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Enhancing Tower Crane Operation Skills in Aerial Construction Factories through Virtual Reality Training: A Controlled Study

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Abstract

This study examines the impact of virtual reality (VR) training on enhancing the skills of tower crane operators in Aerial Construction Factories (ACFs). As ACF operations become increasingly complex with higher safety demands, traditional training methods struggle to simulate high-risk scenarios and provide sufficient hands-on experience. By leveraging VR technology, this study offers an immersive and interactive training environment where operators can practice in risk-free, controlled virtual scenarios. VR-based experiments were conducted to measure performance in task completion time, operational accuracy, self-efficacy, and the frequency of collision warnings during simulated tasks. The results demonstrated significant improvements in both task accuracy and operator confidence, along with reductions in task completion time and collision warnings. These findings suggest that VR training addresses the limitations of conventional methods, offering a more cost-effective, scalable, and safe solution for improving crane operator skills within ACFs. Ultimately, the study highlights the transformative potential of VR technology in enhancing operator proficiency, safety awareness, and accident prevention in the challenging and hazardous environment of ACFs.

1 Introduction

Aerial Construction Factories (ACFs) represent a transformative advancement in modern construction systems, integrating tower cranes, concrete pumps, and other large-scale machinery to streamline operations in high-rise building projects (Melenbrink et al., 2020). Their ability to enhance efficiency, ensure construction quality, and improve safety in complex environments highlights their

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critical role in meeting the demands of modern urban development (Ma et al., 2024). These systems are characterized by their capacity to execute complex, large-scale construction tasks efficiently, often under challenging environmental conditions (Ma et al., 2024). The operational environment of ACFs is inherently complex due to factors such as high-altitude work, limited spatial maneuverability, and dynamic interactions among multiple equipment systems (Cai et al., 2019). Within this context, tower crane operators play a pivotal role, not only managing routine tasks such as lifting and transporting heavy materials but also performing precise and synchronized operations under constrained and elevated conditions (Ali et al., 2024). These heightened operational demands necessitate advanced control strategies and exceptional skill levels to ensure safety and productivity (Ali et al., 2024). The complicated nature of these tasks amplifies the risks of human error, underscoring the critical significance of enhancing operator competencies through targeted training and technological support (Shringi et al., 2023).

Enhancing the control skills of tower crane operators is crucial for ensuring both safety and efficiency in construction projects, particularly within ACFs, where the complexity and risks associated with crane operations are significantly improved (Hammad et al., 2023). Tower cranes in ACFs not only face the usual challenges of lifting and moving heavy materials but also require precise coordination in constrained, high-altitude environments (Chen et al., 2022). These conditions demand greater precision and control to prevent accidents and minimize material handling errors (Ni et al., 2024). Prior studies have highlighted that proficient crane operators can significantly reduce construction time and costs, contributing to the overall success of ACF projects (Sadeghi et al., 2023). As ACFs and other construction projects become more automated and complex, the requirements for continuous skill development and advanced training programs for crane operators become even more critical (Ali et al., 2024).

The skill training of tower crane operators is crucial for realizing safety and efficiency during construction work(Song et al., 2021). However, traditional training methods, such as classroom instruction and on-the-job training, have limitations in addressing complex construction environments and emergencies (Moon et al., 2019). In recent years, VR technology has gained significant attention as an innovative industrial training tool due to its immersive, interactive, and safe characteristics (Nair et al., 2024). The origins of VR can be traced back to the 1960s, when Ivan Sutherland and his team developed the "Sword of Damocles," the first head-mounted display system (Sutherland, 1968). This groundbreaking invention integrated real-time graphics and motion tracking, laying the foundation for modern VR technologies (Steuer, 1992). Over the decades, studies have demonstrated that VR offers significant advantages in operator training (Adami et al., 2021), simulating hazardous scenarios (Cross et al., 2022), providing collision warnings (Li et al., 2018), enhancing self-efficacy (Shringi et al., 2023), replicating complex tasks (Xie et al., 2021), and creating high-altitude work environments (Melenbrink et al., 2020).

The high-risk nature of tower crane operations within ACF makes improving operator abilities very necessary. Inadequate training can lead to heavy accidents, property damage, and even fatalities (Wiethorn, 2018). Human error, often stemming from insufficient training and lack of experience, is a leading cause of crane-related accidents, especially in the challenging environments of ACFs (Zhang et al. 2020). Therefore, effective training programs that not only enhance technical skills but also improve decision-making and boost confidence in high-pressure environments are essential (Z. Zhang et al., 2022). However, despite the significant advantages of VR technology in tower crane operation training, its application in the emerging context of ACFs remains limited. The ACF environment is characterized by high-altitude operations, spatial constraints, and multi-equipment coordination, which impose higher demands on operators' skills and safety awareness (Ma et al., 2024). Currently, studies on VR training systems tailored to the specific operational conditions of ACFs are scarce, highlighting the urgent need for further exploration to address the unique requirements of this domain.

This study explores the effectiveness of VR training for tower crane operators within ACFs by examining key performance metrics such as task completion times, accuracy, self-efficacy, and the frequency of collision warnings. By providing empirical evidence of VR's benefits, this study contributes to the growing body of literature on VR applications in industrial training and aims to inform the development of more effective training programs for improving crane operator skills, particularly in the demanding environments of ACFs.

2 Method

2.1 Procedure

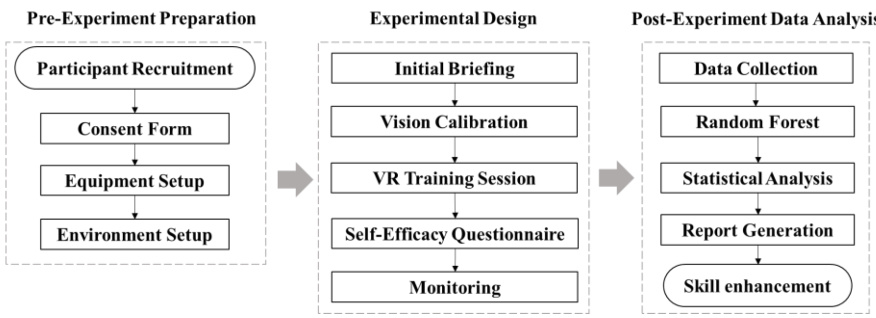


Figure 1: Experimental workflow for VR training in tower crane skills

According to Moon et al. (2019) and Adami et al. (2021), this framework diagram (Figure 1) outlines the comprehensive process of the experimental study conducted within the context of ACFs, divided into three main phases: Pre-Experiment Preparation, Experimental Design, and Post-Experiment Data Analysis, as shown in followed.

In the Pre-Experiment Preparation phase, participants are recruited and provided with consent forms (Shringi et al., 2023). The necessary VR equipment is set up, and the ACF simulation environment is prepared to reflect the complex, high-altitude conditions typical of these environments (Moon et al., 2019). This ensures that the experiment replicates the real-world challenges faced by tower crane operators in ACFs.

In the Experimental Design phase, participants receive an initial briefing, followed by vision calibration to ensure accurate data collection (Xie et al., 2021). They then engage in a VR training session simulating tower crane operations in an ACF setting. After completing the training, participants are asked to fill out a self-efficacy questionnaire (Ye et al., 2022). Continuous monitoring throughout this phase ensures the integrity and accuracy of the collected data, particularly in simulating high-risk ACF scenarios (Adami et al., 2021).

The Post-Experiment Data Analysis phase involves collecting all performance metrics, such as task completion times, accuracy, and collision warnings, followed by statistical analysis to assess the impact of VR training in an ACF context (Song et al., 2021). Reports are generated, and a feedback session is conducted to present the findings. This structured approach, tailored to the unique demands of ACFs, ensures the reliability and validity of the experimental outcomes while addressing the specific complexities of training tower crane operators in such environments (Shringi et al., 2022).

2.2 Pre-Test

(1) Participant Selection

This study recruited 20 individuals from civil engineering-related majors, representing a range of experience levels in tower crane operations, from novices to more experienced professionals. Figure 2 illustrates part of the experimental scene where participants are equipped with VR headsets and controllers (Xie et al., 2021). The selection aimed to include a diverse group of participants to comprehensively evaluate the effectiveness of VR training across different skill sets. Each participant was briefed on the study's objectives, procedures, and potential risks before signing informed consent forms, ensuring voluntary participation and understanding of the experiment (Shringi et al., 2022). The VR technology provided participants with an immersive, realistic environment to practice tower crane operations under various simulated conditions (Song et al., 2021), as depicted in Figure 2.

Figure 2: Participants engaged in VR-based tower crane operation

(2) VR Model Development

The VR model was carefully designed to simulate real-world construction environments, with a focus on the operational challenges within ACFs (Adami et al., 2021). In these environments, complex machine interactions present significant challenges for crane operators (W. Zhou et al., 2018). Figure 3 illustrates the setup of the VR equipment, which includes a VR headset connected to a high-performance computer capable of generating a highly immersive virtual environment (Yang & Goh, 2022). This environment replicates the spatial dynamics of the ACF, including the coordination between tower cranes and other machinery such as concrete placement machines.

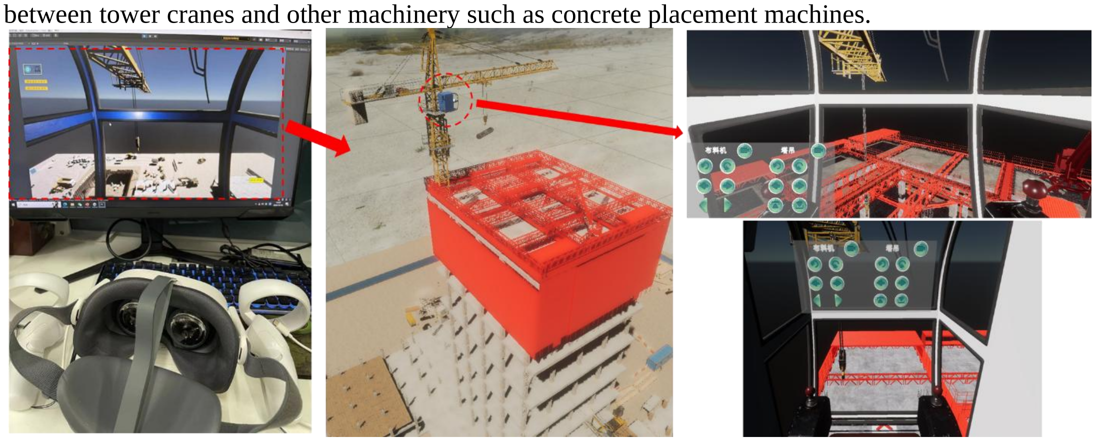


Figure 3: VR equipment and environment setup

The VR model provides detailed visuals from the operator's perspective, simulating crane operations with a high degree of realism (Dhalmahapatra et al., 2021). Participants engage in lifelike training sessions, allowing them to practice operations in a safe, controlled setting that enhances their familiarity with the equipment and the operational complexities of ACF environments (Yang & Goh, 2022).

(3) Establishing a Safety Zone

To ensure the physical safety of participants during the VR training sessions, a designated safety zone was created (Tak et al., 2021). This zone, visually marked in the testing area, provided a secure space where participants could operate the VR equipment without the risk of physical collisions or injury. The boundaries of the safety zone served as a constant reminder for participants to remain within the designated area during the simulation (Sudiarno et al., 2024).

Before starting the experiment, participants were required to sign informed consent forms after being thoroughly briefed on the study’s objectives, procedures, potential risks, and their rights as participants (Shringi et al., 2022). Establishing the safety zone and obtaining informed consent ensured the experiment followed ethical guidelines and offered participants confidence in the safety measures. These precautions were crucial for maintaining both the reliability and validity of the experiment while prioritizing participant well-being (Shringi et al., 2023).

2.3 Experimental Design

(1) Experiments Goal

In the VR experiment, three target points labeled A, B, and C were designated for the crane operator to place the load. These points were chosen to evaluate the operator's precision and control during operation (Weichert et al., 2013). The Euclidean distance between the actual drop points and the target points during the VR training sessions was analyzed as a quantitative measure of the operator's handling skills (Oagaz et al., 2021). A smaller Euclidean distance indicated greater accuracy and precision in the operator's actions, reflecting improved operational capability (Kaplan et al., 2021). This approach not only validated the effectiveness of the training program but also provided valuable insights into areas requiring further improvement, offering a clear and actionable metric for performance evaluation (T. Zhou et al., 2022).

(2) Training Sessions

To further enhance the control abilities of crane operators, an intermediate training tutorial was incorporated between the two main experimental sessions. This tutorial, developed using Python, was designed to simulate a controlled environment where operators maneuver a load around virtual representations of workers and materials to reach a designated target point. The tutorial provided a safe, risk-free setting for operators to focus on improving their precision, dexterity, and operational control (Xie et al., 2021). Through this interactive exercise, operators were challenged to navigate obstacles while maintaining accuracy in load placement, offering a hands-on opportunity to refine their spatial awareness and coordination skills (Yang & Goh, 2022).

The tutorial was not merely a repetition of the VR training but served as a targeted supplement, allowing operators to practice critical techniques in a more focused and interactive manner. By emphasizing tasks that required careful maneuvering and precise execution, it reinforced the foundational concepts introduced during the initial VR simulations (Masiello et al., 2022). Furthermore, the tutorial facilitated gradual skill development by presenting operators with scenarios that mimicked real-world complexities, thereby bridging the gap between theoretical knowledge and practical application (Abdupattayevich & G’ayratovich, 2023). This additional training session proved to be a crucial component in fostering sustained improvement in crane operation proficiency and ensuring that operators were better prepared for the challenges of real-world tasks (Adami et al., 2022).

2.4 Post-Test

(1) Recording Experiment Time

In the VR experiment, task completion time serves as a key indicator of crane operator proficiency (Adami et al., 2021). By tracking the time taken to complete transportation tasks in both VR sessions, we can assess improvements in the operators' control abilities. Shorter completion times typically reflect greater familiarity with the controls and higher skill levels in operating the crane (Fang et al., 2018). This temporal analysis provides a clear, quantifiable measure of operator efficiency.

Comparing the task completion times between the two experimental sessions enables us to evaluate the effectiveness of the training program. A significant reduction in time from the first to the second session suggests enhanced operational competence, demonstrating the operator's increased dexterity and confidence in handling the crane. This method offers a comprehensive evaluation of the training's impact on improving crane operation efficiency.

(2) Recording Operational Accuracy

$$d = \frac{\sqrt{(p_{Ax}^{a} - p_{Ax}^{t})^2 + (p_{Ay}^{a} - p_{Ay}^{t})^2} + \sqrt{(p_{Bx}^{a} - p_{Bx}^{t})^2 + (p_{By}^{a} - p_{By}^{t})^2} + \sqrt{(p_{Cx}^{a} - p_{Cx}^{t})^2 + (p_{Cy}^{a} - p_{Cy}^{t})^2}}{3} \quad (1)$$

In the VR experiment, the accuracy of crane operators was evaluated by measuring the average Euclidean distance between the actual drop points and the target points A, B, and C, as defined by Equation (1) (Schneider et al., 2020). This metric was used to assess the precision of each operator's performance across two experimental sessions. By calculating the mean Euclidean distance, we quantitatively determined how closely the operators positioned the load relative to the intended targets under varying conditions. This method provided a robust measure of accuracy, allowing us to compare the performance of each operator between the two sessions. A decrease in the average Euclidean distance in the second session would indicate improved control and precision, which would suggest the effectiveness of the training and VR simulation in enhancing crane operation skills (Wang et al., 2024). This assessment approach ensures a clear and objective evaluation of each operator's potential progress and overall capability.

(3) Recording Self-Efficacy

Appendix 1 presents a self-efficacy scale, developed based on self-efficacy theory (Bandura et al., 1999; Ye et al., 2022), to assess tower crane operators' perceptions of their ability to control and operate cranes. The scale includes ten statements addressing various aspects of problem-solving, handling unforeseen situations, and managing unexpected events in the context of crane operations. Respondents rate their agreement with each statement on a scale from "Completely Disagree" to "Completely Agree" (Ye et al., 2022). In the VR experiment, this self-efficacy scale is administered to operators before and after participating in the VR training to measure changes in their confidence regarding crane operation. By comparing the pre- and post-experiment scores, researchers can evaluate whether VR training effectively enhances the operators' self-efficacy. An increase in self-efficacy scores after the training would indicate that operators feel more capable and confident in handling crane operations, reflecting improved understanding and control of the tower crane (Song et al., 2021). This suggests that VR training is a valuable tool for enhancing both the practical skills and confidence of tower crane operators (Shringi et al., 2023).

(4) Recording Collision Alert Frequency

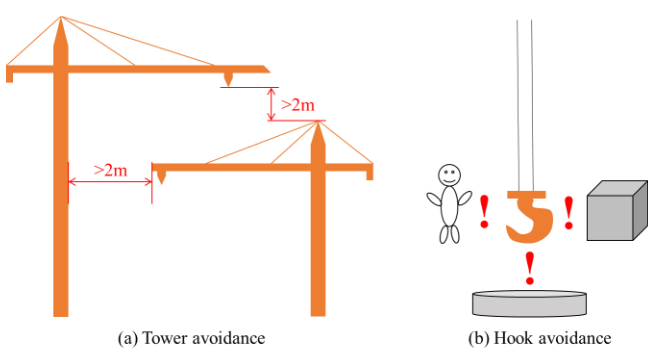


Figure 4: For towers and hooks, the scope of collision warning

Figure 4 illustrates the collision alert mechanism used in a VR experiment for tower crane operators. In Figure 4(a), the diagram outlines the collision alert range between different tower cranes, specifying a safe distance of over 2 meters (Hwang, 2012). Figure 4(b) shows the collision alert range for the crane's hook with humans and materials, highlighting the importance of maintaining a safe operating distance (Hwang, 2012). These visual cues within the VR environment are designed to warn operators of potentially hazardous operations, promoting safer crane operation practices. The primary objective of the experiment is to assess the operational proficiency of tower crane operators by recording the frequency of collision alerts triggered during VR simulations. By analyzing these alerts, researchers can identify areas where operators may need additional training or practice.

3 Results

3.1 Performance Improvements Across Key Metrics

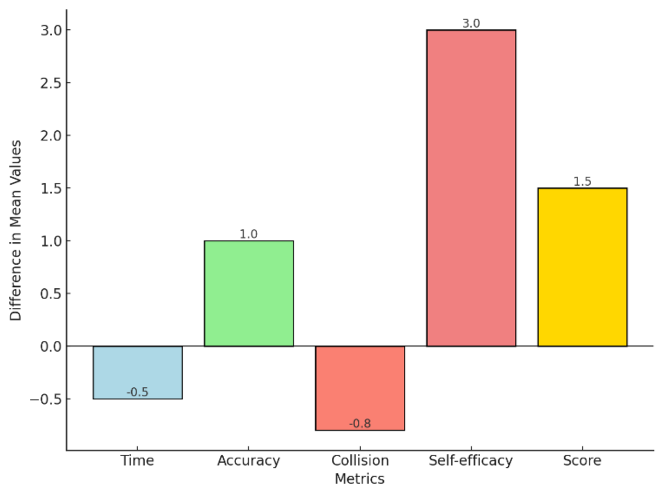


Figure 5: Comparison of performance improvements across key metrics

Figure 5 highlights the improvements observed in key performance metrics during the second experiment. After normalization and averaging, task completion time decreased by approximately 0.5 units, indicating that participants became more efficient in handling the crane, completing tasks in less time. The accuracy of crane operations showed a notable improvement, with a 1.0 unit increase, reflecting better precision in positioning the crane's load. Additionally, the number of collision alerts dropped by around 0.8 units, signifying enhanced control and fewer errors in avoiding hazards.

The most significant improvement was in self-efficacy, with an increase of over 3.0 units, indicating a considerable boost in participants' confidence and ability to handle crane operations. The overall score, which combines various performance factors, also improved by 1.5 units, showcasing the general enhancement in operational proficiency. These improvements demonstrate the effectiveness of the VR-based training program, particularly in boosting confidence, accuracy, and safe crane operation.

3.2 Relationship Between Performance Metrics and Operational Skill Enhancement

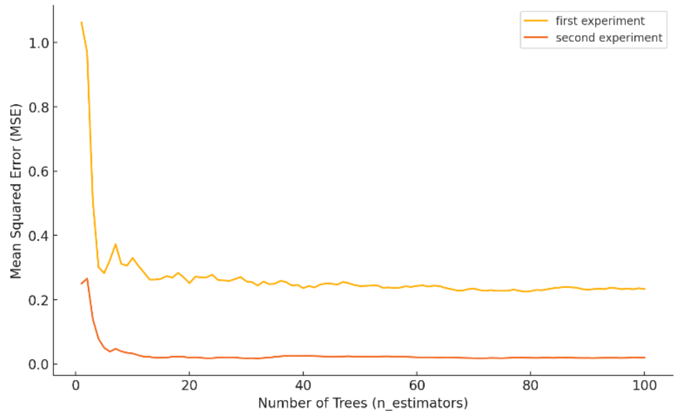
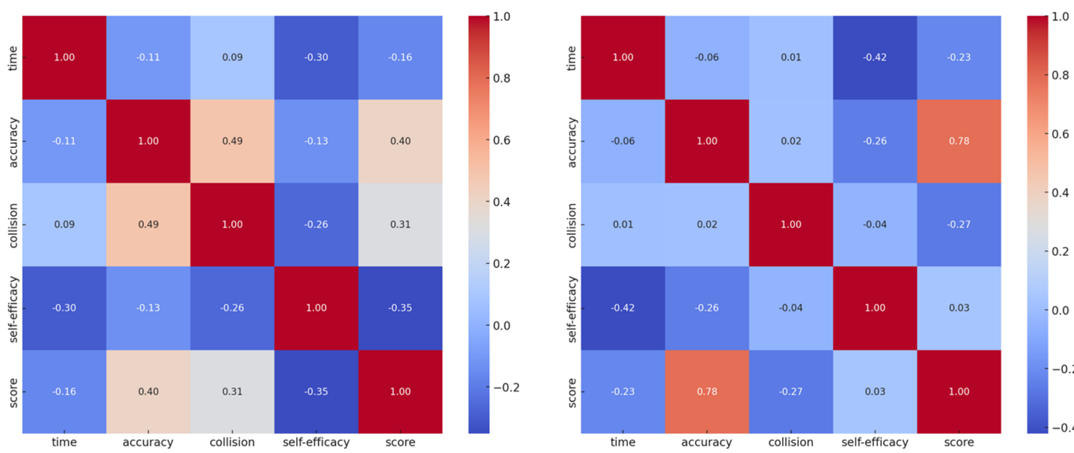


Figure 6: Random forest training iterations vs MSE

As shown in Figure 6, a Random Forest model was employed to evaluate the relationship between key performance metrics and operational performance in both the first and second experiments (Fang et al., 2021). The model's mean squared error (MSE) decreased significantly with the increase in the number of trees (n_estimators), particularly in the second experiment, which showed a much lower and more stable MSE compared to the first experiment. This suggests that participants in the second session exhibited more consistent improvements, with enhanced predictive accuracy, which corresponds to better overall crane operation proficiency.



(a) Heatmap of the relationship between the first operation score and each input item

(b) Heatmap of the relationship between the second operation score and each input item

Figure 7: Heatmaps of the relationship between the first and second operation score and each input item

Figure 7 illustrates heatmaps depicting the correlation between the operational scores and each input feature for both experiments. In the first operation (Figure 7a), accuracy and score are moderately correlated (0.31), while the relationship between accuracy and collision is weak (0.26). However, in the second experiment (Figure 7b), the correlation between accuracy and score strengthened significantly (0.78), underscoring the critical role that improved precision plays in enhancing performance. Additionally, the heatmaps reveal that self-efficacy exhibited a strong correlation with scores in both experiments, but the second experiment (0.82) shows a clear improvement. This indicates that the participants' increased confidence was strongly tied to their overall performance improvements, making self-efficacy a key factor in achieving proficiency.

4 Discussion

The findings from this study demonstrate that VR training significantly enhances the operational proficiency of tower crane operators in ACF environments. Key performance metrics, including task completion time, accuracy, collision alerts, and self-efficacy, showed substantial improvements across two experimental sessions, highlighting the training's impact on crane operation skills. The observed reduction in task completion time, paired with increased accuracy, underscores the effectiveness of VR-based training in enhancing both operational speed and precision. Literature supports that VR simulations provide a risk-free, immersive training environment, allowing operators to refine skills that contribute to greater efficiency and safety (Shringi et al., 2022). As illustrated in Figures 6 and 7, the Random Forest model used in this study indicates a significant increase in the predictive power of these metrics from the first to the second experiment, with the correlation between accuracy and overall score particularly strengthened in the second session. This outcome aligns with studies showing that precision plays a critical role in improving operational performance in complex environments (Cross et al., 2022).

The concept of self-efficacy emerged as a pivotal factor in enhancing operational performance. Participants who experienced an increase in confidence demonstrated a marked improvement in efficiency and were more adept at preventing accidents. Literature suggests that self-efficacy in high-risk operations, such as tower crane handling, is linked to better task execution and fewer errors, as seen in studies where increased confidence correlated with higher accuracy and operational safety (Adami et al., 2021). The strong association between self-efficacy and operational scores observed in the second experiment (Figure 7b) underscores the critical role of psychological preparedness, particularly confidence and decision-making abilities, in crane operations. Furthermore, the observed decrease in collision alerts aligns with findings that VR-based simulations, by enhancing situational awareness, yield safer operational outcomes (Shringi et al., 2023).

Types of issues	Mild	Moderate	Severe
slow operation	Increase practice frequency to improve familiarity with operational details, gradually reducing task completion time without major errors (Gallagher et al., 2005).	Participate in specialized training to gain a deeper understanding of operational methods and optimize workflows, minimizing delays caused by repeated actions (Aziz et al., 2013).	Implement smart systems to simplify operational processes (Maurer et al., 2010).
low operational accuracy	Focus on mastering basic skills through consistent practice and learning from experience to improve precision and avoid errors (Aziz et al., 2013).	Engage in professional training to understand operational requirements better and overcome challenges through frequent practice (Maurer et al., 2010).	Introduce smart technologies to reduce operational complexity (Moniri et al., 2016).
low self-efficacy	Set achievable goals to build confidence gradually, improve familiarity with procedures, and reduce errors through consistent practice (Gallagher et al., 2005).	Strengthen personal capabilities through regular practice and feedback, improving confidence in task execution (Kopp et al., 2020).	Provide additional support and collaborative opportunities to rebuild confidence (Adams-White et

			al., 2018).
frequent collision alerts	Enhance communication to ensure operators fully understand task requirements; encourage slow, deliberate actions to improve safety awareness (Aziz et al., 2013).	Engage in scenario-based simulations to identify and address safety-critical tasks, fostering clear communication and feedback (Gallagher et al., 2005).	Deploy intelligent error-prevention systems to reduce the likelihood of human mistakes (Maurer et al., 2010).

Table 1: Solutions for different severity levels of operational issues in tower crane operations

Table 1 outlines solutions for addressing various levels of operational challenges, including slow operation, low accuracy, low self-efficacy, and frequent collision alerts. For minor issues, increasing practice time and providing opportunities for task repetition are effective. However, for more severe issues, such as frequent collisions or significant delays in task completion, specialized training or implementing smart systems becomes essential. These systems aid in minimizing human errors and simplifying complex operations. Studies suggest that smart systems can significantly reduce error rates in complex operational contexts (Li et al., 2018). Additionally, VR training, by simulating high-risk scenarios and enabling repeated practice, enhances operators' situational awareness and confidence, thereby improving overall operational safety and efficiency (Shringi et al., 2023). The strategies presented in Table 1 offer clear guidance for addressing operational inefficiencies and risks across various severity levels, providing valuable insights for improving operator performance and safety in high-risk environments like ACFs.

5 Conclusions

This study has provided clear evidence that VR training significantly improves the operational skills of tower crane operators, especially within the challenging environment of ACFs. The experimental results revealed that after VR training, task completion time was reduced by approximately 0.5 units, while operational accuracy increased by 1.0 unit. These findings demonstrate that VR training effectively enhances both the speed and precision of crane operations, which is particularly critical in ACFs, where high-altitude work demands precise control and quick execution to prevent costly delays or accidents. Additionally, the frequency of collision alerts decreased by around 0.5 units, further underscoring the role of VR in improving operators' safety awareness and operational efficiency.

The study also highlighted the significance of self-efficacy in determining operational performance. Self-efficacy increased by over 3.0 units in the second experiment, and operators with higher confidence performed better in terms of accuracy and were more capable of handling complex and unexpected situations. Specifically, the correlation between self-efficacy and operational score reached 0.82 in the second experiment, demonstrating a strong link between psychological readiness and operational success. The VR training not only improved technical skills but also boosted operators' confidence by providing repeated exposure to high-risk simulated scenarios, reducing the likelihood of human error and enhancing overall safety.

Furthermore, the analysis of different operational issues in Table 1 emphasized the need for tailored solutions based on the severity of the problem. For mild issues such as slow operation or occasional errors, increased practice time and feedback can lead to significant improvements. However, for more severe challenges like low operational accuracy or frequent collision alerts, more advanced interventions such as smart systems to reduce human error are necessary. The solutions outlined in Table 1 suggest that a combination of VR-based training and targeted technological support can effectively address operational challenges, improving performance and safety in high-risk environments like ACFs.

This study has limitations that should be addressed. The experiment involved students, which may not fully reflect industry conditions, and the small sample size limits the reliability of the results. Additionally, challenges in industry adoption, such as high initial costs, the need for customized content, and resistance to new methods, must be considered. Future research should focus on larger, more diverse samples and demonstrate the cost-effectiveness and long-term benefits of VR training to promote its broader acceptance in the construction industry.

Acknowledgments

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