Using a Virtual Reality-based Experiment Environment to Examine Risk Habituation in Construction Safety

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Abstract –

A majority of safety accidents in construction workplaces stem from workers' unsafe behaviors. Such unsafe behaviors are often caused by "risk habituation," the tendency to underestimate a risk after previous repeated exposure to similar hazardous situations. Understanding the risk habituation process in construction is critical for intervening and preventing the unsafe behaviors that it causes, but the approaches adopted in previous studies, which are retrospective and self-evaluative, pose challenges to gaining an unbiased understanding of the factors affecting this habituation process. In this context, this study exploits virtual reality (VR) as an experimental tool to examine the risk habituation process in construction and demonstrates the validity of the approach. A VR model that engages a subject in a road reconstruction project is designed and developed, and then is used to repeatedly expose subjects to struck-by hazards and warning signals for such hazards. The results from the pilot experiment indicate that the developed VR model is effective in replicating and accelerating the risk habituation process, thereby allowing researchers to more expeditiously study the factors influencing risk habituation process.

Keywords –

Construction safety; Risk habituation; Virtual reality; Unsafe behavior; Safety training

1 Introduction

"Habituation" is the decline of a response to a repetitive stimulus [1]. Similarly, the capability of a stimulus to elicit a response can be diminished when the stimulus occurs repeatedly [2]. Such habituation can result in workers being less cautious about stimuli associated with hazards in workplaces when the stimuli present, and therefore to workers engaging in unsafe behaviors [3]. This problem is relevant to the construction industry, where workers have been found to be prone to becoming habituated to hazards after exposure to repeated hazardous situations [4] at construction sites. Workers who are habituated to hazards tend to underestimate risks and put themselves at jeopardy of being in an accident [5]. This behavioral phenomenon is called "risk habituation" [6], and is considered one of the main causes of workers' unsafe behavior. Many researchers and practitioners are dedicated to understanding why and how workers underestimate risk and engage in unsafe behaviors, but previous studies have mostly relied on the capability of subjects to recall when they were in hazardous situations. Consequently, the results can be biased and cannot clearly explain the developmental process of risk habituation [7–11]. Furthermore, it is extremely difficult to control moderating and influencing factors in risk habituation in field experiments, due to their potential to harm subjects [12]. In this context, this study aims to design and evaluate the validity of a virtual reality (VR) model as an experimental tool to examine an individual worker's risk habituation process.

2 Background

Around 80–90% of all workplace accidents are caused by workers' unsafe behavior [9,13,14]. Previous studies have shown that an individual's risk perception significantly affects his/her unsafe behaviors at construction sites. Repeated exposure to hazards in the workplace can cause a bias to form in workers' risk perception [15]. Even if workers properly identify hazards, they may engage in risky behavior due to improper perception and evaluation of risk [16]. Irizarry and Abraham [17] examined the factors influencing the risk perception of ironworkers, and their results indicate that long tenure in working experience at workplaces is correlated with unsafe behavior caused by bias in workers' risk perception. Majekodunmi and Farrow [4] investigated the risk perception of lift truck operators. Their results indicate that repeated exposures cause workers to become accustomed to the hazards related to their tasks. While these studies indicate that risk

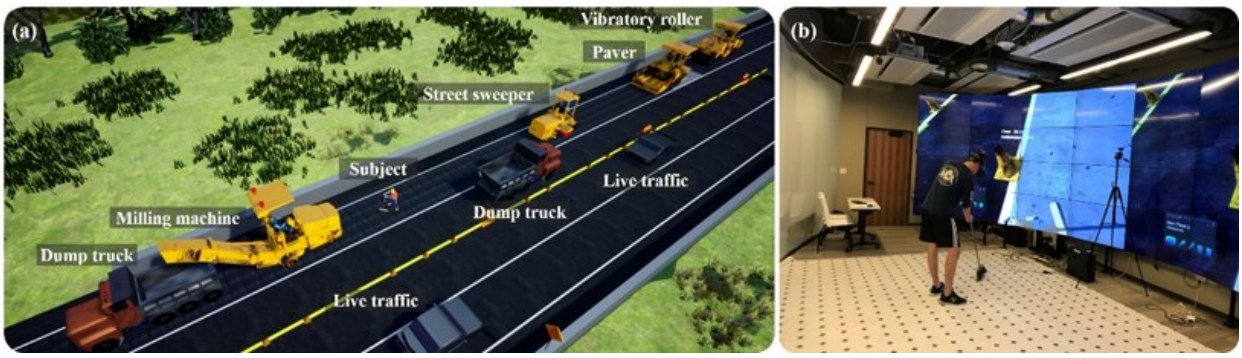

Figure 1. Experimental environment: (a) the landscape of the immersive virtual road construction environment, (b) the Building Information Modeling-Computer Aided Virtual Environment (BIM-CAVE)

habituation is one of the factors causing unsafe behaviors, a knowledge gap still exists as to which specific personal and situational factors critically influence the development process of risk habituation and how this development process can be intervened in, due to the methodological limitations of the approaches adopted in the previous studies, which were uniformly retrospective and self-evaluative.

With the recent development of virtual reality (VR) technologies, VR has emerged as an experimental tool for examining workers' unsafe behaviors. VR-based safety interventions in previous studies have enabled researchers to expose subjects to virtually replicated hazardous situations without any actual risk. Albert et al. [18] showed that as a safety intervention platform, VR can provide close-to-reality simulations. Thus, workers can evaluate the risks of hazard very similarly in the VR environment as in a real environment. Moreover, VR enables researchers to analyze workers' behaviors in near real-time. Many researchers have therefore utilized VR to investigate construction workers' behavior in dangerous situations. For instance, Hasanzadeh et al. [19] attempted to observe a roofer's risk-taking behavior in the virtual environment (VE) and demonstrated that a group of roofers with more safety protection took more risks than other groups in the VE. Shi et al. [20] utilized a VR model as an experimental tool in order to show the effect of accident experiences on workers' fall risk behavior. To this end, this study exploits VR as an experimental tool to address uncertainty in construction workers' risk habituation processes. An immersive VE for road construction is developed to expose workers to repetitive hazardous situations. Leveraging data acquired from subjects' physical responses to hazards in the VE, this paper demonstrates the approach's validity as an experimental tool to examine an individual worker's risk habituation.

3 Methodology

The objective of this study has been accomplished in three phases. An immersive virtual road construction environment was built and a cyber-physical interactive system that synchronizes the actual movement of a subject with a virtual movement in the VE was developed. A pilot experiment was then conducted to observe and evaluate how the risk habituation process in the VE develops. The data from the pilot experiment was analyzed to identify the relationship between repeated exposures to hazards and subjects' responses to repetitive hazards in the VE.

3.1 Designing the Scenario

A road maintenance workplace in which subjects would be part of an asphalt milling crew was selected for the VE development scenario (Figure 1-a), as such a scenario is high-risk and likely to cause risk habituation in the VE. Road construction and maintenance work repeatedly exposes workers to struck-by hazards such as working adjacent to live traffic and heavy construction equipment; 532 workers were killed at road construction work zones between 2011 and 2016 in the United States [21]. The proposed VR model focuses specifically on the construction equipment risk, with a subject at risk of being struck by a dump truck, street sweeper, or other piece of heavy construction machinery.

A normal asphalt removing, and paving work process was modeled in the VE. As the first step of the process, a milling machine removes the surface asphalt of a highway and loads the millings onto a fleet of dump trucks to haul off-site. As part of the cleaning crew, a subject then follows closely behind the milling machine and carefully sweeps the surface to remove debris. Behind the subject, a street sweeper moves back and forth

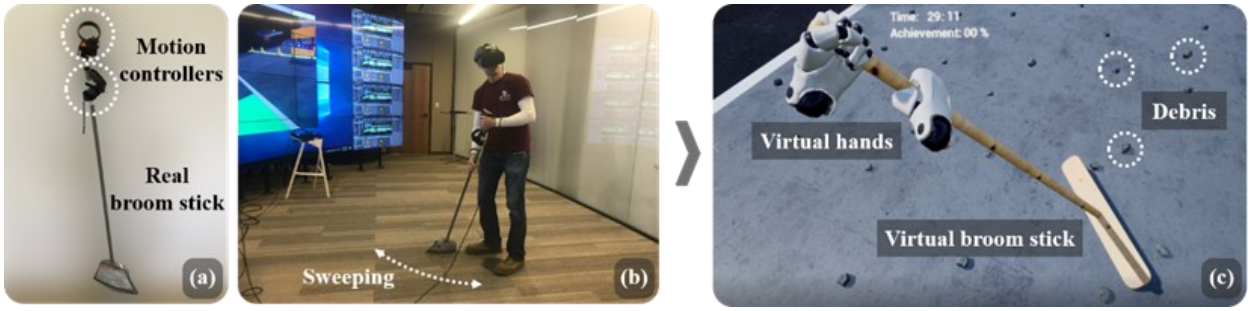

Figure 2. Cyber-physical interactive system for hand-movement synchronization; (a) Motion controllers on real the broomstick, (b) sweeping in the real world, (c) debris on the surface in the VE

continuously. After that, the paver will lay down asphalt, and a vibratory roller will move forward. Next to the lane where the asphalt maintenance takes place, a fleet of dump trucks intermittently moves to supply materials. Live commuter traffic takes place also within the construction work area. In this VE, the various pieces of road construction equipment (e.g., the milling machine, roller, and other machinery) expose each subject to the risk of a struck-by accident and allow researchers to observe subjects' responses to repeated hazards.

3.1.1 Immersive Virtual Road Construction Environment Modeling

Unreal Engine 4 (UE4) was adopted to develop an immersive virtual road construction environment. UE4 offers various project templates, allowing researchers to rapidly develop a VE. All models used in this study are drawn using Maya and 3dStudioMax. Then, all aspects of an immersive virtual environment were created using UE4 with a graphical user interface in order to induce risk habituation in subjects while working in close proximity to live traffic and heavy equipment in the VE.

3.1.2 Hazards and Non-Player Characters (NPC) Setup

Life-threatening hazards in highway construction sites (e.g., adjacent live traffic, heavy construction equipment, and a fleet of dump trucks moving near workers) were simulated in the VE. All the interactive components in the VE respond to behaviors of a subject. Behind a subject, the street sweeper moves back and forth at a constant speed. An alarm sounds as the street sweeper moves forward in order to notify its proximity to a subject. The movement of the sweeper is subject to the distance between a subject and the street sweeper, and repeatedly endangers a subject to struck-by accident. Next to the lane where the road maintenance takes place, dump trucks intermittently pass by very close to the subject, with accompanying warning alarms. These movement cycles of the sweeper and dump trucks will continue while the subject performs the task.

3.1.3 Cyber-physical Interactive System

The level of immersiveness in any VE plays a crucial role in VR-based safety training [22]. Feeling the VE as a real working environment is an important factor in VR-based safety training [23]. To achieve the necessary high level of immersiveness, a cyber-physical interactive system was applied. Motion controllers for a Head Mounted Display (HMD) were attached to a real broomstick (Figure 2-a), and the movements made by a subject sweeping in the real world is then linked to the broomstick in the VE (Figure 2-b). This physical interaction addresses the limitations of previous VR-based safety research that did not consider the influence of actual human body movements in a VE [8]. Moreover, in order to realize a high level of fidelity, around 1,000 pieces of debris were placed on the road in the VE. This debris is responsive to each subject's sweeping movements in the VE. The goal of the subject is to remove all debris and clean the entire surface of the road by sweeping with the broomstick (Figure 2-c).

3.2 Risk Habituation Measurement

In this study, habituation is defined as the decline of a subject's hazard-checking behavior and the increase of the number of deviations in the working lane. For the purpose of observing the risk habituation development process, this model monitors hazard-checking behaviors of a subject and documents the distance to the hazard when a subject undertakes a hazard-checking action as a precautionary action. Hazard-checking behaviors are defined as any movement the subject makes to look for hazards (Figure 3-a); the measurement system that detects subjects' hazard-checking behavior is validated by comparison with video recordings of the experiments. The system documents the distance between the subject and the sweeper when such checking behavior is sensed. In addition, the system records the movement trajectory of subjects in order to detect the moment when a subject deviates from the working lane, regardless of the risk of being struck by the truck. The analysis of the movement

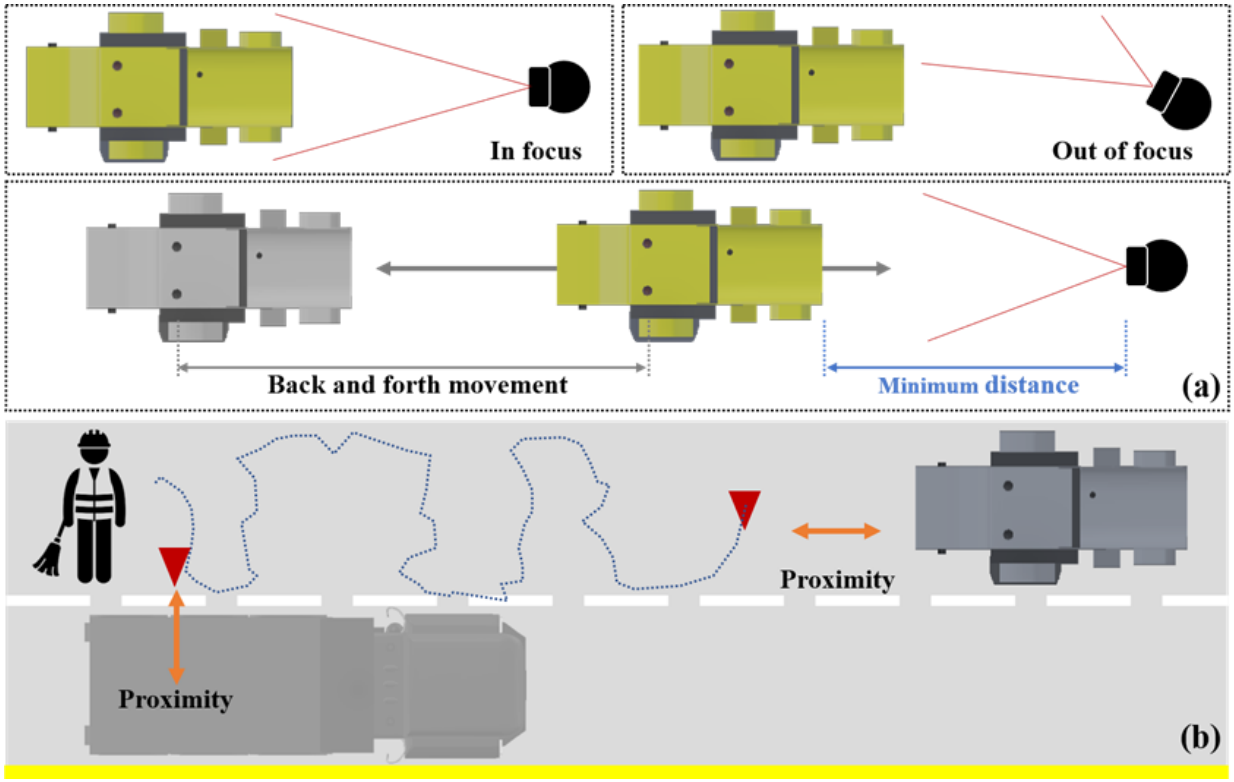

Figure 3. Unsafe behavior measurement system; (a) detecting the hazard-checking behavior, (b) recording the movement trajectory of a subject

trajectory allows researchers to identify when and how a subject becomes habituated to the risk of being struck by accident (Figure 3-b). The location of a subject is collected with a peak frequency of 30 Hz.

3.3 Pilot Experiment Conditions and Procedures

A pilot experiment was performed in the Building Information Modeling-Computer Aided Virtual Environment (BIM-CAVE) at Texas A&M University (Figure 1-b). Three subjects who are graduate students in the department of construction science were recruited for a pilot experiment; none of the subjects had any prior hands-on experience with road construction maintenance work. The following instructions were given: 1) the subjects should follow the milling machine, 2) the subjects should sweep away all the debris from the working lane, and 3) the subjects should pay attention to approaching equipment and warning signals for safety purposes. Completing the overall task in the VE took around 20 minutes, and once a subject ignored the hazards more than 10 times, the experiment was discontinued since this was perceived as a signal that the subject had become habituated to the risk in the VE. A follow-up interview on the perceived immersiveness of the environment was conducted after the experiment.

4 Results and Findings

By analyzing the data directly acquired from the subjects' hazard-checking behaviors, the process of subjects' risk habituation in the VE was observed. Figure 5 demonstrates a relationship between the number of cycles and checking distances of the respective subjects, and the distance between the sweeper and a subject at the moment when s/he undertook an action to check the approaching sweeper at each cycle. The dashed blue lines indicate the designed minimum distance between the sweeper and a subject. If the subject didn't check the sweeper's position until the minimum distance was reached, this was regarded as unsafe behavior. The data points marked with black in the graphs indicate subjects' unsafe behaviors. The highlighted parts of each graph represent the moment where the subjects' unsafe behaviors rapidly increased and give an opportunity to identify which subjects became accustomed to the hazard more quickly than the others. All distances were measured employing Unreal units, the default measure of length within the Unreal Engine environment; one Unreal unit equals one centimeter.

Table 1. Analysis of subjects' hazard checking behaviors in the VE

Subject #	Mean distance	F	p-value	Slope of the line	Correlation coefficient
Subject #1	984.356	10.106	0.003	- 10.023 ± 2.024	-0.459
Subject #2	939.512	32.628	< 0.001	- 14.345 ± 2.021	-0.670
Subject #3	1096.837	44.628	< 0.001	- 54.176± 2.074	-0.818

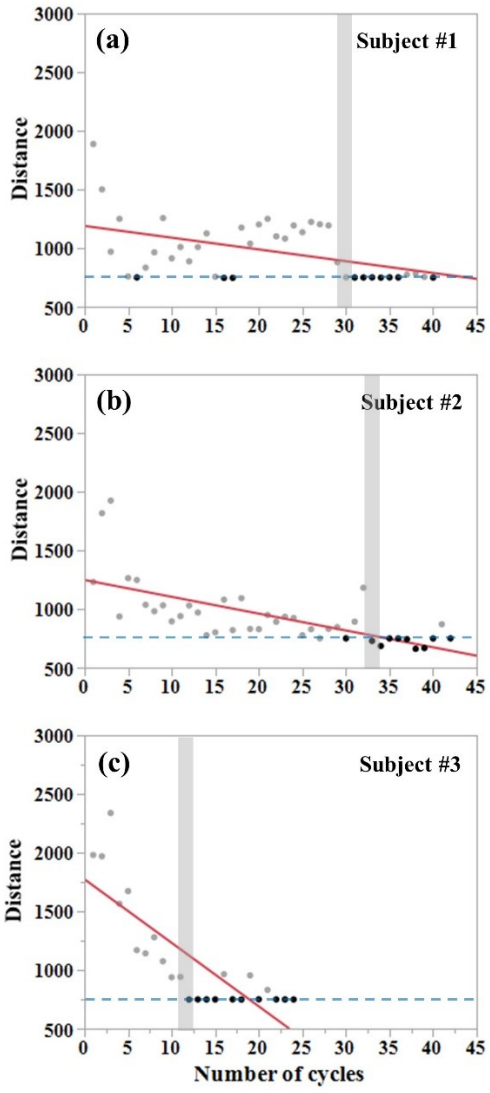

Figure 4. The distance to the street sweeper when subjects checked the proximity of the equipment

To measure the strength and direction of the linear relationship between two variables, the Pearson correlation coefficient, referred to as Pearson's r, was employed. Table 1 shows that there is a statistically significant correlation between checking distances and the number of exposures to the hazard. The checking distance and the number of exposures are moderately negatively correlated in the data from Subject #1 ($r(39) = -.46$, $p = .003$) and Subject #2 ($r(41) = -.67$, $p < .001$), and strongly negatively correlated in the data from Subject #3 ($r(22) = -.82$, $p < .001$). At the beginning of experiment, all subjects immediately responded to the warning sounds and looked back to check the source of warning alarm. However, as the number of cycles (i.e., the number of exposures to the hazard) increased, subjects responded more slowly, and the checking distances gradually decreased in all three subjects. The correlation coefficient and slope of the line of Subject #3 show the strongest negative linear relationship among three subjects. Subject #3 ignored the hazard 10 times out of 22 times. This indicates that Subject #3 became habituated to the hazard more quickly than other subjects (Figure 4). After the experiment, the subjects reported how they felt and why they ignored the hazard. Subjects answered that they no longer paid attention to the hazards and began to act dangerously from the moment when they focused on the completion of the task and started to This debris is responsive to each subject's sweeping movements in the VE believe the surrounding hazards would not hurt them. Interestingly, Subject #1 relayed that he totally ceased to hear the alarm sound of the sweeper when he felt time pressure and started to think about how to finish the task more quickly.

The movement trajectories of subjects were plotted (Figure 5) in order to examine how close the subject moved to the truck when the truck was passing by in the neighboring lane. The highlighted points are the moments where the subject crossed over the lane regardless of the risk of being hit by the truck. Subject #1 relayed the fact that although at the beginning of the experiment he had been thinking about the hazard related to trucks, he unconsciously crossed the lane to sweep debris on the road. This result showed that analyzing the movement trajectory can help in detecting unconscious unsafe behaviors of subjects in the VE. Although the sample size was small and further studies are necessary to confirm these findings, the results of the experiment indicate that repeated exposure to hazards in a VE can lead to subjects' risk habituation, highlighting the utility of VR as an experimental tool in examining safety behaviors.

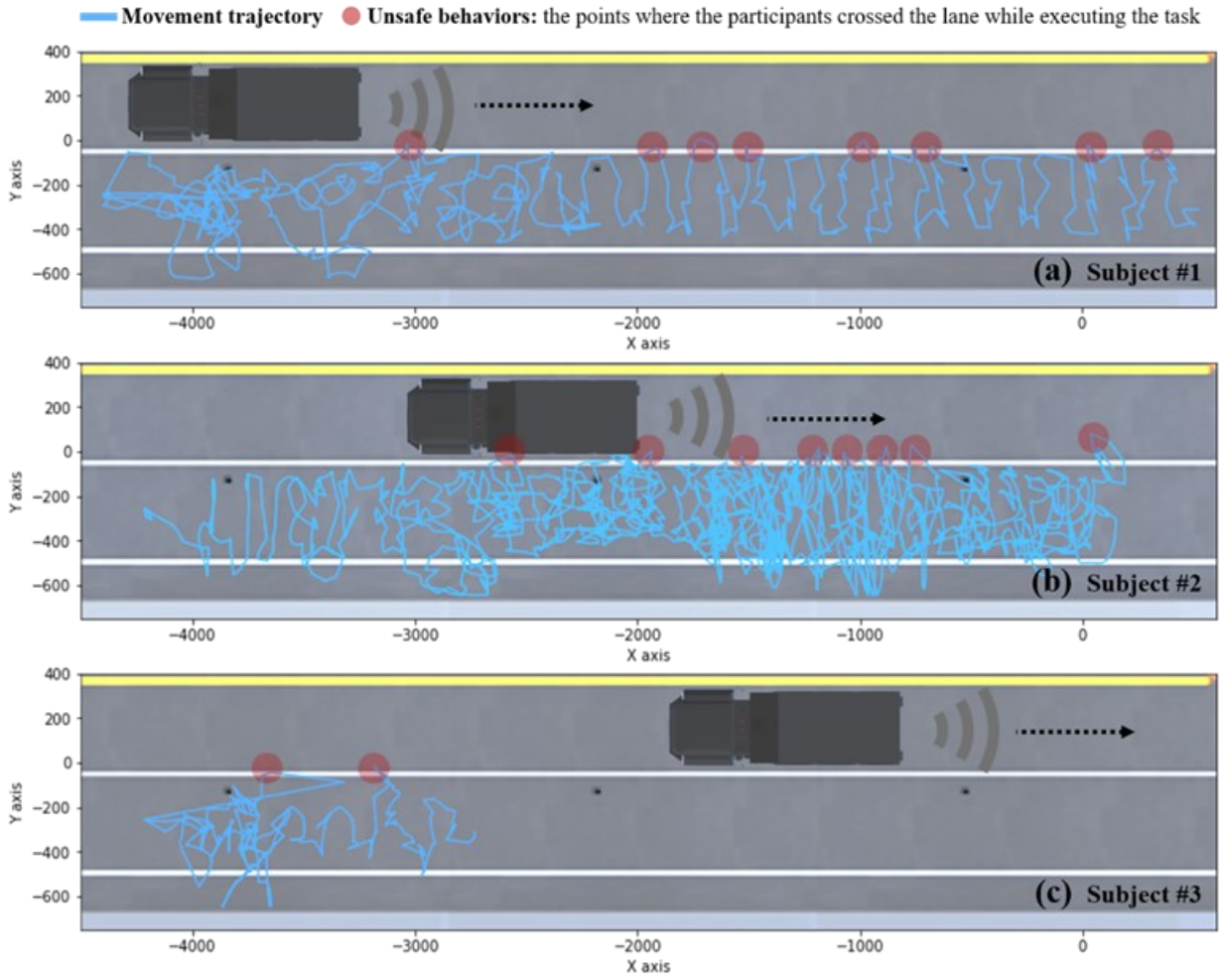

Figure 5. Movement trajectory analysis

5 Conclusion

The results of the experiment indicate that the designed VR model is capable of observing an individual's risk habituation process. Although there were individual differences, all subjects became habituated to repeated hazards in the virtual road construction environment. After a certain period of time, subjects began to ignore the proximity of the construction equipment behind of them and began to cross the lane in pursuit of finishing their cleaning task, regardless of the risk of being struck by the truck. This highlights the opportunities available in analyzing behavioral responses of construction workers to hazards in an immersive virtual construction environment. For example, a similar such VR model could provide a chance to investigate which personal factors (e.g., working experiences, injury experiences, and personalities) and situational factors (e.g., safety rules, the behavior of other personnel in working groups) affect workers' unsafe behavior in construction. Future work will also examine VR-based intervention mechanisms to prevent construction workers from becoming habituated to hazards and engaging in unsafe behaviors that might cause life-threatening accidents at construction sites.

References

[1] D. Bukatko, M.W. Daehler, Child development: A thematic approach, Nelson Education, 2012.

[2] A.R. Lebbon, S.O. Sigurdsson, Behavioral perspectives on variability in human behavior as part of process safety, J. Organ. Behav. Manag. 37 (2017) 261–282.

[3] K. Bogard, T.D. Ludwig, C. Staats, D. Kretschmer, An industry's call to understand the contingencies involved in process safety: Normalization of deviance, J. Organ. Behav. Manag. 35 (2015) 70–80.

[4] A. Majekodunmi, A. Farrow, Perceptions and Attitudes Toward Workplace Transport Risks: A Study of Industrial Lift Truck Operators in a London Authority, Arch. Environ. Occup. Health. 64 (2009) 251–260. https://doi.org/10.1080/19338240903348238.

[5] E. Blaauwgeers, L. Dubois, L. Ryckaert, Real-time risk estimation for better situational awareness, IFAC Proc. Vol. 46 (2013) 232–239. https://doi.org/10.3182/20130811-5-US-2037.00036.

[6] P. Slovic, Perception of risk, Science. 236 (1987) 280–285. https://doi.org/10.1126/science.3563507.

[7] J. Bohm, D. Harris, Risk Perception and Risk-Taking Behavior of Construction Site Dumper Drivers, Int. J. Occup. Saf. Ergon. 16 (2010) 55–67. https://doi.org/10.1080/10803548.2010.11076829.

[8] C. de-Juan-Ripoll, J.L. Soler-Domínguez, J. Guixeres, M. Contero, N. Álvarez Gutiérrez, M. Alcañiz, Virtual Reality as a New Approach for Risk Taking Assessment, Front. Psychol. 9 (2018). https://doi.org/10.3389/fpsyg.2018.02532.

[9] M. Hallowell, Safety risk perception in construction companies in the Pacific Northwest of the USA, Constr. Manag. Econ. 28 (2010) 403–413. https://doi.org/10.1080/01446191003587752.

[10] M. Kreyenfeld, S. Bastin, Blurred Memory, Deliberate Misreporting, or "True Tales"? How Different Survey Methods Affect Respondents' Reports of Partnership Status at First Birth, (2013) 36.

[11] Sun Cenfei, Ahn Changbum Ryan, Bae Junseo, Johnson Matthew, Monitoring Changes in Gait Adaptation to Identify Construction Workers? Risk Preparedness after Multiple Exposures to a Hazard, Constr. Res. Congr. 2018. (n.d.) 221–230. https://doi.org/10.1061/9780784481288.022.

[12] J.R. Bartels, D.H. Ambrose, S. Gallagher, Analyzing Factors Influencing Struck-By Accidents of a Moving Mining Machine by using Motion Capture and DHM Simulations, SAE Int. J. Passeng. Cars - Electron. Electr. Syst. 1 (2008) 599–604. https://doi.org/10.4271/2008-01-1911.

[13] HSE (Health and Safety Executive), Strategies to promote safe behavior as part of a health and safety management system, (2002).

[14] K. Yang, C.R. Ahn, M.C. Vuran, H. Kim, Collective sensing of workers' gait patterns to identify fall hazards in construction, Autom. Constr. 82 (2017) 166–178. https://doi.org/10.1016/j.autcon.2017.04.010.

[15] J. Inouye, Risk perception: Theories, strategies, and next steps, Itasca IL Campbell Inst. Natl. Saf. Counc. (2014).

[16] Tixier Antoine J.-P., Hallowell Matthew R., Albert Alex, van Boven Leaf, Kleiner Brian M., Psychological Antecedents of Risk-Taking Behavior in Construction, J. Constr. Eng. Manag. 140 (2014) 04014052. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000894.

[17] J. Irizarry, D.M. Abraham, Assessment of Risk Perception of Ironworkers, J. Constr. Res. 7 (2006) 111–132. https://doi.org/10.1142/S1609945106000499.

[18] Albert Alex, Hallowell Matthew R., Kleiner Brian, Chen Ao, Golparvar-Fard Mani, Enhancing Construction Hazard Recognition with High-Fidelity Augmented Virtuality, J. Constr. Eng. Manag. 140 (2014) 04014024. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000860.

[19] S. Hasanzadeh, Understanding Roofer's Risk Compensatory Behavior through Passive Haptics Mixed-Reality System, Comput. Civ. Eng. (2019) 9.

[20] Y. Shi, J. Du, C.R. Ahn, E. Ragan, Impact assessment of reinforced learning methods on construction workers' fall risk behavior using virtual reality, Autom. Constr. 104 (2019) 197–214. https://doi.org/10.1016/j.autcon.2019.04.015.

[21] Bureau of Labor Statistics, Fatal occupational injuries by selected characterisitics, (2017).

[22] I. Jeelani, K. Han, A. Albert, Development of Immersive Personalized Training Environment for Construction Workers, in: Comput. Civ. Eng. 2017, American Society of Civil Engineers, Seattle, Washington, 2017: pp. 407–415. https://doi.org/10.1061/9780784480830.050.

[23] R. Sacks, A. Perlman, R. Barak, Construction safety training using immersive virtual reality, Constr. Manag. Econ. 31 (2013) 1005–1017. https://doi.org/10.1080/01446193.2013.828844.