An Integrated Approach to Capture Construction Workers' Response towards Safety Alarms using Wearable Sensors and Virtual Reality

Zhengbo Zou, Suzana Duran Bernardes, Abdullah Kurkcu, Semiha Ergan, Kaan Ozbay
New York University, USA
zz1658@nyu.edu

Abstract. Despite the continuous efforts from federal and state agencies to improve safety at traffic work zones, incidents continue to occur, resulting in 675 fatalities in the U.S. during the last decade. Current safety measures at work zones, such as visual and audible alarms are ineffective due to the lack of calibration studies to evaluate the attention span of workers towards alarms, given variances in the alarm modality, frequency and duration. This study proposes an integrated approach combining virtual reality (VR) and wearable sensors to capture data regarding workers' behaviors towards safety alarms when workers are exposed to simulated dangerous situations in VR. This dataset is needed to understand the relationships between workers' responses (i.e., react or dismiss) and the characteristics of the received alarms (i.e., modality, frequency, and duration). The proposed approach was implemented on an urban intersection from a real-world work zone in New York City for user studies.

1. Introduction

According to Occupational Safety and Health Administration (OSHA), an average of three construction workers died every day in the U.S. during 2013-2018 (OSHA 2018). A recent study that comprehensively reviewed the current safety measures in roadway work zones shows that a significant amount of the fatalities and injuries occur at traffic work zones, when workers come into contact with construction equipment or passing by vehicles (Yang et al. 2014). The Federal Highway Administration (FHWA) revealed that 50% of crashes occur within or adjacent to work zones during construction, putting workers in danger together with drivers (FHWA 2010). The majority of literature on work zone safety focused on driver behavior (Yang et al. 2013; Debnath et al. 2015; Ravani et al. 2015), where speed, aggressive behavior towards workers, distraction, and substance use were identified as factors contributing to work zone incidents. However, work zone safety studies have yet to be coupled with the behavior analysis of construction workers.

Currently, proactive warning approaches implemented at work zones include blinking lights with audible alarms, detection of vehicles crossing a predetermined perimeter, drone radars, and traffic cones with sound alerts (Theiss et al. 2017; TxDOT 2002). One of the major impediments in wide real-world deployment of such technologies is the false and frequent alarms that cause workers to disregard them. Another limitation is the lack of knowledge on the systematic assessment of different modalities of pushing alarms (e.g., vibration, audio, visual) along with the alarm frequency and duration to understand their effectiveness on workers. Hence, this study aims to improve the work zone safety in horizontal construction projects by examining the issues from the workers' perspective and assessing workers' behaviors towards alarms with the aim to calibrate the duration and frequency of alarms as well as determining an effective medium to push these alarms.

With the development of wearable technologies, an increasing number of research studies have been exploring the feasibility of using wearable sensors to push alarms to construction workers (Awolusi et al. 2018; Choi et al. 2017). The advancement of VR enabled researchers to simulate potentially dangerous situations (e.g., speeding vehicles) in work zones without putting workers in harm. Therefore, the combination of VR and wearable sensors provides an opportunity for researchers to study the optimal alarm delivery system with regard to alarm modality, frequency, and duration. This paper proposes an integrated approach utilizing VR and wearable sensors to determine when, how, and at what frequency to push alarms to workers at work zones based on the physiological states of workers collected from the wearable sensors and workers' behavior towards the alarms when they are in dangerous situations in VR. The approach is composed of four steps as: (1) recreating real-world work zones in VR, (2) enabling interactions in VR for construction activities, (3) conducting traffic simulation to obtain realistic traffic patterns near work zones and embedding vehicle movements in VR, and (4) developing a smartwatch application to send safety alarms and monitoring workers' responses as well as their physiological states using wearable sensors.

The sensors used in this study include a smartwatch to receive safety alarms, and a photoplethysmogram (PPG) sensor to monitor workers' heart-rate variability when encountering a dangerous situation in VR and when alarms arrive. Three scenarios based on real incidents were identified as more likely to lead to work zone incidents, including (1) setting up barriers to define a work zone perimeter that is close to an urban intersection (McIntosh 2019); (2) striping/marking a road on an urban highway (Fox and Cook 2018); and (3) installation of traffic sensors on the side of an urban highway (Yang et al. 2014). In this paper, the approach was implemented on an urban intersection VR environment based on a real-world work zone in New York City based on scenario one. The proposed approach fills the gap of quantitative and systematic assessment of different characteristics of alarms (i.e., modality, frequency, and duration) to improve work zone safety.

2. Background

This study builds on the previous research in (1) the current safety measures implemented at work zones to prevent incidents, (2) the feasibility of monitoring human behaviors in VR using wearable sensors, and (3) methods for conducting microscopic traffic simulations.

2.1. Current safety measures at work zones

Safety measures adopted at work zones vary according to the work zone complexity, which depends on the duration of the construction activity. Long-term (i.e., more than 3 consecutives days) and intermediate-term (i.e., more than a daylight period and no more than 3 consecutive days, or more than an hour during night-time) work zones are usually well planned and structured, while short-term (i.e., more than an hour but not more than a daylight period) and mobile (i.e., up to an hour and moves intermittently) work zones have fewer safety guidelines (Pigman et al. 2006). Short-term and mobile work zones are more prone to incidents, and workers conducting tasks out of a secure perimeter have a higher risk of being struck by upcoming traffic (Wong et al. 2011).

The most prevalent work zone safety measures aim to raise drivers' attention around work zones. Such measures include but are not limited to, (1) speed control measures, such as fixed and variable message signs, police enforcement, speed display trailer, and (2) channelizing devices, such as cones, drums, and barricades, flashing arrow panels, Portable Concrete Safety Shape Barrier (PCBs), and high-visibility worker's apparel (Zhang and Gambatese 2017). A noteworthy emerging safety measure is the use of wireless warning systems using sound to either alert drivers to reduce speed due to the presence of a work zone or workers on-foot ahead (Qiao et al. 2016), and/or to alert workers of construction equipment (Park et al. 2016) or vehicle intrusion (Yang et al. 2014). Another area of improvement aims to integrate warning systems for work zones with Connected and Automated Vehicles (CAVs) (e.g., Ozbay et al. 2018). Previous studies showed that infrastructure and wearable work zone communication solutions can be integrated into CAVs to identify dangerous situations and alert drivers and workers. However, the application of CAVs technology is still in its infancy and requires time for wider deployment.

Contradictory findings exist in the literature regarding the impact of traffic control devices on the frequency and severity of crashes in work zones, with studies supporting the use of traffic control devices to reduce the frequency of crashes (e.g., Koilada et al. 2019) and studies that indicate the opposite (e.g., Meng and Weng 2011). Such contradictory findings reveal the need for investigating the existing and emerging safety measures further.

2.2. Feasibility of monitoring human behaviors and bodily states in VR using wearable sensors

With the advances in ubiquitous sensing and computing, it became easier to collect various types of physiological data on workers' bodily responses, health status, fatigue levels, and active/idle status. Wearable sensors such as smartwatches, wristbands, smart glasses are easy to deploy even in harsh construction environments (Hwang and Lee 2017). Various metrics have been proposed to understand the implications of human emotional and physiological states. Commonly used metrics include heart rate, muscle movement, and blood pressure to measure human experiences such as stress, pain, and anxiety (Parsons et al. 1998). Wearable sensing devices enabled researchers to measure and monitor such metrics and to relate those metrics to the events and stimuli presented to the subjects. PPG sensors were especially sought after in previous studies in the area of worker safety due to their ability to monitor elevated/reduced worker stress through heart-rate variability (HRV) (Jebelli et al. 2018). HRV is an indicator of the bodily response triggered by a stimulus (e.g., an alarm received on the wrist), which can be used to capture construction workers' physiological states in dangerous situations (Hwang and Lee, 2017; Jebelli et al. 2018).

Due to the impracticality of creating job site hazards in real-world conditions, VR has been selected as a platform to evaluate worker safety on job sites. VR environments provide the flexibility to rapidly replicate and alter real-world conditions under controlled experiments. Previous studies confirmed that VR provides a high degree of realism for users (Du et al. 2018) and can be used to study user behaviors as in real-world experiences (Heydarian et al. 2015). The combination of VR and wearable sensors has also been validated from multiple previous studies focusing on design evaluation (Ergan et al. 2019), worker stress evaluation (Jebelli et al. 2018), and worker cognitive load under stressful environments (Shi et al. 2019).

2.3. Traffic simulation in work zone studies

The complexity of transportation systems and the difficulties in conducting real-world experiments make computer simulation an efficient tool for evaluating various traffic conditions. Microscopic traffic simulators are essential tools for describing traffic since they can model the interactions and dynamics between individual vehicles. These simulators have been commonly used for over 60 years now to analyze, evaluate, or test traffic management strategies, design changes or emerging smart transportation technologies representing traffic conditions in various locations from a couple of intersections to large city-wide networks (Lieberman 2014). Microscopic traffic simulators describe the behavior of every "driver-vehicle" unit that compose the traffic flow. The inputs for these simulators are dynamic variables such as aggregated traffic volume, turning movement counts, and travel time. The simulation output such as vehicle trajectories (position and speeds), traffic data collected from modelled detectors, travel time are used to analyze target scenarios quantitatively. In this paper, the open-source traffic simulator Simulation of Urban Mobility (SUMO) was used to get the traffic pattern of the roads scanned for each scenario.

Microscopic traffic simulation models have been thoroughly used in work zone studies for traffic risk assessment (Liu et al. 2019), effects of speed control devices and speed limit reduction on the traffic in work zones (Ye et al. 2018), and impact of the work zone presence in the traffic conditions (Bharadwaj et al. 2018). However, these studies have mainly focused on the effects of traffic on the work zone and vice versa but not on the interaction between traffic and workers. There is still a gap in the literature on the use of traffic simulation models to help understand the behavior of workers exposed to traffic in work zones.

This paper identified the potential for improving work zone safety by integrating studies of construction worker behavior using VR technology and wearable sensors with traffic simulation models. From the microscopic traffic model built with SUMO, information such as vehicle, speeds and traffic volume were integrated to the VR application to be used in different scenarios. The integration of the microscopic traffic model with VR guarantees that the application is as close to reality as possible, as the simulation model is calibrated using real field data. Therefore, the reactions and behavior of the participants of the experiments would be closer to those when they are exposed to real-world traffic.

3. An Integrated Platform for Evaluating Workers' Behaviors and their Physiological States towards Safety Alarms

An integrated approach using VR and wearable sensors is proposed to study workers' behavior towards safety alarms they receive in variant modality, frequency and duration. The approach is composed of four steps as: (1) recreating real-world work zones in VR, (2) enabling interactions in VR for construction activities, (3) conducting a calibrated microscopic traffic simulation to obtain realistic traffic patterns near work zones and embedding vehicle movements with potential dangerous situations in VR, and (4) developing a smartwatch application to send safety alarms to monitor workers' responses as well as their physiological states using wearable sensors. In this study, dangerous situations are simulated to be caused by vehicles passing a virtual work zone. A dangerous situation can be caused by either a vehicle speeding or a vehicle invading the perimeter of a work zone, which corresponds to either speeding or collision alarms.

3.1. Reconstruct work zones in VR

This step includes using a laser scanner to capture 3D point clouds of real-world work zones and then recreate 3D models of the work zone in VR. The process of "scan to VR" has been an active research topic in the Architecture, Engineering and Construction (AEC) domain due to the increasing availability of high-resolution scanners and VR headsets. Furthermore, laser scanners provide a fast and accurate way of creating a digital representation of the real-world work zones, hence eliminating the need of a surveyor physically taking measurements of work zones repeatedly. However, there has not been a standard "best-practice" of "scan to VR" that is widely accepted. Two types of methods have been proposed, with the first being "scan-mesh-VR" and the second being "scan-measurements-VR" (Yang et al. 2011), as shown in Figure 1.

"Scan-mesh-VR" takes the scanned point cloud as an input to generate 3D mesh objects. Next, the mesh objects can be exported as common geometrical representation file formats such as .obj or .fbx files and later be imported to game engines where the objects can be modeled from the mesh or used as is. This method promises an automated approach, where no intervention from the modeler is needed. However, in practice, even with the state-of-the-art mesh generating algorithms, the process of scan to mesh does not produce realistic results when the point cloud is not dense enough to form a consistent surface (Chen et al. 2017). On the other hand, "scan-measurements-VR" requires manual efforts. First, measurements of the object of interest (OOI) should be taken (e.g., the width of a street). Given enough measurements of the

OOI, a modeler can use those measurements to recreate 3D objects in a game engine. This method suffers from long implementation time due to the extensive manual efforts from the modeler to take measurements, but it can be more accurate as compared to "scan-mesh-VR" because the measuring points are cherry-picked by the modeler. However, depending on the application domain and its needs, either method could be used.

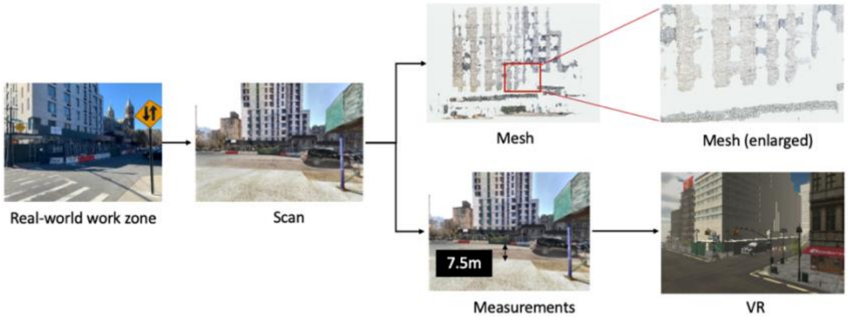

Figure 1. Scan-mesh and scan-measurement-VR process.

In this study, we used the "scan-measurements-VR" approach, where we relied on manual measurements of OOI to recreate the objects in a game engine. The OOI in this implementation is the road where the work zone is located. The width of the road and the length of the block were measured and used as references in recreation of the work zone in the game engine. Models of general objects such as buildings, fences, and traffic signals can be found online with open licenses, hence do not need to be remodeled. We also ignored the exact locations of the smaller objects in the scene such as garbage can and trees and added them at sensible locations. Given the reconstruction of the work zone from the point cloud data, user interactions can be implemented in VR.

3.2. Enable user interactions for construction tasks in VR

VR is widely adopted in the AEC domain for the purpose of design visualization (Ergan et al. 2019), coordination (Du et al. 2018), education (Sampaio et al. 2010), and safety training (Shi et al. 2019). User interactions in these VR studies (i.e., how user control the avatar in VR and get feedbacks from the VR environment) vary based on the specific VR application. However, a consensus exists that natural and realistic VR interactions are more desired because higher level of realism of interaction has been associated with improved user experience and performance in VR (McMahan et al. 2016). The level of realism for interactions in VR can be measured by ***interaction fidelity***, which describes the degree of exactness with which real world actions are reproduced in VR (MaMahan et al. 2016). Interaction fidelity (Figure 2) checks if the user interactions include accurate kinematic and kinetic representations relayed to the VR environments. Kinematic representation describes how well a body motion in the real-world is reproduced in VR. For example, when the user physically turns, his/her field of view changes accordingly due the head movement. On the other hand, kinetic representation describes how well force implemented by the user in real-world is reproduced in VR. For example, grabbing/releasing the controller should correspond to grabbing and releasing objects in VR.

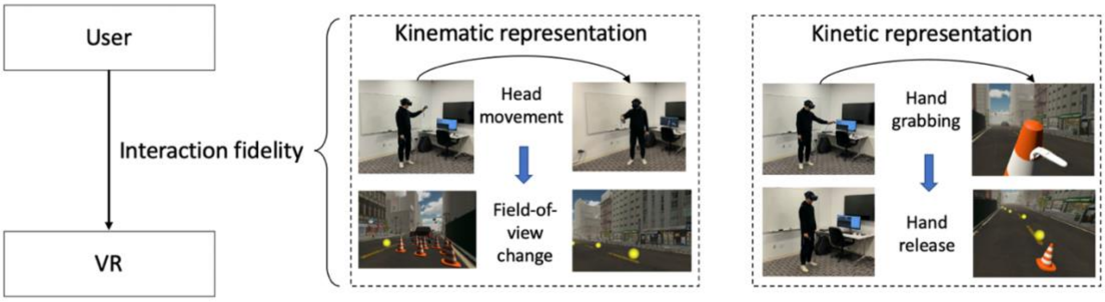

Figure 2. User interactions in VR measured by interaction fidelity.

In this study, worker head and hand movements are tracked and translated in the VR environment to enable worker position tracking and field-of-view change. Additionally, workers can grab the controller using either hand to trigger a grabbing motion in VR. The construction task in this study is setting up a perimeter for a mobile work zone at an urban intersection (Figure 3). Workers are expected to put six orange traffic cones unloaded from a truck (in a red circle in Figure 3) in pre-determined designated locations to finish setting up the perimeter of the work zone. This task was chosen based on previous studies' findings of mobile work zones without a structured perimeter having one of the highest incident rates (Wong et al. 2011). In VR, designated locations of the traffic cones are marked using blinking yellow spheres. Once a worker finished putting one traffic cone, the corresponding location will have a steady green sphere to notify the worker that the cone is in place. When all traffic cones are put in place, the worker will be notified for the completion of the assigned task. This task was customized to ensure that users can finish within an hour according to the institutional review board (IRB) requirements.

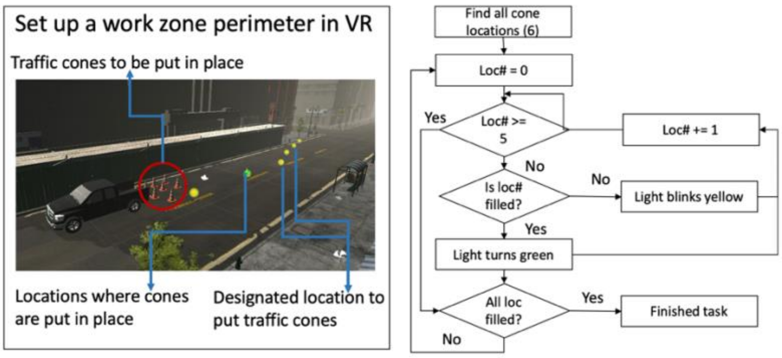

Figure 3. Enabling construction tasks as setting up work zone perimeters in VR.

3.3. Conduct traffic simulation to obtain realistic traffic patterns and embed vehicle movements in VR

Varying traffic patterns, such as increased demand during peak hours and vehicle trajectories containing vehicle positions and speeds in the vicinity of the real-world work zone, were simulated in the open-source micro simulator SUMO. The inputs of the simulation include (1) the network with its roads and intersections, (2) traffic demand, (3) vehicle types and their characteristics, and (4) vehicle routes. Traffic volume and turning movement counts during peak hours (6-10 a.m.) were manually collected at the study intersection and the simulation model was calibrated to represent these observed traffic parameters. The simulation network (an urban segment between two intersections) used in this study was calibrated to represent the observed volumes at the study location. The output of the traffic simulation includes vehicle ID, speed, acceleration, trajectory, and traffic volume.

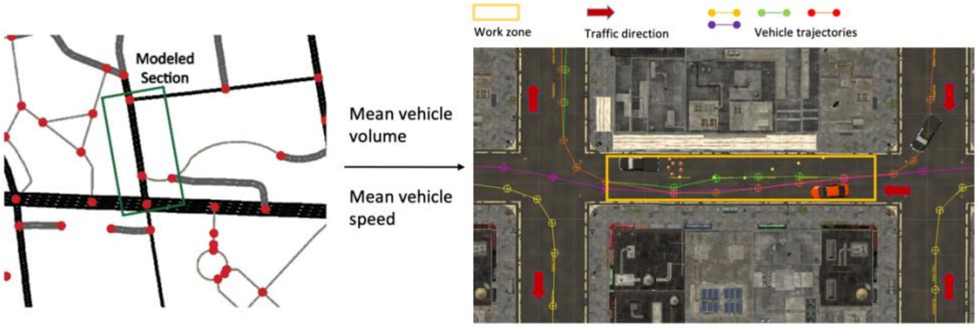

Figure 4. Traffic simulation outputs embedded in VR.

To realistically simulate traffic in the VR environment, the average vehicle speed and volume at the work zone location were calculated using the simulation outputs. By default, the VR work zone is a safe environment, where cars travel at the average speed in an average volume. The simulated dangerous situations were added purposefully, which can be divided into two categories: speeding and invasion of work zone perimeter. Work zones have a strict speed limit usually lower than the regular speed limit of the same road to protect workers. Speeding while passing by a work zone is especially dangerous due to lane changes and narrowed lanes. In this study, when a vehicle is traveling 20% faster than the average speed, it is recognized as a dangerous speeding situation. On the other hand, invasion of work zone perimeter leads to crashes in work zones and causes damages to the work zone structure as well as workers on site. Vehicle trajectories were defined using sets of nodes in VR. Vehicles travel from one node to the next to follow a trajectory. The locations of the nodes were hand-picked by the authors to reflect both safe and dangerous situations. When a vehicle travels on a trajectory that leads to invasion of the work zone perimeter, it is categorized as a dangerous situation.

3.4. Monitor worker behavior towards safety alarms using wearable sensors

This part of the integrated platform has two major components, including a cloud server which handles alarms originated from the VR application, and wearable sensors to receive alarms from the server and monitor workers' physiological states. To elaborate (as shown in Figure 5), the occurrence of a dangerous situation in VR triggers a safety alarm sent to a cloud server through an HTTP request (Figure 5a). The request contains information about the alarm, including alarm ID, type (e.g., speeding, collision), alarm sent time, and the vehicle ID that triggered the alarm.

On the cloud server side (Figure 5b), a queue of safety alarms is maintained containing the alarm information from the VR application. The newly arrived alarm will be added to the alarm queue while the oldest alarm currently in the queue being checked for time-out (i.e., exceeds the maximum time to respond to an alarm). If the alarm is not timed-out, the cloud server then sends the alarm to the smart watch equipped on the worker. The smart watch (Figure 5c) then uniformly draws from a pre-defined set of modalities (e.g., vibration, sound), frequencies (e.g., 3/20 seconds, 6/20 seconds), and durations (e.g., 3 seconds, 5 seconds). Next, the alarm will be delivered to the worker on the smart watch, and the worker can decide to read or dismiss the alarm. In the meantime, the workers' response (i.e., dismiss or read) towards the alarms are being monitored. Additionally, while the workers are performing the assigned tasks in VR, their HRVs are constantly monitored by a PPG sensor. HRV is used to infer the level of vigilance and stress of workers when they receive safety alarms of potentially dangerous situations.

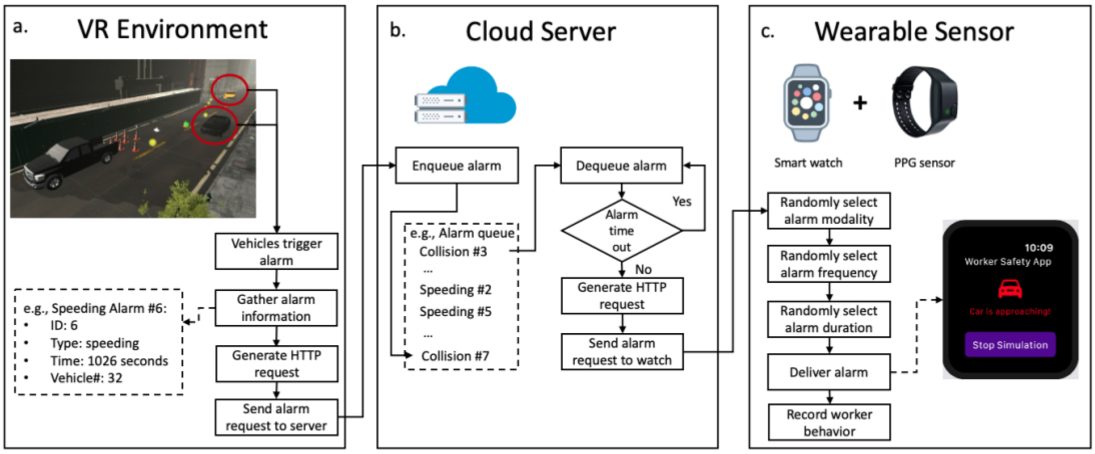

Figure 5. Alarm delivery mechanism from VR to wearable sensors on workers.

4. Conclusion and Future Work

This paper proposed an integrated approach to create a VR plus wearable sensor platform to study when and how to push safety alarms to construction workers at work zones based on their behaviors towards previous alarms. The data collected from the wearable sensors will be used to calibrate an alarm system to optimally deliver safety alarms for maximum worker attention. Towards this goal, within the context of this paper, we introduced the technical details of the system components and how they were integrated over a specific scenario implemented in VR. The content of this paper will extend the current line of research with VR by providing the technical guidance on integrating biometric sensors, traffic simulations, and interaction gadgets (e.g., smart watch) in VR platforms for interactive user studies.

The research team had secured an approval from the institution's IRB with the application number IRB-FY2020-3946 and had started initial alpha tests within the research group with five participants. The participants' response towards the alarms delivered in various modalities, frequencies and duration were monitored and analyzed. During initial testing, the alarms were delivered in two modalities, as vibration and visual alarm. Alarm frequency was set as either 3/20 seconds or 6/20 seconds, and the alarm duration was set as either 1 second or 3 seconds. The hypothesis of the initial testing is that the behaviors of the workers (i.e., read or dismiss) will be statistically significantly different when the alarms are sent in different modalities, frequencies, and durations with a significance level of 0.05. The hypothesis was tested using a paired t-test. From the t-test results, it is apparent that the participants were sensitive to (i.e., the participants' behavior towards the alarm being statistically significant) the alarm modality and frequency but not the duration. Further user tests will be conducted to validate the initial results with a larger subject pool.

The research team is continuing to recruit more participants with transportation work zone construction experience to test the proposed platform. The outcome of this study will (a) inform us whether data from wearables are meaningful to correlate with human responses to alarms and (b) provide a guidance to effectively integrate wearables to work practices at job sites and define a sequence of steps to follow to analyze the collected data. In the long run, as shown in (Xie et al. 2017), it is also possible to use other rich sources of real-world data in addition to the simulated data that is being collected in this study to further analyze safety impacts of different traffic work zones at the network level.

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