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Investigating the Role of Immersive Embodied Interaction in Reducing Mental Workload and Enhancing Training Outcomes in Construction Education

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Abstract: The rapid advancement of digital technologies has transformed education by introducing immersive tools such as virtual reality (VR) and augmented reality (AR), which enhance learning through interactive and adaptive experiences. In construction, data-sensing technologies such as drones and laser scanners are increasingly used for site inspections, monitoring, and real-time decision-making. Training for these technologies often relies on VR simulations; however, traditional VR lacks hands-on realism, limiting users' ability to fully engage with these tools. Research suggests that embodied interaction, where users engage with tangible objects, can improve knowledge retention and task performance. However, its impact on mental workload remains underexplored. Workload, influenced by frustration, cognitive demands, and task complexity, can either enhance intuitiveness or increase strain. This study examines the effectiveness of immersive embodied interaction versus traditional VR in construction education and training. In a pilot study, 21 participants conducted drone-based site inspections under both conditions, with workload assessed using the NASA Task Load Index (NASA-TLX) survey. A paired samples t-test revealed a statistically significant reduction in workload in the embodied interaction condition ($t(20) = -4.31$, $p < .001$), indicating that participants experienced lower cognitive demands compared to the traditional VR method. These findings suggest that embodied interaction not only reduces workload but also enhances knowledge retention and task performance, reinforcing its potential as an effective training method in construction-related educational environments.

Keywords: Virtual Environment, Cognitive load, Immersive Learning, Embodied Interaction, Tangible Objects, Construction Education.

1. Introduction

The construction industry increasingly relies on advanced data sensing technologies, such as drones, Inertial Measurement Units (IMU), GPS, RFID, and vision-based systems like 3D cameras and laser scanners, for monitoring, data collection, and site analysis (Khalid et al. 2024). These technologies enhance project efficiency, safety, and real-time decision-making, making them essential for modern construction workflows. However, despite their widespread adoption, a critical gap remains in training methods that equip students with the skills needed to operate these tools in real-world construction environments (Ogunseiju et al. 2022). As these technologies continue to evolve, the demand for a workforce proficient in data sensing systems grows (Ogunseiju et al. 2022). To bridge this gap, it is essential to implement effective training programs that not only introduce students to these technologies but also provide hands-on experience, ensuring they can apply their knowledge in practical settings and maximize their impact on construction projects.

Traditional classroom-based instruction, which predominantly relies on lectures and theoretical explanations, often falls short in providing students with the necessary hands-on experience required for proficiency with these technologies (Olbina and Glick 2023). While theoretical knowledge is fundamental, practical exposure is crucial to understanding the operational complexities and constraints associated with deploying these tools in dynamic construction sites. However, bringing students to active construction environments for training is frequently impractical due to logistical barriers, safety concerns, and the high costs of specialized equipment (Ogunseiju et al. 2022). Moreover, construction sites are fast-paced and subject to unpredictable conditions, making them less than ideal for controlled learning experiences. As a result, students lack practical exposure to how these technologies function in dynamic construction settings, which can hinder their ability to adapt to industry demands.

To address this issue, researchers have explored alternative pedagogical approaches that emphasize experiential and embodied learning (Anjum et al. 2024). Embodied interaction, in particular, has been shown to be an effective method in construction education (Wolf et al. 2022; Lee et al. 2012), especially when integrated with data-sensing technologies (Anjum et al. 2024). This approach involves engaging users in physical movements, gestures, and tangible interactions that replicate real-world construction operations (Anjum et al. 2024). Studies have argued that embodied interaction enhances knowledge retention and task performance by making learning experiences more intuitive and immersive (Ogunseiju et al. 2022; Wolf et al. 2022, Anjum et al. 2024). By bridging the gap between theoretical instruction and hands-on application, it provides a more effective training method for students preparing to use data-sensing technologies in real-world settings.

While previous studies have demonstrated the benefits of embodied interaction in improving learning outcomes (Wolf et al. 2022; Lee et al. 2012), its impact on mental workload compared to traditional VR learning remains an underexplored area. Mental workload, which is influenced by factors such as cognitive demands, frustration, and task complexity, plays a crucial role in training effectiveness (Criollo-C et al. 2024). Unlike traditional VR, where interactions are purely digital, embodied VR integrates physical objects that replicate real-world tools and equipment, allowing users to interact with them naturally as their movements are tracked in the virtual environment. This approach enhances realism and immersion, potentially increasing engagement and practical skill acquisition. However, the added realism could have dual effects: it may reduce cognitive strain by improving intuitiveness or, conversely, increase mental workload due to the complexity of coordinating both physical and virtual interactions. Given these potential effects, measuring cognitive load is essential for evaluating how embodied interaction impacts mental effort during training. In this study, the NASA-TLX, a well-established subjective workload assessment, was utilized to capture participants' perceived cognitive demands across conditions (Hart 1988). Subjective workload ratings provide valuable insights into how users experience mental effort and task difficulty in embodied VR, helping to determine whether this approach optimally balances engagement and usability without overwhelming learners.

Therefore, this study investigates the effectiveness of immersive embodied interaction (IEI) versus traditional VR interaction in construction education and training, specifically in the context of data-sensing technology. As a pilot study, 21 participants conducted drone-based inspections of construction activities under both conditions. The NASA-TLX results provided subjective insights into cognitive demands associated with each training method. The results indicate that embodied interaction not only helps participants manage workload more effectively but also enhances task performance. These findings suggest that deploying embodied interaction with VR has the potential to serve as an effective training method in construction-related educational environments, bridging the gap between theoretical learning and hands-on application while addressing the challenges associated with traditional training approaches.

2. Research Method

This study evaluates the impact of (IEI) on students' workload during construction-related training tasks. A comparative experiment was conducted with two training conditions: one utilizing IEI with a programmed game controller (PS4), designed to replicate real drone controls, and the other employing

traditional virtual reality (VR) training with a default HTC Vive VR controller. Participants were required to conduct a construction site safety inspection using a drone within a virtual environment, a task aligned with the growing role of drones in construction for monitoring and data collection (Albeaino et al. 2019). To complete this task, they asked to identify predefined safety hazards from a drone's perspective while navigating the top level of the construction site, avoiding dynamic obstacles, and maintaining a safe distance from virtual workers. A total of 21 undergraduate and graduate students were recruited, ensuring participants possessed the necessary academic and cognitive skills. Eligibility criteria included normal or corrected vision and no history motion sickness when using VR. Prior to the experiment, participants received a detailed briefing on the research protocol, provided informed consent, and completed a training session lasting approximately 15–30 minutes, depending on individual learning needs. During this session, participants were familiarized with both control systems including drone functionality, button mapping, and task objectives and were required to demonstrate proficiency by successfully performing all essential drone navigation movements before proceeding to the experimental trials. The study was approved by the Texas A&M University Institutional Review Board (IRB) to ensure ethical compliance.
The overall research methodology for this study is illustrated in Figure 1.

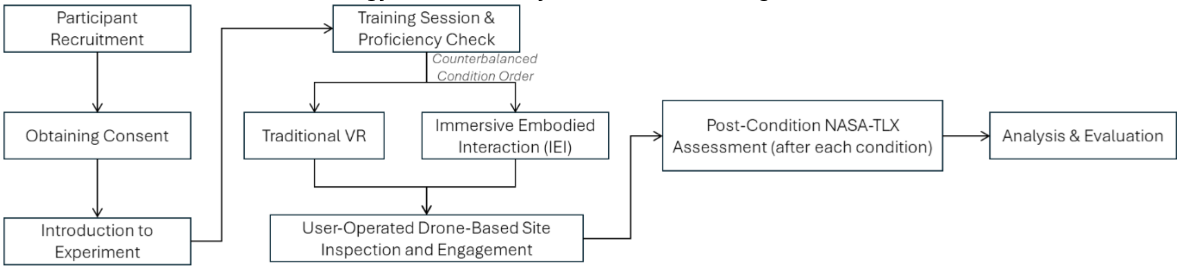

Figure 1: Research Methodology Flowchart

Participants conducted virtual construction site inspections under both training conditions at their own pace, simulating realistic drone operations. They were instructed to identify safety hazards while navigating the virtual site and avoiding obstacles or virtual workers. On average, participants spent 394.98 seconds (SD = 166.30) using the IEI method and 438.59 seconds (SD = 193.57) using the traditional VR method. The task order was counterbalanced to eliminate potential order bias by assigning participants to condition sequences based on their participant ID: those with even numbers completed Condition TRD followed by Condition IEI, while those with odd numbers experienced the reverse order (Bradley 1958). To assess cognitive workload, the NASA Task Load Index (NASA-TLX) was administered after each condition, evaluating six key dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration level. This allowed for a direct comparison of workload differences between the IEI and traditional VR methods. Table 1 outlines the NASA-TLX questions used to assess mental workload after each experiment.

Drones were chosen as the simulation medium due to their increasing application in construction site monitoring (Albeaino et al. 2019). The programmed PS4 controller was selected for its close resemblance to real drone controllers, enhancing the realism of the embodied interaction condition. This design aimed to create a tangible interaction experience, mimicking real-world drone operations. Figures 2 and 3 illustrate the system design and interaction mapping. Figure 2 demonstrates the immersive interaction setup, where participants control the drone using the programmed PS4 controller, receiving real-time visual feedback on a monitor. The button mapping visualization clarifies assigned functions such as image capture, video recording, movement, and rotation. Figure 3 presents the traditional virtual drone control interface, where positive and negative directional values define different movement and rotation actions. The negative direction includes left, down, backward, and turning left, while the positive direction corresponds to right, up, forward, and turning right. By incorporating IEI for drone control mechanics, the study aims to align virtual training more closely with real-world drone operations, making it highly relevant to construction education.

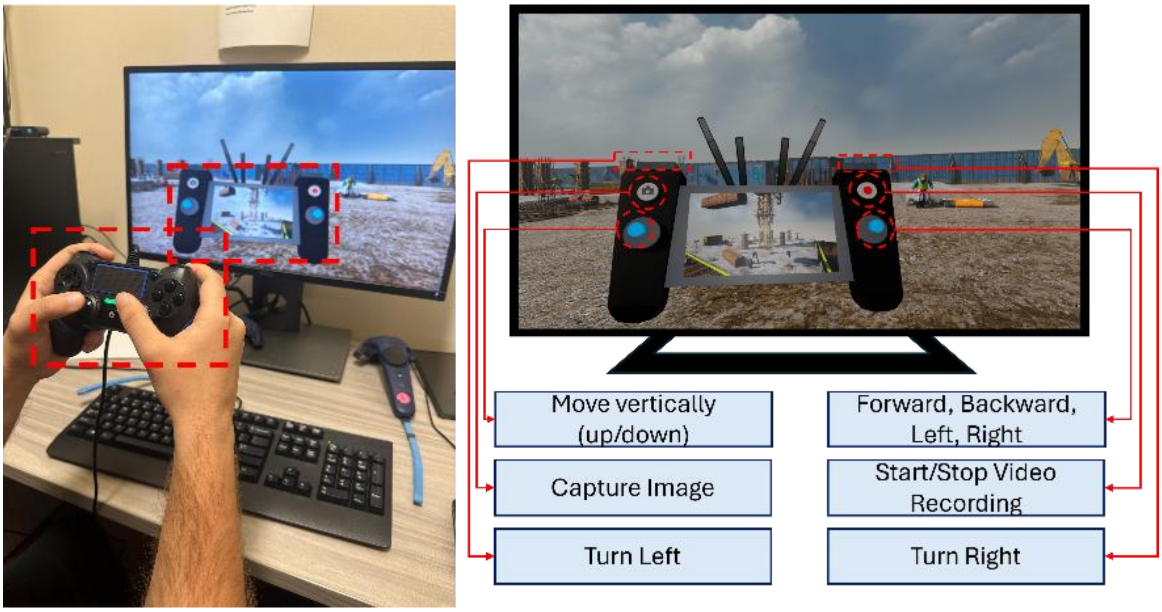

Figure 2: Immersive Drone Control Setup with Embodied Interaction

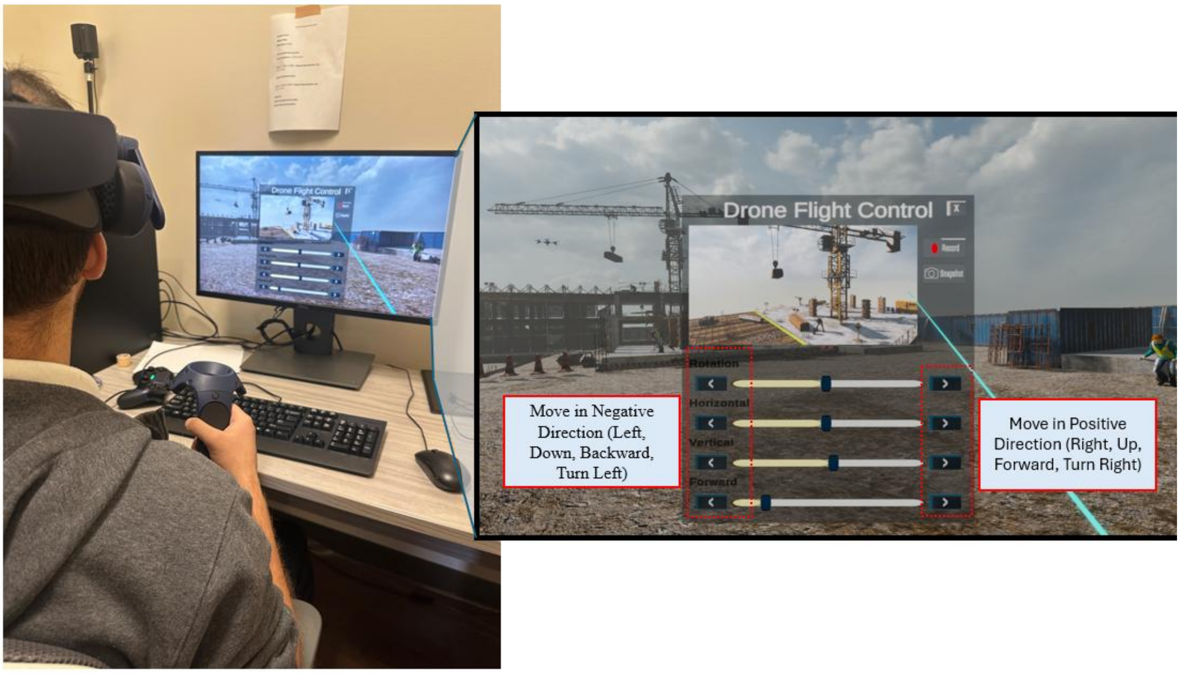

Figure 3: Virtual Drone Flight Control Interface

Table 1. NASA TLX Questions and Response Scales.

Question	Scale
How mentally demanding was the task?	0–100
How physically demanding was the task?	0–100
How hurried or rushed was the pace of the task?	0–100
How successful were you in accomplishing what you were asked to do?	0–100
How hard did you have to work to accomplish your level of performance?	0–100

How insecure, discouraged, irritated, stressed, and annoyed were you?	0–100

3. Data Analysis and Results:

Data from 21 participants were collected and analyzed using Python. Before conducting inferential statistical analysis, the data were evaluated for normality using the Shapiro-Wilk test, which confirmed that the NASA-TLX scores for both the traditional and immersive embodied interaction conditions followed a normal distribution ($p > 0.05$). Given that the normality assumption was met, a paired t-test was conducted to examine whether workload scores differed significantly between the two training methods. Descriptive statistics revealed notable differences between conditions. The IEI condition had a lower mean NASA-TLX score (M = 44.23, SD = 15.37) compared to the traditional VR condition (M = 55.35, SD = 12.79). Scores in the immersive condition ranged from 22.00 to 70.00, with a median of 43.00, whereas scores in the traditional condition ranged from 27.00 to 74.17, with a higher median of 56.00. These differences suggest that participants perceived the immersive approach as less mentally demanding.

The results of the descriptive statistics for each index of the NASA-TLX score revealed several key differences across the various demand and outcome measures. For physical demand, the traditional method (M = 38.10, SD = 23.80) had a higher mean than the IEI method (M = 20.95, SD = 20.23), indicating that participants reported more physical demand in the traditional method context. Similarly, for mental demand, the Traditional Method (M = 59.52, SD = 24.59) showed a higher mean compared to the IEI method (M = 40.95, SD = 25.28), suggesting that the traditional method was associated with greater cognitive load. Regarding temporal demand, the traditional method (M = 47.62, SD = 20.47) also had a higher mean than the IEI method (M = 43.33, SD = 26.90), reflecting a greater sense of time pressure in the traditional method condition. In contrast, for performance, the IEI method (M = 82.38, SD = 17.00) had a higher mean than the traditional method (M = 71.90, SD = 20.64), indicating that participants perceived their performance to be better in the IEI condition. This reflects subjective self-assessment rather than objective performance metrics. For effort, the traditional method (M = 69.05, SD = 19.98) had a higher mean compared to the IEI method (M = 43.81, SD = 26.74), suggesting that more effort was required in the traditional method condition. Frustration was reported to be higher in the traditional method (M = 45.90, SD = 29.97) compared to the IEI method (M = 33.95, SD = 31.32), indicating that participants experienced more frustration in the traditional method.

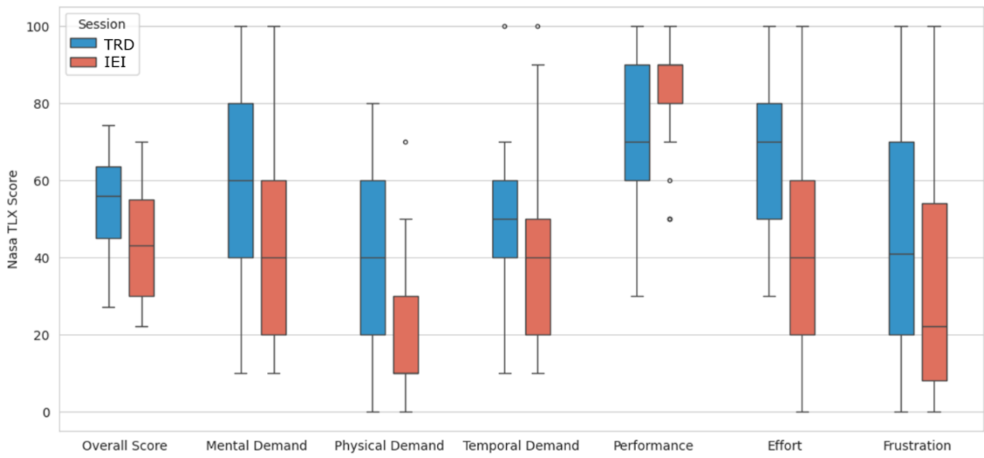

Figure 4: A Box Plot of NASA-TLX Score for IEI and Traditional Method

A paired samples t-test confirmed a statistically significant difference in workload between the two conditions ($t(20) = -4.31$, $p < .001$), indicating that participants reported significantly lower NASA-TLX scores when using the IEI method compared to the traditional VR method. As illustrated in Figure 4, the box plot highlights the difference in workload distribution, with the immersive condition showing a lower interquartile range and median than the traditional condition. These findings suggest that IEI may reduce cognitive load and enhance training efficiency in construction-related VR applications.

4. Conclusion and Discussion

The findings of this study underscore the advantages of Immersive Embodied Interaction (IEI) in virtual environments for reducing participant workload during task execution. The paired samples t-test results revealed a significant reduction in NASA-TLX scores for the IEI condition compared to the traditional approach, highlighting its effectiveness in reducing cognitive demands. These results suggest that the IEI approach offers a more intuitive and efficient alternative, improving participants' overall experience when navigating virtual environments for construction education and training activities.

From a practical perspective, the integration of IEI into construction training programs can enhance learning by allowing trainees to engage with virtual environments through natural movements and interactions. Unlike traditional virtual training methods, IEI provides an immersive and interactive learning experience that closely mirrors real-world construction tasks. This approach can be particularly beneficial for training in equipment operation, safety procedures, and task coordination, where hands-on practice is essential. IEI-based training modules can simulate various construction scenarios, enabling trainees to develop spatial awareness, improve coordination, and familiarize themselves with site conditions in a controlled environment. Additionally, IEI enables a more intuitive learning process by leveraging real-time physical interactions, allowing trainees to execute tasks as they would in actual construction settings. This can help improve task efficiency, accuracy, and confidence before transitioning to real-world applications.

While the study demonstrated a reduction in perceived workload using the IEI method, several limitations should be acknowledged. The laboratory-based virtual environment may not fully capture the complexity and unpredictability of real-world construction sites. Participants interacted with each system for a relatively short period, which may not reflect long-term familiarity or learning effects. Additionally, individual differences such as prior experience with virtual reality, gaming, or drone operation were not controlled, potentially influencing participants' interaction patterns and perceived workload. Acknowledging these factors will help inform future studies and strengthen the generalizability and practical application of the IEI framework in construction training.

Future research should include a larger and more diverse sample to improve the generalizability and real-world applicability of the findings. Incorporating objective physiological measures, such as heart rate variability and skin conductance, would provide deeper insights into participants' stress levels and cognitive states across conditions. Performance metrics, including task completion times and accuracy rates, should also be examined to better capture the practical benefits of IEI. Additionally, incorporating more interactive physical objects and refined motion-tracking systems could further enhance the realism and effectiveness of IEI-based virtual construction training. These directions would contribute to a deeper understanding of the IEI framework's impact on learning outcomes, safety practices, and overall training effectiveness in construction education.

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