Impact of interaction techniques on performance in virtual reality-based drone training for construction

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Abstract

Purpose – This study aims to examine how different input modalities in virtual reality (VR) affect operator performance during drone-assisted tasks in construction. As drones become increasingly integrated into workflows, the demand for effective operator training solutions continues to grow. While prior efforts have demonstrated the utility of VR for simulating drone operations, they often overlook how specific input modalities, both physical controller and interface design, shape the user's ability to perform spatial navigation and operational tasks. This research addresses that gap by examining the impact of input modalities on operator performance, offering insights into designing training systems that align with the cognitive and physical demands of real-world drone piloting.

Design/methodology/approach – A within-subject experimental study was conducted in a simulated construction site environment. Thirty-eight participants completed hazard inspection tasks under two input modalities and their associated control interfaces: (1) joystick-based control via game controller; and (2) slider-based control using standard VR motion controllers. Performance was measured by the number of hazards identified and the time required to complete the task in both conditions.

Findings – Wilcoxon signed-rank test results revealed that joystick-based control yielded a statistically significant 12.3% increase in hazard identification score and a 16% reduction in task time. These findings suggest that realism of input modality can enhance task efficiency and effectiveness within VR-based environments.

Originality/value – This study contributes to the growing literature on VR-based training for drone operators by providing empirical evidence on the effect of input modalities on performance outcomes offering

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practical guidance for developing user-centered VR training frameworks that replicate real-world operational scenarios.

Keywords Virtual reality training, Input modality, Control interface, Drone operator, Hazard identification

Paper type Research paper

1. Introduction

Construction is undergoing a significant digital transformation, driven by the adoption of sensing and data-driven technologies such as drones, wearable sensors, laser scanners and smart cameras. These tools are reshaping how safety is managed on job sites by enabling real-time data collection, enhancing situational awareness and automating site inspections ultimately supporting more informed decision-making and risk mitigation strategies (Bosché and Haas, 2019; Park *et al.*, 2023; Teizer *et al.*, 2019; Zaidi *et al.*, 2024). Drones, in particular, are being increasingly used in construction (Albeaino *et al.*, 2021; Mendes *et al.*, 2022). The U.S. Construction Survey 2024 reports that 45% of civil contractors and 67% of larger firms have fully integrated drones into their workflows, contributing to a market valued at US$1.44bn in 2023, with a projected growth rate of 12.73% by 2032 (Amar C *et al.*, 2020). The use of drones now spans the entire project lifecycle, with applications including aerial site mapping and surveying (Kim *et al.*, 2019; Westoby *et al.*, 2012), material delivery (Zhang *et al.*, 2024), progress monitoring (Keyvanfar *et al.*, 2022), structural inspection and monitoring (Wang *et al.*, 2022) and hazard detection (Martinez *et al.*, 2020). The deployment of drones on construction sites has enabled access to hard-to-reach or hazardous areas, while also allowing tasks to be completed in a safer and more cost-effective manner compared to traditional methods (Lawani *et al.*, 2022).

Nevertheless, the increased on-site deployment of drones has been accompanied by safety concerns. In 2022, there was a reported 60% increase in drone-related incidents compared to previous year (DroneSec, 2023; Siratranont *et al.*, 2025), signaling a growing concern within the construction sector. This rise may be largely attributed to the rapid increase in drone adoption without sufficient and effective training of operators (Siratranont *et al.*, 2025). Prior studies indicate that well-designed training programs can effectively enhance drone operators' understanding and performance in high-stakes tasks (Khuwaja *et al.*, 2018; Sakib *et al.*, 2020). Traditional training methods often fail to address the complex, real-world challenges associated with drone operations, particularly in active construction environments, where operators must physically operate drones through hazardous and spatially dynamic settings while simultaneously interpreting required information through digital interfaces (Albeaino *et al.*, 2021; Nwaogu *et al.*, 2024; Jeelani *et al.*, 2020). Other, more conventional approaches such as instructor-led workshops and on-site demonstrations, also fall short in providing the hands-on experience necessary for operators to safely and efficiently operate drones in construction environments (Lawani *et al.*, 2022; Nwaogu *et al.*, 2024). Therefore, the development and implementation of efficient training protocols is essential to equip drone operators with the skills needed for safe and effective deployment on construction sites.

Given the growing need for effective drone operator training in construction, several researchers have explored technology-enhanced approaches to improve training outcomes. Immersive technologies, particularly virtual reality (VR)-based training enables learners to engage in task-specific experiences in a repeatable and safe manner, thereby supporting experiential learning in critical contexts (Fu *et al.*, 2024; Pedro *et al.*, 2019, 2022; Sabir *et al.*, 2025). For instance, Sakib *et al.* (2020) examined physiological responses of drone operators during immersive VR training and real-world deployment, demonstrating comparable patterns in stress and workload across both environments and highlighting the value of VR in replicating real-world operational demands. In addition, Albeaino et al. (2022a, 2022b) compared simulator-based and real-world drone training environments, demonstrating that virtual training can effectively assess in-flight workload demands and prepare operators for building inspection tasks.

While these efforts have emphasized the importance of VR-based drone training in construction and advocated for its use, little attention has been given to how specific interaction design elements, such as the interaction method and interface design, collectively referred to here as input modality, affect operator performance. Addressing this research gap is particularly important, as insights from broader VR-based training research suggest that input modality plays a critical role in shaping user experience and learning outcomes (Makransky and Petersen, 2021). Moreover, aligning input modalities with real-world tasks has been shown to improve accuracy, reduce cognitive load and enhance training effectiveness, particularly in complex scenarios (Chen *et al.*, 2023). Therefore, to effectively use VR simulations as training tools for drone operations in construction, it is essential to understand how different input modalities influence task performance. This paper investigates the effect of input modality within a VR-based drone training environment using a hazard identification task representative of real-world construction scenarios. The findings of this study aim to inform the design of more effective and intuitive interaction strategies for future VR-based drone training systems.

2. Background

2.1 Importance of input modality in virtual reality-based training in construction

The effectiveness of VR-based training depends on how closely user interactions in the virtual environment support real-world task execution. Input modality, defined as the combined effect of interaction modality and control interface design, fundamentally shapes this relationship (Bonfert *et al.*, 2025; McMahan, 2018). It has emerged as a critical determinant of user interaction and learning efficacy in virtual training environments (Chettaoui *et al.*, 2022; Rettinger and Rigoll, 2023; Schaffer *et al.*, 2015). Input modalities offering natural, task-aligned control enhance spatial navigation and action–perception coupling during operations in simulated tasks. Conversely, poorly aligned interfaces increase cognitive workload and disrupt situational awareness in complex environments such as construction sites (Wickens *et al.*, 2015). Cognitive Load Theory (Sweller, 2011) explains this mechanism: abstract interfaces impose high extraneous cognitive load, requiring users to devote limited working memory resources to managing the interface rather than the task itself. These interaction and cognitive factors directly affect the transfer of training, as skills are more likely to transfer when training preserves the functional characteristics of real-world tasks, including control behaviors and decision-making demands (Hussain *et al.*, 2023; Salas *et al.*, 2012) Together, these perspectives indicate that input modality is a critical design variable in VR-based drone training, shaping operator performance through its influence on interaction fidelity, cognitive load and learning transfer. Thus, the choice of input modality is not merely a preference but a determinant of cognitive efficiency (Kojic *et al.*, 2019).

Recent research emphasizes that these modalities (e.g. handheld controllers, hand tracking) that leverage physical movement and tangible objects allow users to conceptually understand and physically manipulate virtual controls, thereby mimicking real-world operations and making digital environments more intuitive and engaging for trainees (Bonfert *et al.*, 2025; Schaffer *et al.*, 2015; Yuan *et al.*, 2023). Furthermore, the design and quality of the user interface, closely tied to the chosen interaction modality,play a crucial role in shaping user experience, as intuitive and well-matched interfaces can significantly enhance engagement, ease of use and the effectiveness of VR-based learning tasks (Kojic *et al.*, 2019). Building on the significance of input modality in immersive VR training, recent investigations in construction training have also explored the system effectiveness associated with different modalities. For instance, Harichandran and Teizer (2022) compared data gloves versus traditional controllers for automated gesture recognition in crane rigging operations during VR construction safety training, demonstrating how different input modalities can affect communication effectiveness and hazard recognition. Alzarrad *et al.* (2024) developed an interactive VR system for construction fall prevention training that utilized hand-tracking capabilities and found that natural hand interactions enhanced immersion and knowledge retention compared to traditional controller-based methods. The authors investigated both the advantages and the need to consider cognitive load in interface and instructional design. Similarly, Luo *et al.* (2023) compared the effect of both VR environment design and the interactive devices on construction safety VR training scenarios. The sense of presence and completion time showed significant differences when changing the design of the VR environment, while no significant differences when changing the interactive devices. Therefore, it is important to study and understand the impact of input modality on VR-based training systems to ensure that the interaction designs used in construction training environments are optimized for both user engagement and performance.

2.2 Current status of virtual reality-based drone training in construction and research gap

In VR-based drone operation scenarios, where operators must simultaneously manage spatial navigation, equipment control and other operational tasks, interaction methods and interface design can pose excessive cognitive demands that may undermine performance. Previous studies, including those using VR-based environments for drone operator training in construction, have primarily focused on evaluating system effectiveness with varying objectives (Table 1). For instance, Albeaino *et al.* (2022a, 2022b) introduced a VR-based simulator to support drone-mediated building inspections, aiming to replicate real inspection workflows and improve user readiness. Sakib *et al.* (2020) investigated the potential of combining wearable biosensors with immersive VR to assess stress and engagement levels during drone operation tasks. Similarly, Szóstak *et al.* (2024) designed and tested an immersive VR environment to promote safe UAV operations in construction scenarios, focusing on simulating realistic site conditions for hazard awareness and protocol adherence. Furthermore, Albeaino *et al.* (2022b) developed a VR-based training environment designed to enhance drone piloting and building inspection skills among construction students, offering a safe and cost-effective alternative to real-world training.

Despite this growing interest in leveraging VR-based simulations for drone training in construction, the variation of input modality, particularly the choice of interaction tool and control interface, and how they shape VR training outcomes has not been yet investigated. In existing studies, the input modality is treated as a fixed element rather than a design variable, thereby overlooking how different modalities, such as physical joysticks versus VR motion controllers, may influence user engagement, error rates, cognitive load and skill acquisition. This limitation underscores the need for a deeper investigation into the impact of input modality on training outcomes, especially in safety-critical, task-oriented drone operations within construction environments. The absence of such evidence limits the ability to design immersive training systems that align both with technical skill acquisition and operational decision-making required in construction environments. A systematic investigation of these dynamics is necessary to inform the design of immersive VR-based drone training systems

Table 1. Summary of selected training studies related to drone use in construction

Authors	Objectives	Study/training focus	Key contributions
Nwaogu *et al.* (2024)	Assessment of training needs and roadmap for drone competency	Skill gaps, curriculum roadmap	Identified key areas for competency development; emphasized tailored curricula
Szóstak *et al.* (2024)	Development and testing of immersive VR for UAV safety	Safety-critical drone operations in construction	Demonstrated effectiveness of immersive VR in promoting safe UAV practices
Albeaino *et al.* (2022a)	Development of DroneSim VR-based flight simulator	Building inspection simulation	Reported high engagement and improved control using immersive VR interface
Sakib *et al.* (2020)	Experimental study using wearable tech and VR	Multimodal data collection, immersive interaction	Found VR and wearable tech enhanced training effectiveness
Albeaino *et al.* (2022b)	Train construction students in drone piloting for inspections	HMD-based VR simulator with task controls	Technical development and usability testing of training simulator

Source(s): Authors' own work

that can replicate real-world conditions while optimizing both physical interaction and interface design. The following section presents the research methodology designed to investigate these objectives in a controlled experimental setting.

3. Research methodology

This study employed a within-subjects experimental design to examine the effects of two distinct input modalities by varying both the physical input device and the virtual control interface. Following the approach of prior studies that evaluated the effects of input realism and control alignment in simulation-based training (Luro and Sundstedt, 2019; Palombo *et al.*, 2024), the present study adopted a comparative framework to evaluate representative input modalities used in drone operation:

(1) Joystick-based Control with Game Controller Input Modality (JX-IM).

(2) Slider-based Control with VR Controller Input Modality (SVR-IM).

A VR-based training environment was developed to replicate a drone-mediated safety inspection and hazard identification task in a construction site, and participants were asked to complete this task using both input modalities in the VR environment to assess differences in performance. A three-step procedure was adopted in this study (Figure 1). The following subsections discuss each step in detail.

3.1 Scenario selection and task design

Drone-mediated site safety inspection was selected as the focal task for this study, as it directly aligns with the increasing use of drones for safety management in construction environments (Zhu *et al.*, 2022). Drones offer the advantage of capturing real-time data from hard-to-reach areas, enhancing situational awareness and reducing the time and cost of traditional methods (Albeaino *et al.*, 2022b; Nwaogu *et al.*, 2024). While drones provide significant advantages in terms of efficiency and safety, their operation in complex, congested construction environments require high-level skills and focused attention. Operators must navigate tight

1. Scenario Selection and Task Design	2. VR Development	3. Experimental Procedure
Objective: Design a relevant task that reflects drone operation in construction settings.	**Objective:** Develop a realistic VR environment to simulate a construction task and onsite drone operations under two input modality conditions: (1) Joystick-based Input Modality (JX-IM); and (2) Slider-based Input Modality (SVR-IM).	**Objective**: Conduct a user-centered within-subjects experiment where participants go through both VR conditions (JX-IM and SVR-IM) and compare the resulting input modality effect on human performance using two metrics: (1) Hazard Identification Score; and (2) Task Completion Time.

Figure 1. Overview of research method steps

spaces, avoid obstacles, and efficiently identify hazards in dynamic and often cluttered site conditions. Therefore, the task requires precise maneuvering and critical operations to effectively navigate complex jobsite environments, which is key to ensuring the safety and efficiency of site inspections. Thus, site safety inspection serves as an ideal scenario to explore the impact of input modality on drone operators' performance.

To accurately simulate these real-world construction safety conditions, a diverse set of safety hazards was embedded in the VR environment, using a three-stage refinement process. First, potential hazards were classified according to the Occupational Safety and Health Administration (OSHA) "Focus Four" hazards, Falls, Struck-by, Caught-in/between and Electrocution, which collectively account for the majority of fatal incidents in the construction industry (OSHA, 2011). Second, common construction incident reports were analyzed to identify high-frequency accident scenarios that are observable from aerial viewpoints, ensuring the training emphasized high-impact risks suitable for drone-based inspections. Third, a panel of five academic experts with expertise in construction safety and visual inspection independently reviewed the proposed hazards. The panel evaluated each scenario based on two primary criteria:

(1) Relevance to drone-based aerial inspections, ensuring the hazard realistically represented common site safety violations.

(2) Visual detectability from a typical drone operating altitude.

Through this iterative expert review process, the final set of hazards was refined to vary in both risk severity level and visual salience, thereby supporting the ecological validity of the VR training environment and the pedagogical objective of reinforcing hazard recognition using drones.

Table 2 outlines the hazards included in the simulation, their classifications and the rationale for their inclusion based on field relevance and visual detectability from a drone operator's perspective. While the total number of hazards was kept identical across distinct conditions to ensure consistency, the spatial arrangement was deliberately varied. This

Table 2. Classification and rationale of predefined hazards included in the virtual inspection site

Hazard	Hazard type	OSHA category	Justification for inclusion
Missing guardrails	Fall hazard	Fall protection	Represents One of the most cited OSHA violations; highly visible from elevated drone views; critical for perimeter safety
Tripping hazard (rebar)	Trip hazard	Housekeeping	Simulates poor housekeeping – a common real-world hazard; easily observed in drone flyovers
Suspended load	Struck-by hazard	Material handling	Demonstrates critical awareness of crane operations; drone view offers effective hazard assessment of load movement
Electrocution risk	Electrical hazard	Electrical safety	Highlights proximity to energized equipment; supports visual risk detection in power zones
Rolling barrels	Caught-in hazard	Material storage	Represents unsecured material hazards that pose risks when rolled; relevant for area scanning
Missing rebar caps	Impalement hazard	Site preparation	Frequently overlooked hazard; excellent test of visual attentiveness from aerial angles
Continuous hammering	Ergonomic hazard	Overexertion ergonomic	Simulates prolonged vibration exposure; useful for assessing noise-related and ergonomic risks
Kickback (tool use)	Struck-by motion risk	Tool Use-PPE	Represents common tool-related accidents; visible operator animation aids hazard recognition
Heavy load lifting	Manual handling	Ergonomics-Lifting	Represents musculoskeletal risk; used to test participants' interpretation of lifting scenarios

Source(s): Authors' own work

modification aimed to minimize carryover effects, specifically, the possibility of participants memorizing hazard locations from the previous condition (Noghabaei and Han, 2020). By randomizing the hazard positions, the study ensured that performance differences could be more reliably attributed to the type of input modality rather than memory-based recognition.

3.2 Virtual reality development

The VR environment was developed using the Unity© game engine and C# programming language on a Dell© Precision 5820 Tower workstation. An HTC© Vive Pro head-mounted display (HMD) was integrated to facilitate immersive VR interaction. The system was equipped with an Intel(R) Core (TM) i9-10900X processor running at 3.70 GHz with 20 logical cores, 128GB of RAM and an NVIDIA© RTX A4500 graphics card. The virtual interaction design featured two distinct modules for drone-based site safety inspection: SVR-IM module, which employed a conventional slider-based UI with custom VR hand controllers; and JX-IM module, which utilized a game controller as a physical component, and a UI modeled after real-world drone control systems (Figure 2). The virtual environment was dynamic, incorporating simulated construction site conditions with moving equipment and environmental elements to enhance ecological validity. Environmental dynamics, including equipment movement sequences and timing, were scripted identically in both modules, ensuring that participants encountered equivalent environmental complexity regardless of input modality. All non-input parameters including speed, field of view and acceleration of the drone simulation were controlled and held constant across both modules. Participants were required to complete both modules by navigating the virtual drone through the developed VR environment and identifying the predefined hazards for controlled input modality comparison.

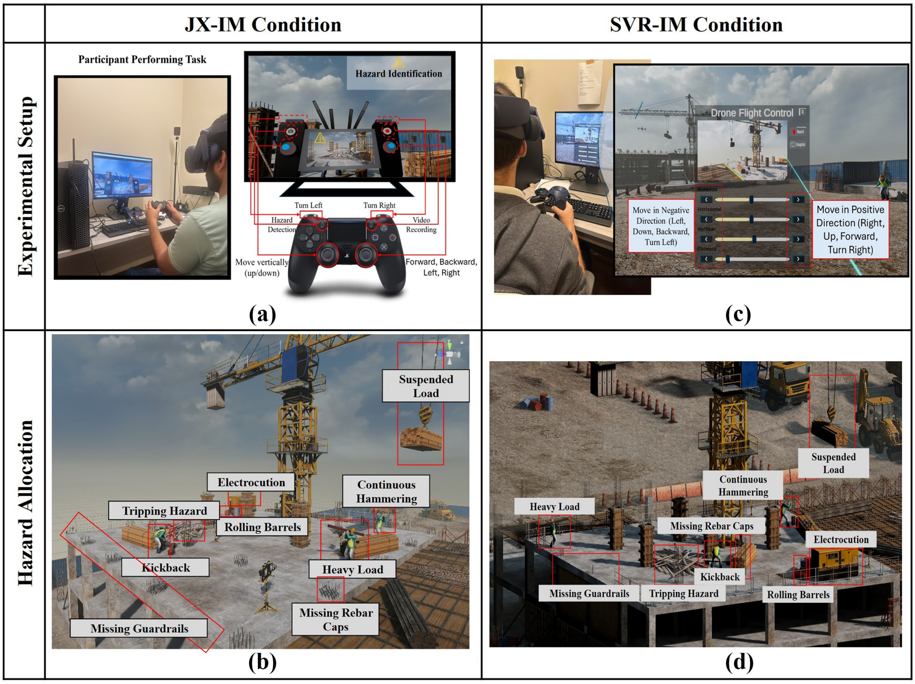

Figure 2. Experimental setup and virtual environment for drone-based hazard identification training: (a) JX-IM (Joystick-based interface with PS4 controller input modality) setup, (b) aerial layout of preconfigured virtual site with safety hazards for JX-IM condition, (c) SVR-IM (Slider-based interface with VR controller input modality) setup and (d) aerial layout of preconfigured virtual site with safety hazards for SVR-IM condition

3.2.1 Module 1: Joystick-based control with game controller input modality (JX-IM). The JX-IM module facilitated a realistic and immersive virtual inspection experience by enabling participants to operate a drone using a Sony© PS4 controller, which closely resembles the physical interface employed in many real-world drone operations. The virtual user interface was designed as an integrated, consolidated telemetry display mirroring the layout of commercial drone control systems. The interface presented real-time flight information and control status in a unified visual layout, including dual-stick maneuvering indicators, directional cues and action triggers for flight stabilization and camera adjustments. This integrated design allowed simultaneous control of multiple movement axes through intuitive joystick inputs [see Figure 2(a)]. Participants can interact through the PS4 controller as a unified, tangible input device, where physical actions, such as tilting joysticks or pressing specific buttons, were instantly translated into drone movements within the virtual environment. This real-time responsiveness was reinforced by a virtual replica of the controller rendered in the VR space, allowing participants to visually confirm and synchronize their hand movements with corresponding drone behavior. The incorporation of familiar drone GUI elements further enhanced the intuitiveness of the control scheme. This configuration was designed to simulate a realistic drone inspection operation scenario. Figure 2 illustrates the setup as well as the aerial layout of the virtual site containing the safety hazards for the JX-IM condition.

3.2.2 Module 2: Slider-based interface with VR controller input modality (SVR-IM). The SVR-IM module was designed so that participants can perform site inspection tasks using a virtual drone operated through a conventional VR hand controller. This condition featured a modular, segmented interface layout with separate slider controls positioned for each movement axis. As shown in Figure 2(c), participants used VR hand controller ray-casting to interact with discrete sliders for vertical (up/down), horizontal (left/right), rotational (yaw) and forward/backward movement. Unlike the JX-IM condition, which enabled simultaneous multi-axis control through joystick input, this segmented slider layout required sequential adjustment of individual axes, thereby reducing the naturalness and fluidity of drone navigation. The setup and navigation approach for this SVR-IM module are illustrated in Figure 2.

3.3 User centered experimental procedure

This study employed a within-subject design, enabling direct comparison of both input modalities with the same participant pool. Participants were recruited through classroom announcements and departmental email outreach targeting students from the Department of Construction Science at Texas A&M University to ensure diversity in the sample. Prior to participation, individuals were screened to verify adequate vision without corrective eyewear and to identify any visual or physical limitations that could impact equitable participation. The study protocol was approved by the Texas A&M Institutional Review Board (IRB), and written informed consent was obtained from all participants.

Participants first underwent a preparatory session designed to familiarize them with the VR setup including both input modalities and the general categories of hazards commonly encountered on construction sites. The session incorporated an OSHA-based instructional video shown on desktop, offering visual demonstrations of common risks such as falls, electrical hazards and struck-by incidents. This preparatory session also included a quiz assessing their understanding of common construction site hazards. Those who scored 80% or higher advanced to the main task, while those scoring below were required to rewatch the video and complete an alternative version of the quiz. While the preparatory session did not reveal the exact hazard instances embedded in the VR scenario, it provided a foundational understanding aligned with the inspection task. This alignment ensured that participants entered the main task with contextual awareness of hazard types, thereby promoting realistic identification strategies without compromising the integrity of the task. Following the training, participants used the HTC© Vive Pro HMD to complete both input modalities in the virtual environment. The VR system automatically recorded performance metrics, including task initiation and completion times using C# scripts that were developed and integrated into in Unity© and the VR environment. Participants were instructed to detect and document hazards using the associated input modality by capturing images of the identified hazard and verbally informing the researchers the type of the hazard identified while accomplishing their tasks in VR. While this approach reduced inter-individual variability, it may introduce potential carryover effects such as learning or fatigue. To mitigate these effects, two techniques were applied. First, although the number of hazards remained consistent across both scenarios, their spatial arrangement was altered to prevent memorization (Noghabaei and Han, 2020). Second, participants were assigned to one of two counterbalanced sequences based on their participant ID. Those with even-numbered IDs completed Condition 1: JX-IM, followed by Condition 2: SVR-IM, whereas participants with odd-numbered IDs followed the reverse sequence. This counterbalanced sequence was used to mitigate potential order effects and ensure the reliability of performance comparisons across input modalities. To minimize potential fatigue and cybersickness effects, a mandatory rest interval of 5–8 min was enforced between the two experimental conditions, consistent with safety protocols in prior VR research (Oh and Son, 2022). During this break, participants removed the HMD to rest their eyes and reorient them to the physical environment.

3.4 Data analysis

Based on this experimental setup, it was hypothesized that the input modality type would have a significant effect on participant performance in terms of both task completion as well as hazard identification. Data collected during the training sessions was recorded in CSV files and later processed for analysis. The performance data was extracted from the experimental logs and analyzed using IBM© SPSS Statistics Version 28. Two primary outcome variables were derived from the system logs for each participant:

(1) Hazard Identification Score (HI_Score).

(2) Task Completion Time (T_{comp}).

The HI score was calculated as the total number of hazards correctly identified by each participant during each session, A binary scoring system was employed where a value of 1 was assigned for each correct identification and 0 for missed hazards. Correct identification required two conditions:

(1) The hazard was clearly visible within the participant's captured image frame.

(2) The participant provided a correct verbal classification of the hazard type to the research team.

Identifications were cross-checked against the preprogrammed hazard locations to ensure accuracy. The score was computed using the following formula: $HI\_Score = \sum_{i=1}^{n} H_i$,Where: $H_i = 1$ if hazard i was correctly identified, otherwise 0, n = total number of predefined hazards in the scenario. This scoring protocol aligns with established hazard recognition assessment frameworks employed in prior construction safety research (e.g. Jeelani *et al.*, 2018; Namian *et al.*, 2016), which prioritize the cognitive identification of safety risks over precise spatial annotation. Task Completion Time was defined as the duration (in minutes) from the system-logged initiation of the drone inspection task in the VR environment to the system-logged termination of the task. The end of the task occurs after the participant completes all hazard identifications, captures all identified hazards through the VR interface, and confirms task completion. This measure encompasses the entire inspection workflow, from the start of drone operation to the completion of hazard documentation. It was calculated using the equation: $T_{comp} = T_{end} - T_{start}$, Where: T_start = system-logged task start time, T_end = system-logged task end time. Since the data violated the assumption of normality (Shapiro-Wilk $p < 0.05$), the nonparametric Wilcoxon signed-ranks test was employed to compare input modalities in this within-subjects design. This test is suitable for related samples with non-normal distributions.

4. Results

4.1 Participant demographics

A total of 41 students initially participated in the experiment, with ages ranging from 18 to 44 years (Table 3). However, due to invalid responses, data from 3 male participants in the 18–24 age group were excluded, resulting in a final data set of 38 participants. Among them, 76.32% were male and 23.68% were female. Most participants had construction-related academic backgrounds (92.11%), with the remaining coming from engineering (5.26%) and architecture (2.63%). The majority (63.16%) had less than one year of construction-related experience, while 34.21% reported having between one and five years of experience. In

Table 3. Demographic overview of the participant sample

Demographics	Categories	Count	%
Age	18–24	33	86.84
	25–34	4	10.53
	35–44	1	2.63
Gender	Female	9	23.68
	Male	29	76.32
Construction industry experience	0–1 years	24	63.16
	1–5 years	13	34.21
	6–10 years	1	2.63
Safety training	OSHA 10	21	55.26
	OSHA 30	3	7.89
	No	14	36.84

Source(s): Authors' own work

addition, 63.16% of participants had received OSHA training, whereas the remaining 36.84% reported no formal safety training. To control for potential confounding effects of prior drone experience, participants' familiarity with robotic systems, including drones, was assessed using a five-point Likert scale (1 = No familiarity; 5 = Very familiar). Results indicated that all 38 participants reported below-average familiarity, with a mean score of 1.7 out of 5.0 (SD = 0.82), thereby minimizing the influence of prior drone operation experience on study outcomes.

4.2 Number of identified hazards

A Wilcoxon signed-rank test was conducted to compare hazard identification scores between the SVR-IM and JX-IM conditions. The results showed that participants identified more hazards in the JX-IM condition (M = 5.37, SD = 1.95) compared to the SVR-IM condition (M = 4.79, SD = 1.86). This difference was statistically significant (Z = 2.13, $p = 0.03$), with a medium effect size ($r = 0.35$), indicating that input modality significantly influenced hazard identification performance. Figure 3 presents a boxplot of hazards identified for each modality, showing the median, interquartile range (IQR), minimum and maximum values. To further examine the consistency of individual responses to both input modalities, participant-level improvement trends were analyzed (Figure 4). The results indicated that 57.9% of participants identified more hazards using JX-IM compared to SVR-IM.

4.3 Hazard identification time

A Wilcoxon signed-rank test was conducted to evaluate differences in task completion time between the SVR-IM and JX-IM input modality conditions. The analysis revealed that participants completed the task more quickly in the JX-IM condition (M = 7.37, SD = 3.13) than in the SVR-IM condition (M = 9.13, SD = 3.03). This difference was statistically significant ($Z = 3.20$, $p = 0.001$), with a large effect size ($r = 0.52$), indicating that input modality significantly influenced task completion time Figure 5 presents a boxplot of task completion times for each condition, showing the median, IQR, minimum and maximum values; the JX-IM condition exhibited a lower median and a tighter distribution, indicating more efficient and consistent performance. To further examine individual trends, participant-level completion times were analyzed (Figure 6), revealing that 68.4% of participants completed the task faster using JX-IM compared to SVR-IM.

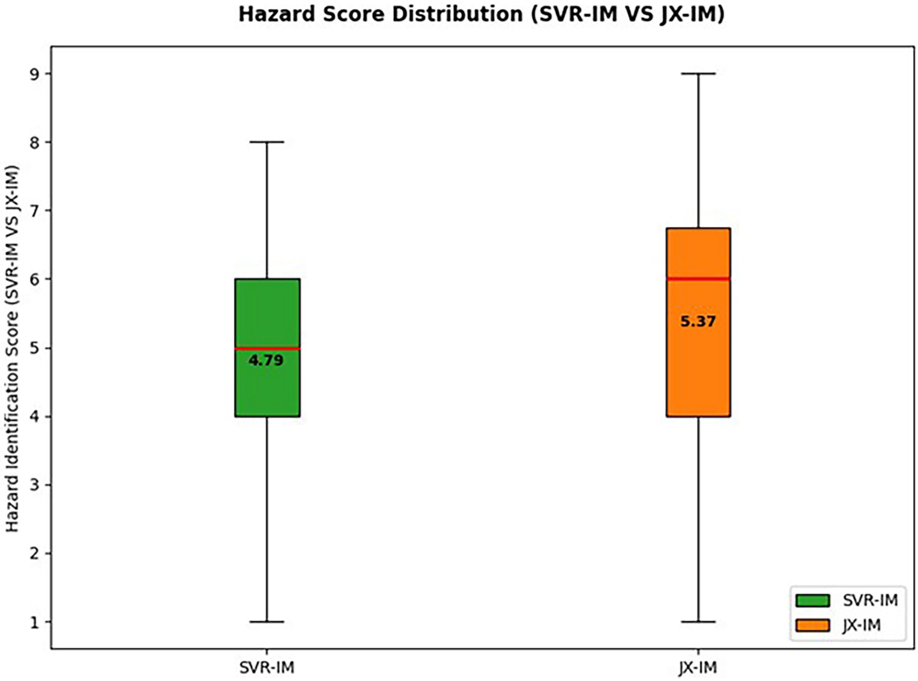

Figure 3. Boxplot comparison of number of identified hazards in SVR-IM and JX-IM modules

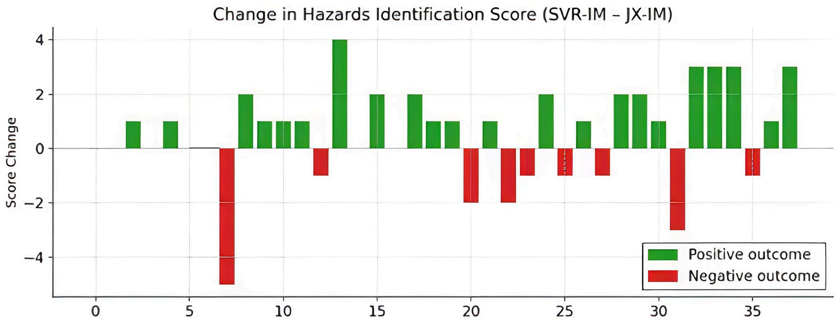

Figure 4. Participant-level changes in hazard identification scores

5. Discussion

A central contribution of this study lies in examining how varying input modalities in virtual environments affect user performance during drone-mediated operation and site safety inspections. The findings indicate that the input modality incorporating a joystick-based interface and physical Sony© PS4 controller (JX-IM) resulted in a superior performance compared to the slider interface with standard motion controllers (SVR-IM) in VR. Specifically, participants achieved a 12.3% increase in hazard identification scores and a

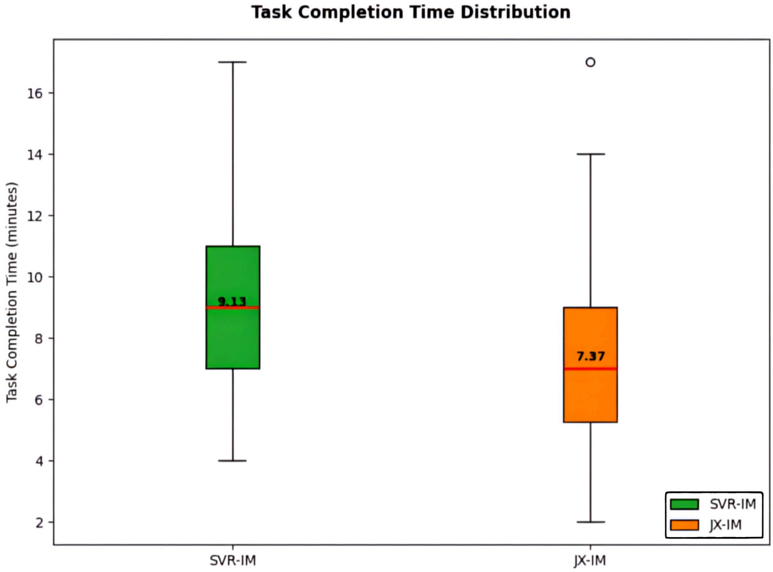

Figure 5. Boxplot comparison of time to identify hazards in SVR-IM and JX-IM modules

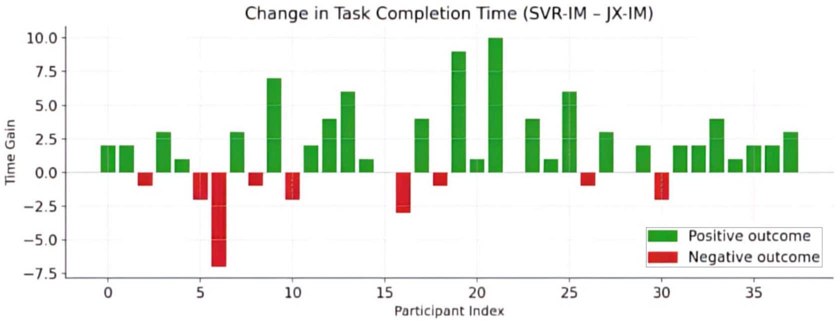

Figure 6. Participant-level changes in task completion time

16% reduction in task completion time in the JX-IM condition. These quantitative gains suggest that realistic input modalities do not merely improve user preference but directly translate into measurable operational benefits, enhancing both the thoroughness of safety inspections and the efficiency of the training process.

The inferior performance observed in the SVR-IM condition can be theoretically attributed to the decoupling of spatial operations and the resulting increase in extraneous cognitive load. Drone piloting is inherently an integral task, requiring simultaneous control of multiple degrees of freedom. The joystick interface (JX-IM) supports this integral process by allowing simultaneous multi-axis manipulation through a single physical input. In contrast, the slider-based interface (SVR-IM) imposes a structural mismatch by forcing the operator to decompose a fluid, multidimensional flight path into discrete, sequential axis adjustments. This separation of integrated dimensions prevents intuitive spatial navigation and forces the user to continually switch attention between the flight task and the interface controls. According to Cognitive Load Theory, this unnecessary interface management consumes limited working memory resources which consequently leaves fewer cognitive resources available for the primary task of visual scanning and hazard recognition (Sweller, 2011).

Beyond mean performance differences, an analysis of data dispersion reveals critical insights into operational consistency. As shown in Figure 5, the JX-IM condition exhibited a markedly narrower interquartile range in task completion times compared to the wider spread observed in SVR-IM. This reduced variability suggests that the familiar, joystick-based interface provided a more standardized interaction framework, enabling most participants to achieve a consistent level of efficiency. In contrast, the high dispersion in SVR-IM times indicates that the abstract slider interface introduced variable levels of difficulty, with some operators struggling significantly more than others.

The obtained results align with prior research indicating that input modalities offering more precise control and intuitive interaction can enhance user attention, spatial processing and overall task performance. For example, Palombo *et al.* (2024) reported that users interacting via VR gloves (offering high interaction realism) experienced greater cognitive immersion and improved spatial awareness. Similarly, Konrað Albertsson (2023) found that input methods supporting high interaction fidelity improved engagement and performance (Konrað Albertsson, 2023). Liang *et al.* (2016) compared Xbox controllers, HTC Vive controllers and a tablet device in VR and found that participants achieved significantly better time performance with joystick-style controls, while also rating joystick-based interfaces as easier to use and more usable (Liang *et al.*, 2016). Ali and Cardona-Rivera (2020) directly compared gamepad controllers against VR controllers in VR experiences and found that gamepad controllers provided more intuitive navigation for movement tasks, particularly those requiring continuous spatial navigation (Ali and Cardona-Rivera, 2020).

In this study, the joystick-based control in JX-IM more accurately replicated drone piloting tools used in practice, which may have supported users' attention and intuitive control, thus improving performance outcomes. In contrast, the SVR-IM condition relied on abstract slider-based inputs via VR hand controllers, which may have lacked the natural mapping and tactile feedback needed to foster precise manipulation (Geurts *et al.*, 2023; Palombo *et al.*, 2024). This less realistic control method likely constrained the user's interaction fluency and hindered the spatial tracking (Geurts *et al.*, 2023). The observed performance gap between the two input modalities reinforces the importance of both interface realism and control familiarity in VR-based training applications, especially those replicating operational tasks like aerial inspections.

5.1 Limitations and future research

This study has several limitations that need to be acknowledged. A primary limitation is the inherent confounding between control device and interface type, both of which were combined under the concept of input modality. Although this design reflects real-world drone-mediated safety inspection scenarios in construction, where hardware and interface jointly influence task performance, future research should isolate the effects of each factor. By independently manipulating control hardware and interface design, subsequent studies could more clearly determine the individual contributions of each variable to user performance in VR settings. Another limitation relates to participant recruitment. All participants were construction management students, many of whom had prior academic exposure to hazard identification tasks. While this ensured a consistent knowledge base, it limits the generalizability of the findings to field professionals. Future research should involve construction workers from diverse roles (e.g. equipment operators, scaffolders, surveyors) to evaluate the ecological validity and practical utility of different input modalities in high-fidelity simulations. Furthermore, while prior familiarity with robotic systems was assessed, participants' prior experience with game controllers or general gaming was not explicitly measured. As such, controller usage experience may represent an uncontrolled covariate and is acknowledged as a limitation of this study. Those more comfortable with digital tools may have navigated both environments more efficiently, whereas novices could have faced usability challenges that affected their task efficiency. Although standardized instructions and demonstrations were provided, future studies should consider stratifying participants by digital literacy and investigating adaptive systems that tailor interface complexity to individual experience levels. Finally, while task scenarios were tightly controlled, they may not fully capture the multitasking demands, time pressure and environmental stressors common on construction sites.

Future research should investigate input modality effects under more complex and dynamic scenarios, potentially integrating physiological sensors such as EEG or EDA to measure cognitive load and stress. The current study focused on two primary outcome variables, hazard identification score and task completion time. However, supplementary measures such as piloting error rates (e.g. number of collisions) and objective cognitive load assessment would provide deeper mechanistic insights into how input modality influences operator performance. Such approaches would provide a more comprehensive understanding of how immersive training tools function under real-world conditions. As part of future research, studies should also examine the long-term effects of repeated exposure to these input modalities. The current study focused on short-term performance indicators, such as task completion time and hazard identification scores, but the sustained impact of prolonged or repeated use on skill retention and operational efficiency remains unexplored. Follow-up studies could adopt longitudinal or mixed method designs to assess how input modality influences skill retention and the transferability of drone operation tasks to real-world safety practices. To assess the generalizability of the study findings, future research should investigate input modality effects across diverse drone operation tasks, including formation flying, obstacle avoidance and precision hovering, to determine whether realistic control interfaces consistently outperform abstract interfaces across the full spectrum of construction drone operations. The implications of input modality design can also be extended to other construction technologies. Robotic total stations, ground inspection robots and heavy equipment training in VR could benefit from input systems that replicate the physical tools used on-site, warranting additional studies.

While the findings of this study support the adoption of realistic input modalities in VR-based drone training, implementation barriers must be acknowledged. The initial capital investment in VR hardware, HMDs and high-fidelity controllers represents a significant upfront cost for construction firms and training organizations. In addition, infrastructure requirements such as computing power, technical support and trained personnel to develop and maintain VR systems can pose logistical challenges for smaller enterprises. However, these costs must be weighed against the long-term benefits of VR training: reduced injury risk through safe, repeatable practice; lower training costs compared to maintaining real-world drone fleets and pilot supervision; and standardized, scalable training delivery across multiple sites and cohorts. As VR technology continues to become more accessible and affordable, the practical feasibility of implementing such systems is expected to improve, particularly for larger construction organizations and educational institutions.

6. Conclusion

This study explored the impact of input modality on drone-mediated operator training within VR environments. Addressing gaps in prior VR-based drone operator training research, a within-subject experiment was conducted to compare two input modalities under simulated hazardous site conditions. By aligning interaction design with real-world drone operation tools, the study examined the impact of input modality on user performance. Results indicated that joystick-based control via game controller led to higher hazard identification scores and faster task completion. These findings highlight the performance advantages of familiar, realistic input modalities that facilitate natural motor responses while underscoring a key design principle: effective VR-based training should not only replicate visual environments but also mirror the operational characteristics of the technologies, tools, and/or equipment being used by trainees. Such design considerations are particularly critical in tasks that involve complex tool manipulation, such as drone navigation in dynamic construction settings. Future interface design should systematically explore how degrees of control modality, interface complexity and user familiarity interact to influence learning outcomes. Moreover, iterative design frameworks that integrate user feedback and task analytics will be essential for refining virtual tools to meet real-world training demands. By prioritizing modality in training design, this research contributes to a growing movement toward performance-driven, user-centered virtual training systems that bridge the gap between digital simulations and physical work environments.

The implications of these findings extend to the design of future operational VR-based training, particularly those integrating advanced aerial and ground robots. Embedding input modalities, via tool-mimicking controllers, motion tracking and real-time feedback, into simulation platforms can foster more effective skill acquisition and decision-making. Such systems also offer scalable, low-risk alternatives to traditional training methods, particularly in situations where hands-on experience may be constrained by cost, safety or logistical challenges. Further research directions should build upon this framework by expanding the range of technologies and user populations investigated, while incorporating physiological and neurocognitive indicators to better understand the dynamics of learning and engagement. Longitudinal studies examining behavioral retention and real-world transfer will be essential to assess the sustained impact of such interventions on workforce readiness. Furthermore, the integration of such systems into formal workforce development initiatives, including certification pathways holds potential for standardizing safety competencies and enhancing long-term learning outcomes. By offering both theoretical insights and practical implications, this approach offers a structured basis for informing the design of future experimental setups and interaction schemes in drone-mediated VR training environments.

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