# Enhancing Human-Robot Teaming in Construction through the Integration of Virtual Reality-Based Training in Human-Robot Collaboration

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**Abstract -**

**Human-robot teaming (HRT) has emerged as a pivotal research area in the construction industry, focusing on collaborative efforts between humans and robots for enhanced productivity and safety. This study delves into the dynamics of HRT within the immersive context of virtual reality (VR) learning environments. The research integrates established theories, including the Transtheoretical Model, the Cognitive-Affective Theory of Learning with Media (CATLM), and the Technology Acceptance Model (TAM), to construct a robust theoretical foundation. Key theoretical insights highlight the interplay of cognitive and emotional factors in influencing learning experiences and collaboration intentions. The study emphasizes the need for ergonomically compliant VR tools, addressing technical challenges to optimize user experiences. Findings underscore the significance of sustained exposure to VR features and the critical role of realism and user control in shaping the level of presence in VR environments. Practical implications emphasize the importance of usability in VR systems, encouraging educators and designers to prioritize user-friendly interfaces. The study suggests that multiple sessions are essential for VR features to substantially influence collaboration intentions. Realism and control over virtual elements are identified as key factors directly impacting the immersive experience. This research contributes to the theoretical depth of HRT in the construction industry, providing practical guidelines for developing and implementing VR systems. The insights garnered have implications for educators, designers, and practitioners, fostering a comprehensive understanding of the intricate interplay between human cognition, emotion, and technology in collaborative construction settings.**

**Keywords -**

**Construction Robot; Virtual Reality; Training; Learning; Collaboration, Human-Robot Teaming;**

## 1 Introduction

In today's swiftly advancing technological terrain, the construction industry confronts various complex challenges that necessitate inventive resolutions [1]. Among these challenges, a crucial solution point emerges in the area of construction human-robot collaboration. While this collaboration holds the potential for heightened efficiency and productivity, it brings forth distinctive obstacles, predominantly centered on training and the potential for injuries [2, 3]. Despite relying on traditional construction methods for decades without substantial advancements in safety and productivity [4], it is imperative to embrace novel systems, innovations, and methodologies to address the ongoing challenges in the industry [2, 5].

The rise of advancements in robotics, artificial intelligence, the internet of things, and intelligent tools presents significant opportunities to propel the built sector beyond outdated traditional methods toward a more efficient and productivity-boosting industry. Among various emerging technologies, robotics has been emphasized as particularly crucial due to its potential to address targeted issues. It is poised to enhance safety by mitigating on-site risks faced by humans while improving productivity and fostering more sustainable labor costs [4].

As the utilization of robotics in construction continues to evolve, cautious consideration is given to the fact that, in numerous applications, robots still necessitate human presence within a collaborative system to accomplish project objectives [5, 6]. Due to the absence of a defined structure at construction worksites, it is essential for on-site workers to engage in collaborative efforts with robots before fully implementing autonomous robotics on construction sites [2, 3]. This collaborative approach allows for the identification of improvement areas, leading to more well-designed solutions. Moreover, it has the potential to mitigate concerns related to job displacement by robots. The imperative for human-robot collaboration (HRC) is underscored by the need to combine the strengths of robots, such as autonomy and the ability to perform repetitive tasks, with the skills possessed by human team members [5, 7]. The evolving role of robots as collaborators in the workplace suggests a complementary relationship with human labor, enhancing overall production efficiency rather than entirely replacing it [5].

Collaborating with robotics in a human-robot team poses challenges, especially considering the limited understanding of the effectiveness of such collaboration, leading to training difficulties [8, 9]. The situation is further complicated by the high costs associated with obtaining on-site training robots and the absence of hands-on experience in classroom instruction focused on human-robot collaboration [2, 3]. To overcome the constraints associated with traditional training methods, there is a proposal to implement immersive virtual reality (IVR) training for the construction workforce. This approach allows participants to immerse themselves in simulated scenarios that would otherwise present significant risks on actual construction sites. Beyond creating secure and cost-effective training environments, IVR technology provides workers with unique safety training opportunities. These opportunities include immediate guidance, empathy development, exposure to consequences, future scenario projection, feedback delivery, and emotional self-regulation, all of which serve as interventions for changing behavior [4, 10].

Moreover, the features of the virtual environment, encompassing its visual interface, immersive characteristics, interactive elements, and sense of presence, present diverse scenarios that have the potential to enhance workers' safety awareness in a physically secure setting [6]. The growing enthusiasm for utilizing virtual reality (VR) in education is well-supported by multiple meta-analyses consistently demonstrating positive educational outcomes when employing VR and simulations [3]. In some instances, these outcomes surpass those achieved through traditional classroom training. Numerous studies have affirmed that VR can impart knowledge and facilitate behavior change [9]. It is crucial to examine this knowledge gap comprehensively to establish a compelling rationale for why VR serves as an effective training method for improving behavior change outcomes in human-robot teaming.

This exploration should then drive the imperative to address all potential risks and hazards essential for ensuring a secure and reliable collaboration between humans and robots [1, 6]. However, it is equally vital to address other knowledge gaps, such as how VR can be employed in skills development, safety training, and hazard awareness in the context of human-robot team collaboration. The absence of research in this specific focus area could impede the effective adoption of robotics in construction work environments, hindering the realization of its full potential.

Hence, when individuals lack the necessary expertise to engage safely, efficiently, and effectively in interactions between machines and humans within these systems, the potential for safety risks and hazards significantly increases due to errors and incorrect assessments, resulting in serious consequences [8]. Additionally, flawed and risky dynamics in the interactions between machines and humans may lead to errors, as humans anticipate linear time behavior while machines exhibit nonlinear behavior [3, 7]. Grasping the intricacies of this relationship is crucial for establishing trust in human-robot teams and ensuring their successful integration. With robots' growing prevalence in personal spaces and workplaces, human-robot relationships are becoming increasingly widespread [6]. To tackle the challenges mentioned earlier, our research has developed a framework centered around Virtual Reality (VR) to enhance collaboration between humans and robots. This framework is designed to seamlessly integrate VR training applications into the realm of human-robot teamwork, with primary goals of improving the quality of collaboration and ensuring the safe integration of robots in built environments. The core aim of this framework is dualfold: firstly, it harnesses the immersive capabilities of virtual reality to provide a comprehensive training experience, equipping individuals with the essential skills to collaborate effectively with robots. Secondly, it endeavors to enhance the overall standard of human-robot collaboration, promoting increased efficiency and safety at construction sites. The primary goal is to foster a harmonious partnership between individuals and robots in infrastructure delivery, ultimately benefiting both the industry and society on a broader scale.

Through the adoption of this VR-based approach, our research aims to transform the training of construction industry professionals and the integration of robots into construction processes. It not only tackles existing challenges but also sets the stage for a future in the construction sector that is more efficient, safer, and technologically advanced.

## 2 Theoretical Framework

In recent years, human-robot teaming (HRT) in the construction industry has emerged as an increasingly popular research topic because of its potential benefits. HRT, or Human-Robot Teaming, refers to the joint effort of humans and robots to carry out construction tasks with high productivity, efficiency, and safety [7]. The study adopted and incorporated technology-mediated learning theories, including the Transtheoretical theory, Cognitive theories (CVTAE), and the theory of planned behavior. These theoretical underpinnings not only provided a robust foundation for the research but also furnished a conceptual framework that guided the study. By integrating these theories, the study established a strong theoretical and conceptual foothold for the investigation, contributing to the theoretical depth and rigor in our field.

As stated by Mngadi [8],the role of theory is frequently to elucidate specific circumstances and occurrences within society. It can be conceptualized as a collaboration of cognitive processes that have gradually aligned in consensus over time. This forms the basis for what is referred to as a theoretical framework, emphasized as a ”structure capable of upholding or bolstering a theory in research work,” akin to a research guide or blueprint. The Technology Acceptance Model (TAM) is a conceptual framework that elucidates the way individuals perceive and embrace novel technologies [9]. The hypothesis of the theory suggests that users' behavior in accepting computers is significantly influenced by their perceptions of usefulness (U) and ease of use (EOU). Perceived usefulness (U) is characterized as the prospective user's subjective likelihood that using a particular application system will enhance their job performance within an organizational context. Perceived ease of use (EOU) pertains to the extent to which the prospective user anticipates that the target system will be effortless to use [10]. The implementation of a technology-driven learning approach has the capacity to offer valuable insights into the effectiveness of virtual reality (VR) technology in the field of education. Technology-mediated learning denotes an educational environment where learners interact with educational materials, peers, and/or instructors through the use of advanced information technologies. This research concentrates on the Immersive Virtual Environment (IVE) learning setting, where learners engage with educational content through the application of Virtual Reality (VR) technology. Thus, employing a technology-mediated learning framework is considered appropriate for this specific investigation. The theory of planned behavior (TPB) is a conceptual framework used to clarify and predict human behaviour. Developed by Icek Ajzen in the 1980s, this model has gained widespread application in the fields of psychology, sociology, and marketing [11].

In Ajzen's [11] theory of planned behavior, the main factor influencing behavioral change is identified as behavioral intention. This theoretical framework adopts a cognitive viewpoint to explain behavior based on an individual's attitudes and beliefs. The Theory of Planned Behaviour (TPB) posits that human behaviour is shaped by three primary determinants: attitudes, subjective norms, and perceived behavioural control. Attitudes encompass an individual's affective evaluations, either favourable or negative, towards a particular behaviour. Subjective norms pertain to the societal influences and pressures that encourage or discourage an individual's engagement in said behaviour. Perceived behavioural control pertains to an individual's self-assessment of their capability to execute the behaviour in question successfully.

While established theories in the cognitive domain provide a thorough framework for understanding the cognitive processes of learning, the interaction between emotional factors and cognitive elements in promoting learning is an understudied area that demands further exploration. The transtheoretical model (TTM) is a theoretical framework used to explain the process of behavior transformation, outlining five distinct stages. These stages encompass pre-contemplation, contemplation, preparation, action, and maintenance. In the pre-contemplation stage, individuals are unaware of the issue and don't actively consider changing their behavior. Moving to the contemplation stage, individuals become conscious of the problem and contemplate making a change in the near future. The preparation stage involves actively planning to initiate the desired behavior change. The action stage sees individuals actively engaging in the desired behavior, while the maintenance stage focuses on sustaining the behavior change over time. This model integrates behavior change processes and principles derived from an extensive examination of twenty-five prominent psychotherapy theories. Widely applied across disciplines such as health, psychology, sociology, and communication, the transtheoretical model, or stages of change model, proves valuable for its comprehensive conceptualization of a multi-stage process [12].

In their research, Lee et. al. [13] employed a structural equation modeling (SEM) approach to introduce a theoretical framework emphasizing the importance of the learning experience. This experience is assessed through individual psychological characteristics and its impact on learning outcomes within a virtual reality (VR) learning environment.

The study revealed that virtual reality (VR) features, such as representational fidelity, immediacy of control, and usability (encompassing quality and accessibility), act as predictors for various intermediate factors. These mediating factors include presence, motivation, cognitive benefits, control and active learning, and reflective thinking. Additionally, it was observed that these mediating factors have an impact on perceived learning, satisfaction, and performance achievement. Furthermore, the model suggests that virtual reality (VR) features indirectly influence these mediating factors by affecting usability. These mediating elements encompass both affective and cognitive factors, aligning with well-established affective frameworks like CATLM, INTERACT, and CVTAE.

A notable distinction between the aforementioned models and the proposed framework lies in its integration of significant factors from media literature, particularly virtual reality (VR) features and presence. These components are deemed indispensable for fostering effective learning in VR environments. Additionally, Lee et al.'s model offers a comprehensive portrayal of cause-and-effect relationships among key variables. Aligned with the Control-Value Theory of Achievement Emotions (CVTAE), established motivational theories like interest theory and the Cognitive-Affective Theory of Learning with Media (CATLM) shed light on the nexus between motivation and learning, providing invaluable insights for their application in VR learning. Interest theory underscores the importance of grasping the motivational allure of e-learning technologies to facilitate the learning process, as situational interest can serve as an initial catalyst for learning promotion.

The CATLM serves as a theoretical framework aimed at elucidating the interconnections among cognitive, metacognitive, and motivational elements within technology-enhanced learning interventions. According to this model, heightened motivation is apt to yield improved learning outcomes. This is attributed to the belief that learners devoid of motivation are unlikely to engage in generative processing, even if they possess the cognitive capacity for it. Moreover, metacognitive factors play a pivotal role in regulating cognitive processing and influencing motivation.

On the other hand, in exploring employees' behavioral intentions concerning the utilization of robots, the Technology Acceptance Model (TAM) is employed to probe the relationship between the perceived ease of use of robots, perceived usefulness, and individuals' attitudes toward collaborating with robots. This inquiry is expanded by factoring in the perception of the risk of physical danger to elucidate how the sense of safety in working with robots impacts their adoption. While extant theories on behavior change and learning experiences adequately describe human behavior, they often fall short in integrating innovative systems such as actions within an immersive virtual environment (IVE). The discourse thus far underscores the significance of the transtheoretical model in scrutinizing behavior change in Human-Robot Collaboration (HRC). It's pertinent to note that this study, centered on the intention to collaborate in HRC through IVE learning, only considers the first two stages of the transtheoretical model.

The Transtheoretical Model encompasses five distinct stages of change: pre-contemplation, contemplation, preparation, action, and maintenance. In the precontemplation stage, individuals are oblivious to the problem and do not actively contemplate changing their behavior. Transitioning to the contemplation stage, individuals become cognizant of the problem and mull over potential changes in the near future. The preparation stage entails planning and gearing up for the desired behavior change, while the action stage witnesses individuals actively engaging in the desired behavior. Finally, the maintenance stage concentrates on sustaining the behavior change over time [12].

For the conceptual framework of this research, the initial two stages of behavior modification, specifically precontemplation and contemplation, are incorporated. In this framework, the features of the VR system indirectly influence collaboration through the mediation of the VR-HRC learning experience. This experience involves psychological factors such as cognitive behaviors (Cognitive, Affective, and Active Learning), presence, and player experience. The learning knowledge stage (contemplation) signifies the initial phase of behavior change, wherein individuals begin to acknowledge a problem, contemplate the need for behavior change, and seek information on potential solutions and activities.

The research includes outcome variables related to behavior change, specifically examining changes elucidated through the human-robot interaction theory. This is evident in the behavioral intention to collaborate with robots, which is derived from both the intention to use robots and the intention to collaborate with them. Additionally, behavior change is observed in terms of satisfaction and intrinsic motivation.

Based on the amalgamation of concepts and theories discussed, specifically employing the Control-Value Theory of Achievement Emotions (CVTAE) and the transtheoretical model, this research anticipates that the evaluation of VR features can be conducted through the metrics of representational fidelity and co-presence. The incorporation of co-presence is additionally influenced by the human-robot interaction theory. Furthermore, the usability of Virtual Reality is assessed based on perceived ease of use, perceived usefulness, intention to use, intention to collaborate, and the perception of physical danger. The theoretical foundation for this assessment is grounded in the Technology Acceptance Model (TAM). A conceptual model has been formulated based on an input, process, and output framework, with a focus on the psychological aspects of learning. This model is designed to serve as a guide for the research design, specifically aimed at evaluating the impact of virtual reality (VR) on behavior change in Human-Robot Collaboration (HRC). The input factors that could influence the learning process, subsequently affecting learning outcomes, include the user's state of mind, VR features, and VR usability. The independent variables are the user's state of mind, measured by enthusiasm and a sense of motivation; VR features, measured by fidelity, copresence; and VR usability, measured by perceived ease of use, perceived usefulness, perceived enjoyment, and risk of physical danger.

The VR learning experience functions as the mediating variable, while the behavior change outcome serves as the dependent variable. In terms of the learning process, internal psychological aspects of the learning experience, such as presence, cognitive behavior, and player experience, are assessed to understand the type of learning experience enhanced by VR and the significance of the learning experience in predicting behavior change outcomes. Additionally, this framework underscores the influence of VR features on behavior change outcomes through mediating factors within the learning experience.

# 3 Research Method

Various methods have been developed and applied to measure a range of phenomena within the construction robotics (CR) field. Questionnaire surveys and reviews of existing literature have been employed to define the study domains [14]. Utilizing virtual reality (VR) training with actual machinery in the construction industry as an initial training method shows substantial promise in comparison to the traditional paper-based or classroom approach. Empirical methodologies are commonly employed in robotics research and have recently integrated virtual reality into experimental pursuits [15].

The increasing popularity of VR can be attributed to its widespread availability and broad utilization in research studies. Nevertheless, its effective implementation requires the collaboration of diverse teams with expertise in both construction and VR/computer programming [16]. As a result, the number of tasks and scenarios incorporated in these studies has been limited. However, this study goes beyond that norm by integrating various tasks representative of a construction site.

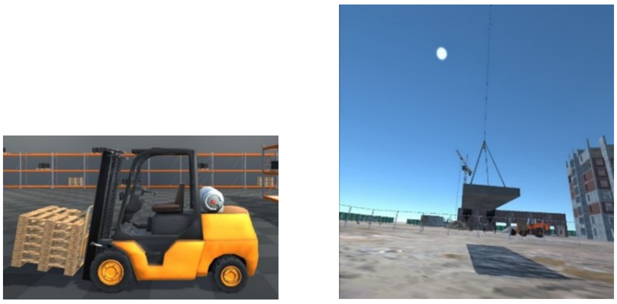
In contrast to previous research, it was concluded that construction operators commonly employ manual techniques are the most suitable individuals to provide valuable insights into their experiences. A notable limitation in earlier experimental approaches is the exclusive reliance on student participants, who often lack practical familiarity with similar systems. Therefore, in this study, operators already using specific simulated construction machines were surveyed alongside students in a between-subjects experiment. The inclusion of input from operators was anticipated to enhance and diversify the quality of the responses.

## 3.1 Experiment in an Immersive Environment

To examine the hypothesis of this research, a between-subjects experiment was carried out, evaluating the evaluation capabilities of both operators and non-operators regarding human-robot collaboration. The study utilizes an immersive virtual environment to gauge participants' perceptions of their interactions with both robots and individuals in a simulated construction site. As part of the experiment, participants were involved in a human-robot collaboration task. A multitasking approach was implemented, mirroring the strategy used in earlier studies. The tasks involved human-drone collaboration tasks, human-forklift collaboration tasks, human-loaders collaboration tasks, and human-cranes collaboration tasks. These were simulated in the virtual environment with human team members responsible for instructing the robots and helping other human team members achieve the tasks. This was achieved through a multiplayer design in the immersive virtual environment. The human-drone collaboration tasks were selected because drones are the most adopted form of robots currently used in the industry. Two, it is already commercially available and has huge potential for adoption. The Crane, forklift and loader tasks were selected as they represent a mix of transporting equipment and earth moving equipment currently largely used and with immense potential for adoption.

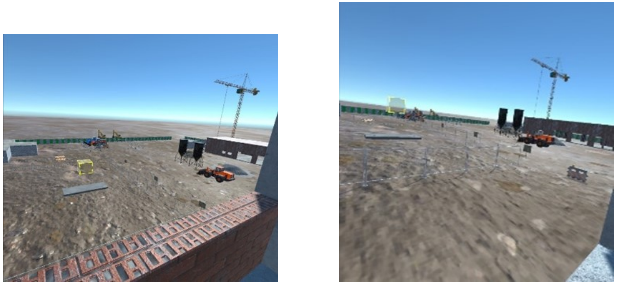
### 3.1.1 Experimental procedure

In order to guarantee safety during the operation, the immersive virtual world implemented a room-scale border, which the participants closely monitored. The implementation of this solution aimed to prioritize the safety of the participants when using the Head-Mounted Display (HMD). The Head-Mounted Display (HMD) limits the field of vision outside of the screen, requiring the presence of a clear and unobstructed area. Two individuals were present in the setting simultaneously alongside the robots, as depicted in Figure 1 (Showing the models and VR environment).



(a) Fork lift truck

(b) Lifting a slab



(c) VR environment first view

(d) VR environment alternative view

Figure 1. Captured scenes of the imported assets and assembled VR environment.

The experimental design comprised three main stages: an initial pre-questionnaire step, an experimental phase involving the robot in an immersive virtual environment (IVE), and a post-questionnaire phase. The initial phase was designated as the preparation step, which involved a 5-minute pre-experiment briefing. This entailed a comprehensive elucidation of experimental protocols and ethical principles. Next, the pre-experiment consent took place, during which participants confirmed their consent and provided their background information. This was determined through the pre-experiment virtual reality (VR) training, where participants familiarised themselves with the VR controls and safety requirements, completing the preparation stage in a total of 14 minutes.

# 4 Results

## 4.1 Participant's Characteristics

The analysis was conducted using empirical data obtained from pre-experiment and post-experiment responses of 42 participants. These participants included both postgraduate students and trade workers in the built environment. The tasks encompassed various scenarios introducing different models of robots, including the Forklift, Crane, Drone, Loader, Dumper, and Dump Truck. The scenarios involved tasks such as picking construction materials, delivering them to designated positions autonomously, and assigning goals and processes to the robots while the human team members observed and learned. The tests involved postgraduate students specializing in Engineering (7%), Construction/Project Management (20.9%), Quantity Surveying (25.6%), and Architecture (9.3%), all of whom were associated with the built environment. The experiment involved the participation of robotized construction equipment operators/trainees, specifically Drone Pilots/Trainees (9.3%), Crane Operators/Trainees (11.6%), Forklift Operators/Trainees (7%), and Dumper/Loader Operators/Trainees (9.3%).

Regarding the respondents' experience with robotic systems, 18.6% reported utilizing drones, 11.6% reported experience with Dump Trucks, 27.9% reported using Cranes, 18.6% reported using Forklifts, and 23.35% reported using Dumper loaders. Subsequent analysis found that these events were reported by operators/trainees of the systems rather than professionals.

The pre-experiment survey also assessed individuals' prior exposure to virtual reality; a mere 20.9% reported having engaged with virtual environments, whilst the majority of participants, 79.1%, had no prior contact with virtual reality

## 4.2 Measurement Model

The measurement model is evaluated for construct reliability and validity at the start of Partial Least Squares Structural Equation Modelling (PLS-SEM) [17]. All constructs in the study were deemed acceptable as they met the threshold of Cronbach's alpha ($\alpha$), $> 0.70$ and composite reliability scores ($\rho_c$), $> 0.70$. Furthermore, it is worth noting that all of the study constructs successfully met the Average Variance Extracted (AVE) test criteria. This indicates their satisfactory performance, as an AVE value greater than 0.5 is considered acceptable. The measuring model has convergent validity and internal consistency, according to the study [18]. The evaluation of the measurement model lays the groundwork for our subsequent analysis of the structural model.

## 4.3 Structural Model Assessment

Our research examines elements that may affect knowledge, motivation, and behaviour. This study focuses on the factors that can improve knowledge, motivation, and self-efficacy through virtual reality as seen in Figure 2. Thus, VR learning requires acknowledging its vulnerability to numerous elements. The variable inflation factor (VIF) established collinearity between the identified constructs. For the inner model, all the VIF values were less than 3.5, suggesting that these subdomains have an independent contribution to higher-order constructs. In addition, we employed bootstrapping to determine the significance of the path coefficients, demonstrating statistical importance at a level of 0.01. The study included five variables: Learner's State of Mind, VR Features, VR Usability, and VR-HRC Learning Experience. Behavioural intention to collaborate was the dependent variable. After testing the direct effect, we assessed the indirect effect through the mediating variables. Both outputs are shown individually. The mediating variable relationship was examined to determine why input-output learning occurred.

# 5 Discussion of Findings

The connection from the mindset of learners to virtual reality features and the learning experience was validated and affirmed as significant. These findings are confirmed by the works of Meyer [19] who illustrated, using an interactive 3D environment, the importance of users' mindset in shaping their learning experience. Additionally, the study highlighted that multiple sessions are necessary for virtual reality features to influence dependent variables related to the intention to collaborate with robots significantly. The study established enthusiasm and sense of motivation as critical in evaluating the state of mind. Hence, the research concludes that when trainees exhibit enthusiasm for learning and are appropriately motivated, their perception of human-robot teaming representation in VR improves. This finding holds both theoretical and practical implications. Theoretically, it underscores that the users' state of mind affects their perception of virtual reality features, thereby influencing their learning experience. On a practical level, it emphasizes the importance of prioritizing VR tool designs that are ergonomically compliant. Also, the correlation between VR features, usability, and learning experiences was examined. The findings indicated a substantial influence of VR features on VR usability. Usability, as defined in the study, encompasses perceived ease of use, usefulness, perceived enjoyment, and the perceived risk of physical danger when collaborating with robots in a VR setting.

The implication of the findings is that the quality of features, particularly in terms of realism, trainee control over robots, and task performance, directly influences the level of presence experienced in the virtual environment. However, intriguingly, the study disclosed no significant correlation between VR features and the learning experience. This lack of influence on learning experiences may be attributed to technical challenges encountered during the experiment, such as strap tightness, first-time virtual reality usage, motion sickness, and other factors impacting participants' experiences. Therefore, the likelihood of a positive learning experience for students may be compromised when the features lack ergonomic suitability.

The study demonstrated that when users perceive the VR environment as conducive to human-robot collaboration, it significantly influences their learning experience. Virtual usability was found to have a statistically significant impact on the VR learning experience. This implies that a more usable and user-friendly VR system positively affects the overall quality of the learning experience. While prior research suggested that human interaction with technology can shape attitudes toward digital tools, this study showed that trainees tend to have a positive disposition when they perceive the technology as easy to use, applicable, and useful. In practical terms, educators, designers, and developers can leverage these findings to design and optimize VR learning environments that prioritize usability, ultimately enhancing the quality and effectiveness of learning experiences. This, in turn, can contribute to more successful educational outcomes and improved user engagement within VR-based educational settings.

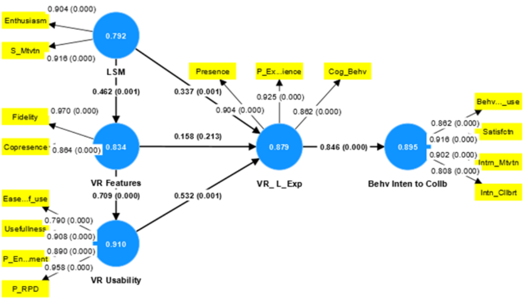


Figure 2. Virtual Reality Based Model to enhance collaboration in human-robot teaming

# 6 Conclusion

In conclusion, this research makes a significant contribution to the understanding of Human-Robot Teaming in the construction industry by integrating a robust theoretical framework, employing empirical methodologies, and exploring the practical implications for VR-based learning. The emphasis on usability, user mindset, and the intricate interplay between VR features and learning experiences enriches the existing knowledge in the field. The study's findings hold relevance for educators, researchers, and industry professionals seeking to harness the potential of virtual reality in improving human-robot collaboration within the construction domain. As technology continues to evolve, this research sets a foundation for further exploration and advancements in the dynamic field of Human-Robot Teaming.

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