and maintenance work zones:

To determining common and high-risk scenarios associated with fatalities at road work zones, the research team carried out analyses on reference data related to construction safety and health (e.g., reports of the Center for Construction Research and Training [CPWR] (*7*) and Bureau of Labor Statistics [BLS] (*3*)). The analysis results show that the majority of fatalities occurred at road construction work zones resulting from struck-by vehicles (*3*, *7*). Accordingly, in order to maintain a feasible scope for the research, the planned development of the VR safety training system and experiments focuses on workers in road maintenance work. The proposed VR environment exposes a trainee at risk of being struck by construction equipment (e.g., a street sweeper and dump truck).

To enrich and validate the designed VR scenario, we interviewed safety managers and road construction crews of construction companies in Texas and incorporate their feedback into the VR scenario. Through this validation process, the VR scenario is designed to make sense to trainees and enhance the immersiveness of the developed VR training environment.

Task 2. Development of VR model: Develop an immersive road construction virtual reality environment that includes the components listed below:

In order to develop an optimized VR model that minimizes the Hawthorne effect and elicits a trainee's risk habituation process by exposing a trainee to repeated similar hazardous conditions, subtasks listed below were carried out carefully.

Immersive virtual road construction environment modeling. Unreal Engine 4 (UE4) was adopted to develop an immersive virtual road maintenance environment. UE4 offers various project templates to enable researchers to rapidly develop a VR environment. All models in this study were created using Maya and 3dStudio Max. Then, all aspects of graphical user interfaces were created to elicit risk habituation while trainees are working in close proximity to live traffic and heavy equipment in the developed VR environment.

Hazards and Non-Player Characters (NPC) Setup. The hazards in highway work zones (e.g., movements of heavy construction equipment, adjacent live traffic, and a fleet of dump trucks moving near road workers) are simulated in the developed VR environment (Figure 4). All interactive objects in VR respond to trainees' behaviors. Behind a subject, the sweeper moves back and forth continuously. When the street sweeper moves forward, warning alarms are provided to alert its proximity to a trainee. The movement of the sweeper is subject to the distance between the street sweeper and a subject and repeatedly exposes a trainee to the risk of a struck-by accident. Adjacent to the lane where the road maintenance takes place, dump trucks pass by close to the trainee, with accompanying warning alarms. These movement cycles of the sweeper and dump trucks continue while a trainee performs the designed task.

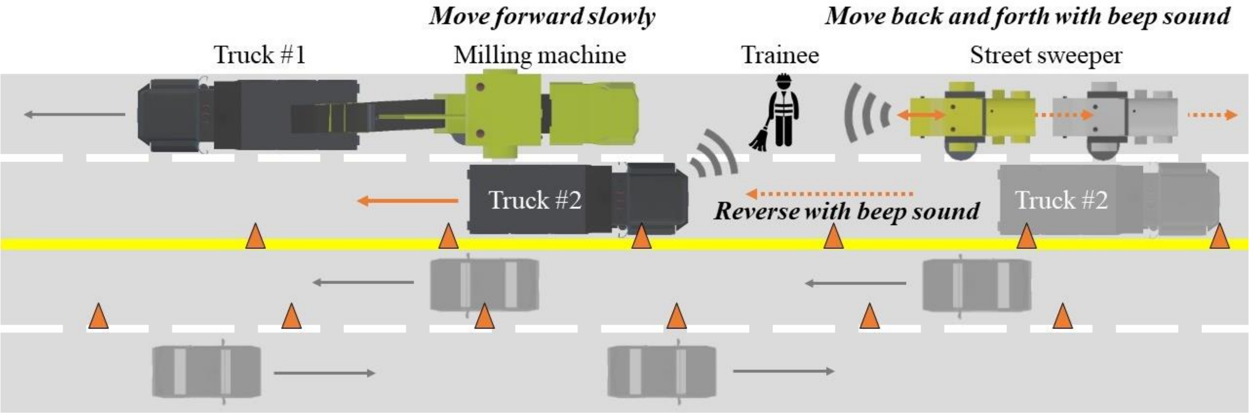

Figure 4. VR environment that exposes a trainee to repeated struck-by hazards at a road work zone (*55*).

Cyber-physical Interactive System and Behavior Measurement. The immersiveness of a VR environment plays an important role in VR safety training (*56*). Feeling the VR as a real environment is an important factor in VR safety training (*57*). To achieve the high immersiveness level, an interactive cyber-physical system was developed. Motion controllers were attached to a real broom (Figure 4-a), and the sweeping movements in the real-world are linked to the brooms in the VE (Figure 4-b). This physical interaction addresses the limitations of previous safety research that adopted VR, which did not measure actual human body movements in a virtual environment (*37*). In addition, to realize a high level of immersiveness, approximately 1,000 pieces of debris were placed on the road in the VR environment. These debris are responsive to each subject's sweeping in the virtual environment. A trainee is required to remove all debris on the entire road by sweeping with the broom (Figure 4-c).

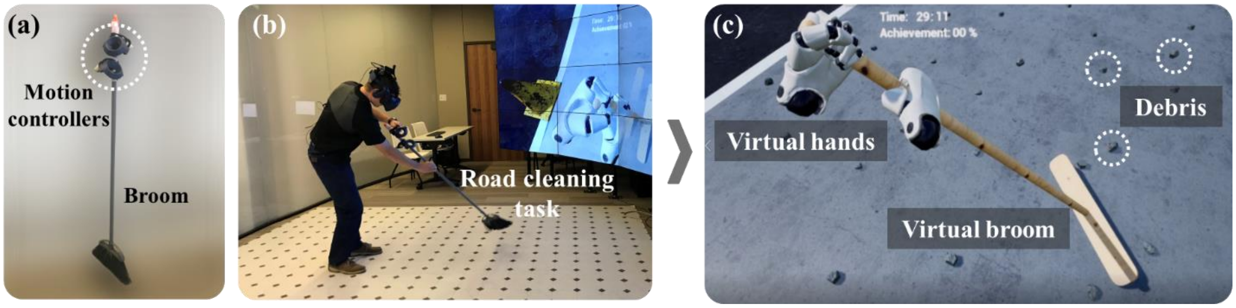

Figure 5. VR system for hand-movement synchronization; (a) Motion controllers and the real broom, (b) sweeping task in the real world, (c) debris on the road in the VR environment (*55*).

Risk habituation measurement module. This study defines risk habituation as the decline of a trainee's vigilant behaviors toward approaching hazards. To accelerate a trainee's risk habituation in a short period of training time, in the experiment, a trainee is repeatedly exposed to approaching hazards (i.e., about 30 exposures for 20 minutes) in the virtual environment. To measure trainees' risk habituation, behavioral responses (i.e., head orienting), and physiological response (i.e., eye movement) a measurement system was embedded in the developed VR training module. The behavioral and physiological responses were collected with a peak frequency of 45 Hz (figure 6).

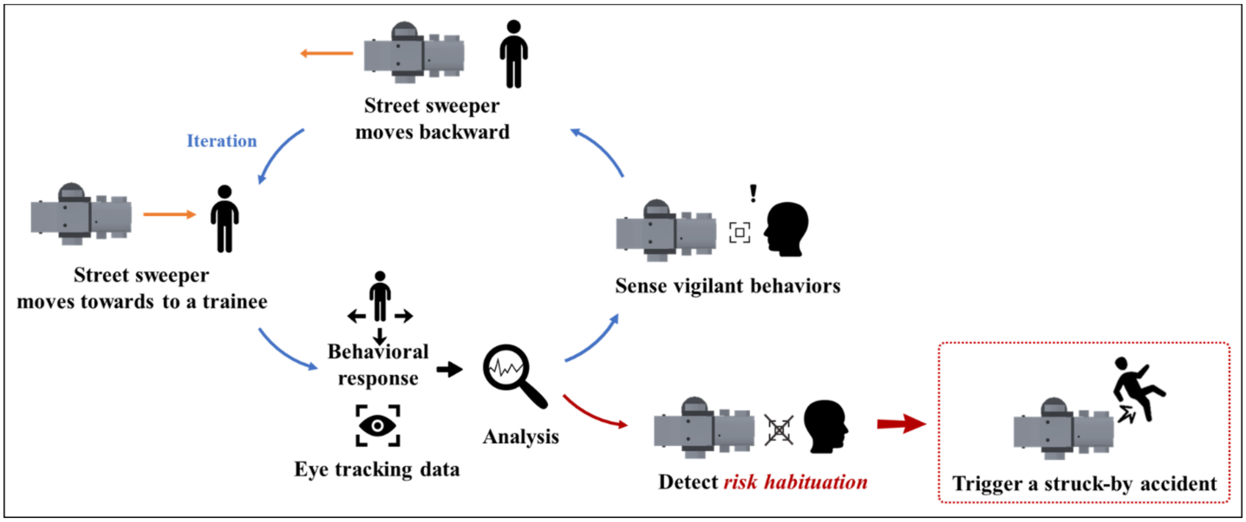

Figure 6. The concept of the risk habituation measurement and the accident simulation

Virtual accident simulation module. A module simulates virtual struck-by accidents with construction vehicles was created (Figure 7). In the VR training module, the accidents are triggered by a trainee's risk habituation (i.e., a decline in vigilance), at which point the NPCs' movements become erratic and faster until they collide with a trainee. The accident simulation includes visual scenes, haptic feedback, and sound effects via HMD controllers. To emphasize aversive feedback, visual scenes are dramatized.

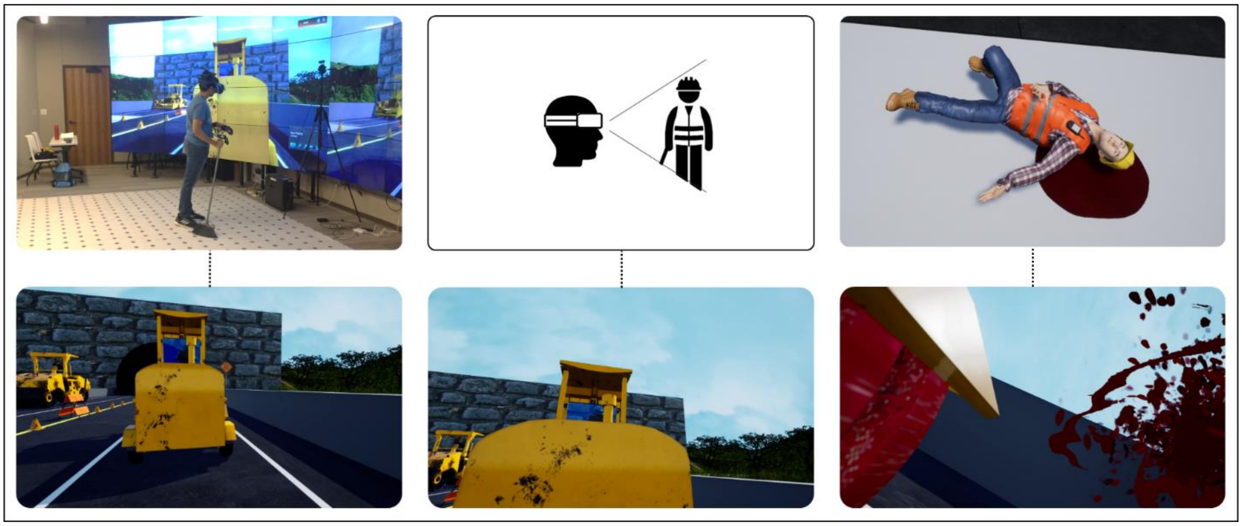

Figure 7. Simulated accident scene.

Task 3. Experiments

To examine the effectiveness of the proposed VR safety training environment, the experiment was designed and conducted. All of the experimental procedures were designed in consultation with TAMU's Institutional Review Board (IRB).

Participants. A total of 32 subjects (26 males, 6 females; $M_{age} = 21.09, SD_{age} = 3.04$) participated in the experiment. All of the subjects were graduate and undergraduate students at Texas A&M University (TAMU) majoring in engineering/construction. More than 50% of the subjects had working experience at construction sites; 19% of the subjects had more than 1 year and less than 5 years of working experience at construction sites. The experiment procedures were approved by the IRB at Texas A&M University. The experiment was conducted in the Building Information Modeling-Computer Aided Virtual Environment (BIM-CAVE) at Texas A&M University, as shown in Figure 8.

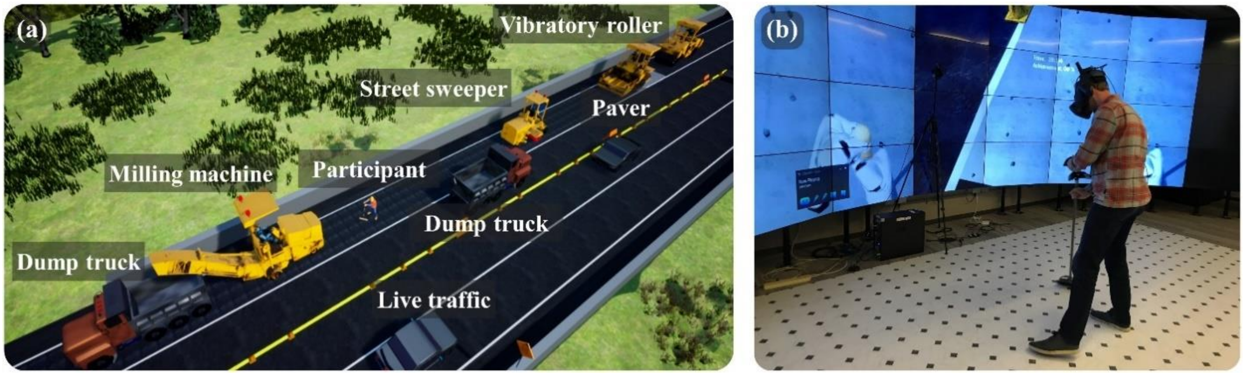

Figure 8. Experiment environment: (a) overview scene of the developed virtual road work zone; (b) the experiment performed at TAMU BIM-CAVE (*55*).

Procedures. All subjects watched a safety training video for highway maintenance work recorded by the Associated General Contractors of America (AGC) and were instructed on how to conduct the task in the virtual environment. Before the main experiment, all subjects had a practice session to acquaint with the virtual environment and learned how to perform the task. In the experiment, participants were instructed to (1) follow the milling machine; (2) sweep all the debris on the working lane; and pay attention to approaching vehicles and warning alarms for safety. During the experiment, subjects experienced the simulated virtual accident if they stopped to pay attention to approaching vehicles. If the accident happened, the experiment was terminated immediately. If the accident did not happen, the experiment was finished 20 minutes after the start time. A follow-up interview was conducted to collect feedback about the subjects' experience in the virtual environment. To examine the effect of experiencing simulated virtual accidents in mitigating risk habituation, each subject participated in the second experiment with a week's interval; The second experiment was performed through the same procedure but without watching the safety training video. Each experiment took approximately 1–1.5 hours per subject, including the VR experiment and other surveys.

Task 4. Analyze the data to examine the training effects

The developed VR system documents (1) the response time, and (2) the frequency of vigilant behaviors. The collected data from the experiment were processed as follows:

1. The response time (*checking distance*): One exposure to the approaching hazard was defined as one cycle of the movement of the sweeper. During each exposure, when a subject looked back and stared at the sweeper for the first time to check its proximity, the distance between the subject and the sweeper was recorded. To eliminate individual differences in *checking distance* range, the min-max normalization was used to normalize the extracted checking distance values without perverting the raw data, thereby mapping the entire range of raw values in each subject's *checking distance* from minimum *checking distance* to maximum *checking distance* is mapped to a range from 0 to 1.

2. The frequency of vigilant behaviors (*checking rate*): In the experiment, when a subject looked back to check the sweeper's proximity, it was considered vigilant behavior. If a subject showed multiple vigilant behaviors during exposure, it was still considered as one vigilant behavior. The *checking rate* of each subject was calculated as the frequency of vigilant behavior across all exposures to hazards using the following equation:

$$CR_i = \frac{TC_{Success}}{TE_{Total}} \qquad [1]$$

where:

$TC_{Success} =$ a total number of checking behaviors of subject i;

$TE_{Total} =$ a total number of exposures of subject i.

To avoid manipulating data, if a subject did not check the approaching sweeper until the minimum distance where the sweeper starts to move backward, that was not contained in the *checking distance* analysis. Thus, analyzing *checking rate* provides additional information to the analysis result of the checking distance by allowing the observation of how often a subject failed to check the approaching sweeper.

Using Python, the collected data was synchronized to build a data set of subjects' risk habituation across the two experiments. In this study, a multiple regression analysis was used on vigilant behavior variability data to determine if the proposed VR intervention affects an increase in subjects’ vigilant behaviors. The statistical package R was used for data preparation and statistical analyses. In this way, the effectiveness of the proposed VR training environment in reducing subjects’ risk habituation was examined.

Task 5. Examine individual differences in the rate of risk habituation

In order to identify the relationship between the risk habituation and individual factors (i.e., personalities) multivariate analyses were carried out using the analyzed response data from Task 4 and pre/post survey results. Based on those analysis results, The factors affecting the individual differences in the rate of risk habituation were examined, thereby providing a theoretical foundation for personalized safety training that effectively prevents workers’ risk habituation.

5. ANALYSIS AND FINDINGS

5.1. Research Hypotheses

5.1.1. Define hypotheses

Although VR offers various opportunities for exposing workers to hazardous situations, evoking consequences of habituation within a short experiment time period is extremely difficult (*58*). Moreover, some subjects may not become inattentive to exposed hazards because of subjects' awareness of being watched during the experiment (*59*, *60*). Thus, few studies have attempted to observe and analyze workers' risk habituation in a virtual environment. To tackle this challenge, this study examines whether inattention to exposed hazards can be evoked as a result of habituation in a VR environment, the following hypothesis was defined:

1. *Hypothesis 1:* Workers' vigilance to struck-by hazards will decline in latency and frequency over successive exposures to struck-by hazards in a VR environment.

Habituation results in reduced attentiveness to repeatedly exposed hazards. Therefore, it can be prevented through a behavioral intervention (*10*). To effectively reduce workers' risk habituation, the implementation of a behavioral intervention should involve time-sensitive feedback along with evaluating the effectiveness of interventions (*35*, *61*). In traditional safety training, it is difficult to provide time-sensitive feedback on workers' inattention to hazards. However, VR safety training can effectively incorporate time-sensitive feedback into the training module. The effectiveness of experiencing simulated VR accidents as a behavioral intervention has been rarely evaluated using direct behavior measures. Furthermore, the long-term impact of simulated VR accidents on workers' risk habituation has not been evaluated rigorously. In this context the second hypothesis was defined:

2. *Hypothesis 2*: Experiencing simulated VR accidents as consequences of workers' risk habituation promotes workers' vigilance to repeatedly exposed hazards, and for a prolonged period of time, this effect will be sustained.

5.1.2. Test Hypotheses

This study tested *Hypothesis 1* through the following steps below: (1) Bivariate linear regression analysis; and (2) Hierarchical linear model analysis. The bivariate linear regression models predicting *checking distance* from *exposure time* to the exposed hazards were performed using the following equation:

$$\hat{y_i} = B_0 + B_1 T + r \qquad [2]$$

where:

$\hat{y_i}$ = *checking distance* at *exposure time* T;

B_0 = the intercept of the regression line at $T = 0$;

B_1= the slope of the regression that describes the variance in *checking distance* $\hat{y_i}$ for each 1-minute increase in *exposure time* T.

In addition, a two-level hierarchical linear model analysis was performed to investigate the association between the variation in the *exposure time* and the variance in the *checking rate*. The hierarchical linear model analysis has been used in psychology research to examine a change in cognitive processes (*62*) and is used for evaluating repeated measures in longitudinal data with various numbers of observations per subject (*63*, *64*). In this analysis, a variable of the first level model was *exposure time*. A variable of the second level was *checking rate* of each subject. The total number of *exposure time* observations at the first level was nested in a subject at the second level. In each trial, *checking rate* was only calculated once per subject. Thus, *checking rate* was modeled as the second level predictor. The equations following were used for the hierarchical linear model analysis:

1. Level 1: The first level model

$$y_{ij} = B_{0j} + B_{1j}T_{ij} + B_{2j}A_{ij} + B_{3j}T \times A_{ij} + r_{ij} \qquad [3]$$

where:
y_{ij} = the sum of the subject intercept;
j = the subject (j = 1, 2, 3 … n);
i = for each measurement (i = 1, 2, 3 … n) within a subject;
B_{0j} = the intercept in subject j;
B_{1j} = the predicted decline in *checking distance* by 1-minute increase in *exposure time* T in subject j;
B_{2j} = the predicted change in *checking distance* by one percent increase in *checking rate* A;
B_{3j} = the slope of the interaction of *exposure time* T and *checking rate* A.

2. Level 2: The second level model

$$B_{0j} = \gamma_{00} + \gamma_{01}A_j + \upsilon_{0j} \qquad [4]$$

where:
A_j = *checking rate*—*checking rate* of subject j;
γ = regression coefficients at the subject level;
γ_{00} = the intercept over subject when all predictors are 0;
γ_{01} = the intercept of *checking rate* A of subject j;
υ_{0j} = the subject level error in the intercept.

$$B_{1j} = \gamma_{10} + \gamma_{11}A_j + \upsilon_{1j} \qquad [5]$$

where:
γ_{10} = the slope of a subject;
γ_{11} = the regression coefficient of *checking rate* A;
υ_{1j} = the subject level error in the slope.

Equation [3], [4], and [5] were nested into Equation [6]. Using the lme4 package in R (Bates et al. 2014; R Core Team 2020), the hierarchical analysis was conducted. The mean-centering was applied to scaled *exposure time* T.

$$y_{ij} = (\gamma_{11}A_j + \gamma_{10} + \upsilon_{1j})T_{ij} + (\gamma_{01}A_j + \gamma_{00} + \upsilon_{0j}) + r_{ij} \qquad [6]$$

The result of the test for the hierarchical linear model denotes how variances in *checking rate* affected the decline in *checking distance*.

This study tested *Hypothesis 2* through (1) multiple regression analysis that estimates *checking distance* at *exposure time* and accident experience in the first experiment, and (2) a paired-samples t-test that evaluates the effect of the intervention on *checking rate* increase for both groups. Multiple regression analysis was performed to examine whether and how a subject's experience of simulated VR accidents in the first experiment affected the subject's attentiveness in the second experiment. To the following equation, a subject's experience of simulated VR accidents in the first experiment was added as a categorical variable:

$$\hat{y} = B_0 + B_1 T + B_2 A + B_3 TA + r \qquad [7]$$

where:
$\hat{y}$ = dependent variable *checking distance* at *exposure time* T and accident experience A;
B_0 = intercept of the regression line in the no accident group $(A = 0)$;
B_1 = change in the intercept for each 1-minute increase in exposure time T;
B_2 = variance in simple intercepts, comparing the accident group $(A = 1)$ with no accident group $(A = 0)$;
B_3 = difference in simple slopes, comparing the no accident group $(A = 1)$ with the accident group $(A = 0)$.

Paired-samples t-tests were performed to investigate the intervention effect of experiencing simulated VR accidents in the first experiment on *checking rate* in the second experiment. The results of the analysis were explained as mean ± SD. The degree of the effect of the intervention was examined using Cohen's effect sizes d (*65*). During the experiment, 4 subjects in the first experiment, 1 subject in the second experiment never showed hazard checking behaviors. The data from such subjects were not included for the analysis of *Hypothesis 1*; those data were only used for the analysis of *Hypothesis 2*.

5.2. Results

5.2.1. Hypothesis 1 Testing

Hypothesis 1 was determined by testing the bivariate regression models for predicting *checking distance* from *exposure time* to the approaching hazard. The coefficients were significant, R^2= .16, F(1, 441) = 83.83, $p < 0.001$ (for the first experiment), R^2= .10, F(1, 694) = 79.67, and $p < 0.001$ (for the second experiment). *Exposure time* to the approaching hazard negatively predicted *checking distance*, B_1= -.023, $p < 0.001$ (for the first experiment), B_1= -.014, and $p < 0.001$ (for the second experiment). The results of both sessions reveal that the subjects' behaviors to check the distance of the sweeper were slowed with the increase in *exposure time* to the approaching hazard (Table 1 and Fig. 4).

Table 1. Regression coefficient, representing the effect of exposure time on the decline in checking distance.

Experiment	Predictors	B_1	S.E.	*p-value*
First	Exposure time	- .023	.002	< 0.001*
Second	Exposure time	- .016	.003	< 0.001*

Note: * Significant at the p = .05 level

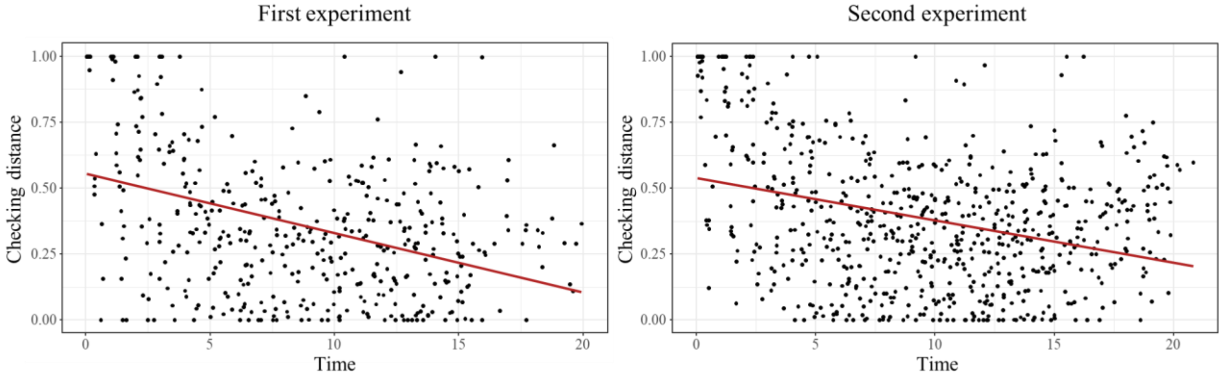

Figure 9. Checking distance when subjects showed vigilant behaviors (*55*).

The results of the hierarchical analysis are shown in Table 2. The coefficient B_3 tended to have a correlation of borderline significance ($p = 0.074$). *Checking rate* and *Exposure time* had positive interaction. This result represents that the subjects with low levels of *checking rates* tended to have a faster decline pattern of *checking distance* over *exposure time*, compared to the subjects with high levels of *checking rates*. Figure. 10 shows the variance in *checking distance* between the subjects who exhibited different *checking rates*. The lines' slopes represent the effect of *checking rate* on the strength of the correlation between *checking distance* and *exposure time* at (a) the mean for *checking rate*, (b) one standard deviation above the mean *checking rate*, and (c) one standard deviation below the mean of *checking rate*.

The follow-up interview results support the results of *Hypothesis 1* testing. To identify the reason for subjects' decreasing vigilance in response to hazards in the experiment, subjects in the accident group were asked to answer why they ignored the proximity of the equipment. Most of them answered that they focused just on sweeping away the debris on the road and thought that the construction equipment was just moving around and posed no risk. Thus, they ignored to look back to check the approaching equipment.

Table 2. Fixed effects of the hierarchical linear model on the checking distance of the exposure time and the checking rate.

Predictors	Estimates	S.E.	*p-value*
B_0 Intercept	0.30	0.06	< 0.001*
B_1 Exposure time	-0.04	0.01	< 0.001*
B_2 Checking rate	0.10	0.09	0.244
B_3 Exposure time * Checking rate	0.02	0.01	0.074

Note: * Significant at the p = .05 level

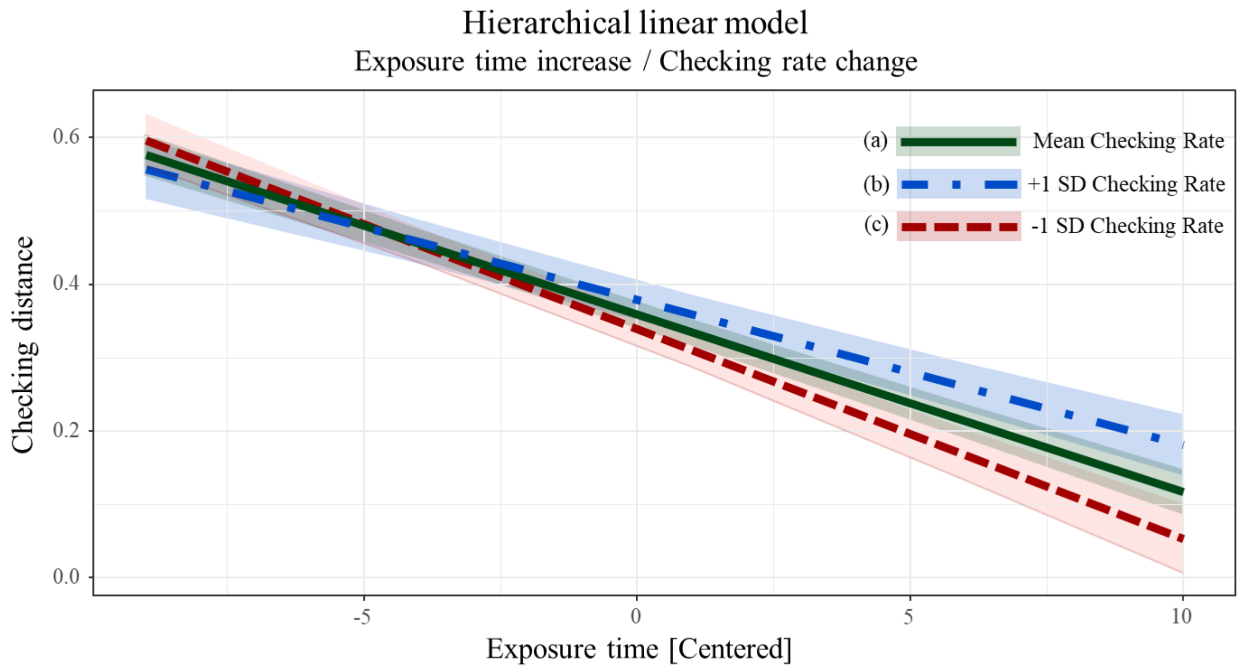

Figure 10. The effect of exposure time on checking distance at (a) the mean of checking rate, (b) one standard deviation above the mean of checking rate, and (c) one standard deviation below the mean of checking rate (*55*).

5.2.2. Hypothesis 2 testing

In the experiment, simulated VR accidents happened in response to a subject's habituated behaviors. In the first experiment, 24 out of 32 subjects experienced simulated VR accidents resulting from their inattention to hazards (i.e., the accident group) and 8 subjects did not experience simulated VR accidents (i.e., the no accident group). In the second experiment, 58% of the accident group did not experience accidents. However, 75% of the no accident group experienced simulated accidents during the second experiment.

Table 3. Classified results according to the accident occurrence during the experiment

First experiment (Total: 32)		Second experiment (Total: 32)		
		No accident	Accident	Subtotal
No accident	8	2	6	8
Accident	24	14	10	24
Sub total	32	16	16	32

The multiple linear regression model for *Hypothesis 2* testing was significant, $R^2 = .11$, $F(3,686) = 28.41$, $p < 0.001$ (Table 4). The result represents a significant interaction between *exposure time* in the second experiment and simulated VR accident experience in the first experiment, $B_1 = .008$, $p < 0.001$. *Hypothesis 2* was confirmed. Simulated accident experience as a negative result of the subject's inattention significantly mitigated risk habituation (Figure. 11).

Table 4. Regression coefficients, indicating the influence of accident experiencing on the checking distance.

Experiment		B_1	S.E.	*p-value*
Second	Exposure time	- .022	.004	< 0.001*
	Experiencing accident in the first experiment	.004	.022	0.369
	Exposure time × Experiencing accident in the first experiment	.008	.004	0.048*

Note: * Significant at the p = .05 level

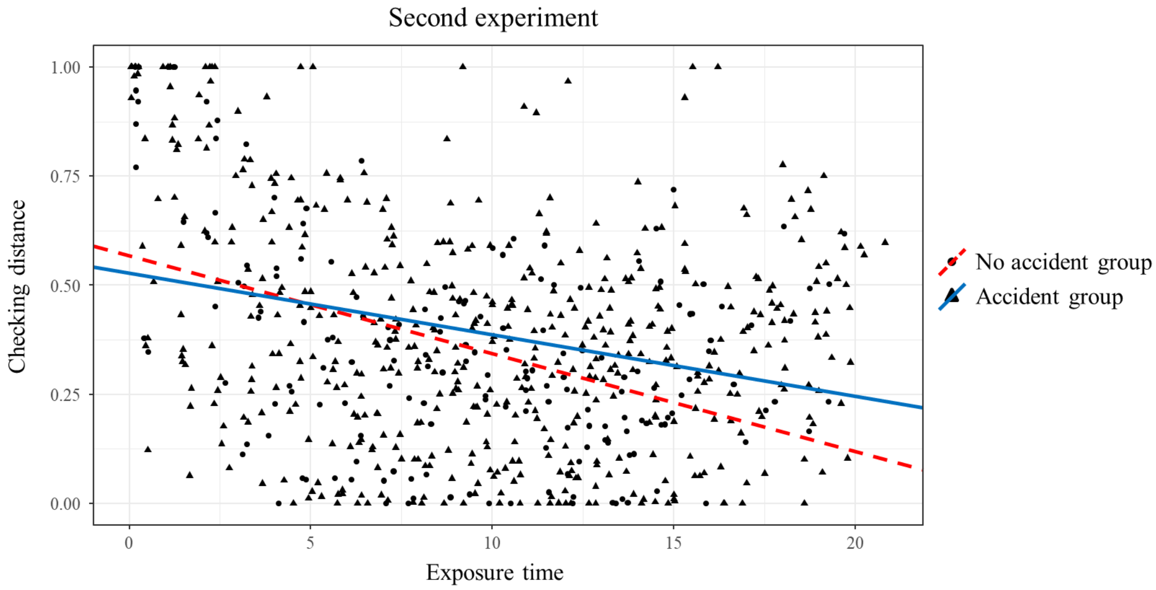

Figure 11. The slopes for the effect of exposure time (*55*).

The *checking rates* from the second experiment were compared with the *checking rates* from the first experiment. For the no accident group, there was a significant variance in *checking rate* for the first experiment (M = 0.38, SD = 0.26) and the second experiment (M = 0.70, SD = 0.27); t(24) = -6.03, p < 0.001. The effect size d was -1.22 large (-1.22). However, in the no accident group, the variance in the *checking rates* between the first experiment (M = 0.71, SD = 0.15) and the second experiment (M = 0.78, SD = 0.20); t(8) = -1.25, p = 0.25 was not significant. The effect size d was small (-0.38), as shown in Table 5 and Figure 12).

Table 5. Effect of experiencing VR-simulated accident on the checking rate: paired sample t-test and effect size.

Simulated VR accident experience	Checking rate					*p-value*	Cohen's d
	First		Second				
	M	SD	M	SD	t		
No accident group	0.71	0.15	0.78	0.20	-1.253	0.250	0.37 (small)
Accident group	0.38	0.26	0.70	0.27	-6.031	< 0.001*	1.22 (large)

Note: * Significant at the p = .05 level

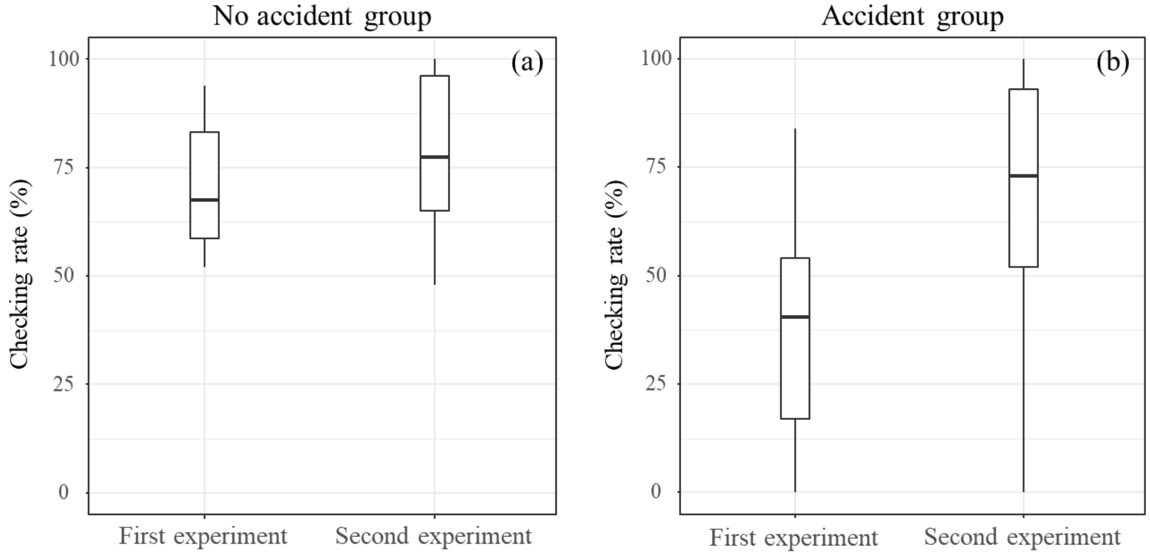

Figure 12. The effect simulated VR accident on the change in checking rate: (a) the variance in checking rate of no accident group in the first experiment, (b) the variance in checking rate of the accident group in the first experiment.

The test results confirmed *Hypothesis 2*. The results of the multiple regression analysis show that the accident group exhibited slower habituation patterns than the no accident group in the second experiment. In addition, the paired-samples t-test results showed that experiencing the simulated VR accidents improved *checking rate* significantly. These results confirmed that the simulated VR accidents reduced the workers' risk habituation caused by repeated exposure to struck-by hazards and the effect was sustained until the next experiment.

5.2.3. Risk habituation and personality

To provide the foundation of personalized safety training that effectively prevents workers' risk habituation, the relationship between the risk habituation and individual factors (i.e., personalities) multivariate analyses were carried out using the collected behavior data. The Big-Five personality traits survey that measures the five dimensions of personalities—Agreeableness, Extraversion, Neuroticism, Conscientiousness, and Openness—was used for the analysis. The results showed a significant positive correlation between a high checking rate and the Agreeableness trait, R^2 = .39, $F(28)$ = 3.52, p < 0.05, β = .003, p < 0.05 (Table 6). This finding indicates that behavioral measurements in a VR training environment would support further study on differences in individuals' safety behaviors. Although there has been interest in the correlation between and safety behaviors and personality traits, previous studies were limited by observing safety behaviors and thus mostly relied on retrospective methods. In this context, utilizing behavioral measurements—measures related to risk habituation—in a virtual environment would help researchers and practitioners provide personalized safety training.

Table 6. The influence of personality on *checking rate*

Predictors	Estimates	S.E.	*p-value*
Extraversion	-0.025	0.022	0.262
Agreeableness	0.038	0.014	0.014*
Conscientiousness	-0.012	0.018	0.519
Neuroticism	-0.021	0.011	0.069
Openness	-0.033	0.017	0.054

* Significant at the p = .05 level

6. CONCLUSIONS

This study developed a Virtual Reality (VR) training system that enables researchers and practitioners to analyze trainees' risk habituation tendencies based on collected behavioral response data (i.e., eye tracking, vigilant behavior in a VR environment), and offers interventions that effectively prevent risk habituation by demonstrating the negative consequences of unsafe behaviors. Moreover, the long-term impact of VR-based behavioral interventions on reducing workers' risk habituation was analyzed. Specifically, this study examined risk habituation towards struck-by hazards associated with mobile construction vehicles. The results of the study demonstrate that the developed VR safety training system can evoke workers' habituation and that the designed intervention simulating VR accidents effectively reduces workers' risk habituation.

Considering practical applications, the adoption of VR behavioral interventions may be beneficial to construction safety efforts. Observing workers' risk habituation in the field takes considerable effort, funds, and time. However, by using a VR environment, safety practitioners are able to measure the development of risk habituation in less time at a much lower cost. Additionally, measuring workers' behaviors in a VR environment can help researchers and safety practitioners identify which workers are more prone to risk habituation, and provide personalized safety training. Personalized safety training enables workers to determine their habituation tendencies toward repeated exposure to workplace hazards and helps workers understand when they behave unsafely while performing a task. Therefore, the developed VR safety training system could motivate workers to improve their unsafe behaviors by themselves. Although the implementation of a VR safety training system requires higher developing costs than traditional safety training, the operation costs of a VR safety training system is very little. Moreover, the cost of implementing VR safety training has been steadily declining with the advancement of VR technology. VR-based behavioral intervention tools can be developed using consumer-grade VR headsets and VR environment creation tools that can be used for educational and training purposes for free. Therefore, the proposed method can be used to offset the limitations of traditional safety training without incurring high costs.

In conclusion, the findings of this study provide new knowledge about how to evoke and observe workers' risk habituation to repeated struck-by hazards and warning alarms from construction equipment, and how behavioral interventions in a VR environment can reduce the habituation and promote safe behaviors.

REFERENCES

1. Fan, W., S. Choe, and F. Leite. Prevention of Backover Fatalities in Highway Work Zones: A Synthesis of Current Practices and Recommendations. *International Journal of Transportation Science and Technology*, Vol. 3, No. 4, 2014, pp. 311–337. https://doi.org/10.1260/2046-0430.3.4.311.
2. Romano, N., D. Fosbroke, and T. Ruff. Improving Work Zone Safety. *Professional Safety*, Vol. 53, No. 4, 2008, pp. 46–48.
3. Bureau of Labor Statistics, U.S. Department of Labor. Fatal Work Injuries down Slightly in 2017 : The Economics Daily: U.S. Bureau of Labor Statistics. https://www.bls.gov/opub/ted/2019/fatal-work-injuries-down-slightly-in-2017.htm. Accessed Jan. 20, 2020.
4. Highway International Private Limited. Milling & Profiling. http://www.highway.com.sg/milling-profiling/. Accessed Jan. 25, 2020.
5. Barriere Construction Co. Asphalt Paving | Barriere Construction Co. https://www.barriere.com/our-services/asphalt-paving/. Accessed Jan. 25, 2020.
6. Pratt, S. G., D. E. Fosbroke, and S. M. Marsh. Building Safer Highway Work Zones; Measures to Prevent Worker Injuries from Vehicles and Equipment. 2001.
7. The Center for Construction Research and Training (CPWR). *Fatal Injuries at Road Construction Sites among Construction Workers*. CPWR, 2018.
8. Majekodunmi, A., and A. Farrow. Perceptions and Attitudes toward Workplace Transport Risks: A Study of Industrial Lift Truck Operators in a London Authority. *Archives of environmental & occupational health*, Vol. 64, No. 4, 2009, pp. 251–260.
9. Bukatko, D., and M. W. Daehler. *Child Development: A Thematic Approach*. Cengage Learning, 2012.
10. Rankin, C. H., T. Abrams, R. J. Barry, S. Bhatnagar, D. F. Clayton, J. Colombo, G. Coppola, M. A. Geyer, D. L. Glanzman, S. Marsland, F. K. McSweeney, D. A. Wilson, C.-F. Wu, and R. F. Thompson. Habituation Revisited: An Updated and Revised Description of the Behavioral Characteristics of Habituation. *Neurobiology of Learning and Memory*, Vol. 92, No. 2, 2009, pp. 135–138. https://doi.org/10.1016/j.nlm.2008.09.012.
11. Daalmans, J. M. T., and J. Daalmans. *Human Behavior in Hazardous Situations: Best Practice Safety Management in the Chemical and Process Industries*. Butterworth-Heinemann, 2012.
12. Duchon, J. C., and L. W. Laage. The Consideration of Human Factors in the Design of a Backing-up Warning System. No. 30, 1986, pp. 261–264.
13. Namian Mostafa, Albert Alex, Zuluaga Carlos M., and Behm Michael. Role of Safety Training: Impact on Hazard Recognition and Safety Risk Perception. *Journal of Construction Engineering and Management*, Vol. 142, No. 12, 2016, p. 04016073. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001198.
14. Baldwin, T. T., and J. K. Ford. Transfer of Training: A Review and Directions for Future Research. *Personnel psychology*, Vol. 41, No. 1, 1988, pp. 63–105.
15. Cromwell, S. E., and J. A. Kolb. An Examination of Work-environment Support Factors Affecting Transfer of Supervisory Skills Training to the Workplace. *Human resource development quarterly*, Vol. 15, No. 4, 2004, pp. 449–471.
16. Golovina, O., J. Teizer, and N. Pradhananga. Heat Map Generation for Predictive Safety Planning: Preventing Struck-by and near Miss Interactions between Workers-on-Foot and Construction Equipment. *The Special Issue of 32nd International Symposium on Automation*

and Robotics in Construction, Vol. 71, 2016, pp. 99–115. https://doi.org/10.1016/j.autcon.2016.03.008.

17. Golovina, O., M. Perschewski, J. Teizer, and M. König. Algorithm for Quantitative Analysis of Close Call Events and Personalized Feedback in Construction Safety. *Automation in Construction*, Vol. 99, 2019, pp. 206–222. https://doi.org/10.1016/j.autcon.2018.11.014.
18. Sakhakarmi, S., J. Park, and C. Cho. Prototype Development of a Tactile Sensing System for Improved Worker Safety Perception. 2019, pp. 555–562. https://doi.org/10.1061/9780784482438.070.
19. Chan, K., J. Louis, and A. Albert. Incorporating Worker Awareness in the Generation of Hazard Proximity Warnings. *Sensors*, Vol. 20, No. 3, 2020, p. 806.
20. Chittaro, L., and F. Buttussi. Assessing Knowledge Retention of an Immersive Serious Game vs. a Traditional Education Method in Aviation Safety. *IEEE Transactions on Visualization and Computer Graphics*, Vol. 21, No. 4, 2015, pp. 529–538. https://doi.org/10.1109/TVCG.2015.2391853.
21. Nnaji, C., J. Gambatese, H. W. Lee, and F. Zhang. Improving Construction Work Zone Safety Using Technology: A Systematic Review of Applicable Technologies. *Journal of traffic and transportation engineering (English edition)*, Vol. 7, No. 1, 2020, pp. 61–75.
22. CDC - National Institute for Occupational Safety and Health. Highway Work Zone Safety - Worker Fatal Injuries. https://www.cdc.gov/niosh/topics/highwayworkzones/default.html. Accessed Jan. 11, 2022.
23. FHWA, F. H. A. FHWA Work Zone Facts and Statistics - FHWA Office of Operations. https://ops.fhwa.dot.gov/wz/resources/facts_stats.htm. Accessed Jan. 16, 2022.
24. Fact Sheet: The Bipartisan Infrastructure Deal. *The White House*. https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/06/fact-sheet-the-bipartisan-infrastructure-deal/. Accessed Jan. 16, 2022.
25. Thapa, D., and S. Mishra. Using Worker's Naturalistic Response to Determine and Analyze Work Zone Crashes in the Presence of Work Zone Intrusion Alert Systems. *Accident Analysis & Prevention*, Vol. 156, 2021, p. 106125. https://doi.org/10.1016/j.aap.2021.106125.
26. Awolusi, I., and E. D. Marks. Active Work Zone Safety: Preventing Accidents Using Intrusion Sensing Technologies. *Frontiers in built environment*, Vol. 5, 2019, p. 21.
27. Hallowell, M. Safety Risk Perception in Construction Companies in the Pacific Northwest of the USA. *Construction Management and Economics*, Vol. 28, No. 4, 2010, pp. 403–413. https://doi.org/10.1080/01446191003587752.
28. Yang, K., C. R. Ahn, M. C. Vuran, and H. Kim. Collective Sensing of Workers' Gait Patterns to Identify Fall Hazards in Construction. *Automation in Construction*, Vol. 82, 2017, pp. 166–178. https://doi.org/10.1016/j.autcon.2017.04.010.
29. Inouye, J. Risk Perception: Theories, Strategies, and next Steps. *Itasca, IL: Campbell Institute National Safety Council*, 2014.
30. Tixier Antoine J.-P., Hallowell Matthew R., Albert Alex, van Boven Leaf, and Kleiner Brian M. Psychological Antecedents of Risk-Taking Behavior in Construction. *Journal of Construction Engineering and Management*, Vol. 140, No. 11, 2014, p. 04014052. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000894.
31. Wilson, F. A. W., and E. T. Rolls. The Effects of Stimulus Novelty and Familiarity on Neuronal Activity in the Amygdala of Monkeys Performing Recognition Memory Tasks. *Experimental Brain Research,* Vol. 93, No. 3, 1993, pp. 367–382.

32. Kasperson, R. E., O. Renn, P. Slovic, H. S. Brown, J. Emel, R. Goble, J. X. Kasperson, and S. Ratick. The Social Amplification of Risk: A Conceptual Framework. *Risk analysis*, Vol. 8, No. 2, 1988, pp. 177–187.
33. Irizarry, J., and D. M. Abraham. Application of Virtual Reality Technology for the Improvement of Safety in the Steel Erection Process. In *Computing in Civil Engineering (2005)*, pp. 1–11.
34. Weinberg, W. A., and C. R. Harper. Vigilance and Its Disorders. *Behavioral Neurology*, Vol. 11, No. 1, 1993, pp. 59–78. https://doi.org/10.1016/S0733-8619(18)30170-1.
35. Zohar, D., and I. Erev. On the Difficulty of Promoting Workers' Safety Behaviour: Overcoming the Underweighting of Routine Risks. *International Journal of Risk Assessment and Management*, Vol. 7, No. 2, 2007, pp. 122–136.
36. Chen, C. J. Theoretical Bases for Using Virtual Reality in Education. *Themes in Science and Technology Education*, Vol. 2, No. 1–2, 2010, pp. 71–90.
37. De Juan Ripoll, C., J. L. Soler Domínguez, J. Guixeres Provinciale, M. Contero González, N. Álvarez Gutiérrez, A. Raya, and M. Luis. Virtual Reality as a New Approach for Risk Taking Assessment. *Frontiers in psychology*, Vol. 9, 2018, p. 2532.
38. Rizzo, A., J. Difede, B. O. Rothbaum, J. M. Daughtry, and G. Reger. Virtual Reality as a Tool for Delivering PTSD Exposure Therapy. *Post-Traumatic Stress Disorder: Future Directions in Prevention, Diagnosis, and Treatment*, 2013.
39. Strickland, D. Virtual Reality for the Treatment of Autism. *Studies in health technology and informatics*, 1997, pp. 81–86.
40. Albert, A., M. R. Hallowell, B. Kleiner, A. Chen, and M. Golparvar-Fard. Enhancing Construction Hazard Recognition with High-Fidelity Augmented Virtuality. *Journal of Construction Engineering and Management*, Vol. 140, No. 7, 2014, p. 04014024.
41. Perlman, A., R. Sacks, and R. Barak. Hazard Recognition and Risk Perception in Construction. *Safety Science*, Vol. 64, 2014, pp. 22–31. https://doi.org/10.1016/j.ssci.2013.11.019.
42. Chittaro, L., C. L. Corbett, G. A. McLean, and N. Zangrando. Safety Knowledge Transfer through Mobile Virtual Reality: A Study of Aviation Life Preserver Donning. *Safety Science*, Vol. 102, 2018, pp. 159–168. https://doi.org/10.1016/j.ssci.2017.10.012.
43. Liang, Z., K. Zhou, and K. Gao. Development of Virtual Reality Serious Game for Underground Rock-Related Hazards Safety Training. *IEEE Access*, Vol. 7, 2019, pp. 118639–118649.
44. Albert, A., M. R. Hallowell, M. Skaggs, and B. Kleiner. Empirical Measurement and Improvement of Hazard Recognition Skill. *Safety science*, Vol. 93, 2017, pp. 1–8.
45. Eiris, R., M. Gheisari, and B. Esmaeili. PARS: Using Augmented 360-Degree Panoramas of Reality for Construction Safety Training. *International journal of environmental research and public health*, Vol. 15, No. 11, 2018, p. 2452.
46. Li, X., W. Yi, H.-L. Chi, X. Wang, and A. P. Chan. A Critical Review of Virtual and Augmented Reality (VR/AR) Applications in Construction Safety. *Automation in Construction*, Vol. 86, 2018, pp. 150–162.
47. Sobhani, A., and B. Farooq. Impact of Smartphone Distraction on Pedestrians' Crossing Behaviour: An Application of Head-Mounted Immersive Virtual Reality. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 58, 2018, pp. 228–241. https://doi.org/10.1016/j.trf.2018.06.020.

48. Duffy, V. G., P. P. W. Ng, and A. Ramakrishnan. Impact of a Simulated Accident in Virtual Training on Decision-Making Performance. *International Journal of Industrial Ergonomics*, Vol. 34, No. 4, 2004, pp. 335–348. https://doi.org/10.1016/j.ergon.2004.04.012.
49. Hafsia, M., E. Monacelli, and H. Martin. Virtual Reality Simulator for Construction Workers. 2018.
50. Blaauwgeers, E., L. Dubois, and L. Ryckaert. Real-Time Risk Estimation for Better Situational Awareness. *IFAC Proceedings Volumes*, Vol. 46, No. 15, 2013, pp. 232–239.
51. Curry, D. G., R. D. Quinn, D. R. Atkins, and T. C. Carlson. Injuries & the Experienced Worker. *Professional Safety*, Vol. 49, No. 9, 2004, pp. 30–34.
52. Burke, M. J., M. L. Scheuer, and R. J. Meredith. A Dialogical Approach to Skill Development: The Case of Safety Skills. *Human Resource Management Review*, Vol. 17, No. 2, 2007, pp. 235–250. https://doi.org/10.1016/j.hrmr.2007.04.004.
53. Carstensen, L. L. The Influence of a Sense of Time on Human Development. *Science*, Vol. 312, No. 5782, 2006, pp. 1913–1915.
54. Bhandari, S., M. R. Hallowell, and J. Correll. Making Construction Safety Training Interesting: A Field-Based Quasi-Experiment to Test the Relationship between Emotional Arousal and Situational Interest among Adult Learners. *Safety Science*, Vol. 117, 2019, pp. 58–70. https://doi.org/10.1016/j.ssci.2019.03.028.
55. Kim, N., B. A. Anderson, and C. R. Ahn. Reducing Risk Habituation to Struck-By Hazards in a Road Construction Environment Using Virtual Reality Behavioral Intervention. *Journal of Construction Engineering and Management*, Vol. 147, No. 11, 2021, p. 04021157. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002187.
56. Jeelani, I., K. Han, and A. Albert. Development of Immersive Personalized Training Environment for Construction Workers. In *Computing in Civil Engineering 2017*, pp. 407–415.
57. Sacks, R., A. Perlman, and R. Barak. Construction Safety Training Using Immersive Virtual Reality. *Construction Management and Economics*, Vol. 31, No. 9, 2013, pp. 1005–1017.
58. Vance, A., B. Kirwan, D. Bjornn, J. Jenkins, and B. B. Anderson. What Do We Really Know about How Habituation to Warnings Occurs Over Time? A Longitudinal FMRI Study of Habituation and Polymorphic Warnings. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, Association for Computing Machinery, New York, NY, USA, pp. 2215–2227.
59. Andujar, C., and P. Brunet. A Critical Analysis of Human-Subject Experiments in Virtual Reality and 3D User Interfaces. In *Virtual realities*, Springer, pp. 79–90.
60. Jones, S. R. Was There a Hawthorne Effect? *American Journal of sociology*, Vol. 98, No. 3, 1992, pp. 451–468.
61. Skinner, B. F. The Shame of American Education. *American Psychologist*, Vol. 39, No. 9, 1984, p. 947.
62. Maxwell, S., K. J. Reynolds, E. Lee, E. Subasic, and D. Bromhead. The Impact of School Climate and School Identification on Academic Achievement: Multilevel Modeling with Student and Teacher Data. *Frontiers in psychology*, Vol. 8, 2017, p. 2069.
63. Peugh, J. L. A Practical Guide to Multilevel Modeling. *Journal of school psychology*, Vol. 48, No. 1, 2010, pp. 85–112.
64. Volpert-Esmond, H. I., E. C. Merkle, M. P. Levsen, T. A. Ito, and B. D. Bartholow. Using Trial-level Data and Multilevel Modeling to Investigate Within-task Change in Event-related Potentials. *Psychophysiology*, Vol. 55, No. 5, 2018, p. e13044.

65. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*. Academic press, 2013.