MazeWorld: A Multiplayer 3D Research Testbed for Human Teaming, AI Agent Integration, and Multiple XR Disciplines

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Abstract. Many research testbeds are created with specific studies in mind, which limits their use for cross-disciplinary research. This paper introduces MazeWorld, an open-source, multiplayer Unity virtual environment application designed to accommodate multiple research disciplines. In MazeWorld, three players take on specific interdependent roles to solve a maze-based challenge and speak via an audio channel. Features of the maze, the player avatars, and task difficulty can be varied per the researcher's goals. MazeWorld can be played using a virtual reality headset, and players each use their own device. MazeWorld, a research testbed, logs player behaviors and game states extensively.

Keywords: Virtual Reality · Collaborative Problem Solving · Multiplayer Game

1 Introduction

Virtual testbeds are useful for creating ecological experiments that allow researchers to balance naturalistic conditions with experimental control. They are especially flexible for handling multiple players, which is key for research areas focused on teaming. One promising research area ripe for utilizing virtual testbeds is the study of human-agent teams. Virtual testbeds provide a platform where human players can seamlessly interact with agents whose features may vary by autonomy, skill, etc. Tightly controlled experimental settings allow experimenters to vary task difficulty and the context in which teamwork occurs, and to simulate changes in team members' states and available resources. We describe the development of a 3D multiplayer testbed designed for cross-lab collaboration, its initial use of investigating human-agent teams (HAT), and its potential secondary uses for researching cybersickness as an example case.

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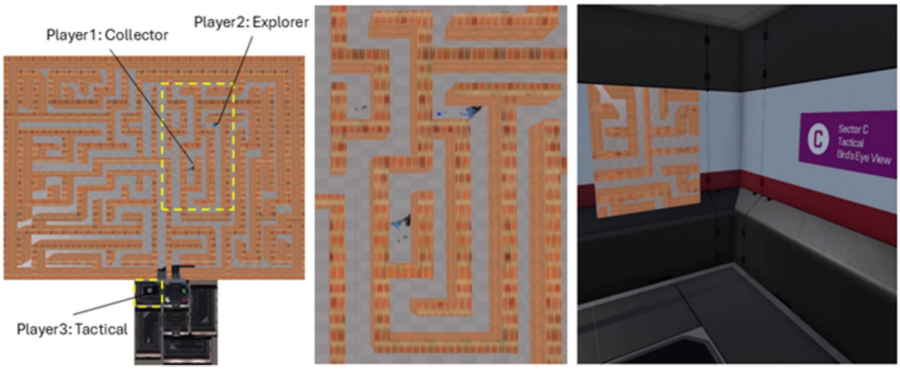

Fig. 1. MazeWorld 3.0. Three players collaborate in a series of interdependent tasks in a virtual maze to collect coins.

1.1 Why Do We Need Another XR Testbed?

An extended reality (XR) research testbed differs from a simple virtual environment or game in that it is specifically designed to facilitate extensive data collection. A research testbed outputs time-stamped log files of complete user state (e.g., the user moved to x1, y1, z1 and is looking at x2, y2, z2 and holding a basket) and the environment state (e.g., there is 20% cloud cover, and 12 alligators are near) in such detail that the user's experience can be replayed from the log file. Logs typically include audio and text communication as well. Ideally, a multiplayer research testbed allows for the measurement of relational behavioral markers [56] like team trust or the average conversational distance, not just counts of player actions. Some example research domains follow.

Researchers in social VR have explored social presence [44], communication [20], and group dynamics [15]. However, much of the current work has focused on relatively simple social exchanges or predesigned scenarios. A more flexible testbed could allow the exploration of more complex and spontaneous interactions. A multiplayer XR testbed can also be useful for studying the collaborative development of spatial skills [7, 23] and the effects of competition vs cooperation on spatial task performance and spatial knowledge [34]. Cybersickness has been widely studied [16, 53, 54, 62], but researchers have focused on single-player VR environments. A multiplayer testbed could allow exploration of how social dynamics affect cybersickness.

2 Background

2.1 Human-Agent Teaming

As AI agents (both virtual and embodied) become increasingly sophisticated and common, it is important to understand how humans and agents can work together as teammates [1, 2]. In human-agent teaming, also referred to as human-AI teaming or human-autonomy teaming (all HAT), researchers are exploring how teamwork principles like communication, collaboration, and trust apply to human-agent teams (HATs) [3, 4]. However, building virtual AI agents for research can be time-consuming, so flexible research testbeds can enable researchers to study HATs without needing to build a new agent for every study. An ideal HAT testbed should allow researchers to manipulate inputs as independent variables and to measure the mediators and outputs as dependent variables. Some previous studies used testbeds that were designed specifically for HAT studies [5, 6], while others repurposed existing applications to study HAT [7, 8]. Existing applications have also been used to study HAT. The Strike Group Defender game [9], TNO Trust Task [10], Predator-Prey game [11], and Blocks World for Teams (BW4T) [7] have all been adapted for HAT by replacing a human player with an agent. Commercially available video games like Overcooked 2 [8] are sometimes utilized for HAT studies, sometimes using the Wizard of Oz method [12] to simulate an AI agent.

The studies cited above provided insights used to design the MazeWorld testbed. Like other HAT testbeds, MazeWorld features interdependent roles that can be filled by humans or agents, and the team must communicate and collaborate to complete the shared goal. Additionally, MazeWorld uses a neutral task and environment that does not require domain expertise. The inclusion of human-like avatars in MazeWorld enables researchers to include embodied agents and study teamwork skills like non-verbal communication. Finally, giving researchers greater control over the experimental task, environment, and output variables supports a range of research on HAT interactions.

Non-verbal Communication and Embodiment. Non-verbal communication and implicit coordination occur in all-human teams, particularly in constrained situations where natural language is not possible, but they are less frequently studied in HATs [13, 14]. Gestures [15], which include specific movements and shape of body parts, carry specific meanings, support the understanding of speech content and can communicate a team member's intent without speaking. Analyzing the body movements of two or more members provides further insights into their communication. The proximity between individuals can be an index of their relationship [16–18]. Grahe and Bernieri [18] demonstrated that observers could estimate rapport based on visual cues, including proximity. Similarly, eye contact is another critical nonverbal cue, influencing, for example, the level of trust or attraction [19]. When team members align their actions (often studied in the extant literature as behavioral synchrony), teams communicate better which often leads to enhanced team performance. Behavioral synchrony has been linked to increases in feelings of group cohesion and social bonding [20, 21], and cooperative and prosocial behaviors [20, 22]. Along with these positive outcomes, behavioral synchrony can also produce negative effects such as a decrease in team creativity [23]. Due to its associations with team performance, behavioral synchrony has often been used to index team states such as listeners' attitudes [24] and alignment of internal representations [25].

These topics cannot be addressed unless participants recognize their own body and other members' bodies and observe each other's movements. Based on this requirement, MazeWorld authors added humanoid avatars to allow researchers to investigate non-verbal and body movement-related research questions. Ideally, eye contact and facial expressions would be represented as well, perhaps in a future version.

2.2 Cybersickness Research

As noted above, a multiplayer 3D XR environment presents an opportunity to advance research on cybersickness in social settings. Multiplayer environments introduce new variables, leading to research questions such as: How does the presence of other players influence the onset and severity of cybersickness symptoms? How does first-person vs third-person view of one's avatar when interacting with others affect cybersickness? How does quality of avatar eye contact affect cybersickness? How does the quality and completeness of full body representation via avatar affect it? How do effects like shared spaces, others' avatar movements, and synchronized actions between player's impact cybersickness? Investigating these questions could provide valuable insights into effective cybersickness mitigation strategies. Ideally, a research testbed like MazeWorld could include affordances to answer these questions.

Cybersickness arises from sensory conflicts between the visual and vestibular systems [26] or issues in postural imbalance [27]. This conflict often results from technical factors like latency [28], frame rates [29], and movement methods [30] in XR environments, as well as individual differences in susceptibility and video game experience [31]. A platform like MazeWorld could allow the adjustment of these variables.

The concept of presence, which is the psychological state in which users feel as though they are truly within the virtual environment [32] is another important factor in XR experiences. Studies suggest a negative relationship between presence and cybersickness [33], and multiplayer interactions may further this relationship, but a limited number of studies have been conducted thus far. A testbed like MazeWorld could allow researchers to vary the parameters that affect presence.

Locomotion is another significant factor for cybersickness research, which controls how the user navigates within the virtual environment, can also greatly affect cybersickness and presence. Common movement methods in XR include teleportation [34], smooth locomotion via joystick or controller input [35], and natural walking, where users physically walk within a limited tracked space [24]. MazeWorld enables modular switching of locomotion methods, allowing for studies on their effects on both cybersickness and presence.

3 MazeWorld

There have been three versions of MazeWorld. The idea of MazeWorld began in a vertically integrated project [36] in 2019 led by authors Dorneich and Gilbert at Iowa State University as they sought a reasonable platform for researching human-agent team dynamics in small groups [37]. The initial intention was to develop a platform with adjustable parameters to allow for the evaluation of specific elements such as team structure, communication, leadership, and mutual trust [38]. Author Segal developed MazeWorld 1.0 in Unity with inputs from the team, and a first study was run [38], demonstrating its feasibility as a research platform.

Three to four non-co-located participants navigated a maze of interconnected rooms and collected coins within a specified time limit. The three player roles included: 1) the Explorer opened doors, 2) one or two Collector(s) collected coins that counted towards the team's score, and 3) the Tactical had a bird's eye view to assist with teammates' navigation. Participants used a mouse and keyboard to control their characters, displayed as cylinders. Text chat offered communication.

An initial study was conducted using MazeWorld 1.0 [38]. Three metrics were used to evaluate team performance: team task ability, efficiency, and team workload. Results highlighted the need for increased task interdependence, as the factor that most affected performance was familiarity with the environment rather than any form of teamwork.

In 2023, authors Deal, Lovig, Newendorp, and Shah Abadi at Iowa State University began an "interaction metrics" class project [39] on MazeWorld, analyzing the team dynamics and recommending improvements in the game rules to promote player role interdependency and refine the task difficulty. Author Segal had moved to Cornell University to work with author Won, where he created MazeWorld 2.0 based on feedback from stakeholders at both Iowa State University and Cornell. Version 2.0 added a more traditional maze, similar to the one shown for v3.0, and added further independencies in the task roles to promote tighter teamwork. The authors in the class project evaluated MazeWorld 2.0, which generated pilot results used as input to the creation of v3.0.

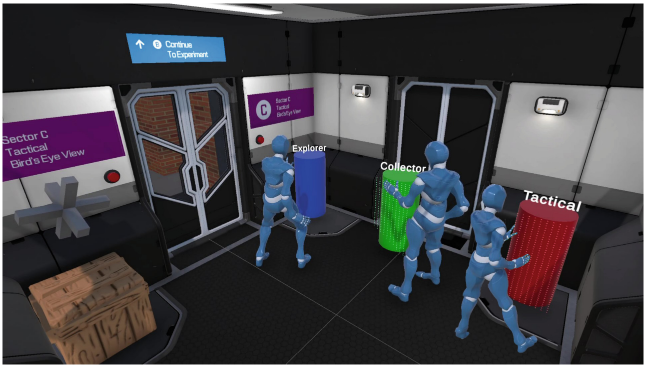

Fig. 2. Role selection room in MazeWorld 3.0.

In 2024, authors Matsumuro, Sharma, and other students at Cornell (guided by authors Won and Lauharatanahirun with colleague McLeod) created MazeWorld 3.0 (Fig. 2) based on additional requirements for collaborative research studies across Iowa State University, Cornell University, and Penn State University. There were three major changes for MazeWorld 3.0. First, it was implemented in an immersive VR environment, where players control humanoid avatars, which allows them to communicate using gestures and other body movements. Second, we added further role-specific interdependent tasks, where team members were required to frequently communicate by spoken voice to successfully achieve team goals. Another change included the capability to adjust the difficulty of each player's task. Finally, MazeWorld 3.0 provides players with two additional locomotion methods: joystick input and teleportation. This added locomotion capability allows researchers to assess the effects of locomotion movements on cybersickness [40].

3.1 More Independent Task Roles

MazeWorld 3.0 expanded on the original testbed by increasing the amount of role interdependency. In the updated version, each role must support and be supported by both other roles. This was accomplished by several changes to the game play, including different coin types and a limited-capacity battery pack for the Explorer that is drained by coin activation. Another addition was a "fog of war" effect, which makes undiscovered areas unpredictable. In MazeWorld 1.0, there were only one-way interdependencies, while in MazeWorld 3.0, there are bi-directional interdependencies among all three team roles (Fig. 3).

Fig. 3. Interdependency of roles in MazeWorld 3.0 [41].

3.2 Immersive VR/Embodiment

One of the biggest advantages of using a VR environment is the ease of recording players' body movements. MazeWorld 3.0 has a log function that records the global coordinates and rotations of an avatar and the local coordinates and rotations of a specified avatar's body parts. Other actions and events during a task like activating a coin and dropping a battery are recorded in the same file. Therefore, event-related body movements are easily detected and analyzed.

Players' heads and both hands' movements are collected from their head-mounted displays (HMDs) and hand-held controllers and reflected in real-time on a humanoid avatar (Fig. 2). Participants can observe their avatar from the first-person perspective, enhancing the sense of presence within MazeWorld. The three-point body tracking allows the players to communicate using their head and hand movements, such as waving their hands to each other when they meet and nodding their heads to show their agreement with another player. These naturalistic behaviors allow for non-verbal communication and the subjective sense of copresence between teammates.

3.3 Locomotion UI

Three primary movement methods are functional in MazeWorld. First, players can navigate the maze using their physical walking movements. This method of locomotion is the most intuitive and immersive because the physical body position and the avatar position are perfectly concordant [40]. However, a space as vast as the maze is required. The second method involved joystick-based navigation, which controls both movement and rotation and provides precise control over both the avatar's speed and direction. The third method, teleportation, is provided to mitigate cybersickness.

3.4 MazeWorld 3.0 Example Session

A session of MazeWorld is conducted with three players each wearing virtual reality HMDs. A session begins with players loading into the program's lobby. Inside the role selection room (Fig. 2), the players select one of three roles (Explorer, Collector, Tactical) and can review tutorial information for their selected role. After all players select their roles, the doors to the maze open and the players have a set amount of time to collect as many coins as possible.

At the beginning of a session, the Explorer and Collector players enter the maze. The Tactical player moves to a special room (Fig. 1, right) and directs the Explorer to the activatable coins in the maze. The Collector player must collect coins in a specific order. They communicate which coin is next in the collection order (e.g., "We need to collect a triangle next.") The Tactical player then either finds a triangle coin on the map and directs the Collector to it or asks the Explorer player to activate more coins until a triangle is found. As the Collector acquires more coins, they slow down and become encumbered, incentivizing them to return to the starting area to deposit coins.

The session continues, with the Tactical player directing the Explorer to activate coins, the Collector communicating what coins they need to collect next, and then having the Tactical player direct them to that coin. The session ends when time runs out, and players are returned to the MazeWorld lobby where they can select a different role. One round of MazeWorld, including time spent in the lobby selecting rolls and reviewing instructions, takes about 15 min.

4 Limitations

While many of the initial goals of MazeWorld have been achieved, there are still limitations. There are three main aspects from the original MazeWorld 1.0 discussions that are not yet included within the project: fully functional agents, task separation, and focused parameterization. While MazeWorld is designed to allow modular integration of software agent players, it has not yet been tried. Also, the creation of interconnected tasks where all participants rely on each other but still function to a high degree of autonomy is quite complex. Various cooperative video games such as Overcooked2 and KeyWe have tasks that require turn-taking or simultaneous collaboration, for example [42]. Currently in MazeWorld the Explorer and Collector roles are tightly connected and usually function more as one role instead of separately. The enhancements from MazeWorld 2.0 to

3.0 attempted to address this limitation but the connectedness of these two roles persists to some degree. Lastly, MazeWorld has limited customization of teaming parameters such as controlled randomness, variable tasks, and predefined parameters validated to produce desired effects.

5 Discussion of Future Research

There is a long tradition of researchers in virtual reality sharing knowledge on developing virtual environments or sharing templates for environments with the aim of standardizing virtual reality research [43]. The recent NSF-funded project VERA (the Virtual Experience Research Accelerator) aspires to facilitate cross-lab collaboration. The authors intend MazeWorld to be a tool that could fit within VERA, allowing modular configuration options to enable multiple labs to run different studies, e.g., some with immersive VR, and some with desktop VR.

One future research direction is creating AI agents with the ability to learn adaptive communications that can be probed using multi-agent reinforcement learning [44]. MazeWorld 3.0 can be viewed as a fully cooperative sender-receiver game in which there is a sender (the Tactical) and two receivers (the Explorer and the Collector), and players transfer information to reach their common goal.

Additionally, one can use MazeWorld as a testbed to validate an agent-based simulation model of a cooperative game similar in mechanics to MazeWorld. If validated, the simulated model could be used to generate teamwork data without any human players. This approach would allow for faster, more automated data collection, which is valuable when experimenting with a range of variable combinations.

6 Conclusion

In this paper, MazeWorld, an expanded virtual testbed focused on studying human-agent teaming was presented. Following a successful first version, the testbed was expanded to include two-way interdependency among all roles, user embodiment capabilities, and various types of locomotion. This work enables collaboration with a fully open-source program that allows for research avenues outside of those presented in this paper, providing a synergistic way to identify knowledge gains for the greater scientific community.

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