StuckInSpace: Exploring the Difference Between Two Different Mediums of Play in a Multi-Modal Virtual Reality Game

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Abstract

With the rising popularity of Virtual Reality (VR), there is also a rising interest in co-located multiplayer experiences, as people want to play VR games together with their friends. As having multiple VR headsets is out of reach to the average consumer, we need to look into different possible ways of including multiple people in this play space. We have created a multi-modal co-located multiplayer VR game, *Stuck in Space*, that introduces a second player in two ways — one with a PC (the baseline that a lot of current games do), as well as a tracked Phone that can be used as a 'window into the virtual world'. We have conducted a user study ($n = 24$) where we explore the difference in immersion and co-presence between the two versions using two questionnaires (*IPQ* and *NMMoSP*), as well as a thematic analysis of the subsequent interview data, from which 5 themes emerged. Surprisingly, we found no significant difference in co-presence or immersion based on the quantitative data. However, the qualitative analysis helps reveal one of the main reasons why that is — maintaining a mental model of the real world while also being in the virtual world makes it harder for the person wearing the headset to immerse themselves and feel co-present. From these themes and sub-themes we theorize that each of the two versions has positives and negatives that cancel each other out in the quantitative data, and for there to be a difference we would need to accentuate or change certain elements of the game. The results show that introducing a second player through a Phone is not detrimental in terms of co-presence and immersion and that it is a viable way of doing so, although certain design considerations would have to be taken into account to minimize the negatives.

Index Terms: Human-centered computing—User studies; Human-centered computing—Virtual reality; Human-centered computing—Collaborative interaction; Applied computing—Computer games;

1 Introduction

Virtual Reality (VR) headsets are becoming more and more popular and as a result there is a large amount of research into VR experiences. This ranges from its use in education [7, 10, 43] and healthcare [23, 25, 27] to remote collaboration [35] and making the user feel more present in another space through virtual reality [21] (for example in a teleconference). Nevertheless, the majority of people associate VR with games [29].

In VR, the user wears a Head Mounted Display (HMD) that covers their whole field of view, and becomes totally isolated from the real world (as well as to other players in the room), immersed in the virtual environment. While there are multiplayer games in VR (shooter *Pavlov* [14] or online chatroom *VRChat* [44]), the percentage between the local multiplayer VR games and the total number of VR games is very small.

VR devices are still expensive (and unwieldy) enough that a group of friends that want to play together may only have access to a single HMD. Typically, people outside of the VR can only watch, although there are games like *Keep Talking and Nobody Explodes* [13] and *The Playroom VR* [41], where the second player is either reading a manual to help the VR player, or playing with a controller and watching on a TV screen. These games show that engaging a second player, directly or indirectly, is a valid way to make VR experiences more inclusive to an outside viewer, even when the players only have access to a single head mounted display.

Currently, the most popular way of adding a second player is through the machine that is running the game, where they can use a mouse and keyboard to participate [11, 12, 40]. As this style becomes more commonplace, the need to understand and design for social VR is going to increase [18]. This raises new questions and challenges: does adding a second player create a positive experience for the HMD user or does it decrease their immersion? What are the best ways to include a second player to increase the feeling of co-presence in both players? And what new types of interaction are possible between HMD and non-HMD players?

These are critical questions if VR is to successfully become "*part of the social living room environment*" [18, 19] — there will need to be different levels of play, where one person might only just want to watch, while somebody else would want to participate much more significantly. This wide range of experiences needs to be carefully crafted, as creating a VR game that reduces immersion of the HMD user because of interactions with bystanders is the opposite of what the technology is trying to achieve.

In this paper we present *Stuck in Space*, a multi-modal local VR game that introduces a second player to the VR world via either Augmented Reality (AR) on a smartphone (a Phone player), or a traditional mouse and keyboard setup at a desktop computer (a PC player). This creates a co-present space in which the HMD player can interact with one of these other types of players in order to solve challenges and complete the game.

This game then becomes an experimental platform to explore how the medium of play of a second player affects the immersion and co-presence of both HMD and non-HMD players.

The contributions of this work are:

- the design and implementation of *Stuck in Space*, a multi-modal co-located multiplayer VR experience, using technology that is normally available to an average consumer;
- a user study examining the differences in immersion and co-presence when the HMD player is interacting with either the PC or Phone player; and
- a discussion in light of the results of the study of the design considerations for creating such co-located multi-modal experiences.

The remainder of the paper is structured as follows: Sect. 2 introduces Related Work, in which we summarize the fields that our

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Figure 1: Phone player uses a phone in one of their hands and a controller to track their position in the other (no need for any holder as we wanted this to be as accessible as possible)

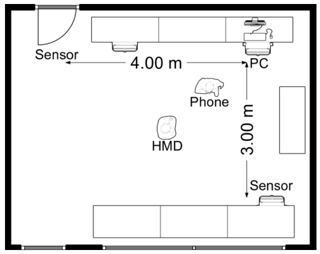

Figure 2: Floor plan of room used for the experiment that shows two of the users (for HMD-Phone) and the position of the PC (for HMD-PC)

paper takes from; Sect. 3 introduces the Design and Implementation of the system that we created to test immersion and co-presence; Sect. 4 introduces the Methodology of the study; Sect. 5 introduces the Results from the study; Sect. 6 is the discussion of the Results, in which we give some suggestions for future studies using such technology; and Sect. 7, in which we summarize the paper.

2 Related Work

This paper focuses on two different research fields in VR and, more broadly, MR (Mixed Reality): *Co-presence* and *Immersion* (also sometimes known as *Presence*). However, we also draw inspiration from prior work into (co-located) asymmetric experiences.

2.1 Co-presence

The term co-presence, as defined by [16] and [37], refers to the perception of the Other together with you, and the feeling of them perceiving you — two distinct elements [16, 37]. In the case of co-located VR, co-presence would be how the HMD user perceives and feels the non-HMD user(s) around them, and vice-versa.

When talking about co-presence, the term "social presence" is sometimes used. [32] explains how this is different from co-presence — he refers to social presence as based more on how the medium affects the user's perception, whereas co-presence concentrates more on the possible interactions between people [32]. [2] define social presence as the *"awareness of the co-presence of another person together with a sense of engagement with them"* [2] — in this case co-presence is part of social presence.

[46] further breaks this up into four groups based on the factors "proximity" and "representation" of the other [46]. In this view "proximity" can be either physical or electronic, where one person could be close to you in physical space (in the same room) or close in the electronic space (in a teleconference where instant two-way communication can happen). "Representation" on the other hand is how the other person is simulated, either through a physical or digital simulation — a robot/virtual agent located in the same space (physical or virtual) enables the person to interact with the other.

2.2 Immersion/Presence

The terms immersion and presence are very closely related to one another. Thus, we need a concrete definition for both. There are several existing definitions — for example, [36] defines immersion as a measurable property of the system [36], like field of view, screen size, etc., while [45] define immersion as the way the person responds to the system [45]. Presence, on the other hand, is a very subjective experience and thus measuring it is harder. It is referred as a "*subjective experience of being in one environment, even when physically in another*" by [45].

In this paper, we use [45]'s definition of presence, but refer to it as '*immersive response*' or simply '*immersion*' (as [36] does), so as to minimize confusion between the terms co-presence and presence.

Factors that impact immersion have been extensively researched in the work of [34]: for example, one of their factors is *user characteristics*, where they talk about how the type of person, their ability to focus and their experience with games affects immersion [34]. [39] mentions that suspension of disbelief plays a role in immersion [39], and [1] find that control plays a major role in immersion, where a lack of any control makes a person less immersed [1].

2.3 Co-Located Asymmetric Experiences

In recent years, due to the advancements in HMD and GPU technology, many researchers have begun exploring ways of making the solitary VR experience more sociable, by including the non-HMD users in different ways [8, 9, 18, 19, 24, 47].

FaceDisplay [19] do it through a number of touch displays attached to the HMD that show what the person with it sees inside, and lets bystanders interact with the HMD user through a number of Leap Motion sensors that detect hand gestures. They have created 4 different levels of interaction - just observing, through an external device (such as a smartphone), through hand gestures, and through touch. They found out that their method was able to introduce a non-HMD player and have them interact with the HMD player, although "*the former had a higher level of dominance and responsibility over the latter*" [19]. A few other papers (*FrontFace* [6] and *See What I See* [31]) also show a number of prototypes with a display attached to the front of the HMD (both papers use mobile phone VR) to help with social interaction between the HMD user and observers.

The authors of *Astaire* [47] on the other hand take another approach — the non-HMD user has to "dance" with the HMD user in order to play the game. They have to hit notes as they come, which encourages them to be close to each other. The non-HMD player watches a screen and has the ability to see where a note will be one second in the future (but only on a two-dimensional grid), while the HMD player can see the note's position more precisely in three dimensions. A thing to note is that they do not concentrate on just the HMD player (like *ShareVR* [18]) or the non-HMD player (like *TurkDeck* [9] and *HapticTurk* [8]), and they try to make a "*well-balanced asymmetrical play experience*" [47].

CatEscape [24] is an interesting multi-modal game where there can be a maximum of 3 players in different modes — one in VR (that plays a survivor game), one that uses a tablet (a strategy game), and one that uses AR (where they play an explorer game). The AR version here is interesting as they have chosen to use a mini-projector attached to the Vive controller to use it as a "torch" and see the shadows of the VR world. One of the suggested applications is for a wider audience to be able to see "into" the virtual world without having to look into a stationary monitor, and being able to more easily interact with the players.

Similarly, in the work of [18], they have created *ShareVR* [18], a prototype system that uses projections onto the floor, as well as portable tracked displays to help the non-HMD user communicate and interact more easily with the HMD player. Concerning the portable display, they talk about using it as a 'window into the other world', which is the same way we refer to the mobile phone screen in our AR setup. Before creating the prototype of *ShareVR*, they did a preliminary study to gauge the interest in such a technology, and they show that people indeed express a demand to interact with the world the HMD player is in while not necessarily using a headset themselves. Some of their results from the experiment itself showed that their game did improve presence (immersion) versus the baseline version, and showed that social interaction was significantly affected by the mode.

The authors of [8] explored how one can include outside viewers as players by making them help the HMD player in some ways —

Figure 3: The view from the drone's perspective — the astronaut head can be seen (which is directly mapped to the headset position), as well as the hand which the astronaut uses

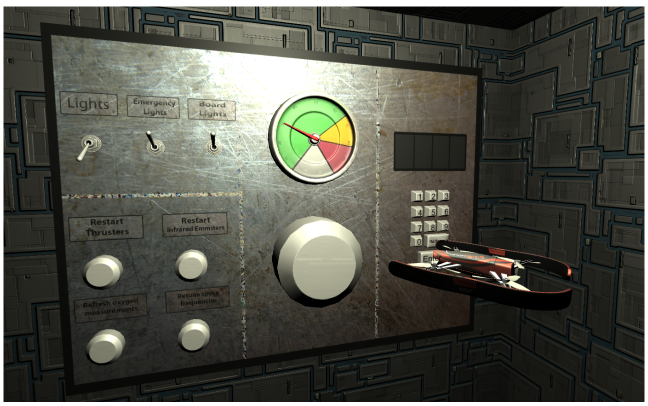

Figure 4: The view from the astronaut's perspective — the drone takes up a small amount of the FOV, and its position is directly mapped to the second controller's position

using them as human actuators that aid the HMD wearer's experience by moving physical props (*TurkDeck*) [9] or manually supporting the wearer above the ground playing a flight simulation (*Haptic Turk*) [8]. They show that even though the 'human actuators' are not necessarily playing the game, they do still feel enjoyment from such a game — aiding the VR user to have a better experience and watching them have fun are main driving factors.

From the listed papers, one can see that there have been a number of different approaches to including non-HMD users into a VR game. Systems like *TurkDeck* and *Haptic Turk* show that even secondary participation in a game (like helping) can lead to a better experience, while *FaceDisplay* and *FrontFace* show us that social interaction is beneficial, although it needs to be more carefully made. *Astaire* shows that physical touch is something that can help both HMD and non-HMD users, as well as observers. Finally, *ShareVR* further explores physicality and other ways of including a non-HMD user in a study, discovering that the different modes that they tested were affecting social interaction differently, as well as immersion. In our work we attempt to replicate the multi-modal aspects of *ShareVR*, but extend our study to include the impact of different modes on co-presence and immersion, focusing not only on the impact of a mode on the player in the same mode, but also the impact on the HMD player of participating alongside other players in a different mode.

3 Design and Implementation

The game that was designed for the purposes of the experiment is called *Stuck in Space*, an asymmetric co-located collaborative multi-modal VR game. The player wearing the HMD is an astronaut in their space station during an emergency (Fig. 3, Fig. 4), while the second player, who plays as a drone through a Phone (Fig. 1) or a PC, has special information about how to solve the problems that occur.

One of the main goals when creating *Stuck in Space* was to use technology that is readily available to the consumer, such as phones and desktops (Fig. 1, Fig. 2), rather than projectors and specialized physical props, to see if multi-modal VR experiences can be brought to the living room easily — one of the reasons to do that is that there is a demand for co-located experiences with VR (as [18] showed with their online survey).

We explicitly designed the game to be asymmetric, as *ShareVR* does [18], to engage the non-HMD user more and include them more fully in the experience.

As the findings of [8] show, engaging the second user even just by having them help the HMD player increases their enjoyment [8]. We tried to use that to our advantage, thus, we chose a scenario for the game that suits cooperation — an astronaut that needs to fix their space station with the help of a drone.

This scenario also strengthens the feeling of isolation from the real world that an HMD user would normally feel (being all alone in space), in which case introducing a second player would have a greater impact than normal. This would in turn help with testing the effect of co-presence more easily and observing whether there is a difference between the two different modalities of play.

The design of the multi-modal game was inspired by games like *Keep Talking and Nobody Explodes* [13], *CatEscape* [24] and *Astaire* [47] — the way that asymmetry of information is presented to players in those games had a large influence in the way we have created *Stuck in Space*, as well as the actions and tasks themselves. In our case, we have divided the game into two segments — the tutorial, and the main game. The tutorial is needed to help both players get used to the controls and understand what to do when the game starts. There are seven actions that players are prompted to take, as shown in Table 1.

- 'Button wall' refers to a section of the play-area that has twelve red buttons which must be pressed in a certain order. Only the non-HMD user can see the order in which the buttons must be pressed, meaning that the two players have to communicate to complete it. The number of buttons to be pressed in order to continue steadily increases to keep up with players' skill level;

- 'Pressure button' (Fig. 3) is a button that only the HMD user has to press in order for a constantly rising pressure gauge to remain in the 'green zone'. When it gets too high an alarm starts sounding (only to the HMD player) so as to have them remember to press the button. In later stages the speed of it increases in order to enact a sense of urgency - as the alarm is only heard by the HMD player, the non-HMD player can keep track of it and warn the HMD player before it gets too much. It should be noted that this does not lead to any game over state if left on its own, it only forces the HMD player to move around the room more to silence the alarm;

- The 'keypad' and 'specialized buttons' (Fig. 3) are another way of making the information available asymmetric, as only the non-HMD user can see the keypad code/the button that needs pressing in order to continue (a 4-digit code/button is randomly generated and has to be communicated to the HMD player);

Table 1: List of actions, showing the player that does it and information exchange between the players if any

Action	Enacted by	Information flow
1. Button wall	HMD	Other to HMD
2. Pressure button	HMD	N/A
3. Keypad	HMD	Other to HMD
4. Specialized buttons	HMD	Other to HMD
5. Light panel	HMD	N/A
6. Flashlight	Other player	N/A
7. Fix drone camera	HMD	Both ways

- The second player has a 'flashlight' on their disposal, which they can use to guide the HMD user whenever the lights go out in the game, as well as using it to aid communication;
- 'Fix drone camera' is needed when the screen on the non-HMD user's device becomes gray-scale and they are unable to tell the order of the buttons needed. Thus, they have to communicate to the HMD user that they need to be fixed to continue the game — this is done by the HMD player getting close to the "drone" and pressing a button on their controller.

There are nine stages, with a set type and number of actions, with the solutions to these actions being randomly generated. This ensures enough difference between play sessions that players cannot just repeat their actions, while ensuring that every player experiences each type of puzzle. We chose to not punish players for failing in-game tasks as we did not want to measure their performance, but rather the interactions they experienced, which would be hindered by ending the game prematurely. For example, pressing an incorrect button on the 'wall' task does not lead to a failure state; instead, the player must simply try again.

To differentiate between the two possible modalities in our study, we use the designations $\text{HMD}^{\text{Phone}}$ and HMD^{PC}. If no platform is specified, it is applicable to both groups of HMD users.

When looking at the possible types of co-presence in our system, we can see how [46] has divided these types based on proximity between the two people and whether they are present in the physical space (in person) or simulated virtually (or a mix of these). Our co-presence types fit into this taxonomy:

- The first type is what the $\text{HMD}^{\text{Phone}}$ player feels when they play with the Phone user — the other is in physical proximity (Fig. 2), but using a virtual representation of themselves (in the form of a drone) in VR;
- The second type is when the HMD^{PC} user plays with the PC user — in this case, they still see the same virtual representation, but this time they do not feel the physical proximity to the same degree, as the PC user is sitting away from them (Fig. 2);
- The third type is with the Phone player — they see the $\text{HMD}^{\text{Phone}}$ user both as a virtual representation in the game as well as seeing their physical form, and they feel the other in physical proximity;
- The last type, using the PC, proximity is less than the Phone, and the non-HMD user in that case does not see the HMD^{PC} player as much because their attention is on the screen and they have their back facing the HMD^{PC} player (although they have the ability to do so).

3.1 Hardware Implementation

The game was built using an HTC Vive (although compatibility across platforms should be easily achievable). The headset itself uses a lighthouse based tracking system: two sensors on opposing corners of the play space point at the headset and controllers to enable tracking.

We needed to devise a way of tracking the phone screen as to make it act as a "portal to the other world" — we decided on using one of the controllers, just as *ShareVR* [18] did, to enable tracking of the phone in the play space (Fig. 1). This way, the non-HMD user can not only be easily tracked, but they can also use the controller to interact with the virtual environment, giving them more presence in the virtual space. The game is designed to be able to run on a wide range of Android phones (the one used in the experiment being a Samsung Galaxy Note 9).

For the PC version, we used the same machine that is running the game, controlling it using a keyboard, and testing on a Dell 34″ curved monitor (3440x1440) — ensuring that the monitor was positioned in such a way that the HMD user would be *behind* the PC player (Fig. 2).

3.2 Software Implementation

The game was created using Unity, a popular free engine that has support for multiple platforms, including VR and Android. It was made using the official SteamVR plugin.

For the Android version we had two choices — either stream the rendered video from the desktop to the phone, or send just the tracking data and let the phone render the scene. We decided on the second approach, as sending more data (a video stream in this case) would introduce higher latency, as well as being harder to implement.

The game starts a server on the desktop and waits for a connection from the phone. This can also be used for people who are not playing the game but still want to see what is happening. The PC version does not start a server, as the game is already running on the same machine, but creates a different instance to let the player control the view.

One of the design decisions we made for the game was using the different modalities in ways that enforce their uniqueness, which is also what [18] suggest. For the HMD version, we also followed some general guidelines and best practices when creating the experience, for example we have tried to minimize motion sickness [26] by using hardware that is powerful enough to keep the recommended 90 FPS, as well as not moving the player at all during the game. As [26] mentions, we also tried to have consistent and realistic graphics.

Another important guideline that [18] mention is designing the experience with the shared physical space in mind — we knew that, in the case of the Phone version, people would be close to each other, and maybe even bump the other unintentionally, which is why we had virtual representations of both players. This way, the HMD user would be able to see where the drone is and be more careful. We also made the drone a specific size, bigger than the controller, in order to minimize risk of hitting the other player accidentally.

We also tried to distribute the power level between the two players, where both players would feel like they are needed to complete the game, and increase levels of cooperation.

With the Phone version, the goal was to have the person hold the phone with one hand and the controller with the other (Fig. 1). We wanted to achieve minimal lag between input and output so that the player feels like they are in control of something in real time.

When considering porting the Phone version onto desktop, we had to choose one control scheme which we wanted to be as close to what the current standard is on the market — for this reason, we chose to use a keyboard to move the drone in the game. This control scheme is also similar to how a real drone would be operated, where there are two sticks that control yaw, pitch and roll — in our case the "WASD" keys control horizontal movement, while the arrow keys control the elevation and rotation.

One major design decision we took was having the non-HMD user be more of a helper role and not have as much power over the world, with the reasoning that, as [8] show, this would still be enjoyable to the player.

In terms of audio, the tutorial for both players was played through the HMD headset and the Phone/PC speakers (subtitles were included to help people understand more easily if they misheard something). There were minor sounds cues for the HMD player like flipping switches and pressing buttons in order to help the player know when they have done the action. As we used an HTC Vive, which does not have any headphones included, we had to provide headphones ourselves — in our case we chose over-ear headphones, as they are comfortable and fit a wide range of people.

4 Methodology

We set out to conduct a user study in order to see if introducing a non-HMD player to the VR game would impact the co-presence and immersion of the HMD player. The two ways we test are through a Phone or a PC — the desktop version of the game is the baseline, as it is what is mostly used in the industry right now ([13, 15, 40]), and the AR Phone version is what we compare it to, to see whether there is a significant difference.

We use 2 main questionnaires in the study — the *NMMoSP* [2,20] and the *IPQ* [33]. In their paper, [2] *(NMMoSP)* create a list of factors affecting social presence, such as *Isolation/Inclusion*, *Mutual Awareness*, *Mutual Understanding* and more. When creating the interview questions, those factors were taken into consideration. We chose this questionnaire as it has already been used in research in this sphere [3, 17, 30, 42], including in a modified context to focus on a particular factor of the experience.

Concerning measuring 'immersive response', we chose the *iGroup Presence Questionnaire (IPQ)* as it has sub-scales that allow for a more in-depth view into the measurements and is not as long as the one [45] have created, which currently is the most cited immersion questionnaire[1] (that one was also criticized by [36] for the subjectivity of their factors).

4.1 Study Design

We decided on a mixed design where a group of two people would play through one version of the game (HMD-PC or HMD-Phone) twice. The players would swap on their second try so as to experience what the other person experienced. The independent variable is *platform* — either $\text{HMD}^{\text{Phone}}$, HMD^{PC}, PC or Phone.

Dependent variables are *co-presence* and *immersion*. *Co-presence* was measured by a modified version of the *NMMoSP* [20] questionnaire — we used the first 4 items from the *Co-presence* subdimension, 2 from the *Attentional Allocation* dimension, and 2 from *Perceived Message Understanding*.

Immersion was measured through a modified version of the *IPQ* [33]. We used 3 sub-scales: 1 question from *General Presence* (a term taken from [38]), 2 from *Spatial Presence* and 4 from *Involvement*. For both dependent variables, we took the Aggregated score from each of the questionnaires.

We want to see if there is a difference between each mode for the HMD player, as well as for the non-HMD player, so we want to explore the relationship between each platform in terms of Copresence and Immersion.

We also decided to use the *Software Usability Scale (SUS)* [5], as to be able to show that the game we have created is usable and to provide evidence that the findings from the experiment are valid (as opposed to being negatively influenced by a poor experience). The *SUS* is a short ten question 5-point Likert scale questionnaire that we gave to each participant after every playthrough.

A semi-structured interview was conducted at the end of the whole session with the two players together, where questions of the interview were based on the *NMMoSP* and *IPQ*, as well as any observations made during the experiment, for example, if one group of players had used a lot of physical cues and movement to play the game. Our analysis is therefore both quantitative and qualitative.

Times to complete each game were also logged in order to be able to show that each game was played to the finish, thus making sure that all intended interactions were experienced by the participants, as for the game to progress, each person had to finish their respective task.

The study was approved by the University of Southampton's Ethics board (ERGO 54456) before commencing with real participants.

4.2 Setup and Procedure

Everything took place in a university lab with an HTC Vive setup with over-ear headphones, 3x4 m^2 play area, running on a Windows 10 desktop computer (Intel Core i7-7700 3.60GHz, NVidia RTX 2060 Super, 16 GB RAM). Participants were University students recruited using posters around campus, and divided equally into two groups at random — the HMD-PC version and the HMD-Phone version.

The study consisted of the participants playing through the game once, after which they individually completed the *SUS*, *IPQ* and *NMMoSP* questionnaires. Players then swapped roles and went through the game again, completed the same surveys for the second experience, and then took part in a semi-structured interview in which they were asked questions about their experience of co-presence and immersion. This interview was later transcribed, and we undertook a process of inductive coding in order to identify codes, and to group those codes into themes.

5 Results

In total, 5 females and 19 males took part of the study, with the average age being 21.46 ($SD = 1.52$). The majority of players had minimal first-hand experience with VR, as a lot of people tried VR for the first time in the study, although many people expressed familiarity with the game *Keep Talking and Nobody Explodes* [13], one of the main inspirations of *Stuck in Space*. Only 4 people (2 groups) were made up of strangers who did not know each other before the experiment.

We divide the results into a number of categories for easier understanding: HMD^{All} (the statistics for all HMD play sessions combined, $n = 24$), HMD^{PC} and $\text{HMD}^{\text{Phone}}$ (only HMD sessions that were either with a PC or a Phone, $n = 12$ for both), and PC and Phone — the two non-HMD versions, $n = 12$ each. It should be noted that half of each category consists of people who either played it on their first or second try.

The game on average took 9.77 minutes to play, but as expected, the first playthrough's average was longer (11.09 minutes) than the second (8.45 minutes), as players already knew the game.

The total SUS score for all 48 data points is 80.89 ($SD = 12.27$), which is considered as being in the acceptable range [4], thus, we can say that the quality of the game is sufficient for our experiment. Table 3 summarizes the scores for the different versions.

5.1 Quantitative results

The results from the two questionnaires can be seen in Table 4. They were analyzed through a one-way ANOVA between HMD^{PC}, $\text{HMD}^{\text{Phone}}$, PC and Phone. It revealed no significant difference in the Aggregated Co-Presence score between versions ($F(3,44) = 0.999, p = 0.402$), and a significant difference in the Aggregated Immersion score ($F(3,44) = 13.98, \mathbf{p < 0.001}$). A post hoc Tukey test showed that the HMD players' Immersion differed significantly at $\mathbf{p < 0.005}$ — from Table 4 one can see that the HMD has a **higher** Aggregated Immersion score than the non-HMD players. The results of the Tukey test can be seen in Table 5.

[1] as of April 2020

Table 2: Observations: Themes, Sub-Themes, and Example Quotes

Theme	Sub-theme	# of codes Co-presence +ve	Co-presence -ve	Immersion +ve	Immersion -ve	Example Quotes
Cognitive Engagement	Conversation	5	0	8	2	"We're communicating in real life so I (...) could feel his presence" (P13, CP+)
	Collaborative task	8	2	10	1	"It felt like teamwork, you're (...) both doing part of the same task" (P1, CP+)
	Maintaining a mental model of the real environment	1	0	6	6	"You have that fear of bumping into something" (P13, I-)
Embodiment	Narrative embodiment	1	0	5	0	"P10 got in the role of being the drone" (P3, I+)
	Physical embodiment	1	4	3	2	"I (...) connected the drone with the voice that I'm hearing" (P2, I+)
Sensory Perception	Observability of avatar	6	3	0	0	"I saw P21 pushing buttons, so I didn't feel alone" (P6, CP+)
	Observability of body	9	1	1	6	"I bumped you and then I was more aware that you're there" (P4, CP+)
	Observability of virtual environment	0	1	0	3	"It felt like I was just trying to look in through a tiny little window" (P7, I-)
	Observability of real environment	2	3	0	7	"With the VR, I wasn't very aware of the (real) world, I only sensed the cable" (P3, I-)
Knowledge	Prior experience	1	2	1	0	"I've played VR (...), so I'm used to it and forgot about the outside" (P6, I+)
	Rationalizing experience	3	2	0	0	"I don't feel alone, because I know there's another person" (P13, CP+)
Agency in the virtual world	Control of the world	0	0	7	0	"I feel like I have control, makes me feel like I'm in the game" (P18, I+)
	Interface mapping	0	0	2	2	"flicking the switch, and putting the numbers on the keypad really feels real" (P5, I+)

Table 3: Mean scores of the SUS, together with sample size and standard deviation.

	n	Mean Score	SD
Phone	12	79.58	12.00
PC	12	81.25	12.97
HMD^{All}	24	81.35	12.55
All	48	80.89	12.27

There was no significant difference in co-presence between any of the versions as measured by the NMMoSP. This means that the experience of co-presence was unaffected by the medium of play (HMD, Phone, or PC) and that the HMD player was unaffected by the medium of play used by the other player (Phone or PC).

As might be expected, the HMD player's immersion was significantly more than the PC or Phone players' as measured by *IPQ*, but there was no significant difference between the two HMD versions and between the PC and Phone. This means that the experience of immersion is similar on PC and Phone, and that the HMD player's experience of immersion was unaffected by the medium of play used by the other player (Phone or PC).

The results are, to an extent, surprising. We expected players using the Phone to have increased feeling of co-presence because the two players are within the same physical play space, as well as increasing the immersion because of the added sensory information provided by the physical presence of the other player.

To explain these results, we need to go into the codes and themes created from the qualitative interviews.

5.2 Qualitative results

Our inductive coding resulted in 13 codes spread over 5 themes: *Cognitive Engagement, Embodiment, Sensory Perception, Knowledge,* and *Agency in the Virtual World*. A second coding activity using the same code book was then undertaken four months after the initial coding to confirm the reliability of the results — the intra-rater reliability was 80% agreement and the Cohen's Kappa was 0.64, indicating substantial agreement [22].

The 13 themes are shown in Table 2 with the number of positive and negative occurrences, and example quotes from one of the participants (from P1 to P24) with CP or I showing whether that particular quote was coded against Co-Presence or Immersion respectively, as well as a '+' or '-' sign indicating whether it was considered a positive or negative comment. The codes were shared between Co-presence and Immersion, with the exception of "*Control of the world*" and "*Interface mapping*" (which were unique to Immersion) and "*Observability of Avatar*" and "*Rationalizing Experience*" (which were unique to Co-presence). The following Sections describe each theme.

5.2.1 Cognitive Engagement

This theme is about people mentally engaging in the activity. This could be through *Conversation* with the other player, or through a *Collaborative Task*:

> "I felt that someone is constantly guiding me as the drone, so (...) it wasn't lonely at all" P5 CP+

It could also be the overhead of *Maintaining a Mental Model of the Real Environment*. The mental model arises because the HMD user playing with a Phone user has to not only work in the virtual environment, but also think about the physical one:

> "The drone started to run around me and I was thinking 'Oh wait, there's a person running around me as the drone, I don't want to hit them' " P9 I-

5.2.2 Embodiment

Embodiment describes the way in which the player feels they have 'become' the avatar — by this we mean how one might see a drone

Table 4: The mean scores with standard deviation for the two questionnaires, with each sub-category used.

	Phone	PC	HMD^All	HMD^Phone	HMD^PC
Aggregated Score (NMMoSPQ)	5.30, $sd = 0.72$	5.72, $sd = 0.86$	5.50, $sd = 0.79$	5.32, $sd = 0.70$	5.68, $sd = 0.59$
Co-Presence	5.90, $sd = 0.86$	6.46, $sd = 0.99$	6.10, $sd = 0.76$	5.79, $sd = 0.61$	6.42, $sd = 0.79$
Atentional Allocation	4.29, $sd = 1.64$	4.83, $sd = 1.64$	4.60, $sd = 1.55$	4.46, $sd = 1.68$	4.75, $sd = 1.45$
Perceived Message Understanding	5.71, $sd = 0.89$	5.88, $sd = 0.61$	5.79, $sd = 1.03$	5.70, $sd = 1.05$	5.88, $sd = 1.05$
Aggregated Score (IPQ)	3.71, $sd = 1.4$	4.20, $sd = 1.41$	5.95, $sd = 0.63$	6.06, $sd = 0.58$	5.85, $sd = 0.68$
General immersion	4.33, $sd = 1.30$	4.83, $sd = 1.53$	6.54, $sd = 0.66$	6.67, $sd = 0.65$	6.42, $sd = 0.67$
Involvement	2.79, $sd = 1.42$	3.48, $sd = 1.51$	5.13, $sd = 1.06$	5.33, $sd = 0.73$	4.94, $sd = 1.31$
Spatial presence	4.00, $sd = 2.03$	4.29, $sd = 1.67$	6.19, $sd = 0.84$	6.17, $sd = 1.05$	6.20, $sd = 0.62$

Table 5: Tukey test results of one-way ANOVA for Immersion

Comparisons (Immersion)	p-value
Phone - PC	$= 0.686$
HMD^PC - PC	$= \mathbf{0.003}$
HMD^Phone - PC	$< \mathbf{0.001}$
HMD^PC - Phone	$< \mathbf{0.001}$
HMD^Phone - Phone	$< \mathbf{0.001}$
HMD^Phone - HMD^PC	$= 0.97$

in VR, know it is a real person, but still embody or feel the drone avatar as the person, we termed this *Physical Embodiment*:

> "In VR I kind of attached their voice to the drone, so whenever I'd hear P12's voice I'd think 'Ok, this is the drone, it's speaking to me' " P16 I+

Narrative Embodiment on the other hand is more about the players getting into the role assigned to them (role-playing):

> "You have to be more forceful in terms of proactively immersing yourself into the game if you're on the phone" P18 I+

5.2.3 Sensory Perception

This theme centers about perceiving the other through one's senses; we therefore mean observability not only through sight, but all the other senses as well. It refers to both the player (as Observability of either their physical *Body* or their virtual *Avatar*, and the environment (both the *Virtual Environment*, and also the physical *Real Environment*.

5.2.4 Knowledge

In some cases people had either *Prior Experience* with VR or games in general, or they tried to *Rationalize the Experience*. In the first case, players either talked about never playing the game so they did not know what to do exactly, or they have played cooperative games before:

> "It feels like that I'm at home and I'm playing a video game with my phone and I'm alone in the room, and the person is playing inside the game, like a character inside the game" P18 CP-

People also came with the preconceived idea that they would be playing together with another player:

> "I know P23 is still there watching over me and stuff, so I totally feel their presence" P13 CP+

5.2.5 Agency in the Virtual World

This theme was unique to Immersion. Non-HMD players found that having some kind of *Control of the World* makes them more immersed:

> "(...) when I was with the phone, and had to turn on the flashlight, so I had even more presence in P22's side" P4 I+

This type of agency is about the ability to influence the world in general, rather than specifically referring to interactions through an avatar [28].

People also commented on the fact that having the game actions mimic the actions in the physical world (flipping a switch, pushing a button in) helps with immersion — we call this *Interface Mapping*:

> "I forgot I had the controller in my hand, (...) because what you could see is your hand, so I was like 'It's fine, I'm just poking things' " P15 I+

6 Discussion

From the quantitative data we found that there was no significant difference between any of the versions in terms of co-presence, and the only significant results for immersion being the levels between the HMD^{All} players and the Phone or PC players, which is an expected outcome (because VR is recognized as being more immersive). Analyzing the interviews and the codes gives us some insight into the lack of impact of the different mediums of play.

When looking at the themes, some relationships start to emerge. We can see how *Prior experience* and *Embodiment* are connected — if you knew what to expect it is easier for you to embody the role physically and narratively. Some non-HMD players mentioned that they did not know what they looked like at the beginning of the game, they did not know the size and shape of the drone, which made it harder for them to embody the role — having a **mirror in-game** might have helped them with that.

Physical embodiment and *Observability of body* also seem connected — an increase of bumping (into the other player) leads to an increase of *Physical embodiment* for the HMD^{Phone} players because now they have a sensory input other than voice, whereas for the PC version of the game that is not the case (PC players did not mention *physical embodiment* at all).

When talking about *conversation*, HMD players mention that the voice they heard (observed) either helped them with immersion, or not. In most cases, it helped them, but some people mentioned that if the voice came from within the headphones they would be more immersed, or in other words — **taking the real world and putting more of it in the virtual world** would have helped. Connecting it to the themes we can say that taking *observability of the body* and turning it into *observability of the avatar* would make for a more immersive experience (when the other player is a mix of virtual and physical stimuli, it is more distracting as you have to keep two instances of the player in mind).

This further shows how *Maintaining a mental model of the world* and *Observability of the body* are connected. The difference between the physical and virtual world (the fact that the phone player is beside the HMD player and there is not a 1:1 mapping of the real body to the virtual avatar) increases the mental strain of keeping the model of the real world in mind. One way that this might be alleviated would be to have a **more direct mapping between the real body and the avatar** (in the case of the Phone player). Some players on the other hand got completely engrossed in the VR world, being reminded of the physical one only by bumping into the other player.

These inner-relationships between the themes and sub-themes is what we can build upon when talking about the differences in the versions of the game, both between PC and Phone, and the two HMD versions. The data shows how the Phone player's immersion is negatively affected by the *observability of the body* and *world*, whereas the PC player does not have these problems. One way to explain that is the fact that the phone is a small screen that takes a tiny amount of your field of view, while the monitor used in the experiment is much bigger and thus makes it easier to lose yourself in the virtual world. Moreover, being on the phone with an HMD player in front of you can distract you because they would be moving a lot, taking your concentration away from the screen. On the other hand, co-presence is positively affected by this — the Phone players had more positive comments than the PC players, as seeing the physical body next to them helps them feel more co-present.

Narrative embodiment seems to be easier to achieve on the Phone, as there was a lack of comments from the PC side. One way to explain this is looking at the ways that the two versions interact with the virtual world — one has to physically move to go around, while the other can mostly just sit without moving significantly. This in turn would help the Phone player 'feel' more in the role of a drone, rather than controlling a drone separately with PC controls. One person mentioned how they actually found the PC version more immersive because they did not have a fear of bumping into something, which further shows how *Maintaining a mental model of the real world* can affect immersion — even when there was nothing to bump into on the HMD version, they still experienced the fear.

We have noticed that *control of the world* increases immersion for both non-HMD players, which is similar to what [18] talk about in their paper, where giving the second player more power to interact with the virtual world increases enjoyment rather than immersion [18], as well as what [1] say about control [1].

An important difference between the two HMD versions is the *mental model of the real world* — this theme shows up in a lot of places, and from our interviews it seems it is a very important part of immersion. In our case, the model negatively impacts the HMD player's immersion when being with a Phone player, but it helps with physical embodiment — when the HMD player feels something around them, or perhaps bumps into the Phone player, although they get reminded of reality, it enforces the fact that there is a physical object around them which coincides mostly with the drone avatar. This makes *embodiment* much easier than on the PC, and thus can help with co-presence.

In most cases, *Conversation* leads to an increase in immersion and co-presence for the HMD player — multiple people mentioned the fact that because they were **talking about the game world and not about something outside of it**, they felt more co-present and immersed. It should be noted that an important factor is where the voice is coming from — **within the headset/earphones or from outside**. Some people could not hear their partner's voice as well, which led to them having to concentrate more on the voice rather than on the experience. This can partly be helped by using either a headset that can pass through noise from the outside, a more open speaker design (such as the Valve Index[2]), or even having the voice of the second player be recorded from their Phone/PC and be transmitted to the HMD player in their headset simultaneously.

These relationships suggest that there are different features that affect (and mitigate) each other. For example, the aforementioned *Cognitive Engagement*, in which the overhead of maintaining a mental model of the physical space supports co-presence but detracts from immersion. Similarly in *Embodiment* the HMD player's sense of co-presence benefits from the Phone player being in the same physical space because their spatial proximity matches their avatar, but at the same time physical interactions (literally bumping into the other player) detract from immersion. Balancing each of these interactions between the different modes can lead to a more immersive or co-present experience.

[2]https://www.valvesoftware.com/en/index/deep-dive/ear-speakers

7 Conclusions

For VR to become more mainstream among people, we need to think about the 'living room environment' [18] and ways to make it more accessible for bystanders to take part. We created a multi-modal co-located co-op VR game to look at the difference in co-presence and immersion when introducing a second player either through a traditional PC interface or an AR app on a Phone. We used two questionnaires (*NMMoSP* [2] for Co-presence and *IPQ* [33] for Immersion) and conducted a semi-structured interview for each pair of players. We analyzed the results from the quantitative and qualitative data, coded the interviews, and identified 5 themes and 13 sub-themes. These 5 themes were *Cognitive Engagement*, *Embodiment*, *Sensory perception*, *Knowledge* and *Agency in the Virtual World*.

We found that there was no significant difference in co-presence between the modes, meaning that the sense of co-presence is not affected as much by the platform you are on, contrary to expectations. Immersion was found to have a significant difference only between the HMD and non-HMD players ($\mathbf{p < 0.005}$), which was expected, while there was no significant difference between the two groups of HMD players (meaning neither mode of the second participant detracts from the immersion) and the non-HMD players.

Future studies in this field of multi-modal VR interactions should take into consideration what they want to achieve by including non-HMD players, or even other HMD players — as our results show, to affect immersion and co-presence, specific design decisions should be undertaken (keeping in mind that one choice can negatively affect one dimension and positively the other). We suggest that future studies use qualitative data alongside the quantitative, as while our questionnaire results showed no significant difference where we expected one, the interviews revealed effects that were not visible in the quantitative data.

This paper shows that there are several ways of introducing a second player to a VR game, and that using a PC or Phone (or other mobile device) is a viable alternative to an HMD, with satisfactory levels of Immersion and Co-Presence, although design decisions could maximize the advantages of each medium of play. We hope that in the future, a person would be able to put on a VR headset and play with friends, in a shared social space, regardless of medium, allowing them to use the strengths of the platforms at hand to their fullest.

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