Designing Immersive Cooperative VR Experiences for Skill Acquisition and Collaborative Learning

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Abstract

Location-based virtual reality (VR) applications are normally focused around solo experience, limiting face-to-face cooperation and skill acquisition. This paper explores a two-person VR platform to support cooperation through asymmetric roles: the first person drives a mockup vehicle through an obstacle course world, and the other operates a defensive turret to fend off threats. The system utilizes custom hardware — a modified cockpit, specialized controllers, and motion tracking — grounding the experience in physical space. Additionally, shared goals, real-time communication, and force feedback enhance cooperative play. This paper explores the design process, and how the platform encourages communication, spatial awareness, and problem solving in a team. Existing literature supports the theory that co-located, fully immersed VR experience, such as this, holds promise in the consumer and educational arenas, and offers a model for the integration of cooperative, embodied VR into skill acquisition domains.

Keywords: Cooperative VR, Collaborative Learning, Immersive VR, Skill Acquisition, Virtual Reality, Location-based VR

1 Introduction

Integrating cooperative virtual reality (VR) into skill acquisition has garnered significant attention due to its potential to enhance both technical and nontechnical competencies. Research suggests that cooperative VR environments provide substantial benefits compared to traditional, individual-based training methods. For example, in surgical training, team-based VR simulations have been associated with increased procedural efficiency, reduced error rates, and improved teamwork dynamics [6]. These advantages stem from VR's immersive and interactive nature, which effectively replicates real-world scenarios, allowing users to practice and engage in complex skills within controlled, risk-free environments [27, 29]. Similarly, studies on engineering students utilizing collaborative VR platforms have documented notable improvements in spatial reasoning and cognitive engagement, underscoring the potential of VR in fostering advanced spatial skills essential for STEM professions [4]. Shared virtual environments enable participants to visualize and manipulate objects collaboratively, facilitating a deeper understanding and retention of spatial concepts. Such interactive engagement not only reinforces technical skills but also enhances learners' ability to process and apply spatial information more effectively [4, 22].

Beyond technical proficiency, cooperative VR environments have been found to promote learner motivation and optimize cognitive resource utilization compared to individual learning scenarios [22]. This motivational advantage is primarily attributed to cooperative VR's inherently social and interactive nature, which fosters a sense of accountability and collective achievement among participants. These environments cultivate a heightened sense of social presence, allowing users to interact in real time and engage with each other in ways that closely mimic face-to-face communication [11, 21]. This presence encourages individuals to take responsibility for their contributions and remain committed to their collective goals. Features such as avatar-based representation and dynamic virtual spaces further enhance engagement by reinforcing teamwork through realistic interactions and immediate feedback [28, 16]. By fostering positive emotional connections and trust among participants, cooperative VR strengthens interpersonal bonds, making collaboration more effective and meaningful [15, 21].

Moreover, these environments simulate realistic team dynamics, enabling the development of essential soft skills such as communication, coordination, problem-solving, and leadership [29]. These competencies are particularly valuable in professional fields such as healthcare, emergency response, education, and corporate management, where effective teamwork is critical for success [27]. Therefore, cooperative VR may serve not only as a platform for technical skill refinement but also as a training ground for interpersonal and collaborative abilities in con-

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texts closely aligned with real-world professional settings.

An additional benefit of immersive cooperative VR environments is their ability to enhance feelings of co-presence—the psychological perception of being physically present with others in a virtual space. This heightened sense of co-presence fosters more equitable participation among team members, ensuring that all individuals actively contribute to the collaborative process [29]. Such an inclusive dynamic is essential for effective teamwork, as it promotes engagement, strengthens group cohesion, and ultimately improves overall team performance and learning outcomes [10, 27].

2 Background

Many consumer-facing VR experiences are designed with individual immersion in mind and often lack integrated collaborative features. Traditional VR head-mounted displays (HMDs) are typically optimised for single-user experiences, which can isolate bystanders or non-HMD users from the virtual environment, thereby limiting opportunities for shared engagement and cooperative interactions [12]. As a result, much of the existing research on skill acquisition in VR has concentrated on single-user experiences, primarily because of their wider availability and ease of implementation, demonstrating notable benefits such as enhanced motor skills in sports training [17], improved procedural competencies in medical imaging [13], and increased confidence and psychomotor proficiency in technical fields like welding [1]. However, this individual-centric design paradigm has contributed to a relative scarcity of multi-user VR applications despite growing recognition of the advantages of collaborative VR for skill acquisition.

A key challenge in developing cooperative VR systems lies in the technical barriers of real-time data synchronisation across multiple users. Multi-user VR environments require robust networking infrastructure to maintain consistent and low-latency data exchange, a requirement that poses significant demand on bandwidth and computational resources [9]. Ensuring a uniform quality of experience for all participants is particularly challenging in dynamic virtual environments, where fluctuations in network performance can result in latency, desynchronisation, or inconsistent rendering of shared virtual spaces [30]. Beyond technical constraints, accessibility remains a major limiting factor in the widespread adoption of cooperative VR. Many collaborative VR systems depend on specialised hardware, such as high-performance VR headsets and external tracking systems, making them costly and space-intensive. While portable and self-contained VR solutions are under development, their capabilities remain limited compared to fully immersive, tethered systems [24]. Additionally, user adoption continues to be hindered by usability concerns, including difficulty navigating virtual environments and common physiological discomforts such as motion sickness and blurred vision. Improving interface design and user training is essential to address these adoption barriers [14].

Another critical challenge in developing cooperative VR platforms is designing virtual environments that foster meaningful social interactions while accommodating individual user needs, including physiological responses such as visual strain or balance issues. Striking a balance between social immersion and personalised usability remains an ongoing challenge in VR research and development [25].

Despite these obstacles, recent advancements in VR technology are gradually reducing these limitations. Techniques like viewport-adaptive streaming and edge computing help lower latency and improve scalability for smoother real-time collaboration. The integration of 5G-enabled edge computing has also enhanced untethered VR by pooling computational resources across distributed networks, reducing lag and improving overall experience. [3]. Likewise, improvements in VR locomotion techniques, such as walking-in-place and teleportation, are being refined to optimise ease of use while maintaining high levels of immersion [2]. Advances in display technology and tracking systems also improve visual clarity and reduce motion sickness, making VR more accessible to individuals with visual impairments and other sensory limitations [8].

3 Related work

While immersive VR technology has advanced significantly, its application in co-located, synchronous collaboration remains an emerging field due to persistent technical barriers and a lack of established design frameworks. Many existing studies focus on asymmetric interactions – such as mixed HMD and non-HMD user experiences – yet systematic methodologies for designing collaborative VR systems are still in development [20, 12]. Research has highlighted the necessity of structured design strategies to facilitate effective co-located collaboration, including role-based interaction models, enhanced communication mechanisms, and well-defined task structures [9, 10]. While co-located VR holds significant potential for improving spatial skills, teamwork, and social presence, further investigation is required to refine its implementation and optimise usability [4, 29].

What is known thus far is that practical collaborative VR design benefits from authentic representations, interactive elements, and carefully distributed roles to enhance problem-solving efficiency while mitigating cognitive load. However, the integration of these features requires extensive development resources [26]. In this regard, Moharana [19] explored the impact of role distribution – such as leader versus follower roles – on collaboration quality. Their findings suggest that leaders in collaborative VR environments often experience higher cognitive loads, highlighting the need for role-balancing mechanisms to ensure equitable participation and prevent cognitive overload among certain users.

3.1 Key case studies

Despite the outlined challenges in designing collaborative VR experiences, several researchers have explored its application across various domains.

- A study by Ke [18] investigated how children with High-functioning Autism (HFA) collaborated within a VR-based architectural design project. The system was designed to enhance social skill development, cognitive flexibility, and norm construction, providing a structured environment for participants to practice social interactions. The study found that the structured VR setting improved the children's ability to navigate social situations, enhance their adaptability, and form a stronger sense of identity.

- Elvenzio [7] developed a VR system for real-time, low-latency collaboration between therapists and patients in motor rehabilitation exercises. The system supported symmetric and asymmetric interaction, allowing therapists to guide and adjust rehabilitation tasks dynamically. The results demonstrated the feasibility of collaborative VR in rehabilitation settings.

- Taylor [23] combined multi-user VR platforms with video conferencing to enable remote collaboration in designing a VR-based training experience. The study demonstrated an entirely virtual workflow for immersive collaboration, which proved particularly beneficial in restricting environments, such as during the pandemic. The results suggested that integrating VR with existing remote communication technologies could enhance team-based design processes while maintaining the flexibility of virtual workspaces.

- Derouech [5] developed a user-centered, gamified VR platform to enhance teamwork and engagement in workplace settings. The platform was built in Unity and followed a user-centered design (UCD) approach, ensuring accessibility and practical usability by involving users throughout the design process. Game-based elements, such as implementing collaborative quizzes and interactive problem-solving challenges, were integrated to promote engagement and user motivation. The study concluded that incorporating game mechanics into collaborative VR can foster a more dynamic and interactive group experience, leading to more effective and enjoyable virtual teamwork.

4 Proposed design

Our proposed design aims to facilitate skill acquisition, collaborative learning, and team-based problem-solving by leveraging the nature of immersive cooperative VR systems. This design is structured around three interdependent components: customized hardware, software, and user-centered design. The hardware framework provides the necessary physical interface for interaction. At the same time, the software architecture ensures real-time synchronization, dynamic environmental responses, and seamless communication between participants to foster a sense of co-presence. The user-centered design approach informs the system's ergonomic considerations and safety protocols, optimizing user comfort and accessibility while addressing the cognitive and physiological demands of extended VR engagement for users unused to the experience. This section will thoroughly examine the proposed hardware specifications, ergonomic configurations, networking infrastructure and potential enhancements for a more immersive experience.

4.1 Hardware

The proposed hardware configuration consists of two tethered HMDs with optional wireless functionality, specifically the Oculus Quest 3 or newer devices that adhere to OpenXR standards. These HMDs are considered for their high-resolution displays (2064 × 2208 pixels per eye) and high refresh rates (up to 120Hz), both of which are essential for ensuring visual clarity and immersion and minimizing user discomfort associated with latency or a restricted field of vision (FOV). The tracking system under consideration is Oculus Insight, which enables six degrees of freedom (6DoF) tracking through built-in cameras, potentially eliminating the need for external sensors. This could simplify the setup process and reduce deployment costs, making it particularly advantageous for demonstrations, testing scenarios, and large-scale implementation.

A fundamental aspect of this design is the differentiation of roles between the two users. One user is responsible for vehicle control, necessitating an interface that enables realistic and intuitive driving mechanics. The design incorporates a PlaySeat racing chair mounted on a durable metal framework to support this functionality, ensuring an ergonomic and stable driving posture. This seated configuration is expected to improve comfort over extended usage periods and provide a grounding effect, which may help mitigate VR-induced motion sickness. The driving interface consists of a Logitech G29 steering wheel, securely affixed to the frame, its associated pedal system and an optional driving force shifter to introduce additional complexity and challenge. The force-feedback mechanics of the Logitech G29 are considered a key component in enhancing realism as they replicate real-world vehicular dynamics, including steering resistance and vibration-based tactile feedback. Furthermore, the adjustability of pedal stiffness is proposed to allow users to customize braking resistance, making the experience more reflective of real-world driving conditions.

Figure 1: Prototype Installation with Steering and Turret Controls

The second user assumes the role of the turret operator, requiring an accurate tracking system to ensure precise turret movement within the virtual space. Two potential tracking solutions are considered: the HTC Vive Tracker, which offers high accuracy and low latency via SteamVR base stations, and the Sony MOCOPI, a wireless tracking solution that provides a cost-effective alternative while maintaining sufficient fidelity for turret control. To ensure safety and ergonomic usability, the tracking device is intended to be mounted onto a controller designed for turret operation, which is affixed to a stable pivot joint with a 3D-printed component constructed from durable ABS material. These proposed physical constraints limit unintended movement and reduce the likelihood of accidental physical contact between users. The turret operator will be seated on a rotational stool with a tracking device attached to its base to detect rotational movement. At the same time, an additional tracker will be mounted directly onto the turret, allowing for precise vertical movement control within the virtual environment.

Another key consideration in the proposed system is the networking infrastructure, essential for maintaining real-time interaction between the two users. To achieve a stable and low-latency connection, the system is designed to operate over a Local Area Network (LAN), interconnecting two high-performance VR-ready PCs to ensure smooth data transmission and minimized lag. The system architecture follows a client-server model, with one machine acting as the authoritative server, responsible for handling game logic, synchronizing physics calculations, and ensuring consistency within the shared virtual environment. This network structure is expected to maintain latency below acceptable thresholds, thus providing a fluid and synchronized cooperative experience.

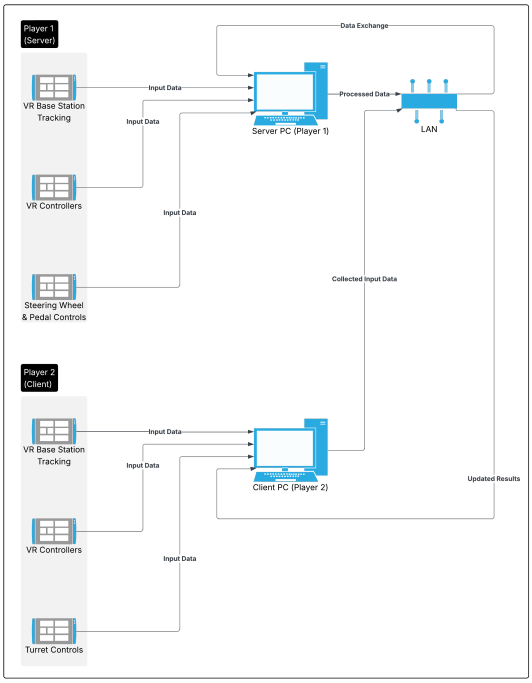

Figure 2: Client-Server Setup and Peripheral Integration

The ergonomic and safety aspects of the design are also carefully considered, particularly in light of the potential physical strain associated with extended VR use and the possibility of VR-induced discomfort. The seated configuration of both users is proposed to reduce fatigue while ensuring stable posture throughout interactions. For the turret operator, the rotational seating arrangement facilitates effortless movement, minimizing strain on the wrists, shoulders, and upper body. The physical structure of the VR setup is designed to align closely with its virtual counterpart, ensuring that the real-world vehicle framework corresponds accurately to the digital representation. This alignment enhances spatial awareness, reduces disorientation, and mitigates collision risks between physical and virtual objects. Additionally, effective cable management solutions are to be integrated to eliminate tripping hazards, ensuring a safe and obstruction-free interactive space.

To further enhance immersion, the integration of sensory feedback systems is also under consideration. One proposed enhancement involves airflow simulation, which could be implemented using strategically placed fans or portable air conditioning units. This feature is expected to reinforce the sensation of movement while also helping to alleviate motion sickness by introducing external sensory input that aligns with the perceived motion in VR. Another potential addition is incorporating haptic feedback mechanisms, such as haptic vests or vibration transducers embedded within the seating arrangement. These devices could simulate physical sensations associated with environmental interactions, such as vehicle motion, turret recoil, or terrain impact. However, the integration of haptic feedback must be carefully evaluated, as excessive or improperly calibrated feedback could intensify motion sickness for users unaccustomed to prolonged VR experiences.

4.2 Software

We developed the prototype of our proposed VR experience in Unity 6, selecting it for its high-quality rendering and dependable support for real-time, networked interactions. Unity's integrated VR multiplayer template served as the foundation, providing ready-to-use assets such as the Network Game Manager, Interaction Controller, and player prefabs. The template also included Vivox Voice Chat to support real-time voice communication among participants. By building on Unity's standardized packages rather than creating a custom framework, we ensure long-term maintainability and future compatibility with engine updates.

The system operates on a locally networked client-server architecture. A high-performance machine acts as the authoritative server, while a second machine functions as a synchronized client, maintaining real-time interaction with minimal latency. This configuration supports consistent state management and responsive multiplayer performance. The current VR experience uses placeholder assets for the vehicle, environment, environmental hazards, and player characters to allow for rapid iteration and efficient testing of project builds. The final vehicle model is planned to be reconstructed using Gaussian splattering to capture fine surface detail, followed by optimization in Blender for real-time performance. The remaining assets—including the environment, hazards, and avatars—are being developed entirely in Blender and will be textured using Substance Painter to achieve a high level of visual fidelity while maintaining performance efficiency.

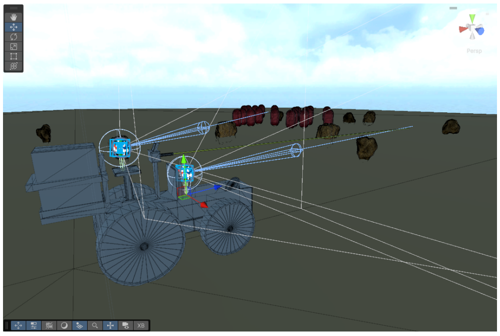

Figure 3: Early Prototype Environment in Unity

At this stage of development, onboarding relies on a traditional menu-based interface with slider controls provided by the default VR template, allowing quick and flexible tweaking of settings. In the final implementation, this system is replaced by an interactive calibration sequence where users input body measurements—such as height and arm span—and adjust audio preferences like music volume. We decided to use stylized robotic avatars rather than humanoid models to avoid the uncanny valley effect. Robots are generally better received in VR contexts, even with limited facial expressiveness, and help maintain immersion without distracting from the core experience. Shifting to an interactive onboarding process further reduces the likelihood of user error and strengthens the player's sense of embodiment by closely aligning the avatar with their physical presence.

At present, a simple interface is used to convey only basic information to test participants, serving as a lightweight solution during development. In the final version, this interface is replaced by a spherical, visor-like HUD embedded directly into the VR environment. Key gameplay information—such as directional cues, vehicle status, and defensive alerts—is delivered non-verbally within the player's field of view to minimize reliance on text overlays. Voice communication is handled through Vivox, with built-in noise cancellation for clarity, and is supported by gesture-based controls and pre-configured visual symbols to accommodate a range of communication preferences.

4.3 Core Gameplay

The gameplay is about a cooperative delivery mission in which two players guide an ever-changing environment while defending their vehicle against enemy creatures displaying swarm-like behaviour. The gameplay consciously separates tasks into two specialised roles: the vehicle pilot and the defensive gun operator. Two players are seated next to each other without overlapping their body space, so they must talk and use symbols to coordinate. The pilot manages vehicle movement, steering, accelerating, and braking, yet cannot stop the vehicle. While inside the physical VR setup, yet outside of the actual level space, immersive movement is achieved by dynamically loading and unloading terrain chunk prefabs under the vehicle using a 6x6 grid moving against the direction of current facings for the vehicle. These prefabs include level ground with environmental obstacles like rocks and cacti, which players must carefully navigate to keep ideal vehicle speed. A similar strategy is used for managing enemy entities, preloading most at level startup, spawning additional instances as needed, and reusing inactive enemies by moving them outside of view to avoid frequent object creation and destruction, causing performance lag.

The fundamental task is to get the cargo and its truck

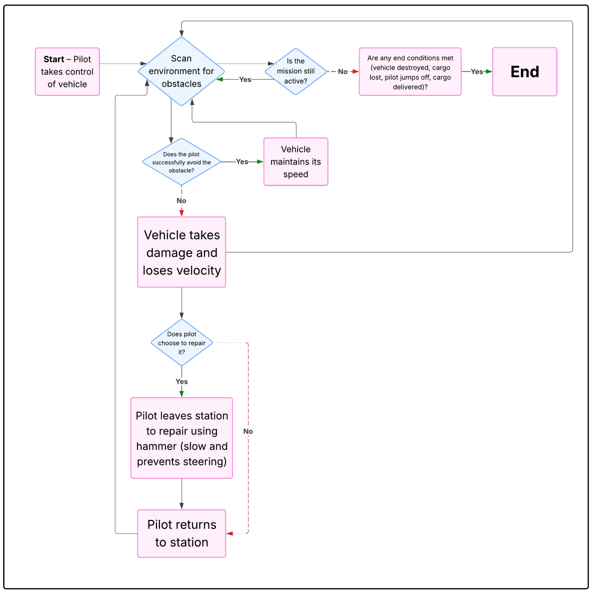

Figure 4: Role-Specific Game Logic for Pilot Player

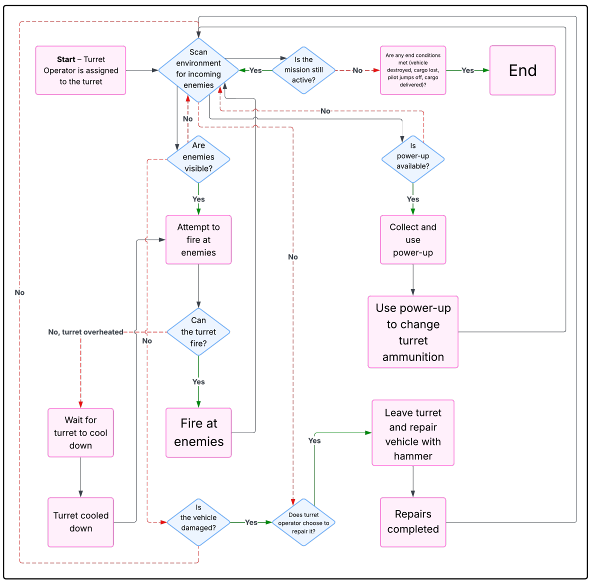

Figure 5: Role-Specific Game Logic for Turret Operator Player

to their destination, incurring as minor damage as possible for as high a score as possible. The game ends when the cargo is lost, the truck is destroyed, or one or all players decide to jump off.

To maintain player immersion and avoid VR sickness caused by feeling stuck when moving in simulation, player sight is intentionally restricted by using a sandstorm VFX cone to occlude terrain transition points.

The turret operator actively protects the vehicle against hostile targets who approach from within the sandstorm effect's area, mainly from in front. Hostiles can attack from other angles at other times to sustain play. Variant enemies include standard enemies, elite variants, and bosses with different aggression points, velocities, and attack tactics to test coordinated player cooperation. The turret has an overheating mechanic that disallows constant fire, so cooldowns must be managed tactically.

Temporary bonuses are awarded when players reach specific points, such as killing an enemy count, surviving extensive amounts of time without taking severe vehicle damage, temporarily altering ammunition for the turret and promoting strategic play. The pilot is guided by suggestive visual and audio cues incorporated within the sandstorm effect while still offering exploratory yet intuitive gameplay. Weather conditions remain fixed for each mission at dawn or dusk, maximising performance by minimising horizon rendering. Vehicular damage becomes an endemic gameplay feature, although part of this can be mitigated through an optional manual repair. Players can temporarily abandon fundamental roles for short periods to perform limited and laborious fixes using a hammering tool. Damage affects vehicle strength and speed, forcing players to balance repairing possibilities against core goals judiciously.

The game's visual appearance in terms of its stylised, gritty assets is achieved through mid-to-low poly models to maximise its suitability for use in different virtual reality headsets. Real-time physics calculations are reduced as animations have been precomputed based on blend shape baking. Level-of-detail (LOD) rendering renders near-player local objects in high detail, distant assets, and items outside the direct player view in low detail without affecting frame stability while still engaging in immersion.

5 Conclusions and Future work

This paper outlines an immersive virtual reality experience using conventional and custom-built hardware to encourage learning of technical and social abilities through collaborative gameplay. The setup facilitates communication, organization, and leadership in an embodied, co-located setting, leveraging existing research in virtual reality, spatial cognition, and collaborative learning. Combining head-mounted displays, steering input devices, and sensor-based controllers, the prototype explores embodied interaction's potential for increasing user engagement and learning.

Our design draws upon emerging theory and research in embodied and cooperative VR and aims to address gaps in current solutions. Rather than offering a definitive solution, this approach is an evidence-based effort to build upon proven concepts—highlighting where design, hardware integration, and interaction structure can be optimized. With underutilized input mechanisms and a focus on co-presence, embodiment, and accessibility, the platform serves as a modest yet pragmatic template for future implementations. Through this, we hope to contribute to ongoing discussions around how VR can better support rich shared experiences—especially those that reduce space requirements while maximizing the potential for social and cognitive growth.

While the system shows promise, it remains a prototype with limited visual fidelity and occasional software instability. As such, it functions primarily as a technical proof-of-concept rather than a refined user experience. Constraints include high setup costs and space demands, which may limit broader use. A stronger theoretical framing—particularly regarding solo vs. shared VR—would also help contextualize the project within current research.

Future research should focus on three areas: improving technical stability and visual design, conducting user studies to evaluate learning and collaboration outcomes, and exploring downscaled or modular configurations to increase accessibility. Interdisciplinary input from visual design and human-computer interaction can further improve system usability and effectiveness. Developing age-appropriate, context-specific scenarios could also expand the platform's relevance in education, training, and entertainment. With continued iteration, the system has the potential to evolve into a more accessible and research-informed tool for embodied collaborative learning in VR.

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