ABSTRACT
A multi-platform Virtual Reality (VR) approach is proposed to complement the traditional approaches for construction safety training.
Visual simulations of a highway construction project were developed and presented through the developed platforms, aiming at giving students immersive experience of actual construction environments. The simulated worksite scenarios included active traffic, multiple worker roles and heavy equipment, and was rendered at different times of day and weather conditions. We used this material in an undergraduate class activity with 50 students. During a session in our visualization lab, students experienced the scenarios presenting day shift, afternoon shift with adverse weather and night shift and were asked to develop daily report of their job site observation. The scenarios were presented via the following platforms: TV projection, Mobile Phone, Head-Mounted Display (HMD), and CAVE projection room. The results demonstrate that the multi-platform immersive experience has the potential to significantly improve hazard recognition skill of construction students.

CCS CONCEPTS
• Applied Computing → Education; • Human-Centered Design → Human Computer Interaction (HCI); Visualization.

KEYWORDS
Digitally-Enhanced Education, Immersive Training, Extensible 3D

1 INTRODUCTION
Each year, the construction industry spends approximately 15 billion dollars in direct costs associated with occupational injuries. The highway sector is the most dangerous sector in the construction industry. Highway workers have to work in close proximity to construction equipment as well as high-speed traffic, exposing them to an elevated risk of collision, which can lead to serious injuries/fatalities. Exposure of roadside workers to struck-by and caught-in-between hazards is a major safety issue faced by state departments of transportation (DOTs). The increasingly dynamic and complex construction working conditions require that construction workers and professionals acquire the safety-related knowledge they need to make safety-conscious decisions.

Many studies have identified the lack of proper safety knowledge and training of workers as the fundamental cause of these frequent incidents [Le et al. 2015; Mazlan et al. 2019; Park and Kim 2013]. Safety training has a direct impact on the prevention of construction accidents. Safety education is most effective when it is engaging and contextually relevant, and draws on learners’ experiences [Burke et al. 2007; Evanoff et al. 2016; Gilkey et al. 2003; Robson et al. 2010]. The construction worksite is dynamic, thus trainees need in-depth comprehension of complex construction information, on-site scenarios, and practical knowledge and experience. Conveying the complexity of a construction worksite is challenging in a conventional classroom setting using 2D media such as text, graphics, and videos. Such learning approach is passive with learners engaged at a very low level, and do not receive exposure to realistic worksite situations. Additionally, the current trainings are designed to train workers individually, thus the benefits of collective engagement in learning is largely ignored. VR enables active learning, learner to content interaction, abstract concept exploration [Sherman and Craig 2003; Wickens 1992; Winn and Jackson 1999], and authentic contexts and cognitive apprenticeship [Lo and Tsai 2022]. Learner interaction within meaningful contexts, for example, an active construction site, is a key capability of VR for learning with due consideration to situational context. Such learning approach influences not only what is learned [Tulving 1993], but also one’s ability to recall [Smith et al. 1978]. VR can be multi-user, but when using HMDs, the ability for users, e.g., trainers and trainees, to interact naturally is hindered by the device itself. Therefore, using VR HMDs cannot be easily integrated into the current setting of construction safety education, in which an instructor needs to teach a large group of trainees.

Our goal was to offer a group learning experience to senior construction students taking Construction Law and Contract Administration course and evaluate how the immersive experience can impact their hazard recognition ability. The course requires students to understand, recognize and avoid hazards in a worksite, so they can mitigate the identified risks and interpret their legal implications. Innovative content-based Virtual Reality (VR) scenarios were developed that enables a seamless learning experience for the construction students, taking into account the specific job environments they will be imposed to. Rather than a remote multi-user installation [Carlsson and Hagsand 1993; Ens et al. 2019], a co-located group experience was provided, benefiting from the Visionarium facility in the Advanced Research Computing Laboratory at Virginia Tech. The multi-user approach of the project made the content visible to a group of students, and enabled collective student engagement in recognizing hazardous situations while preserving the interactivity between instructors and students.

2 APPROACH
We developed an interactive daily report preparation assignment for Construction Law and Contract Administration class. The class Learning Objectives are to: 1) understand the legal context of construction operations, 2) distinguish between the parties to construction contracts and their relationships, 3) analyze and evaluate the language of construction contracts, and the associated risks, including differing site conditions, delays, disruptions, and acceleration, and 4) analyze professional decisions based on ethical principles and risks mitigation.

2.1 Development of VR Content
Scenario-based training in VR can help students immerse into highly realistic and detailed representations of actual highway work zones without risking their safety. VR-based content was created to simulate various scenarios of the hazardous situations that workers face in highway work zones. The VR content covered the safety knowledge that is directly or indirectly related to highway construction hazards. In addition, in order to create a realistic experience for the students, the training included spatial sound to accurately replicate the noisy environments faced in highway
worksites. Among the fatal four hazards identified by the Occupational Safety and Health Administration (OSHA)—falls, struck by objects, caught-in or caught-between and electrocutions—we focus on the "caught-in-between" and "struck-by" situations as they are more relevant to highway accidents. The struck-by hazards occur due to misplaced objects, loose or shifting materials, and vehicle or equipment strikes. Caught-in or caught-in-between hazards involve workers caught in or between machines, devices, or tools. Furthermore, various factors including the variety of background knowledge of the students were taken into account in developing appropriate content for the scenarios. This is essential as some trainees, e.g., construction students and novice workers, may not know or have direct experience in the highway environment and would need more progressive and detailed scenarios to grasp the required knowledge.

2.2 Development of Immersive VR Scenarios

We reviewed traditional training material and the common practices to identify the areas that could benefit from VR augmentation. The content was translated into scenarios that were simulated through VR. The power of VR in the context of safety training lies in its ability to allow showcasing hazardous situations that cannot be experienced safely in the real-world. In this experiment, the immersive media is used to assess students’ knowledge, skills, and abilities in an authentic context. A roadside worksite, is a spatial environment with various cues, including sound and multiple tasks in process concurrently: multiple pieces of heavy equipment, differing weather conditions, differing time conditions (daytime versus night), and vehicular traffic conditions. The scenarios included components that significantly influence safety and hazard recognition ability of students: day shifts with and without noisy environment, night shift, high-speed traffic, adverse weather, various worker roles—e.g., flagger, driller, etc. The scenarios also involved vehicle and worker movement, tools, equipment, and personal protective equipment, to represent struck-by and caught-in-between hazards.

Iterative design via script building and storyboarding was used to develop the components and actions required in each scenario. The activities are both pre-designed and designed on the fly by the instructor considering alignment with the envisioned learning objectives. Environment design of the scenarios included a combination of collecting data (e.g., noise) from real work sites and creating virtual work sites, characters, and equipment. Additionally, scripted actions of characters (workers in different roles, vehicle traffic, on-site heavy equipment) were programmed as part of the
environment design. Spatial audio is an important part of hazard recognition. Spatial sound was used to create a more immersive experience for the learners (e.g., jackhammering, equipment warning alarms). The scenario design involved required programming to allow the instructor to alter the scenario—change the time of day, change the number of pieces of equipment moving, load a different scenario, pause for feedback, etc.—as well as the artwork required to create a usable interface for both the instructor and the students.

The 3D scenes of the construction site were rendered from each viewpoint for each of the weather and time conditions. The render output to 360-degree equi-rectangular projection videos at 2K, 4K, and 8K resolution. The videos were 2.5 minutes each and looped. We created a REACT-driven X3D scene that included these videos mapped as video textures on the inside of sphere. The laptop, phone, and headset versions were delivered with the open source javascript library X3DOM. To deliver the scenes in our CAVE, we used InstantReality to render the scene.

3 EVALUATION

Fifty senior construction students participated in the experiment. Prior to this course, students had to take various fundamental courses related to site logistics, and construction means and methods. All students had also completed a safety course that includes OSHA 10-hour certification. All of the students in the course have had at least one summer internship experience in the construction industry and were familiar with construction environments. This course specifically focuses on legal applications of construction, and students learn to develop on-site documentation in the form of daily reports that can subsequently be used in arbitration, or in court if a legal issue arises. The accuracy and detail of daily reports as well as the responsibility of the competent field personnel completing the daily report was emphasized prior to the start of the assignment. In the assignment, the students were asked to experience at least two of the VR presentation platforms and prepare daily reports, including information about who is on-site, what they were doing, and what hazards, safety issues, or other conditions were observed throughout the day, using the VR scenarios.

Following this activity, an in-class discussion was conducted highlighting the fact that conditions and safety hazards change throughout the day and in different locations of the same job site. Even though the daily report is a single document, best practices suggest updating it to include all changes in weather conditions, as well as on-site crew and activities. This was enabled in the assignment through the option to view the site in fog, and at night with different or fewer crews working during those time frames.

4 RESULTS

From a teaching perspective, the opportunity to safely bring a large group of students to an ‘unsafe’ job site that they otherwise would have no opportunity to experience on a real field trips provided the greatest value of this experience. In traditional classroom setting, students are not provided with the opportunity to observe unsafe practices, and document them in an assignment. On the other hand, during field trips to job sites where the construction companies invite instructors to take their students to visit, there is no circumstance in which anyone allow students looking for, or documenting safety issues for a class activity for legal reasons. To further evaluate the learning outcomes of the experiment, the students were asked to fill out surveys commenting on their preference regarding different platforms and whether/how the immersive experience impacted their ability to detect hazards and complete daily reports. Based on this grading rubric, 50 percent of students (25 students out of 50) were able to recognize all requested information from the combination of content presented in different platforms. This result demonstrated 20 percent increase compared to similar site report assignments based on site visits and/or images.

The results also demonstrated that presentation of the same content in different platform helps students identify more issues than seeing them on site or only in one platform. This suggests a combinatorial approach may provide a better means for improving hazard recognition through VR simulation. 76 percent of students believed that this type of experiential training will better inform and prepare new trainees who do not have prior site experience for entering construction worksites. The ability to experience the site hazards first-hand and at their own speed, as well as the possibility to collaborate with peers and discuss different situations were recognized as the main advantages of such system compared to classroom-based learning and limited site visits. Additionally, the collaborative experiences provided through hypercube and stationary and mobile stations were deemed more engaging and helpful compared to solitary VR experience by students.

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