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Collaborative VR: Solving riddles in the concept of escape rooms

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Abstract

The recent state of VR technology enables users to have quick and easy access to multiple VR functionalities, prompting researchers to explore various aspects of user experiences in virtual environments. In this work, we study alternative means of user communication in collaborative virtual environments (CVEs). We are especially interested in how users manage to convey messages to each other while not being able to see, hear, or text one another. We aim to understand how users choose to utilize the tools provided to them in virtual environments and report their feedback i.e., how this affects engagement level, performance, etc. The objective of our work is to be able to determine the effects of integrating alternative means of communication in users' experience in VR; to examine this, we choose a case study of a collaborative VR escape room. We carry out a user study to evaluate our hypotheses on the effects of nontraditional communication means when performing computer-supported cooperative work (CSCW). We find that players manage to complete their tasks similarly to real-life scenarios, even when not allowing for traditional ways of interpersonal interactions. Through our user survey, we also conclude that it is worth integrating this communication option in other applications as well, which poses further questions as to what is the full potential of incorporating several alternative functionalities that people subtly use in real-life, in VR.

CCS Concepts

• ***Computing methodologies*** → ***Virtual reality;*** *Mixed / augmented reality;* • ***Applied computing*** → ***Collaborative learning;***

1. Introduction

Recent advancements of virtual reality (VR) technology has led to a surge of interest in fields like entertainment, education, healthcare, and even military training. Thus, researchers have been exploring new concepts and functionalities through their VR applications, exploring its potential as a powerful tool for teaching, learning, and simulations. An area of particular interest is the development of collaborative virtual environments (CVEs) that enable multiple users to interact in a shared VR space. This emerging field, known as collaborative VR, builds upon the idea of CVEs and is distinguished from single-user VR experiences by its focus on computer-supported cooperative work (CSCW). According to Li *et al.* [LLW*22], collaborative VR allows for the representation of all users in VR to each other, creating a truly collaborative experience.

Current multi-user VR functionalities enable multiple users to coexist in virtual environments, but they lack full support for collaboration and direct communication between users. To overcome this limitation, traditional communication methods like text and audio are commonly used. However, we aim to explore the potential of VR for collaborative and competitive interactions by moving beyond these standard modes of communication. Our version of collaborative VR challenges users to employ a range of skills that require ingenuity and adaptability, as we strive to enhance communication within the virtual environment.

Our research aims to extend the capabilities of users in CVEs by investigating alternative forms of communication for CSCW beyond traditional means such as hearing, texting, or seeing other users. To achieve this, we impose constraints that force users to come up with unconventional communication methods in order to succeed in the task at hand. Our work centers on an escape room scenario, which we use as a case study to test this concept in a multi-user CVE.

Escape room games involve individuals or teams progressing through designated "rooms," solving challenging puzzles to unlock the final door and "escape" within a fixed time. These puzzles test problem-solving and awareness skills and often require clues from previous riddles or items in the room. Escape rooms stand out for their emphasis on collaboration, interaction with the environment, and sometimes competition with other teams to complete the room quickly. This makes them appealing for VR applications [PMB*17], where communication with other users and the virtual environment is crucial.

While VR escape rooms are typically designed for single-user experiences, there are a few examples of multi-user escape rooms. However, these multi-user rooms often rely on traditional forms of communication, such as audio and visual cues. In contrast, our multi-user escape room scenario requires users to solve puzzles individually and collaboratively without the ability to see, text, or hear each other. This unique approach encourages users to explore alternative methods of interaction and progression through the rooms. By doing so, it expands their skill sets, fosters creative thinking, and teaches them to utilize their surroundings for problem-solving, even in situations where traditional audiovisual communication methods are unavailable. We have carefully selected these alternative modes taking into consideration the needs for interaction and communication for each riddle. We looked up for similar online games in the internet to get inspired, and then we have modified the games so as to work for these unconventional communication types. We believe that developing a diverse range of skills enhances overall awareness and problem-solving abilities. Through our focus on VR escape rooms as an experimental platform, we aim to empirically test and apply this concept.

Our contribution lies in pushing the boundaries of research in collaborative VR and broadening the range of capabilities in this field by creating these types of CVEs. This has the potential to positively impact various applications, including aiding and promoting inclusion for individuals with disabilities, such as enhancing vision for low-vision users [ZKC*19]. In our case study, two users must solve riddles both individually and collaboratively to progress through the rooms. Eventually, they will have to compete with each other without the ability to use text or sound for communication. We provide the necessary communication tools but do not enforce a strict method of communication, allowing users to determine how to effectively use them to solve the puzzles. Since previous works commonly rely on text and sound to enable user communication, and VR escape rooms focus on only one aspect (individual, collaborative, or competitive), our contribution is twofold:

- We explore alternative means of communication in VR, beyond the conventional audiovisual methods,
- We provide a comprehensive evaluation and analysis of this collaborative VR concept through a user study of our multilevel, collaborative VR escape room test case.

This work aims to enhance the understanding of human communication in VR through exploring the perception, challenges, benefits, and impact of alternative communication methods in CVEs. Key questions addressed include the effect of increased difficulty on puzzle-solving engagement, opportunities for user creativity, and enjoyment within these limitations. Ultimately, our insights can help VR providers decide whether to incorporate alternative communication methods in their development processes.

2. Related Work

The development of VR technology has led to the integration of various external concepts and frameworks, enabling researchers to test theories, train users, and improve concepts in diverse domains such as entertainment, education, training, and psychology [BBRG96, LZI18]. Multi-user VR has opened the door for collaborative or competitive interaction between multiple users [SB92], paving the way for more complex and interesting ideas to be incorporated and evaluated in the VR setting [CLL*20, LLS*19, CLL*21a]. In addition to the familiarization, interaction, and handling of the virtual environment, users in multi-user VR need to integrate a whole new set of skills to achieve necessary communication and complete tasks. These advancements have unlocked multiple functionalities, sparking the interest of researchers across various fields.

The growing interest in CVEs and VR applications has led to numerous impressive and useful works [BKOAO22, CPMM21]. Especially the interest in CSCWs has resulted in several past works that deal with certain applications of CSCW like document editing and information gathering [KORW22, MLW10], with some extending their frameworks to integrate immersive VR experiences such as video conferencing and editing [HS97, NDHL17] or interacting with virtual objects [BWPM21, CCNY19]. One such concept receiving significant attention is that of digital twins e.g., [iNi, ILKA22]. This concept enables user interaction with the environment and virtual characters, allowing for natural social interactions. However, an important aspect of every multi-user VR framework is the medium via which the users will be able to communicate with each other. The majority of current approaches rely on traditional methods such as audiovisual signals, which allow users to converse, see, or communicate through text [Ran16, CLL*21b]. In real-life scenarios, though, people often encounter situations that require alternative communication skills beyond written or spoken language.

In this work, we have developed a collaborative VR environment in the form of an escape room game. Escape rooms are popular interactive games that are intuitive and engaging for users, making them ideal for use in user studies to enhance the accuracy of evaluations and increase participation [DAC*19]. The multi-level structure of escape rooms makes them a complex and desirable game to explore in VR, offering a wide range of themes, from mystery and horror to fantasy and adventure. They can be used as a tool for team-building and problem-solving in corporate or academic environments and can be customized to meet specific educational needs [MPS21]. With their accessibility, flexibility, and varied themes, VR escape rooms offer a unique and entertaining form of engagement suitable for a broad audience. Some of the most popular VR escape room games include The Room VR: A Dark Matter [The], Belko VR: An Escape Room Experiment [Bel], and Statik [Sta].

Collaborative VR escape room games rely on various tools and features to facilitate communication and collaboration between players. In-game communication is the most common method, allowing players to use voice, text, or visual communication to share information and coordinate actions [CMP*18]. Assigning different roles or tasks to players is another way to encourage collaboration, requiring them to work together to achieve a common goal. A more recent approach is the ghost mode, allowing players to see hidden clues or give advice to other players. VR escape rooms use a combination of text, audio, and video elements to challenge players to think creatively and collaborate to escape. While previous works on VR escape rooms have attempted to expand the range of communication types between users, such as Hanus *et al.* [HHLM19] who added passive haptics as an additional interaction element, this is still limited to environment interaction and not interpersonal communication since players could only "see" each other in the collaborative virtual environment.

3. Implementation

Our work aims to explore novel methods of communication in CVEs to enhance teamwork in CSCW. Unlike previous works, we deliberately restrict the use of text and sound to encourage the development of new communication methods and evaluate user engagement, satisfaction, and success in communicating with each other, aiming to discover innovative means of communication that enable effective collaboration and puzzle-solving, and assess their significance. To achieve this, we conducted a case study using a VR collaborative-competitive escape room. The game comprises two players who work together and compete against each other on separate floors, each consisting of three interconnected rooms accessible through corridors and doors. Although the two floors are identical, certain room components differ slightly between the players' environments to complement the corresponding rooms in the other player's environment. Importantly, verbal and visual communication between the players is disabled, emphasizing the need for cooperation and interaction through the provided tools in order to solve the puzzles and successfully escape from the room.

3.1. Unity Implementation

In order to implement and setup the VR escape room, we utilized the Unity Development Platform editor, version 2020.3.29f1. Within Unity, we made use of various features such as animations, materials, and scripts to bring the escape room to life. For the props in the game, we relied on game objects available in the Unity Asset Store and Sketchfab, leveraging their diverse range of assets. To enhance the immersive experience, we incorporated sound effects sourced from Pixabay. The VR environment itself was constructed using Unity's XR Plugin Management and XR Interaction Toolkit packages, along with the oculus-controller-art-v1.5 asset to integrate Oculus controllers seamlessly.

3.1.1. Rooms

In each room, we paid careful attention to lighting, furniture, and textures to establish a captivating atmosphere that feels natural and comforting. The game immerses two players in a challenging multi-level escape room experience where communication is intentionally restricted between two players who find themselves in separate environments. Each environment consists of three levels, each containing three unique rooms (see Figure 1). In order to progress, players must unlock each room by successfully solving riddles and navigating through interconnected corridors. The riddles have been thoughtfully selected, drawing inspiration from online games to ensure they align with the theme's interaction requirements. We then adapted them to suit our unconventional communication types. To enhance the immersive escape room atmosphere, each room is designed with its own unique theme:

- Level 1/ Room 1: Mathematics
- Level 1/ Room 2: Color Theory and Geometry
- Level 1/ Room 3: Lighting (Collaborative)
- Level 2/ Room 1: Travel
- Level 2/ Room 2: Mystery
- Level 2/ Room 3: Technology and Space (Collaborative)
- Level 3/ Room 1: Technology and History

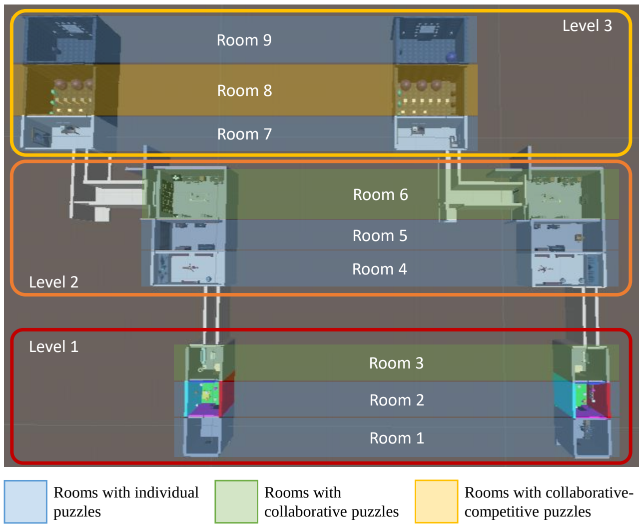

Figure 1: *Top-down view of escape room layout. Player one's escape room environment (left) and player two's (right) escape room, both consisting of three levels, each with three rooms (Individual/Collaborative puzzles are color-coded).*

- Level 3/ Room 2: Magic (Collaborative)
- Level 3/ Room 3: Magic

The puzzles become progressively harder as the game advances, with each level consisting of three rooms that can be accessed by the players after unlocking them. The first two rooms of each level contain individual puzzles, while the final rooms require collaboration between the players. The collaboration involves one player having the key to the solution and the other having the interface to input the correct key. The last puzzle in the last level creates a shift from collaboration to competition since it determines the winner (see Section 3.2 for puzzle details). The room design sets the necessary undertone to encourage the players to find a way to exchange key-solution details and work together.

3.1.2. Multi-user Communication Servers

To enable the game for two players, we leveraged the Unity Networking and Netcode Software. We implemented a Network Manager script to establish the game's network infrastructure, while the SpawnPos script determined the specific set of rooms assigned to each player. To facilitate seamless communication between players, we made use of the Unnamed String Message Handler provided by Unity Networking and Netcode Software. This messaging feature allowed the host and client to exchange messages, such as when the host discovered a key code and needed to notify the client to unlock their door. The OnReceivedUnnamedMessage function was employed to receive and process these messages, executing the appropriate actions based on their contents. We relied on this messaging system in various instances where communication was essential throughout the gameplay experience.

3.1.3. User Functionalities

The game is specifically designed for a captivating experience using two Oculus VR headsets, each accompanied by its own set of controllers. This setup offers players an immersive gameplay environment, engaging them from a first-person perspective. By concealing the in-game character, players are fully immersed in the virtual space, creating a strong sense of presence. Navigating through the rooms mimics real-world movement, allowing players to physically walk or utilize the controller joysticks for seamless locomotion.

By simply turning their heads, players can observe the different rooms in the game. Interactivity plays a vital role in the game, empowering players to interact with objects within the rooms to aid them in puzzle-solving. Through the use of the VR beam, players can point at objects and press the trigger button on the controller to interact with them. They can also grab game objects using the same method, enabling them to explore multiple rooms and levels, search for clues, and progress in the game.

The rooms are carefully crafted with a variety of interactive objects, ranging from altering numbers on locks to pinpointing locations on maps, and manipulating and relocating objects. However, it is important to note that not all objects contribute directly to puzzle solutions, adding an element of challenge and critical thinking for players to discern which objects are relevant and which are not.

3.2. Escape Room Puzzles

We designed two types of puzzles, *single-user* and *multi-user*, which require individual and collaborative problem-solving, respectively. The intention behind the two types of puzzles is to train and familiarize each player with the puzzle-solving mindset (single-user) so they are more prepared for the collaborative ones. Also, some keys found in single-user puzzles can be used for solving multi-user puzzles. Each level has two single-user puzzles and one multi-user puzzle. The difficulty of the escape room puzzles increases as the game progresses. The gradual increase in difficulty is intentional in the game design to ease players into the escape room concept, keep them engaged, and encourage them to come up with alternative ways of communication. The puzzles test critical thinking skills, basic mathematics knowledge, and observational awareness. If players take too long to progress to the next room, hints are given to help them (more details are given later).

3.2.1. Single-User Puzzles

There are a total of six individual puzzles; the puzzles start with simple arithmetic equations (single puzzle one - room one) and progress to more complex ones that require observation and attention to detail (single puzzle four - room five). In the final level, which is the most challenging, the initial puzzle (single puzzle five - room seven) requires navigation through previous rooms to collect clues and agility to realize the puzzle is connected to other rooms. A simplified outline of the rooms and puzzle types can be found in Figure 1.

The last individual puzzle (single puzzle six - room nine) differs from the rest since it comes after the competitive-collaborative one.

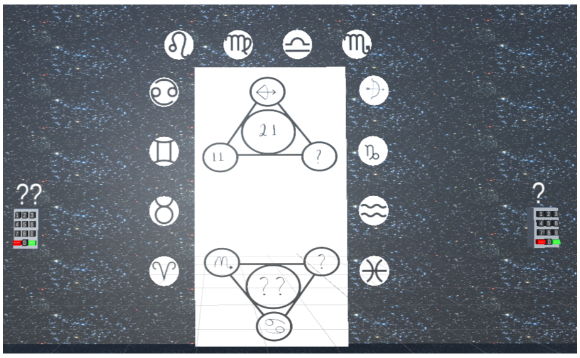

Figure 2: *Snapshot of single-user puzzle. Symbols correspond to numbers that must be found to satisfy the top riddle (right-hand keypad) and then used to solve the bottom riddle (left-hand keypad).*

This means that depending on the outcome of the latter, one player has an advantage over the other and so solving the last puzzle the quickest will declare the winner. Figure 2 illustrates this last individual puzzle that will determine the outcome of the game. For this, the player needs to make the connection between the numbers and symbols for the top puzzle, and based on that proceed to solve the bottom one, hence unlocking the final door with the keypad locks. Overall, the individual puzzles serve as a training and engaging way to familiarize the players with solving riddles and interacting with the virtual environment. However, as the focus of our study is on the collaborative aspect, providing detailed descriptions of each puzzle is beyond the scope of this study.

3.2.2. Multi-User Puzzles

While individual puzzle-solving is important, the collaborative aspect of the escape room is the focal point of our study. In these collaborative rooms, two players must work together to find a way to communicate effectively in order to unlock the next door. Each collaborative puzzle provides different tools to each player, allowing them to develop a unique communication system that is specific to each riddle. In the following paragraphs, we will provide a detailed description of the collaborative puzzles in the escape room, including the different tools available to each player and how they can work together to solve the riddles and progress through the game.

In the initial collaborative puzzle (Figure 3), player one's objective is to input a sequence of four numbers into a lock. To accomplish this, player two wields a controller capable of adjusting the colors of spotlights in player one's room. An illustration of this effect is depicted in Figure 4. Player one has already obtained the four required numbers through prior puzzle-solving endeavors but relies on player two's assistance to determine their correct order. Player two possesses the correct sequence of numbers, acquired from a separate set of four numbers solved earlier (e.g., 2, 1, 3, 4), where the first number should be placed second. With these tools in their possession, we anticipate that the players will utilize them as follows: the player holding the number sequence modifies the spotlight colors in the correct order to continuously communicate the placement of each number to the other player. For instance, if player two's numbers are represented as one-red, two-green, three-

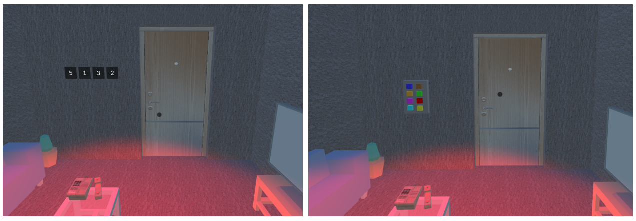

Figure 3: *Snapshot of the 1st collaborative puzzle. Player one's room (left) needs a 4-digit code, the order of which must be transmitted through player two's (right) color-controlled tool.*

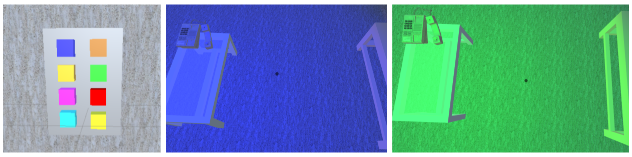

Figure 4: *Available tools for the 1st collaborative puzzle. Player two must transmit the order of four digits to player one through a color-controlled pad (top) which yields a color switch effect (bottom).*

blue, and four-yellow, they would adjust the spotlight colors to red-green-blue-yellow. Consequently, player one can decipher that the red number should be placed first, followed by the green, blue, and finally the yellow.

In the second level, the collaborative puzzle requires players to enter the correct number-letter pair on the lock of the room. One player knows the correct combination, e.g. 3D, and must guide the other player to that position on a two-dimensional grid using the available tools shown in Figure 5. Through this puzzle, we anticipate that one player will act as the guide (with the 4-directional arrow keypad), while the other will serve as the checker (indicating whether it is possible to move in that direction).

The last collaborative puzzle, as hinted in Figure 6, includes an additional competitive aspect. In this challenge, both players have six stands in front of them and only three symbols from previous challenges. The objective is to correctly place each symbol on its designated stand. For instance, player one's first symbol should be placed on the third stand, while player two's first symbol should be placed on the first stand. Every time a player places a symbol on a stand, the other player receives feedback. For instance, if player one places their first symbol on the first stand, player two's first stand will turn red, indicating an incorrect placement. If a player sees a green light, it means that their symbols should go on the remaining stands, and they only have to permute three stands for three symbols instead of six. In this riddle, the two players have to work together while also trying to help their teammates as little as possible to gain an advantage and reach the final room more quickly, where the winner will be determined.

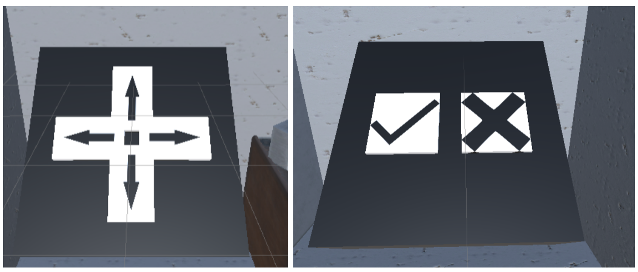

Figure 5: *Available tools for the 2nd collaborative puzzle. One player needs to guide the other according to a map by giving feedback (right) based on suggestions (left).*

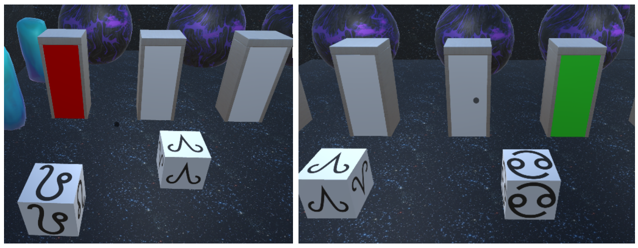

Figure 6: *Snapshot of the competitive-cooperative puzzle. Each player places three symbols on three of six columns. The other player receives feedback on the 1st player's choice by red/green colors (wrong signal-left, right signal-right).*

In this particular riddle, we anticipate that players will initially place their first symbol on a stand randomly. The objective is to narrow down the potential positions for one's own symbol by observing the opponent's correct or incorrect placements. The player does not have direct knowledge of their own correct placement, but can deduce it based on the opponent's actions. If, at any point, one of the six possible positions is indicated by a green color, this implies that the player should not place their symbol in that particular position since it corresponds to the opponent's symbol placement. By following this approach, the player will eventually be left with only three remaining positions, each corresponding to one of their symbols. These three symbols can be arranged into six possible combinations, and the player must systematically test these combinations until the correct arrangement is found and the door opens.

4. Methodology

Procedure: We conducted a user evaluation of our escape room to investigate and analyze users' behavior and reactions when confronted with non-traditional means of communication in VR for collaborative tasks. We hypothesize that our findings will provide evidence as to the degree to which users benefit from the challenging aspect we introduce, motivating further research to study the effect of alternative ways of interaction as well as future applications to integrate this aspect into their frameworks; please refer to Section 5.3 for the explicit hypotheses. The game and the accompanying questionnaire were designed to assess the users' success in solving the puzzles under the communication constraints and to evaluate how these constraints influenced their overall experience, including factors such as engagement, challenge, difficulty, and creativity. Ultimately, our study aimed to determine whether

VR providers should explore alternative methods of communication in their development processes.

Participants: We recruited a total of 11 pairs of volunteers to participate in our experiment, where they were tasked with completing the collaborative VR escape room that we developed. Due to resource constraints, the two players in each pair were physically present in the same room within our controlled lab environment. However, it's important to note that they were unable to communicate with each other verbally, visually, or through text. Both participants used the Oculus Rift CV1 headset [Ocu] for their VR experience, and they remained stationary during the game. Throughout the duration of the game, the progress of both users was observed via monitors to closely monitor their actions and intervene if necessary.

Conducting an evaluation and analysis of our framework is a critical aspect of our work. To achieve this, we conducted a user study involving eleven teams of two who participated in the VR escape room experience. The participants were composed of 45.5% females and 54.5% males. Regarding the relationship status within each pair, 81.8% of the participants were friends, while 9.1% were related in some way. This choice was influenced by previous studies showing that people tend to be more engaged when playing with friends [ZGCA13], as they have established a pre-existing level of familiarity and personal communication. It is worth noting that all participants belonged to the young adult age group, specifically between the ages of 19 and 24.

Data Collection: Following the study, each participant completed two online questionnaires to provide feedback on their experience. The first questionnaire focused on their overall VR experience within the virtual environment. The second questionnaire took the form of an interview, allowing participants to provide detailed insights and reflections on the alternative methods of communication in collaborative VR.

5. Results

5.1. Statistics

In general, participants demonstrated a high level of success in solving the individual riddles. The success rates for the first and second collaborative puzzles were 100% and 81%, respectively. On average, participants were able to complete these puzzles in approximately 8.45 minutes and 9.55 minutes, respectively. These results indicate that participants quickly adapted to the non-verbal and non-written communication requirements for the simpler puzzles, with only 27% of teams receiving hints for the first puzzle and 55% for the second puzzle.

However, the success rate decreased for the more complex collaborative-competitive puzzle. In this puzzle, all teams received bonus hints, and only 36% of teams successfully escaped the rooms. On average, the successful teams took approximately 15.5 minutes to complete the puzzle. This drop in success rate and the increased time required suggest that the collaborative-competitive puzzle posed greater challenges and required more strategic thinking and coordination among the players.

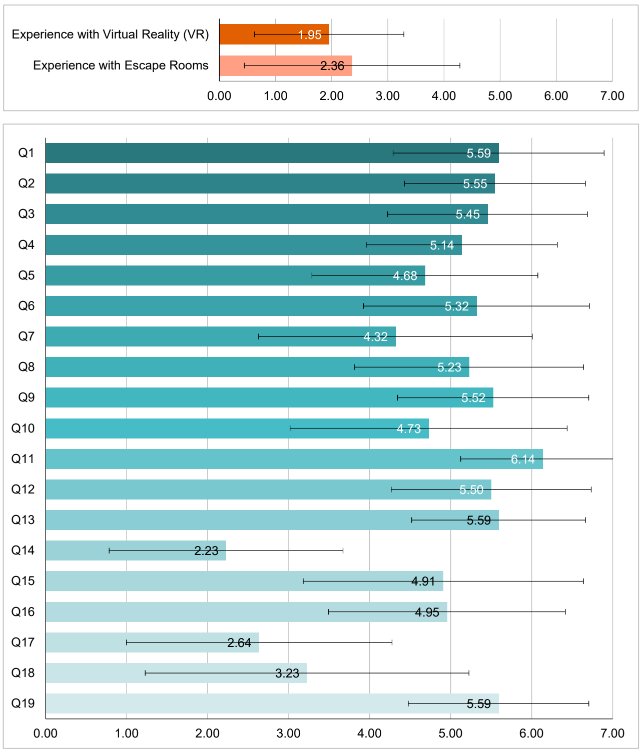

Figure 7: *Summary of user feedback regarding their VR experience.*

5.2. VR Experience

Upon finishing the escape room experience, both players were asked to complete a questionnaire to provide feedback on their VR experience. We utilized the Presence Questionnaire (PQ), on a 7-point response scale, which was originally developed by Witmer and Singer [WS98] and later revised by Witmer *et al.* [WJS05]. The PQ is a well-established tool specifically designed to measure presence in virtual environments. By using this questionnaire, we aimed to assess the level of presence experienced by the users during their VR encounter.

The results of the PQ are visualized in Figure 7 (bottom), where it can be seen that on average this experiment's participants had a satisfactory experience. This is even more prominent given that most of the participants were novice users of VR tools (Figure 7 (top).)

5.3. User Survey and Interviews

Using the second questionnaire and conducting complementary interviews, we seek to test the three main hypotheses we formulated for this experiment. Our objective is to apply the deductions derived from the analysis of our test case results, specifically the user evaluation of the VR escape room, to the broader field of collaborative VR. The interviews follow a semi-structured format, where the questions are predetermined but allow users the flexibility to provide brief, non-structured answers. This intentional design allows us to gather responses that will serve as evidence supporting or challenging our hypotheses. More specifically, we hypothesize:

- *H1:* Alternative ways of communication can be used in CVEs that are non-textual nor audio-based.
- *H2:* Users want alternative ways of communication in addition to traditional means to be included in VR experiences.
- *H3:* Users come up with innovative and diverse ways of alternative communication when given the same tools.

To test our hypotheses within our experimental setup, we created a second questionnaire that we administered to the users after their completion of the VR experience. The questionnaire included specific questions formulated to gather responses that would either support or reject our hypotheses. Table 1 provides an overview of the questions we asked, along with the corresponding hypotheses they address. The users provided their answers using a 7-point response scale.

Table 1: *Interview questions.*

No.	Question	Hypothesis
1	Did you manage to receive/transfer the necessary information to the other user?	*H1*
2	How easy/challenging did you find it to communicate with the other user?	*H1*
3	How pleasant was the challenge level of this game?	*H2*
4	How engaging was the game compared to real-life escape rooms?	*H2*
5	How engaging was the game compared to other VR escape rooms?	*H2*
6	How engaging/pleasant was the competitive aspect in the last collaborative puzzle?	*H2*
7	How likely are you to consider playing more collaborative games that have the choice of alternative communication on top of the traditional types e.g. seeing/hearing/texting the other player?	*H2*
8	Would you like to see these types of alternative communication integrated in other games?	*H2*
9	How were you able to communicate with the other player in the 1st collaborative puzzle?	*H3*
10	How were you able to communicate with the other player in the 2nd collaborative puzzle?	*H3*
11	How were you able to communicate with the other player in the 3rd collaborative puzzle?	*H3*
12	If you played it again, what do you think would be different? (e.g. how you act, speed, hints)	*H3*

Figure 8 illustrates the results of the second questionnaire, which correspond to our first and second hypotheses. Regarding H1, the average responses are above the mean value of 3.5 on the 7-point response scale, indicating evidence that VR users are capable of using alternative ways of communication in CVEs. For the second set of questions, corresponding to H2, the results exhibit even higher scores compared to the first set. This provides robust evidence in support of H2, indicating that adding alternative ways of communication on top of the traditional ones is a desirable quality for VR games.

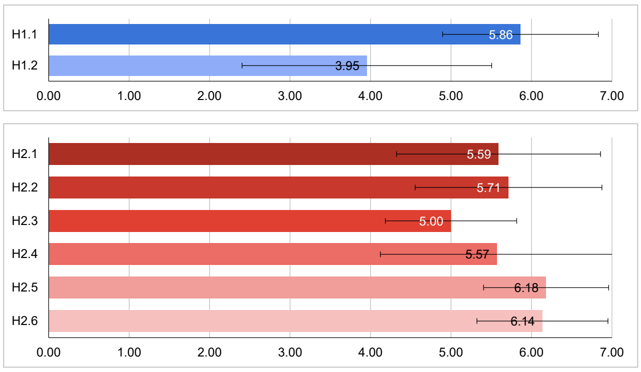

Figure 8: *Summary of the results obtained from the user study.*

Finally, to assess the validity of H3, we examined the responses to the short-answer interview questions. The findings demonstrate that the overwhelming majority of participants succeeded in the first collaborative puzzle by triggering the environment colors in the correct order, as we had anticipated. Player two triggered the spotlight color in the other room, and player one understood that it represented the order in which they needed to place the numbers. Similarly, in the second puzzle, the interaction unfolded as expected. Player one, being aware of the correct goal point, used the arrows on their keypad to provide directions to the other player, who provided feedback based on their ability to move in that direction.

The last inter-user puzzle, with its collaborative-competitive nature, proved to be the most challenging, with only a few teams successfully solving it. In these cases, each player attempted to deduce which stands corresponded to their symbols by interpreting the red-light/green-light feedback from their opponent's attempts. Notably, one of the users exhibited a particularly interesting reaction by adopting a clear strategy; try nothing and focus on memorizing the opponent's feedback, and once confident enough reordering his symbols between the three correct pillars.

5.4. Discussion

Regarding H3, the users appear to have been able to use the provided tools in a relatively straightforward manner, with only some indication of disruption but not at a significant level. However, when asked about what they would change if they were to play the game again, most players indicated that they would be faster, establish clearer communication codes, and interpret hints more easily. This suggests that repetition in such tasks can significantly help to equip users with alternative communication skills.

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Furthermore, the data from this experiment supports H2, indicating that it is good practice to design games in CVEs that allow communication without relying solely on text and audio, or to consider alternative means of communication in the design plans of other collaborative tasks. This opens up an interesting research question for further exploration.

Overall, the success rates for the collaborative puzzles in the VR escape room are similar to those found in real-life escape rooms (which typically range from 20% to 35% escape rates). However, the fact that the first two collaborative puzzles have high success rates, along with some evidence supporting H1 and the expectation that users would improve by playing this type of game again, suggests that training users in these types of game setups could increase their interpersonal and problem-solving skills.

It is also worth mentioning that perhaps the communication nature for each collaborative puzzle could affect the players' performance. Arithmetic and color-coded signs are easier to associate and interpret since humans are more familiar with them. Shape-based signs like the directional arrows, ticks and crosses in the 2nd puzzle, are also intuitive for adults hence requiring less time and effort to associate with puzzle-solving. This potentially explains the success rate of the first two collaborative puzzles and at the same time suggests that specific symbols e.g., ones used in the 3rd puzzle as well as combinations thereof are harder to grasp and put to use. Even so, further experiments are required to shed light into the pros and cons of such alternative communication means.

6. Conclusions

In this work, we developed a collaborative VR escape room to examine the use of alternative communication methods in CVEs. We hypothesized that by limiting users' ability to see, hear, and message each other, they would be forced to explore new ways of interacting and using available tools to accomplish a collaborative task. Our user study confirmed that users can use non-traditional means of communication by conveying innovative ways to complete their tasks. We observed an increased level of engagement among users who were able to successfully complete their collaborative puzzles. Our findings suggest that it is valuable to design games in CVEs that enable communication without relying on text and audio, and we encourage future design plans to consider alternative means of communication. This research direction opens the door for additional experiments and evaluations that can enhance user satisfaction and contribute to advancements in the VR research community.

6.1. Limitations and Future Work

Our framework works well within the conditions that we provided. However, there are several aspects to our experiments that were not included in the user evaluation setup. For example, taking a look at the performance between each task i.e., having a separate questionnaire after each room is completed, or clustering users beforehand to allow for inter-group comparisons e.g., female pairs, male pairs, mixed pairs. Our evaluation framework has another limitation related to the physical setup of the evaluation sessions. Due to practical constraints, the users were not placed in separate rooms, which may have inadvertently introduced bias into the results. Additionally, the inclusion of a control group in our user evaluation for the case study would have further enhanced the validity of our work.

In the future, we aim to explore the user survey setup in more detail, aiming to study the satisfaction per room or per level. Also, it would be interesting to compare our observations when verbal or text communications are enabled and thus compare the difficulty in solving the riddles, the engagement, how interesting it was, etc. with the aim to prove or disprove our hypothesis that alternative ways of communications add an extra element of realism and engagement when combined with the traditional means.

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