VR-BASED TRAINING METHODS IN ENHANCING COMMUNICATION WITHIN HUMAN-ROBOT TEAMS IN CONSTRUCTION

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The integration of robots into construction sites, propelled by advancements in robotic technologies, has generated interest in its application to transform the construction sector in terms of safety, productivity, and the quality of work. This human-robot collaboration is seen as beneficial, allowing humans to focus on tasks beyond the capabilities of robots. However, its implications for an already fragmented construction work environment and varying perceptions of robot adoption remain a concern. Despite the potential advantages of human-robot teaming (HRT), insights into challenges associated with traditional human-human teaming, such as adapting to flexible and responsive work setups, communication issues, suggest that the complexities of human-to-human relationships will be exacerbated in human-to-robot collaboration. Based on an experimental study of Virtual reality-based human-robot collaboration of 42 participants, this paper investigates how VR-based training methods enhance communication among human team members in the context of using robots in construction. It explicitly addresses communication breakdowns using the computer-mediated communication (CMC) theory, emphasising the impact of these disparities on flexible HRT work arrangements and how they contribute to challenges in effective collaboration.

Keywords: Human-Robot Teaming; collaboration; communication; training; Virtual Reality; miscommunication; trust

INTRODUCTION

Recent developments in artificial intelligence, sensors, and robotic systems have opened opportunities for novel automated systems to transform the construction sector in terms of safety, productivity, and the quality of work (Liang *et al.,* 2021; Shayesteh *et al.,* 2023). One promising solution involves leveraging robotic technologies to automate repetitive and physically demanding tasks on construction sites. While the integration of robots into construction sites offers numerous potential benefits, such as allowing humans to focus on tasks beyond the capabilities of robots, it also introduces new challenges, particularly in terms of communication (Storm *et al.,* 2022). As mentioned by Marvel *et al. (*2020), at present, the teaming aspect of collaborative robots primarily pertains to physical proximity. These robots are utilised in conventional automation tasks and often function autonomously, disregarding their

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surroundings (Jeelani and Gheisari, 2021). While suitable for current applications, this approach constrains the technology's potential (Paliga, 2022). To achieve greater effectiveness in construction industry settings, robots must evolve into intelligent, supportive tools for skilled human workers (Bounouar *et al.,* 2021). This transition entails interactions extending beyond simple collision avoidance and touch sensitivity, necessitating advancements in system diagnostics, prognostics, situational awareness and effective communication between humans and robot (Pan and Zhang, 2021). Insights from traditional human-human teaming suggest that challenges such as adapting to flexible and responsive work setups, communication issues, and trust are significant factors that can impact collaboration (Salehzadeh *et al.,* 2022). These challenges may be further exacerbated in human-robot collaboration due to the complexities of integrating robots into the work environment and the potential for miscommunication.

The effectiveness of human-robot teaming (HRT) relies heavily on the establishment of suitable communication systems and practices (Liang *et al.,* 2021). Addressing communication breakdowns arising from cultural, behavioral, and organisational differences is essential for fostering a culture of collaboration within HRTs (Green *et al.,* 2002). By investigating into these challenges and their impact on flexible work arrangements and collaboration, our paper aims to shed light on the importance of addressing communication issues in human-robot collaborations in the construction industry (Le *et al.,* 2022). Miscommunication is a critical concern in effective human-robot teaming within the construction industry due to its potential to lead to errors, delays, and safety hazards (Ozumba and Shakantu, 2018). In an environment where tasks are often complex and time-sensitive, clear and accurate communication is essential for coordinating actions between human workers and robots (Wang *et al.,* 2015). Failure to address miscommunication can result in inefficiencies, rework, and even accidents, ultimately undermining the productivity and safety goals to be achieved by human-robot teaming on construction projects (Matoseiro *et al.,* 2020). Therefore, prioritising effective communication strategies is paramount to ensure successful collaboration and optimise the benefits of integrating robots into construction workflows.

Furthermore, in transitioning to human-robot teaming in the construction industry, two criterias must be met. First, HRT communication must be user-friendly to ensure effective and efficient task performance. Secondly, the human operators' responses to the communication must be positive (Marvel *et al.,* 2020). Lowry *et al. (*2006) affirmed that communication in HRTs can be face-toface (FtF) or digital (Computerised) across distances and not include physical presence or proximity to the robot. Lowry *et al. (*2006) further argued that when communication is digital (computerised), there is often a reduction in the number and type of cues that facilitate communication through nonverbal channels that are harder or perhaps impossible to perceive when a group is distributed.

In addressing miscommunication within Human Robot Teaming (HRT), contemporary training methodologies emphasize the adoption of immersive virtual reality (VR) (Rodrigues *et al.,* 2023). This approach holds distinct advantages over conventional training methods as it offers ease of deployment, enhanced safety measures, and repeatability, unlike physical robot interactions (Adami *et al.,* 2021). Nonetheless, the efficacy of digital communication facilitated by virtual reality in fostering effective HRT remains uncertain (Adami *et al.,* 2022). This highlights the need for empirical investigation into the effectiveness of VR-based training methodologies in enhancing communication within human-robot collaboration settings. In response, using the Lowry *et al. (*2006) computer-mediated communication theoretical model (CMC), we investigated the effectiveness of VR-based training methodologies in enhancing communication within construction human-robot teams. It answers the question, how can VR-based training methods enhance communication among human team members in the context of using robots in construction. Computer-mediated communication (CMC) theory examines how people interact and communicate through digital platforms, rather than face-to-face. Key elements of CMC include the transmission of messages, the role of technology in shaping interactions, and the impact on the quality and effectiveness of communication. In the context of human-robot teams in construction, CMC theory provides a framework to analyze and improve the ways in which humans and robots exchange information and collaborate Salehzadeh *et al. (*2022). The application of computer-mediated communication (CMC) theory in VR-based training methods offers a promising approach to enhancing communication within human-robot teams in construction. By leveraging the immersive and interactive capabilities of VR, training programs can prepare human workers for effective collaboration with robots, ultimately leading to improved efficiency, safety, and productivity on construction sites. As technology continues to evolve, further research and development in this field will be crucial for maximising the potential of human-robot teams in the construction industry

METHOD

While numerous studies within the construction sector have probed into the efficacy of VR-driven training in contrast to conventional training methods concerning skill and knowledge acquisition, performance, and mental workload, there remains a dearth of research exploring its effectiveness in fostering communication among team members in HRTs (Adami *et al.,* 2021). In this study, construction workers undertook training in operating a virtual forklift robot via teleoperation as seen in Figure 1 and 2. The research involved 43 construction workers and professionals who provided written informed consent prior to participating.

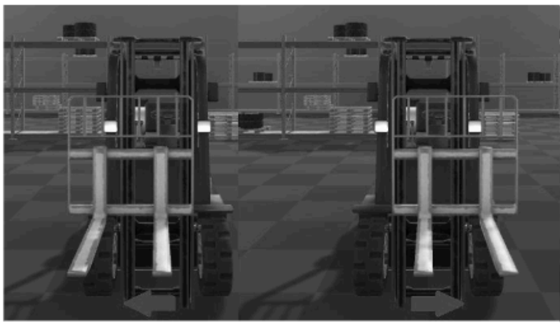


Figure 1 Modelled virtual Robot

Figure 2 Modelled Forklift Robot

Participants' backgrounds and demographics were assessed using a series of survey items, including education level, employment status, and industry experience. Also, participants reported any prior experience with VR or forklift robots. Unlike previous studies that relied solely on subjective evaluations, this study employed both objective assessment through logfiles recording experimental performance and subjective assessment via survey questionnaires. This paper focuses solely on the findings from the survey questionnaire, which comprised 17 multiple-choice questions evaluating participants' comprehension of tasks, the quality of group discussions, communication appropriateness, richness, and openness.

Communication among group members in the VR platform was facilitated using a multiplayer system, where two to three members operated a robot jointly to accomplish tasks. Following the completion of training by all teams, participants were asked to complete the survey to gauge the effectiveness of communication among team members in the VR training system. The study simulated a dynamic construction site, featuring virtual construction workers utilising various construction equipment in a shared environment. Environmental conditions such as dust, rain, sunlight, and uneven terrain were incorporated to offer trainees a realistic construction job site experience. The behavior of the demolition robot and objects within the virtual construction site was programmed using the C# programming language. Trainees interacted with virtual objects and workers using Oculus and HP Reverb 2 Head-Mounted Displays (HMDs), providing a sense of presence and full immersion during training. To provide realistic and immediate feedback throughout the training, the study integrated Particle Systems API for visual effects (e.g., wall thickness, surface materials), VR Audio Spatialiser for audio effects (e.g., demolition sounds), and physical simulations for materials (e.g., rigid bodies, joints, characters, robots).

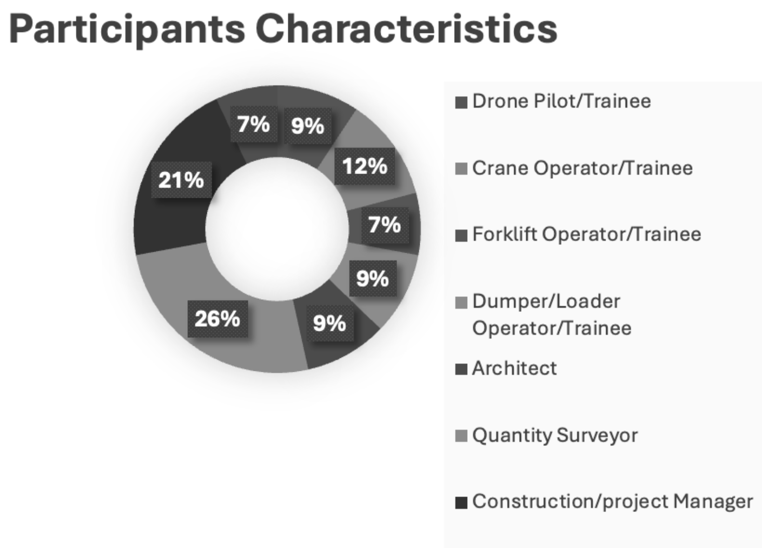
The VR-based training offered trainees the opportunity to practice operating the robot in various scenarios and execute tasks using different strategies based on learning content and prior experience. The content of the questionnaire was adapted from Lowry *et al. (*2006) to allow reliability of the constructs. The study adopted a non-probabilistic sampling stance with 43 responses confimed sufficient as seen in pevious studies (You *et al.,* 2018). The data obtained from the survey undertook quantitative analysis. Quantitative techniques, including descriptive statistics such as frequencies and percentages, were employed to illustrate the overall trends and patterns observed in the data. Reliability analysis was conducted using Cronbach's alpha and revealed that the study is reliable with a value of 0.896.

FINDINGS AND DISCUSSION

Postgraduate students involved in the experiments specialised in the built environment, with concentrations in Engineering (7%), Construction/Project Management (20.9%), Quantity Surveying (25.6%), and Architecture (9.3%). Also, participants included operators/trainees of construction equipment represented as robots, comprising Drone Pilots/Trainees (9.3%), Crane Operators/Trainees (11.6%), Forklift Operators/Trainees (7%), and Dumper/Loader Operators/Trainees (9.3%).

Figure 3 revealed 88% of the sample comprised males, with females accounting for 12% who were construction managers, quantity surveyors and Architects. The study placed emphasis on recruiting participants with prior involvement in the built environment, particularly within construction sites, to ensure the reliability of responses. Thus, site experience served as a crucial criterion for selecting study participants, with 53.5% having less than five years of experience, 32.6% possessing 5-10 years of experience, 9.3% having 11-15 years of experience, and 4.7% with 20 years of experience. The demographic characteristics of the respondents ensured a robust and credible dataset, reflecting the perspectives of operators and professionals within the construction sector. The results of the study are presented in table 1 showing the mean, standard deviation and significance of the constructs.

Figure 3 Participants Characteristics



Group/Team Discussion Quality

In terms of the quality of team discussion, participants generally reported a high level of understanding regarding the tasks performed with the robot (Mean = 4.116, SD = 0.793), with a significant result (p = 0.003). The effectiveness of information sharing among team members about the project was perceived positively (Mean = 4.139, SD = 0.709), though not statistically significant (p = 0.114). Task output satisfaction resulting from teamwork was rated highly (Mean = 4.186, SD = 0.787), with a significant result (p = 0.012). Overall, team discussions were seen as effective for task performance (Mean = 4.162, SD = 0.714), but not statistically significant (p = 0.077). Participants generally demonstrated a high level of task understanding performed with the robot, and task output satisfaction resulting from teamwork was rated positively. This suggests that effective task comprehension and satisfactory task outcomes are achievable within human-robot teams in construction settings. However, the effectiveness of information sharing among team members about the project was perceived positively but not statistically significant, indicating potential areas for improvement in communication regarding project-related information.

Communication Appropriateness

Participants generally reported focusing on other team members when they were speaking (Mean = 3.930, SD = 0.677), though not statistically significant (p = 0.325). Politeness during communication was rated positively by participants (Mean = 4.139, SD = 0.804), with a significant result (p = 0.038). Participants felt that other team members treated them politely during communication (Mean = 4.325, SD = 0.894), with a significant result (p = 0.007). Participants reported a positive perception of politeness during communication, both in terms of their own behaviour and that of other team members. This highlights the importance of maintaining professionalism and respectful communication within human-robot teams, which can contribute to a positive team dynamic and collaborative atmosphere.

Communication Richness

A rich amount of information was perceived to be shared during discussions (Mean = 4.186, SD = 0.763), with a significant result (p = 0.024). Participants felt they received sufficient information from others when they spoke (Mean = 4.279, SD = 0.796), with a significant result (p = 0.039). Participants reported being able to provide vivid information when needed (Mean = 4.139, SD = 0.861), though not statistically significant (p = 0.056). The perception of a rich amount of information being shared during discussions, along with participants feeling they received sufficient information from others, suggests that communication within human-robot teams is generally comprehensive and informative. This is crucial for effective collaboration and decision-making within construction projects, where clear and detailed communication is essential for task completion.

Table 1: Factors in Human-Robot Teams Communication Effectiveness

Items	Mean	Standard Variation	Significance (p)
Group/Team Discussion Quality			
I correctly understood the Task that I had to perform with the robot	4.116	0.793	0.003
The team members effectively shared information about the project.	4.139	0.709	0.114
The task output produced by the teamwork was satisfactory	4.186	0.787	0.012
The overall team discussion was an effective means of performing the task	4.162	0.714	0.077
Communication Appropriateness			
I focused on other team members when they were speaking.	3.930	0.677	0.325
Other team members focused on me when I was speaking	3.860	0.603	0.056
I treated other team members politely during communication	4.139	0.804	0.038
Other team members treated me politely during communication	4.325	0.894	0.007
Communication Richness			
A rich amount of information was shared during the discussion.	4.186	0.763	0.024
Others provided me with enough information when they spoke.	4.279	0.796	0.039
I could provide vivid information on the subject when needed	4.139	0.861	0.056
Communication Openness			
It was easy to communicate openly with all group members.	3.930	0.609	0.091
I enjoyed talking to other group members in the VR environment	4.023	0.801	0.078
Communication Accuracy			
I often had to go back and check the information I received.	4.046	0.871	0.105
I often did not understand what others were saying.	3.930	0.704	0.532
I often had to re-explain statements I had previously made.	3.860	0.614	0.628

Communication Openness

Ease of open communication with all group members was perceived moderately (Mean = 3.930, SD = 0.609), though not statistically significant (p = 0.091). Enjoyment in communicating with other group members in the VR environment was rated positively (Mean = 4.023, SD = 0.801), though not statistically significant (p = 0.078). While participants reported moderate levels of ease in communicating openly with all group members and enjoyment in communicating within the VR environment, these perceptions were not statistically significant. This implies that while communication openness is important, there may be room for improvement in fostering a more open and comfortable communication environment within human-robot teams, particularly in virtual settings.

Communication Accuracy

Participants reported occasional need to verify received information (Mean = 4.046, SD = 0.871), though not statistically significant (p = 0.105). Understanding others' statements was perceived moderately (Mean = 3.930, SD = 0.704), with no statistical significance (p = 0.532). There was occasional need to re-explain previously made statements (Mean = 3.860, SD = 0.614), with no statistical significance (p = 0.628). Participants reported occasional need to verify received information and occasional difficulties in understanding others' statements, indicating potential challenges in maintaining communication accuracy within human-robot teams. This suggests the importance of clarity and precision in communication to mitigate misunderstandings and ensure effective task execution.

CONCLUSIONS

Collaborative work entails the sharing of ideas, knowledge, skills, and information to achieve a common objective. Successful collaboration relies on effective communication among team members. The significance of clear group communication becomes more pronounced as information exchange grows in complexity, whether verbal or digital. It's imperative for group members to articulate information clearly and directly to facilitate effective collaboration. However, many groups encounter process losses that hinder effective communication, such as conformity, evaluation apprehension, and production blocking. Miscommunication in HRT can therefore be impacted by task, group size, or level of social presence (Lowry *et al.,* 2006).

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