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Virtual Interaction on Concept Learning for Construction Safety Training

Huiryeong Kang[1], Eunbyul Yang[1], Seungho Choe[1] and Jeeheon Ryu[1]

[1] Chonnam National University, Gwangju, South Korea
jeeheon@jnu.ac.kr

Abstract. This study aims to design and develop extended reality (XR) content to enhance concept learning for construction safety training. Given the increasing importance of safety education for construction site workers, understanding and adhering to the proper use of personal protective equipment (PPE) is essential for maintaining health and safety standards on construction sites. This study focuses on creating an XR-based training program that simulates realistic construction scenarios and provides a structured learning process across four phases: task presentation, risk evaluation, PPE application, feedback, and results. The program incorporates a physical mannequin to enable embodied interaction, allowing learners to physically place virtual PPE while observing its real-time application. Combining theoretical principles with practical implementation in the proposed program fosters learners' engagement and improves workers' ability to evaluate risks, make informed decisions, and apply safety concepts effectively in a controlled and interactive environment.

Keywords: Extended Reality, Immersive Learning, Embodied Learning, Construction Safety.

1 Introduction

Construction safety training is a critical yet challenging domain, particularly in ensuring proper understanding and adherence to personal protective equipment (PPE) protocols among workers. Traditional training methods, such as lectures or printed materials, often lack engagement and fail to provide the hands-on experiences necessary to prepare workers for real-world challenges [1, 2]. As construction remains one of the most hazardous industries globally, there is a pressing need for innovative approaches to improve safety education [2]. Extended reality (XR), encompassing augmented reality (AR), virtual reality (VR), and mixed reality (MR), has emerged as a promising solution to address these challenges. XR technologies create immersive and interactive environments that integrate virtual and physical elements, allowing learners to actively engage in realistic safety scenarios. Research has shown that embodied mixed-reality environments significantly enhance situational awareness and decision-making skills by aligning real-world actions with virtual feedback [3]. This approach bridges the gap between theoretical safety knowledge and practical application, fostering deeper understanding and knowledge retention [1, 3]. This study utilizes Microsoft HoloLens 2, a head-mounted mixed reality (MR) device, to develop and implement an effective XR-based training program. Unlike conventional VR-based training, which fully immerses users in a virtual space, MR enables real-time interaction with both physical and digital objects, preserving the learner's connection to the real-world workspace. The HoloLens 2's gesture-based interactions, spatial mapping, and high-fidelity holographic overlays facilitate embodied learning by allowing learners to physically place PPE onto a mannequin while receiving real-time feedback. These features reinforce procedural knowledge, making the safety training experience more engaging and contextually relevant.

A key component of XR-based training lies in its ability to create embodied learning experiences. By integrating physical actions with virtual representations, XR training fosters procedural knowledge acquisition and reinforces critical safety concepts [3]. Building on these principles, this study presents an MR-based training framework for construction safety education, focusing on PPE application and hazard assessment. The program features three task scenarios—painting, welding, and power drilling—each designed to simulate real-world construction challenges. Following a structured four-phase sequence (task presentation, risk evaluation, PPE application, and feedback and results), the training program combines physical and virtual interactions to overcome the limitations of traditional methods. Through this approach, the study aims to enhance engagement, strengthen decision-making, and improve overall safety competency among construction workers.

2 Design and Development

The XR-based training program was specifically designed to address critical challenges in construction safety training, particularly in understanding and applying personal protective equipment (PPE) effectively. The program aimed to enhance learners' ability to analyze risks and make informed decisions in realistic construction scenarios by integrating theoretical principles with practical implementation.

The program was structured into three progressively challenging stages, each simulating a distinct construction task: painting, welding, and power drilling. These tasks were carefully designed to reflect real-world working conditions, allowing learners to engage with context-specific safety scenarios. Each task followed a consistent four-step sequence:

1. **Task Presentation:** Learners were introduced to a realistic work scenario featuring unsafe practices, such as workers performing tasks without proper PPE.
2. **Risk Evaluation:** Learners analyzed the presented scenario using a checklist of potential safety hazards, identifying key risks and evaluating appropriate responses.
3. **PPE Application:** Based on their evaluations, learners selected and applied the correct PPE to a physical mannequin, ensuring alignment with task requirements.
4. **Feedback and Results:** Learners received immediate feedback on their performance, including explanations for incorrect choices and a visualization of the potential consequences of improper PPE usage. Successful completion of each stage culminated in an animation showing a digital human avatar safely completing the task wearing the correct PPE.

This structured design ensured that learners progressed through increasingly complex scenarios, reinforcing their understanding of safety principles while providing opportunities to apply their knowledge in a hands-on, interactive environment. By guiding learners through this step-by-step process, the program facilitated the acquisition of critical safety skills in a realistic and engaging learning environment.

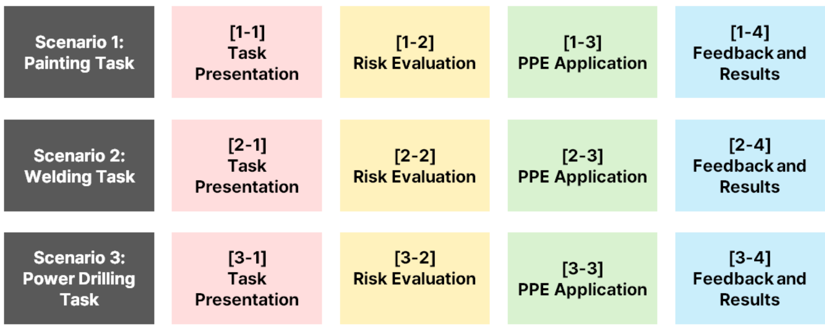

Fig. 1. Structural Workflow of the XR-Based Training Program: Task Scenarios and Progressive Steps.

2.1 Key Features of the XR Training System

A distinguishing feature of the program was incorporating a physical mannequin into the XR environment, allowing learners to interact with virtual PPE in a tangible and embodied manner. An initial calibration process was introduced to ensure accurate alignment between the virtual and physical spaces. Instead of manually adjusting individual body parts, the system employed a grabbable virtual cube, which served as a unified control mechanism for defining the mannequin's key trigger zones, including the head, hands, and feet.

Prior to interaction, these trigger zones were predefined based on the mannequin's actual dimensions, ensuring that they maintained consistent relative positioning. By linking these zones to the grabbable cube, users could simply move the cube to adjust the entire calibration structure without needing to reposition each individual body part. This design also allowed the program to dynamically compensate for variations in users' initial standing positions when activating the HoloLens 2.

During the calibration phase, users grabbed and aligned the virtual cube with a designated area on the mannequin's torso. Once the cube was placed correctly, the system automatically established the spatial reference point for the training content, ensuring that all virtual elements—including interactive PPE and task-related objects—were properly positioned within the MR environment. After calibration, learners proceeded with a brief tutorial to familiarize themselves with essential XR interactions, such as toggling menus and manipulating objects, further enhancing their immersion and usability in the training scenario.

Fig 2. Designated Calibration Area for Spatial Alignment in XR Training.

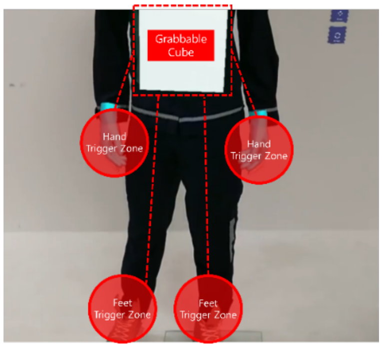

Fig. 3. Grabbable Cube-Based Trigger Zone Calibration for Interactive XR Training.

The training tasks were designed to progressively develop learners' skills in analyzing safety risks and applying appropriate PPE. Each task began with a Task Presentation, where learners observed a realistic depiction of unsafe practices in a simulated work scenario, such as workers operating without proper PPE. During the Risk Evaluation phase, learners used a checklist of potential hazards to identify key risks and choose appropriate safety measures. For example, in the painting task, they recognized chemical hazards and selected corresponding PPE, such as gloves and respiratory protection. Immediate feedback was provided for each selection: correct choices were reinforced with visual cues, while incorrect selections prompted corrective messages and the opportunity to retry. This iterative process not only reinforced correct decision-making but also helped learners build confidence in their evaluations.

The second phase of each task, PPE Application, involved physically placing virtual PPE onto the mannequin, ensuring correct alignment and application. Learners interacted with virtual PPE items, such as helmets, gloves, and masks, placing them onto specific areas of the mannequin, including the head, hands, or feet. This interaction created a seamless connection between the physical and virtual elements, enhancing the embodied learning experience. The virtual PPE appeared to physically "attach" to the mannequin in real-time, creating the illusion of actual equipment placement and improving the realism of the interaction.

To support learners during this phase, the program incorporated multiple guidance systems:

1. **Correct Checklist Access**: Learners could refer to the correct answers identified during the Risk Evaluation phase. These answers were displayed during PPE placement, helping learners align their decisions with the task requirements.
2. **Reference Guide**: A "Reference Materials" button near the checklist allowed learners to view detailed information about each PPE item, including images, descriptions, and usage instructions.
3. **Tooltip System**: Activated after two consecutive incorrect attempts, tooltips provided contextual pop-ups directly on the PPE items, displaying names, functions, and additional guidance. This system reduced the difficulty of the selection process while ensuring concept reinforcement and guided learners toward successful completion of the task.

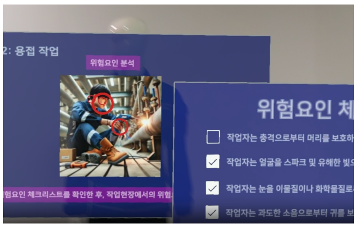

Fig. 4. Risk Evaluation Phase: Identifying Hazards in a Welding Task.

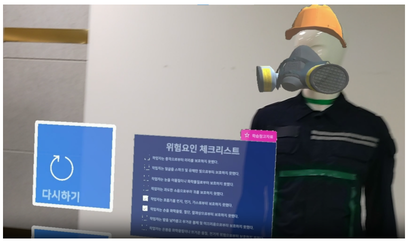

Fig. 5. PPE Application Process.

Once all PPE was placed, the system evaluated the learners' selections. If errors were detected, detailed feedback was provided, highlighting the consequences of improper PPE usage. For example, in the painting task, failing to apply respiratory protection would trigger a warning about the risks of inhaling harmful chemicals, accompanied by a visual explanation. This iterative feedback ensured that learners could refine their decisions and fully understand the importance of proper PPE selection and application.

To enhance realism and engagement, the program concluded each task with a Feedback and Results phase, featuring an animation of a virtual worker safely completing the task while wearing the correct PPE. For instance, in the painting task, learners observed a digital human avatar, augmented by the mannequin, effectively completing the task while fully protected. This animation reinforced the importance of their decisions and provided a sense of accomplishment. The avatar's actions demonstrated how proper safety practices could ensure successful and hazard-free work outcomes, bridging the gap between virtual training and real-world applications.

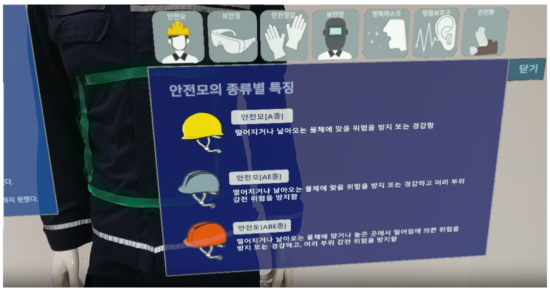

Fig. 6. Reference Guide for PPE Types and Functions.

Fig. 7. Augmented Digital Avatar Demonstrating Safe Task Execution in PPE.

2.2 Technical Implementation

The program was developed using Unity3D (version 20.3.27f1) and the Mixed Reality Toolkit (MRTK 2.8) and deployed on Microsoft HoloLens 2. Virtual PPE models were meticulously designed to match the size, appearance, and functionality of real equipment, ensuring an authentic user experience. Gesture-based interactions allowed learners to manipulate objects and navigate menus seamlessly, creating an intuitive and immersive learning environment.

The development process followed an iterative refinement approach using the Successive Approximation Model (SAM), which ensured continuous improvements based on usability testing and expert feedback. This iterative process allowed for early prototyping, followed by internal usability testing and iterative feedback sessions, enabling the program to evolve effectively and meet the specific needs of learners.

To ensure the accuracy and safety of the content, safety professionals from the Gwangju Worker's Health Center conducted expert validation. They assessed the realistic representation of safety hazards and PPE application and offered refinements to enhance content accuracy, risk representation, and learning progression. For the visual representation of PPE application and task completion, Character Creator and iClone were employed to generate lifelike avatars demonstrating proper PPE usage and safe task execution. These avatars, augmented by the mannequin model, reinforced learning by showing the consequences of incorrect PPE usage and demonstrating correct safety practices in the final training phase.

The program systematically recorded task completion data, accuracy rates, and response times to assess learner performance and training effectiveness. Each training session generated a structured dataset, which was automatically logged and extracted as CSV files for further analysis. During each session, the accuracy per round (accuracy_round) was calculated as the percentage of correctly applied PPE items (answer_correct) relative to the total required PPE (answer_total) using the following formula:

$$\text{accuracy round}=\frac{\text{answer correct}}{\text{answer total}}\times 100$$

This session-based accuracy was then dynamically averaged across multiple rounds (accuracy_average) to measure learners' progression over time. The system maintained an iterative tracking mechanism, updating cumulative accuracy statistics in real time to provide insights into the learner's overall improvement. The extracted data included timestamps, frame counts, session durations, and completion status, enabling a granular evaluation of task performance, response efficiency, and error patterns. By structuring the data in CSV format, the system allowed for quantitative analysis of learners' PPE application skills, facilitating iterative refinements to enhance the effectiveness of the training program based on empirical performance trends.

round	timestamp	frame	date	time	fps	duration	answer_correct	answer_total	completed	accuracy_round	accuracy_average
1	1727687857	5656	2024-09-30	12:35.3	30	05:44.0	3	5	FALSE	60	60
2	1727687897	6849	2024-09-30	13:15.1	30	00:39.8	4	5	FALSE	80	70

Fig. 8. Extracted Performance Data: Session-Based Accuracy Metrics in XR Training.

3 Discussion and Conclusion

This study introduced an XR-based training program designed to address critical challenges in construction safety education, focusing on improving learners' understanding and application of personal protective equipment (PPE). By integrating embodied interaction with structured, scenario-based tasks, the program provided learners with a hands-on and engaging learning experience that bridged the gap between theoretical knowledge and practical application.

The program demonstrated the potential of XR technologies to deliver immersive training experiences. Through its four structured phases—task presentation, risk evaluation, PPE application, and feedback—the program enabled learners to analyze risks, make informed decisions, and practice applying PPE in realistic scenarios. Using a physical mannequin provided a tangible connection to the training tasks, enhancing the embodied learning experience. However, this approach also highlighted certain limitations, such as learners' inability to view their own avatars wearing PPE, a feature commonly available in VR environments. Future iterations could explore hybrid solutions incorporating avatar-based feedback to address this gap.

Another limitation was the simplified failure simulations. While the program offered auditory and visual feedback through panels and voice guidance, more immersive failure consequences, such as simulated visual impairments or injuries, could enhance the emotional impact of the training. These additions could help learners better understand the seriousness of safety compliance in high-risk environments. Similarly, the lack of auditory feedback during PPE placement was noted as a missed opportunity to enhance sensory immersion. Incorporating realistic sound effects could further improve the overall user experience and align with embodied cognition principles.

Despite these limitations, the study highlights the transformative potential of XR-based training programs to create engaging and effective educational tools for high-risk industries. The program lays a foundation for improving safety training outcomes through technology by offering structured and interactive scenarios. A practical next step involves refining the program's core features, such as sensory feedback and failure simulations, to enhance its realism and effectiveness. Additionally, pilot studies could be conducted to gather user feedback and assess the program's usability before scaling it for broader applications.

In conclusion, this research contributes to XR-based educational interventions by presenting a framework for designing and implementing immersive training programs. The insights gained from this study underscore the potential of XR technologies to transform safety training practices, paving the way for future advancements in workplace safety education.

Acknowledgments

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