Revitalizing Students' Perception and Knowledge of Construction Safety: Leveraging Virtual Reality as an Experiential Learning Tool for Construction Robotic Safety Education

Amit Ojha, S.M.ASCE[1]; Shayan Shayesteh, S.M.ASCE[2]; Houtan Jebelli, Ph.D., A.M.ASCE[3]; Abiola Akanmu, Ph.D., A.M.ASCE[4]; Scarlett Miller, Ph.D.[5]; and Priya Sharma, Ph.D.[6]

[1]Dept. of Civil and Environmental Engineering, Univ. of Illinois Urbana-Champaign, Champaign, IL. Email: amito2@illinois.edu
[2]Dept. of Architectural Engineering, Pennsylvania State Univ., University Park, PA. Email: sks6495@psu.edu
[3]Dept. of Civil and Environmental Engineering, Univ. of Illinois Urbana-Champaign, Champaign, IL (corresponding author). Email: hjebelli@illinois.edu
[4]Myers-Lawson School of Construction, Virginia Tech, Blacksburg, VA. Email: abiola@vt.edu
[5]School of Engineering Design and Innovation, Pennsylvania State Univ., University Park, PA. Email: shm13@psu.edu
[6]Dept. of Learning and Performance Systems, Pennsylvania State Univ., University Park, PA. Email: psharma@psu.edu

ABSTRACT

Traditional lectures have difficulties instilling pragmatic skills in construction engineering students due to the inability to illuminate the complexities within the human-robot collaborative construction environment. While on-site can acclimatize construction students to reality and construct knowledge that can solve safety challenges, it is challenging to organize on-site training trips owing to the dangerous nature of construction workplaces. This research aimed to explore virtual reality (VR) as a tool to enhance students' perception and knowledge of construction robotic safety. For this purpose, the study developed a virtual training platform for providing construction engineering students with safety knowledge on interacting with simulated robots within the virtual environment of construction sites. A self-assessment approach was leveraged among 20 recruited students to demonstrate the efficacy of students' engagement and learning outcomes from the proposed learning approach over the traditional learning approach. Results indicated a statistical difference in students' learning outcomes and engagement levels between the developed approach and the traditional approach. Findings demonstrated the implications of VR as an experiential tool to enhance the students' learning of robotic safety in construction.

INTRODUCTION

The construction industry is a vital sector of the US economy, representing 4.1% of the country's gross domestic product (Musarat et al. 2021). Despite the economic importance, the construction industry has been struggling with a shortage of skilled labor for years, with no end in sight. The labor shortage has resulted in slower productivity and higher labor costs, which in turn, have led to higher construction costs (Karimi et al. 2018). Moreover, the industry's high injury and fatality rates, coupled with the intense physical demands of construction work, have made it difficult to attract younger workers (Karimi et al. 2018). With recent technological advancements, there has been a growing interest in exploring the use of robotic technologies to enhance diverse construction operations. Experts have predicted that around 81% of construction firms worldwide are planning to adopt robots into their construction operations within the next 20 years (de Vries et al. 2020). In this regard, nearly half of the construction-related tasks could potentially be automated in the coming decades (de Vries et al. 2020). As the construction industry moves towards embracing the use of robots, a shift in skills and abilities becomes evident, highlighting the need to prepare students and future engineers for highly technological work environments. In this regard, it is imperative for Construction Engineering and Management (CEM) programs to recognize and embrace technological change to equip their graduates with the necessary knowledge and competencies to safely work and collaborate with robots in the construction industry. However, the current construction curriculum falls short of equipping CEM students with the required set of multidisciplinary competencies to handle different mechanisms while working alongside construction robots. There is a glaring lack of an effective learning environment that provides a hands-on learning experience to develop the required competencies.

At an institutional level, teaching strategies in current construction curricula mainly rely on passive pedagogical methods, such as lecture-based sessions that use multimedia content. However, these methods are unable to provide an experiential learning experience, which can result in reduced skill retention (Scott 2016). Towards that end, hands-on learning can be an alternate option to help learners to assimilate practical competencies about safe human-robot collaboration (HRC) in construction operations (Kwon 2019; Le et al. 2015). Given that in-person training may not be feasible in many situations due to the safety risks, it may impose on the trainees, cost and equipment requirements, and disturbance of the work on-site, virtual reality (VR)-based training can be an effective method to provide students with hands-on learning experiences. VR-based learning can empower classroom equity by offering an optimal learning experience for students and institutions with limited or no access to actual construction robots.

Recent innovations in the field of immersive technologies have facilitated the widespread use of VR among institutions of higher education (Le et al. 2015). This availability has created opportunities for leveraging immersive technologies in academic settings to improve learning. Learning environments designed using immersive technologies are usually task-oriented with simulated scenarios that promote learning by doing through exploration in a virtual environment. Such an experiential understanding helps learners to assimilate practical knowledge in an optimal manner. In this regard, immersive virtual environments can be leveraged to avoid time-consuming and prohibitively expensive prototype building for imparting knowledge related to construction operations. Towards this end, the study aims to develop new safety training modules to enhance students' perception and knowledge of robotic safety knowledge during HRC in construction operations. As robots are getting popular in construction operations, the use of the safety training module will equip the students with pragmatic safety knowledge for working alongside these robots. This experiential understanding of the safety aspects of HRC will mold the students for the highly technological environments of the future. Considering the impending ubiquity of HRC in construction work, this project will address the urgent need to augment student learning of safety in HRC in the context of the construction operation.

IMPORTANCE OF ROBOTIC SAFETY KNOWLEDGE IN THE CONSTRUCTION SECTOR

In the construction industry, the implementation of robots has gained considerable attention as a means of relieving workers from dangerous, repetitive, and uncomfortable tasks in construction operations. The integration of robotic systems with the already dynamic and unstructured environment of construction sites poses several safety concerns for CEM professionals. These concerns range from collision risks to adverse physiological conditions (Liu et al. 2021). Additionally, robotic systems have yet to achieve the technical maturity necessary to operate independently in the field, which requires human supervision, intervention, and control (Liang et al. 2021). As HRC becomes more prevalent in the construction sector, it is crucial to develop knowledge of HRC in CEM education to address the ambiguities of interacting with robotic technologies. The absence of proper safety knowledge puts future workforce at risk of physical and mental stress and, consequently, can increase the risk of accidents during HRCs. Therefore, there is an urgent need to enhance students' understanding of safety in HRC within the context of construction operations. However, the current construction curricula are insufficient in providing CEM students with the requisite skills, knowledge, and competencies to interact with construction robots efficiently and safely. CEM professionals need to develop a general trust and a critical attitude towards technology while understanding the relations between processes, information flows, possible disruptions, and building solutions in a highly technological collaborative construction environment. Further, these professionals also need to have the competency to interact with the technological systems through appropriate interfaces to adapt to the robotic technologies. In this regard, the implementation of robots in the construction industry necessitates student learning of safety in HRC within the context of construction operations.

POTENTIAL OF IMMERSIVE TECHNOLOGIES FOR REVALORIZING STUDENT LEARNING

The transmission of essential knowledge related to construction processes has traditionally been limited to a passive pedagogical approach, lecture-based sessions accompanied by multimedia content such as images, videos, slide presentations, or pamphlets. However, due to the complex and hazardous nature of construction workplaces, these methods fall short of effectively conveying the necessary information for learners' retention (Scott 2016). While two-dimensional media aids learners in visualizing complex construction scenarios, they offer limited interaction and engagement, resulting in suboptimal knowledge and skill retention (Scott 2016). Recent innovations in immersive technologies have facilitated the widespread use of immersive technology for assisting hands-on learning (Le et al. 2015). The integration of well-established game engines with immersive technology delivers realistic virtual environments that abide by physics rules in the scene, enable 3D stereo sound systems, and provide image-based textures for hyper-reality experiences. Further, the use of lightweight trackers, controllers, and hand trackers allows users to interact with every element in the reconstructed construction environment. These facilitators, along with an array of animations, collision simulations, and artificially intelligent characters, afford the opportunity to promote learning by doing through exploration and cooperation in a virtual environment. The integration of immersive technologies in construction education offers a practical solution to overcome the limitations of traditional lecture-based learning, providing learners with a comprehensive understanding of dynamic and unstructured construction–related scenarios. The simulated scenarios in immersive environments enable learners to explore the learning environment at their own pace and give them control over their progress. Learning in these simulated settings is often based on seeking and synthesizing experiences rather than individually locating and absorbing information from a single source.

Such experiential understanding will help students assimilate practical competencies about safe HRC in construction operations (Getuli et al. 2021; Xu and Zheng 2020; Zhang et al. 2022).

IMMERSIVE TECHNOLOGIES-BASED LEARNING OF CONSTRUCTION ROBOTIC SAFETY AND ITS IMPACTS ON STUDENTS LEARNING

This research aims to explore VR as a tool to enhance students' perception and knowledge of construction robotic safety. For this purpose, the study developed a safety training module for construction engineering students to enhance students' perception and knowledge of safety knowledge during HRC in construction operations. To examine student perceptions on the use of VR tool to enhance students' perception and knowledge of construction robotic safety as part of their experience, this study comprises two main steps, as shown in Figure 1. Firstly, a simulated learning environment was designed to teach the aspects of safety measures in HRC. Secondly, to distinguish the ability of immersive VR to augment students' learning of robotic safety, statistical analysis was performed to understand the significant difference between traditional learning systems (slides) and developed learning system on the student's learning outcome and engagement level.

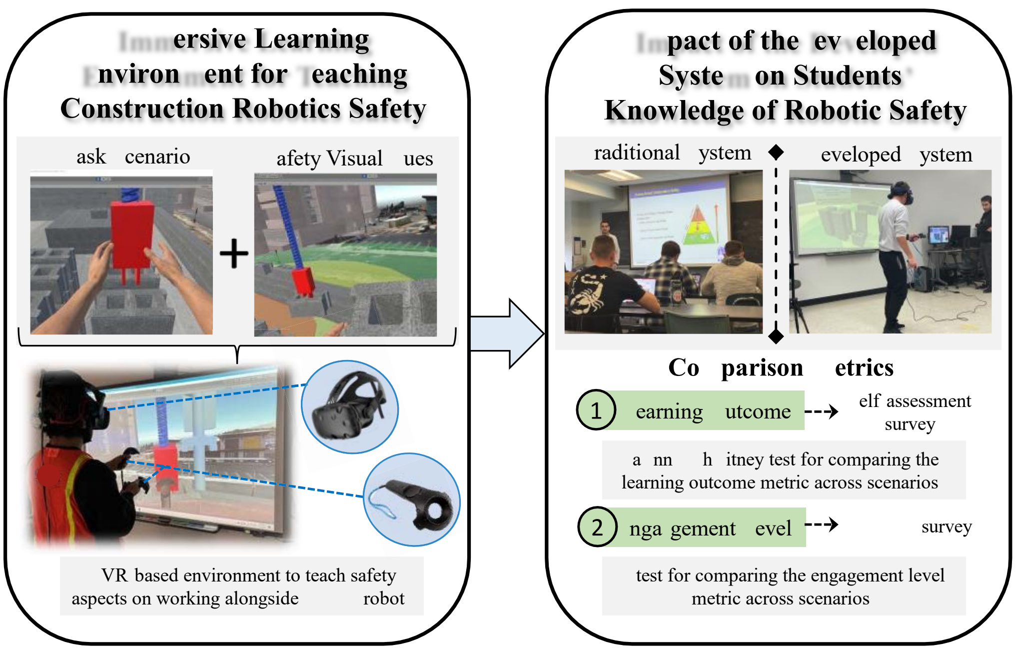

Figure 1. Overview of the proposed steps for understanding the impact of immersive technologies in students' knowledge of construction robotic safety

To compare the performance of the developed learning system with the traditional approach, the authors recruited 20 students from Pennsylvania State University. These participants were divided into two groups, with 10 students experiencing the traditional learning system and the other 10 experiencing the developed learning system. Students were carefully divided into two distinct groups based on their prior familiarity with virtual reality (VR) devices. Those without prior experience in using VR were grouped into the traditional learning system, while those with previous VR experience were assigned to the developed learning system. Then, a self-assessment technique was leveraged to measure the learning outcome across the two learning scenarios. In addition to the assessment of students' learning outcomes, the authors also compared the engagement level of students learning in the traditional learning environment with the engagement level of students learning through the developed platform. To that, all the recruited students took turns in experiencing the developed and traditional learning environment, respectively. Prior to the experiments, all the subjects were provided with informed consent forms explaining the confidentiality of the data and participants' rights. After the informed consent forms were signed, all the subjects were asked for any history of health problems. All the participants had normal or normal to corrected vision. Likewise, none of the subjects reported any signs of oculomotor or neurological pathology.

Immersive Learning Environment for Construction Robotic Safety Education. The learning environment was created and rendered in VR using the Unity game engine, as shown in Figure 2. For this purpose, a construction jobsite was modeled in Autodesk Revit and imported into the Unity game engine. Also, different elements of the immersive environment, such as equipment and personnel, were created as Game Objects featuring collider and Rigidbody components to show realistic physical properties. Several scripts (written in C#) were developed in the game engine, allowing objects to demonstrate different functions and trigger animations for specified actions (e.g., equipment operation). In addition to that, a virtual construction robot was added to the scene to provide the human-robot collaborative task at the construction site. For this purpose, a material lift enhancer robot (MULE robot) was selected for this purpose due to its relatively wide adoption in practice, as seen in Figure 2-A. Further, a human-robot collaborative task was designed in which the users must work alongside the MULE robot and pick up concrete blocks and lay them to build a masonry wall. In the designed collaborative task, the MULE robot performed the block-laying task, sharing a common workspace with the worker. More specifically, the collaborative task consisted of MULE robot picking up the concrete blocks, and humans grabbing and placing blocks in a specific order to build a masonry wall.

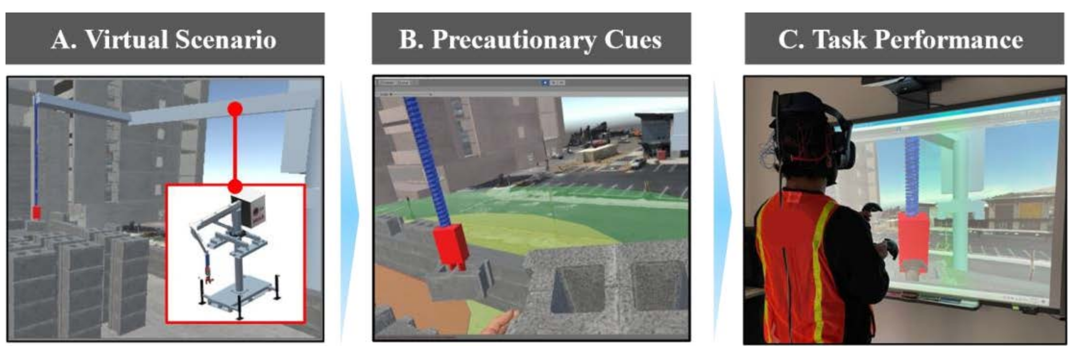

Figure 2. Development of VR-based setting for learning construction robotic safety: A) Immersive virtual scenario; B) Precautionary safety cues; C) Developed VR-based learning environment.

To provide safety knowledge to users while performing the collaborative task, the learning materials were offered to trainees through precautionary visual cues as well as written and auditory instructions. For instance, color-coded visual cues were employed to demonstrate safe and dangerous working zones, instilling the students with experiential knowledge in maintaining a safe distance with the robot, which can be seen in Figure 2-B. To deliver safety knowledge, the contents were embedded in different UI panels available to the students in the vicinity of the robot. During the learning scenario, colliders were used for event triggering. Several scripts were developed for synthesizing virtual learning contents and adjusting their properties (e.g., position, brightness) during the learning process. Figure 2-C illustrates the developed VR-based learning environment in which users perform the human-robot collaborative task alongside the construction robot.

nfer ences on Students' Learning Outco e s and n gage ent Level. To examine the potential of VR as a tool to enhance students' perception and knowledge of construction safety, the learning outcome of the students learning from the traditional approach, i.e., learning through the slides with the learning outcome of the students learning from the developed platform, as shown in Figure 3. In this regard, a self-assessment technique was leveraged to measure the learning outcome across the two learning scenarios. Specifically, the learning outcome of the subjects was measured by two comparable tests. A prior test was administered before the subjects participated in the learning activity to establish a baseline to evaluate the learning outcome. Likewise, a post-test was administered after the students completed their learning on respective configurations. Both tests consisted of 9 multiple-choice questions related to robotic safety in construction. The reliability of the test was 0.84, as determined by the following procedure as introduced in (Ojha et al. 2022). The learning outcome obtained from students learning in simulated learning platforms was compared with the data obtained from students learning through the traditional approach. To analyze the statistical differences among the learning outcome across the groups, the Mann-Whitney U-test (with a significance level of 0.05) was performed.

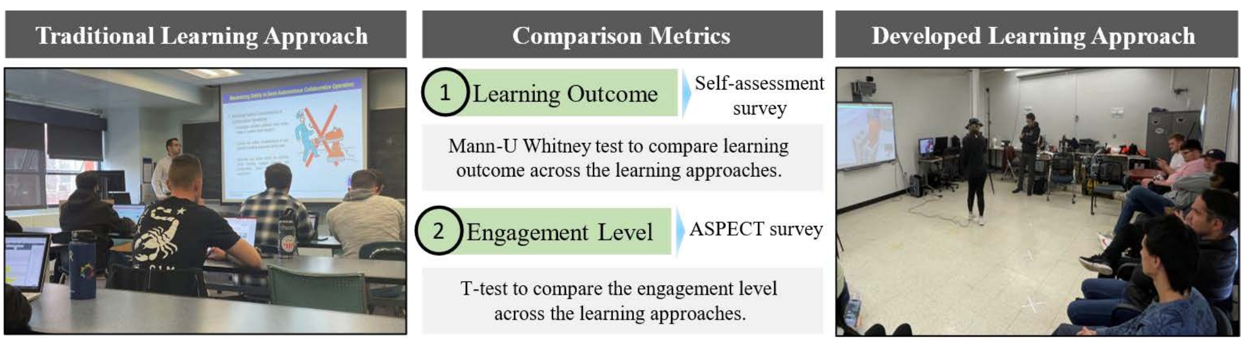

Figure 3. Illustration for the case study in assessing the impact of the developed VR-based learning on students' learning outco e s and engage e nt level.

Likewise, the authors also compared the engagement level of students learning in traditional learning environments with the engagement level of students learning through the developed platform, as shown in Figure 3. For this purpose, the authors leveraged the Assessing Student Perspective of Engagement in Class Tool (ASPECT) to capture the engagement level of subjects across the learning scenarios. ASPECT involves the use of 16 sets of statements that are administered to students to gather their perception of engagement in their learning environment using a 6-point Likert scale (i.e., 1 = Strongly Disagree; 2 = Disagree; 3 = Somewhat Disagree; 4 = Somewhat Agree; 5 = Agree; and 6 = Strongly Agree). The ASPECT survey analyzed the three major aspects of engagement, which include: **i) Activity Influence on Learning:** This aspect focuses on the extent to which students feel that the activities in the learning environment are conducive to their learning. In the ASPECT survey, 9 of the statements assessed the activity's influence on learning; **ii) Personal Effort:** This aspect focuses on the extent to which students feel that their own effort and engagement are contributing to their learning experience. In the ASPECT survey, 3 of the statements assessed the personal effort; and **iii) Instructor Contribution:** This aspect focuses on the extent to which students feel that the instructor is contributing to their learning experience. In the ASPECT survey, 4 of the statements assessed the instructor's contribution o analyze the statistical differences among the engagement level across two different learning scenarios, a T-test (with a significance level of 0.01) was performed.

RESULTS AND DISCUSSION

Following the data collection process, the data were labeled according to the learning configurations. Regarding the learning outcome, the prior test was leveraged to establish a baseline across two experimental groups. Further, a Mann-Whitney U-test was performed to evaluate the possible difference in the prior knowledge of students across two groups. The test substantiated that there was not any significant difference between the knowledge of students across the experimental groups before attending the learning sessions (p-value = 0.4765 > 0.05). After the students from each experimental group attended the learning session, the post-test was leveraged. Mann-Whitney U-test was performed on the obtained scores from the post-test of the subjects to determine any potential statistical significance between the learning configuration, as seen in Figure. 4. The test corroborated a statistically significant difference between the learning outcome of the students across two different learning configurations (p-value = 0.00152 < 0.05).

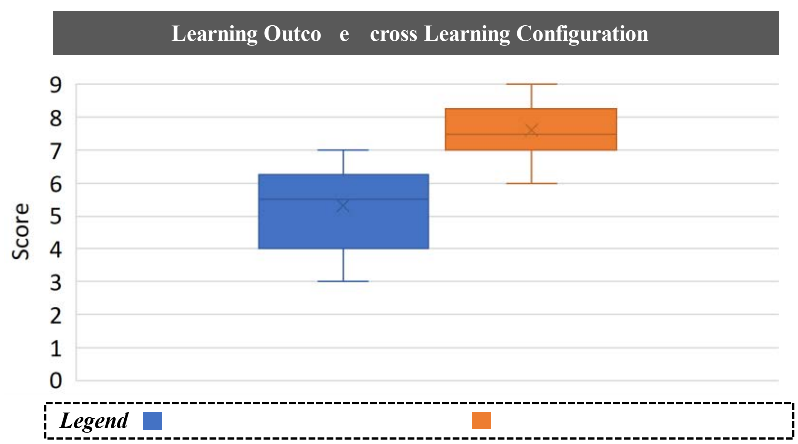

Figure 4. Learning outcome of subjects across learning configuration (post-test)

Regarding the engagement level of students, the ASPECT survey was leveraged to analyze the three major aspects of engagement: i) Activity influence on learning, ii) Personal effort, and iii) Instructor Contribution. The results of the survey across the learning configuration can be seen in Figure 5. Results indicated that each of the students was more positive towards activity influence on learning and personal effort aspect of engagement in the developed learning platform, as seen in Figures 5-A and 5-B. However, the results showed that there were no major changes in the instructor contribution factor of engagement in the developed platform, as seen in Figure 5-C. Further, a t-test was performed to evaluate the possible difference in the three major aspects of engagement across the learning configurations. The test corroborated a statistically significant difference between the activity influence of learning and the personal effort aspect of the engagement (p-value < .01). However, the t-test delineated that there was not any significant difference between the instructor contribution aspect of the engagement (p-value > .01).

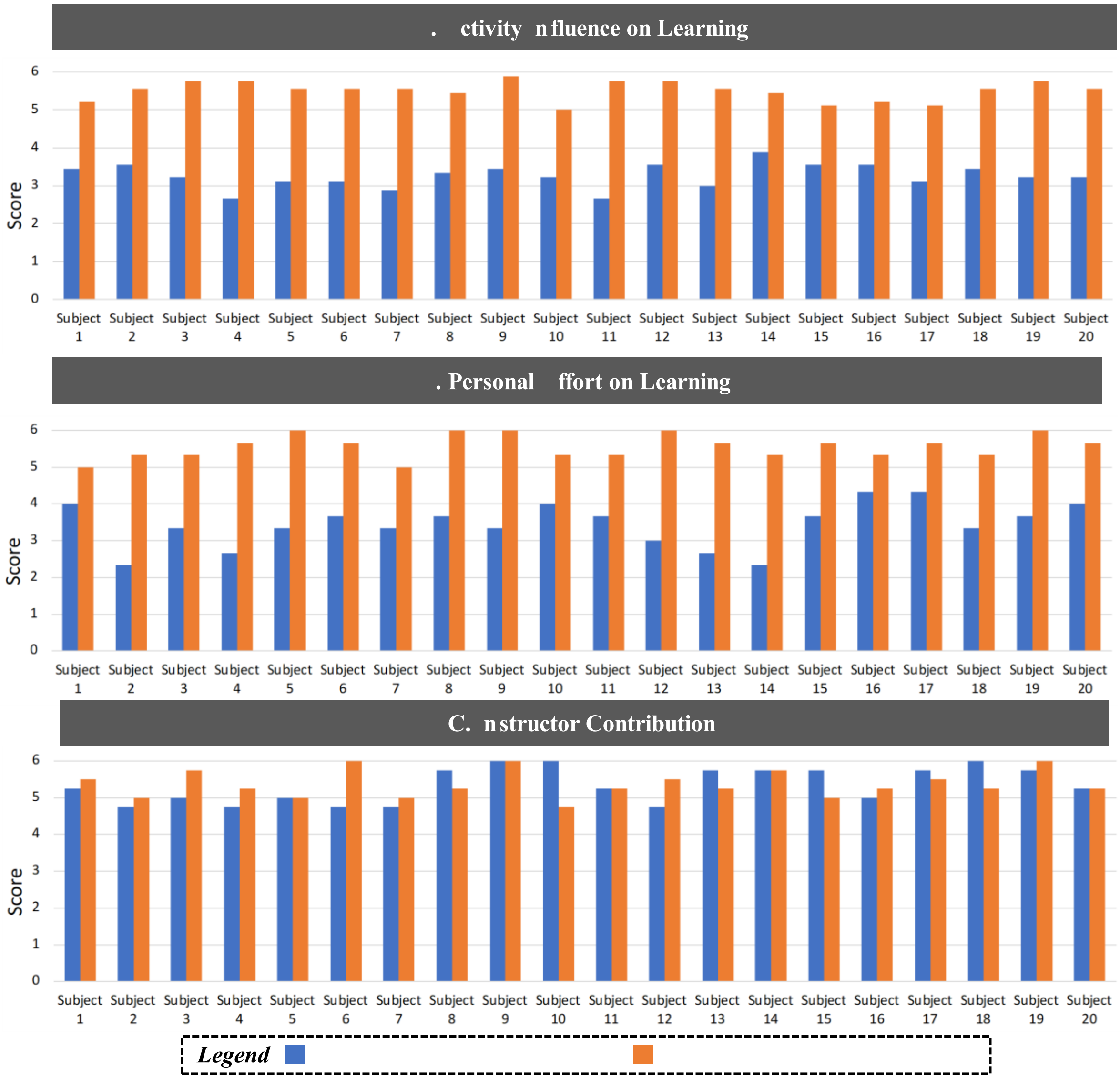

Figure 5. Comparison between traditional learning approach and developed learning approach on three major aspects of engagement: A) Activity influence on learning; B) Personal effort on learning; C) Instructor contribution.

Based on the results, it can be inferred that the use of VR technology may have contributed to the positive impact on students' engagement levels in terms of activity influence on learning and personal effort. One possible explanation of the results can be attributed to the immersive nature of VR technology, which may have allowed students to experience the learning environment in a more realistic and engaging way, contributing to their positive perception of the activity influence on the learning aspect of the engagement. Additionally, the use of VR technology may provide students with a sense of control and ownership over their learning, which can further promote self-directed learning and increase their personal effort toward learning. However, the lack of significant changes in the instructor contribution aspect of engagement may suggest that the VR technology alone may not be sufficient to enhance the role of the instructor in promoting student engagement. Therefore, it may be necessary to explore other strategies to enhance the instructor's contribution to student engagement in the VR-based learning environment.

CONCLUSION

This study aimed to explore VR as a tool to enhance students' perception and knowledge of construction robotic safety. For this purpose, the authors developed a VR-based learning environment that allowed the students to adapt to and interact with the virtual environment of construction sites to enhance engagement and promote the learning experience of robotic safety in construction. The findings of the experimental study revealed that a VR-based experiential learning environment led to significant changes in the learning outcome of students. When the subjects were studied on the developed learning platform, students' learning outcome was significantly higher. Further, the use of VR technology contributed to the positive impact on students' engagement levels regarding activity influence on learning and personal effort. Overall, the study highlights the potential of virtual reality technology for improving the construction curriculum and equipping future construction professionals with the necessary competencies for safe HRC. The findings of this study can be used by educational institutions to develop effective learning environments that provide hands-on experience to students in a safe and cost-effective manner. By adopting these experiential learning environments, future construction professionals can be better prepared to handle the challenges of safe HRC in construction operations. However, it is important to acknowledge the limitations of the study, such as the small sample size and the limited scope of the learning modules. Future research should address these limitations and further explore the potential of virtual reality technology in enhancing the construction curriculum and preparing students for highly technological work environments.

ACKNOWLEDGEMENT

This material is based upon work supported by the National Science Foundation under Grant No. DUE-2235490. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

Getuli, V., P. Capone, and A. Bruttini. 2021 "Planning, management and administration of HS contents with BIM and VR in construction: an implementation protocol " *Engineering, Construction and Architectural Management*, 28 (2): 603–623. Emerald Group Holdings Ltd.

Karimi, H., T. R. B. Taylor, G. B. Dadi, P. M. Goodrum, and C. Srinivasan. 2018 "Impact of Skilled Labor Availability on Construction Project Cost Performance " *Journal of Construction Engineering and Management*, 144 (7): 04018057. American Society of Civil Engineers (ASCE).

Kwon, C. 2019 "Verification of the possibility and effectiveness of experiential learning using HMD-based immersive VR technologies " *Virtual Real*, 23 (1): 101–118. Springer London.

Le, Q. T., A. Pedro, and C. S. Park. 2015 "A Social Virtual Reality Based Construction Safety Education System for Experiential Learning " *Journal of Intelligent and Robotic Systems: Theory and Applications*, 79 (3–4): 487–506. Kluwer Academic Publishers.
Liang, C.-J., X. Wang, V. R. Kamat, and C. C. Menassa. 2021 "Human–Robot Collaboration in Construction: Classification and Research Trends " *Journal of Construction Engineering and Management*, 147 (10): 03121006. American Society of Civil Engineers.
Liu, Y., M. Habibnezhad, and H. Jebelli. 2021 "Brainwave-driven human-robot collaboration in construction." *Automation in Construction*, 124 (November 2020): 103556. Elsevier B.V.
Musarat, M. A., W. S. Alaloul, and M. S. Liew. 2021 "Impact of inflation rate on construction projects budget: A review " *Ain Shams Engineering Journal*, 12 (1): 407–414. Elsevier.
Ojha, A., M. Habibnezhad, and H. Jebelli. 2022 "Feasibility of Embodied Virtual Agents for ug menting tudent s' Knowledge of Robotic Safety in Construction." *Construction Research Congress 2022: Health and Safety, Workforce, and Education - Selected Papers from Construction Research Congress 2022*, 4-D: 70–80. American Society of Civil Engineers.
Scott, L. M. 2016 "Theory and research in construction education: the case for pragmatism " *Construction Management and Economics*, 34: 552–560.
de Vries, G. J., E. Gentile, S. Miroudot, and K. M. Wacker. 2020 "The rise of robots and the fall of routine jobs " *Labour Economics*, 66: 101885. North-Holland.
Xu, Z., and N. Zheng. 2020 "Incorporating Virtual Reality Technology in Safety Training Solution for Construction Site of Urban Cities " *Sustainability* 2021, Vol. 13, Page 243, 13 (1): 243. Multidisciplinary Digital Publishing Institute.
Zhang, M., L. Shu, X. Luo, M. Yuan, and X. Zheng. 2022 "Virtual reality technology in construction safety training: Extended technology acceptance model " *Automation in Construction*, 135: 104113. Elsevier.