



Validation of a Virtual Reality Environment for Research on Human-Drone Interaction in Construction

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Drones have been increasingly adopted in the construction industry to address labor shortages, enhance productivity, and reduce inefficiencies. This growing adoption has made human-drone interaction inevitable on jobsites, raising concerns about potential safety impacts on human workers and underscoring the need for systematic investigation of relevant human factors. Human-centered experiments are essential for directly examining these factors, where virtual reality (VR) offers a controlled, repeatable, and risk-free environment for simulating high-risk construction scenarios and observing safety-critical behaviors. This study presents the development and validation of a VR environment designed to serve as a realistic and engaging platform for human-drone interaction research in construction. The workflow for VR development is outlined, followed by a pilot study to evaluate the feasibility of the developed VR environment. The evaluation quantitatively examined sense of presence, perceived workload, motion sickness, VR technical reliability, and scenario design relevance. The findings validated the feasibility of the developed VR environment as an experimental platform for advancing human-drone interaction research, which will ultimately support the development of safer and more productive construction practices.

Keywords: human-drone interaction, robotics, construction safety, VR, virtual reality

Introduction

Recent technological advancements and sensor miniaturization have accelerated the adoption of automation and mobile collaborative robots in construction to address challenges such as skilled labor shortages, low productivity, and reduced efficiency (Shourangiz et al., 2025). Among these technologies, drones have become increasingly prevalent. In fact, the construction industry is the fastest-growing commercial adopter of drones, with usage increasing by 239% in a single year (DroneDeploy, 2022). Drones' ability to capture real-time visual data, access hazardous or hard-to-reach areas, and perform tasks with high precision has enabled their applications throughout the project life cycle, ranging from preconstruction (e.g., site surveying and planning) to construction (e.g., inspection and material handling) and post-construction (e.g., damage assessment) (Albeaino and Gheisari, 2021; Rakha and Gorodetsky, 2018). This increasing integration of drones on jobsites is expected to continue and inevitably lead to more frequent human-drone interaction (HDI).

Despite drones' benefits, their deployment also introduces new occupational safety challenges that remain insufficiently addressed, particularly in dynamic and high-risk construction environments. Understanding how workers perceive, interpret, and interact with drones is therefore critical for

developing safe and efficient collaborative frameworks (Albeaino and Gheisari, 2021). Virtual Reality (VR) provides a safe, controlled, and repeatable environment for studying such human-drone interactions (Wohlgenannt et al., 2020). Furthermore, prior research has demonstrated that VR can elicit behavioral and physiological responses comparable to those in real-world conditions (Kisker et al., 2021). These advantages make VR an effective platform for examining safety-critical behaviors without exposing participants to physical risk, and it has been widely used in construction research, including studies on HDI, across topics such as safety, training, and task efficiency (Shourangiz et al., 2025). However, the majority of existing VR-based HDI studies do not report validation of the VR environment used as an experimental platform. This validation is important because human experiences in VR can be influenced by VR-related factors such as sense of presence and additional workload (Bareišytė et al., 2024; Halbig and Latoschik, 2021; Kisker et al., 2021). Therefore, this study aims to address this gap by proposing a framework for developing and validating VR environments for HDI research, featuring a realistic collaborative task design, multimodal assessment, and expert-based feasibility evaluation. Specifically, the study first presents the scenario content design and technical development of the VR environment. This is followed by a user-centered pilot test, where participants performed the designed collaborative task and were asked to evaluate the developed VR environment using a set of subjective questionnaires to assess perceived presence, perceived workload, and motion sickness. In addition, participants evaluated the technical reliability of the VR interactions and the relevance of the scenario design. An open-ended feedback question was also provided to allow participants to share additional insights regarding their experience in the developed VR environment. This study contributes to the body of knowledge by proposing and demonstrating a framework for developing and validating VR environments for HDI research in construction, providing feasibility evidence to support ecologically grounded future HDI studies.

Methodology

This study evaluates, through a two-step process, the feasibility of a developed VR environment for studying HDI in construction. The first step involved designing the scenario content and developing the VR environment to simulate a human-drone collaborative brick-wall painting task. The second step involved conducting a user-centered pilot study in which participants performed the VR painting task and evaluated their perceived presence, workload, motion sickness, VR technical reliability, and scenario design relevance. The following subsections describe the scenario content design, technical development of the VR environment, as well as the experimental procedures and evaluation.

Scenario Content Design

The scenario was designed to provide a realistic task context, close HDI, and sustained participant engagement within the VR environment. Accordingly, the selected task was intended to represent practical drone applications in construction while maintaining continuous interaction between the human and the drone. A brick-wall painting task was selected based on several considerations. First, drones have been successfully utilized in diverse real-world painting applications, such as artistic works and architectural surface finishing (Atluri et al., 2024; Susbielle et al., 2025; Vempati et al., 2018; Vidyullatha et al., 2023). Second, despite these successful cases, drones currently lack the precision required for fine-detail painting (e.g., cutting-in and color gradients) due to environmental disturbances and mechanical limitations (Galea et al., 2016; Galea and Kry, 2017; Susbielle et al., 2025; Vempati et al., 2018). This limitation necessitates collaborative interaction between the human and the drone, where drones perform large-area spray painting while human workers handle detailed finishing. Third, masonry wall painting keeps workers cognitively and visually engaged, as masonry construction requires high precision in block alignment and color patterning, demanding continuous attention and spatial reasoning (Memarian and Mitropoulos, 2011). Based on these considerations, the

brick-wall painting task provides a suitable scenario for implementing and examining HDI within the developed virtual environment.

Technical Development of the Virtual Environment

The virtual environment was developed in Unity®, where models of jobsite elements, including buildings under construction, tower cranes, construction machinery, and trailers, were imported to replicate a realistic construction site. Additional 3D models of workers and heavy machinery (e.g., forklifts) were added. Worker activity animations were imported from Adobe® Mixamo (Adobe Systems Incorporated, 2025) to create lifelike construction operations. Animations of machinery movement and visual effects, including dust and tire tracks, were also implemented, and construction noises recorded from real jobsites were integrated to enhance realism. A rotary-wing quadcopter—the most common drone type in construction—was modeled and further animated using C# scripts, with audio recorded from a DJI® Phantom 4 Pro, which is a widely used drone model in construction (Albeaino et al., 2023). The spatial blend feature was enabled in Unity® to simulate spatial audio and enhance environmental realism.

The collaborative painting task was positioned along a 24 ft-wide, 10 ft-high exterior brick wall (Figure 1). The wall contained a designated work zone divided into two adjacent sections with identical brick layouts: a Drone Painting Section and a Worker Painting Section. Boundaries between sections were delineated by blue masking tapes. In the drone section, the bottom seven brick courses each featured two random bricks (14 in total) that had been pre-painted in light orange, forming a staggered pattern. This section was prepared for the drone to apply a clear protective topcoat as the final finishing layer. The worker section was unpainted and needed to be hand-painted by participants. Painting actions were simulated using the VR controllers, where the right-hand controller functioned as a virtual brush, and the left-hand controller as a paint bucket (Figure 1). Haptic vibration feedback on both controllers was added to simulate brush contact with the wall and collisions with nearby components, enhancing immersion in the task. The paint on brush ran out after every 15 seconds of cumulative brushing, requiring participants to refill it by dipping the brush into the virtual bucket (left-hand controller). The developed VR environment and interactions were experienced through a Varjo® XR-4 (Focal Edition) VR headset.

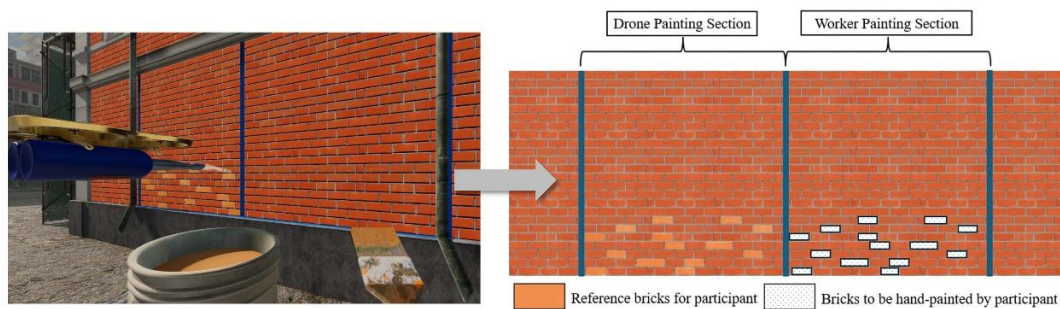


Figure 1. VR environment and work zone configuration

Experiment Procedure and Evaluation

A total of twelve participants took part in the pilot study to evaluate the feasibility of the developed VR environment. Five participants were professors or postdoctoral researchers with six to ten years of experience and recognized expertise in construction safety, human-robot interaction, robotics, or VR development. The remaining participants were graduate student researchers with three to five years of

experience in the same domains.

Before the experiment, participants completed the Simulation Sickness Questionnaire (SSQ) (Kennedy et al., 1993) to establish baseline motion sickness levels as recommended in prior study (Stanney et al., 1997). The SSQ is a validated and widely used survey for assessing motion sickness in VR environments, one of the key factors in VR evaluation (Bareišytė et al., 2024). After completing the pre-test survey, the participants started performing the human-drone collaborative painting task. During the task, the participants used a brush (right-hand controller) to paint the Worker Painting Section, replicating the color pattern in the Drone Painting Section (Figure 1). Simultaneously, a drone sprayed a clear protective topcoat on the Drone Coating Section as the final step of the painting workflow. Participants completed the task at their own pace, averaging approximately four minutes per session. After finishing the task, participants completed the SSQ again, along with two additional validated questionnaires. These included NASA-TLX (Hart and Staveland, 1988) for measuring perceived workload and Igroup Presence Questionnaire (IPQ) (Schubert et al., 2001) for sense of presence, which are also commonly examined in VR evaluations (Bareišytė et al., 2024; Halbig and Latoschik, 2021). In addition, participants completed a customized questionnaire assessing VR technical reliability and scenario design relevance, and were then asked to provide feedback through an open-ended feedback question, allowing them to share additional insights regarding their experience while completing the human-drone collaborative task in the VR environment.

Results and Discussion

Sense of Presence

Participants' average scores (M: mean; SD: Standard Deviation) on a 7-point Likert scale (-3 to +3) across four IPQ dimensions—*General Presence*, *Spatial Presence*, *Involvement*, and *Experienced Realism*—as well as the average score of all 14 IPQ items, are presented in Table 1. The IPQ was analyzed using the -3 to +3 scale to enable direct comparison with established benchmarks in the literature (Tran et al., 2024), ensuring consistency and contextual relevance in result interpretation.

The average score of the 14 IPQ items indicates that participants experienced very high levels of presence in the developed VR environment (M = 1.25, SD = 0.62). Compared with benchmarks established in the literature, which analyzed 180 HMD-based VR studies using the IPQ (Tran et al., 2024), this mean value (M = 1.25) fell within the “Very High” presence range, reflecting a strong sense of immersion among participants. This finding aligned with the high rating on the *General Presence* item (Q1, M = 2.25, SD = 0.62), which corresponds to the “Exceptional” range established in the literature, indicating that participants felt a strong sense of “being there” in VR. Overall, these two high ratings validated that the developed VR environment realistically simulated a construction site experience and made participants feel deeply immersed.

For *Spatial Presence*, participants reported a very high sense of engagement and connection with the virtual environment. They strongly felt “surrounded” by the virtual world (Q2, M = 2.00, SD = 1.21), and expressed moderate-to-high sense of acting within the virtual environment rather than operating it from outside (Q5, M = 1.50, SD = 1.24). Additionally, they felt highly present in the virtual construction site (Q6, M = 2.17, SD = 0.83), strongly disagreed with perceiving the virtual environment as mere pictures (Q3, M = -2.08, SD = 0.79), and reported a moderate-to-high sense of connection with the virtual space (Q4, M = 1.33, SD = 1.67). It is important to note that the calculated overall average score for *Spatial Presence* (M = 1.82, SD = 0.65) fell within the “Very High” range according to literature benchmarks, indicating very high levels of sense of being physically present within the virtual environment compared to other VR environments (Tran et al., 2024).

Regarding *Involvement*, participants demonstrated a high degree of attention to the painting task within the virtual environment. They indicated moderate awareness of the real world surrounding them during VR task (Q7, $M = 0.58$, $SD = 1.78$) and slightly agreed with being entirely detached from their physical environment (Q8, $M = 0.25$, $SD = 2.26$). Participants also reported some loss of attention to real-world elements, as reflected by their moderate disagreement with paying attention to their surroundings (Q9, $M = -0.75$, $SD = 2.01$). Additionally, they expressed a moderate-to-high sense of being captivated by the virtual environment (Q10, $M = 1.50$, $SD = 1.24$). It should be noted that the overall average *Involvement* score of 0.77 ($SD = 1.04$) falls within the “High” range according to benchmarks (Tran et al., 2024), suggesting that participants were highly focused on the human-drone collaborative painting task within the virtual environment and maintained a relatively low connection to their physical surroundings.

Table 1. IPQ (Mean and SD reported on a 7-point Likert scale: -3 to +3)

Questions	Mean \pm SD
Presence	
Q1. In the computer-generated world, I had a sense of "being there" (-3 = not at all, 3 = very much).	2.25 \pm 0.62
Spatial Presence	
Q2. Somehow, I felt that the virtual world surrounded me (-3 = fully disagree, 3 = fully agree).	
Q3. I felt like I was just perceiving pictures (-3 = fully disagree, 3 = fully agree).	
Q4. I did not feel present in the virtual space (-3 = not felt present, 3 = felt present).	1.82 \pm 0.65
Q5. I had a sense of acting in the virtual space, rather than operating something from outside (-3 = fully disagree, 3 = fully agree).	
Q6. I felt present in the virtual space (-3 = fully disagree, 3 = fully agree).	
Involvement	
Q7. How aware were you of the real world surrounding while navigating in the virtual world (i.e. sounds, room temperature, other people, etc.) (-3 = extremely aware, 3 = not aware at all)?	
Q8. I was not aware of my real environment (-3 = fully disagree, 3 = fully agree).	0.77 \pm 1.04
Q9. I still paid attention to the real environment (-3 = fully disagree, 3 = fully agree).	
Q10. I was completely captivated by the virtual world (-3 = fully disagree, 3 = fully agree).	
Experienced Realism	
Q11. How real did the virtual world seem to you (-3 = completely real, 3 = not real at all)?	
Q12. How much did your experience in the virtual environment seem consistent with your real-world experience (-3 = not consistent, 3 = very consistent)?	0.77 \pm 0.67
Q13. How real did the virtual world seem to you (-3 = as real as an imagined world, 3 = indistinguishable from the real world)?	
Q14. The virtual world seemed more realistic than the real world (-3 = fully disagree, 3 = fully agree).	
Average Score of 14 Items	1.25 \pm 0.62

In terms of *Experienced Realism*, participants perceived the virtual environment as highly realistic. They reported a very high degree of realism compared to the real world, as reflected in answers to

both “how real did the virtual world seem to you” questions with moderate-to-high averages of -0.58 ± 2.35 (Q11) and 1.33 ± 1.44 (Q13), as well as a strong sense of consistency with real-world experiences (Q12: $M = 1.92$, $SD = 0.67$). However, the score on Q14 ($M = -0.75$, $SD = 1.36$) suggests that participants distinguished the virtual environment from the real world, indicating an authentic but not exaggerated experience of realism. The overall *Experienced Realism* average score ($M = 0.77$, $SD = 0.67$) fell within the “Very High” range when compared to benchmark thresholds in the literature (Tran et al., 2024), demonstrating that the developed VR effectively replicated real site conditions.

Perceived Workload

Participants’ average NASA-TLX scores (range: 0-20) across the six workload dimensions (Mental, Physical, Temporal, Performance, Effort, and Frustration) are presented in Table 2. Broken down into the six workload dimensions, participants indicated that completing the human-drone collaborative painting task in the developed VR environment required a moderate level of mental effort (Mental Demand: $M = 9.00$, $SD = 5.17$), suggesting that while the task involved some cognitive engagement, it was not overly demanding. Physical demand was low (Physical Demand: $M = 6.08$, $SD = 4.87$), possibly because the task primarily required moderate upper-limb movements without overhead or repetitive full-body motions. Temporal demand was also low (Temporal Demand: $M = 5.83$, $SD = 4.04$), likely because the self-paced nature of the task allowed participants to proceed without time pressure. Participants rated their task performance relatively good (Performance: $M = 5.92$, $SD = 4.85$), reflecting a strong sense of success in task completion. Effort was rated as moderate (Effort: $M = 8.25$, $SD = 4.73$), suggesting that task completion required some effort but was manageable overall. In terms of frustration, participants reported low to moderate levels (Frustration: $M = 7.83$, $SD = 6.00$), indicating that while the experience was generally smooth, some technical or perceptual discomfort was encountered. Responses to the open-ended feedback provided further insight into potential sources of frustration. One participant highly rated the realism of the virtual environment but noted a technical issue: “*I felt a bit dizzy because there were some lags between the view in the VR headset and my head motion*”. This lag was possibly due to poor ambient lighting that interfered with the VR headset’s in-side-out tracking. Such latency could have contributed to occasional discomfort. In addition, two participants reported that the drone’s presence in the virtual environment felt distracting and induced mild annoyance, which may have influenced their frustration ratings. Although negative, these reactions suggest that the VR scenario effectively stimulated realistic human-drone interaction, where drones could attract some of individuals’ attention (Albeaino et al., 2023; Han et al., 2025). The overall average NASA-TLX score (range: 0-100) ($M = 35.76$, $SD = 14.31$) was found to be lower than benchmarks obtained from a meta-analytic review of 322 studies using NASA-TLX (Hertzum, 2021). Specifically, the obtained score fell below the average reported for VR-based studies ($M = 41$, $SD = 15$), indicating that the workload experienced by participants in the developed VR environment was manageable compared with typical VR applications.

Table 2. NASA-TLX Questionnaire

Workload Dimensions	Mean \pm SD
Mental Demand (0 = Low, 20 = High)	9.00 \pm 5.17
Physical Demand (0 = Low, 20 = High)	6.08 \pm 4.87
Temporal Demand (0 = Low, 20 = High)	5.83 \pm 4.04
Performance (0 = Good, 20 = Poor)	5.92 \pm 4.85
Effort (0 = Low, 20 = High)	8.25 \pm 4.73
Frustration Level (0 = Low, 20 = High)	7.83 \pm 6.00
Overall Average NASA-TLX Score (0 = Low - 100 = High)	35.76 \pm 14.31

Motion Sickness

Participants' SSQ ratings were recorded on a 4-point Likert scale (0 = none to 3 = severe) across sixteen motion sickness symptoms before and after performing the VR task. The differences between pre- and post-test scores were calculated to determine the level of motion sickness experienced, as recommended in previous studies (Bimberg et al., 2020). The average ratings across participants are presented in Table 3.

Table 3. SSQ (Mean reported on a 4-point Likert scale: 0 = none to 3 =severe)

Symptoms	Pre Test	Post Test	Δ Pre-Post	Δ N	Δ O	Δ D
General discomfort	0.25	0.58	0.33	0.33	0.33	
Fatigue	0.50	0.50	0.00		0.00	
Headache	0.25	0.58	0.33		0.33	
Eyestrain	0.67	1.08	0.42		0.42	
Difficulty focusing	0.42	0.33	-0.08		-0.08	-0.08
Increased salivation	0.08	0.17	0.08	0.08		
Sweating	0.08	0.08	0.00	0.00		
Nausea	0.00	0.58	0.58	0.58		0.58
Difficulty concentrating	0.33	0.58	0.25	0.25	0.25	
Fullness of head	0.33	0.58	0.25			0.25
Blurred vision	0.17	0.58	0.42		0.42	0.42
Dizzy (eyes open)	0.00	0.42	0.42			0.42
Dizzy (eyes closed)	0.17	0.50	0.33			0.33
Vertigo	0.00	0.08	0.08			0.08
Stomach awareness	0.00	0.08	0.08	0.08		
Burping	0.08	0.08	0.00	0.00		
Subscale Total Raw Score Difference				1.00	1.67	2.00
Calculated Subscale Severity Difference				12.72	12.63	27.84
Overall Motion Sickness Severity Difference					18.70	

The pre-test results showed that participants already exhibited low levels of motion sickness symptoms before exposure to the developed VR environment. Post-test responses indicated small but inconsistent changes across symptoms. In particular, increases were observed in general discomfort ($\Delta = 0.33$), headache ($\Delta = 0.33$), eyestrain ($\Delta = 0.42$), increased salivation ($\Delta = 0.08$), nausea ($\Delta = 0.58$), difficulty concentrating ($\Delta = 0.25$), fullness of head ($\Delta = 0.25$), blurred vision ($\Delta = 0.42$), dizziness with eyes open ($\Delta = 0.42$) and closed ($\Delta = 0.33$), vertigo ($\Delta = 0.08$), and stomach awareness ($\Delta = 0.08$). The increases in these symptoms are commonly reported during VR exposure and are generally considered tolerable (Stanney et al., 1997). Fatigue, sweating, and burping remained stable ($\Delta = 0$), while difficulty focusing slightly decreased after task completion ($\Delta = -0.08$). A statistical analysis (Wilcoxon test) on individual symptom scores confirmed that none of these changes were statistically significant ($p > 0.05$), suggesting that although minor discomfort occurred in some participants, overall physiological and perceptual effects were minimal and within tolerable limits.

The pre- and post-test differences in the sixteen symptoms were used to calculate the severity changes of three non-exclusive SSQ subscales—Nausea (N), Oculomotor (O), and Disorientation (D)—according to the standard weighted scoring procedure (Stanney et al., 1997). The Nausea and Oculomotor subscales showed moderate increases ($\Delta N = 12.72$, $\Delta O = 12.63$), suggesting that performing the VR task induced mild stomach upset and eye discomfort. However, the Disorientation subscale exhibited a larger rise ($\Delta D = 27.84$), indicating that participants experienced greater spatial disorientation and balance disturbance after the VR task. This greater increase aligns with prior

findings that HMD-based VR experiences tend to elicit stronger disorientation symptoms (Stanney et al., 1997), and was likely due to slight latency between the visual scene in the headset and head movements, which caused a mismatch between visual and motion sensory inputs. The overall motion-sickness severity difference was 18.70, remaining below the threshold typically associated with severe motion sickness (20), but continued monitoring is recommended (Stanney et al., 1997). These descriptive results indicate that participants experienced an acceptable level of motion sickness in the developed VR environment, primarily characterized by Disorientation rather than Nausea or Oculomotor symptoms. However, statistical analysis revealed that only the increase in Nausea was statistically significant ($p = 0.028$), while Oculomotor ($p = 0.239$) and overall motion-sickness severity ($p = 0.097$) were not, and Disorientation exhibited a near-significant trend ($p = 0.065$). The significant rise in Nausea likely reflects consistent but mild gastrointestinal discomfort across participants, whereas the near-significant Disorientation increase was likely influenced by high variability driven by one participant who reported high symptom scores across all Disorientation items. Taken together, these findings indicate that the VR task triggered mild but tolerable motion-sickness effects—mainly moderate nausea and disorientation—rather than severe or widespread adverse symptoms. Therefore, the developed VR environment was considered suitable for experimental use.

Technical Reliability and Scenario Design Relevance

Participants completed a customized questionnaire to further evaluate the technical reliability of the VR interactions (Q1-Q2) and the relevance of the scenario design (Q3-Q4). Responses were recorded on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree), and the average score of each item is presented in Table 4. For *Technical Reliability*, participants agreed strongly that the VR interactions during the painting task were responsive and smooth, with minimal lag (Q1, $M = 4.33$, $SD = 0.98$). This indicates that the control and feedback mechanisms of the VR system were technically stable and provided a seamless user experience. The visual and auditory effects were also rated highly (Q2, $M = 4.25$, $SD = 1.06$), suggesting that the sensory feedback effectively reflected real-world construction site conditions. As for *Scenario Design Relevance*, participants reported that performing the wall-painting actions in VR felt natural and realistic (Q3, $M = 3.92$, $SD = 0.90$), demonstrating that the implemented interactions successfully represented the physical and visual dynamics of real painting tasks. In addition, the HDI was perceived as highly realistic (Q4, $M = 4.08$, $SD = 1.00$), indicating that participants viewed the designed teamwork between the human and drone as a realistic representation of emerging collaborative workflows in future robot-assisted construction contexts. Overall, these high ratings confirm that participants found the developed VR environment technically responsive, perceptually realistic, and conceptually relevant, supporting its feasibility for controlled experimental use.

Table 4. Customized Questions (Mean reported on a 5-point Likert scale: 1 = strongly disagree to 5 = strongly agree)

Questions on Technical Reliability and Scenario Design Relevance		Mean \pm SD
Q1.	The VR interactions for the painting task (using the controllers, VR headset) were responsive and smooth, without noticeable lag.	4.33 \pm 0.98
Q2.	The VR visual and sound effects were reflective of real-world construction jobsite conditions.	4.25 \pm 1.06
Q3.	Performing the wall painting actions in VR felt natural and realistic, appropriately reflecting a painting task on construction jobsites.	3.92 \pm 0.90
Q4.	The collaboration between the human and drone realistically represented a futuristic human-drone collaborative task on future robot-populated jobsites.	4.08 \pm 1.00

Conclusion

This study aims to evaluate the feasibility of a developed VR environment for HDI research in construction. A pilot test involving a realistic brick-wall painting task was conducted. Twelve participants with expertise in VR, construction safety, human-robot interaction, and robotics assessed the environment in terms of sense of presence, perceived workload, motion sickness, VR technical reliability, and scenario design relevance. The results indicated exceptionally high presence, suggesting that participants felt deeply immersed and engaged within the VR environment. The perceived workload remained within an acceptable range, suggesting that the VR task was cognitively engaging yet not fatiguing. Motion sickness rating was below the threshold for a bad experience, suggesting an acceptable level of discomfort, though close monitoring is required. Participants also moderately to strongly agreed that the VR interactions were smooth and reflective of real construction operations, and that the scenario design realistically represented potential future HDI on jobsites. Despite the optimal feedback, one technical issue was observed—occasional desynchronization between head motion and headset visuals—likely caused by inside-out tracking interference from overexposed ambient lighting. Participants also suggested enhancing realism by incorporating additional moving workers, equipment, and construction sounds. Future work will focus on addressing these limitations and refining the environment to improve its reliability and realism, thereby advancing the use of VR as an effective platform for HDI research in construction.

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