Synchronized Co-located Interreality Collaboration

Analysis, Design, and Usage of a Prototype Research Environment

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February 2020

Master Thesis Interaction Technology

Faculty of Electrical Engineering, Mathematics and Computer Science

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Abstract

Synchronized Co-located Interreality Collaboration (SCIC) occurs when co-located agents synchronously collaborate between different realities. This form of collaboration can offer several advantages over face-to-face collaboration but can also bring about a number of problems.

Related work and the experiment performed in this research project hint at several challenges that are likely to surface (such as communication mishaps and the lack of teammate awareness) but also demonstrate several strategies to help mitigate or prevent some of these challenges (such as using a suitable communication medium, allowing teams to adapt to opportunities and constraints, and helping teams maintain awareness).

These strategies were tested in a prototype research environment which includes features that support location-sharing and teammate-awareness. How people used the system and what they thought of it was tested in an experiment which showed that participants used the location-sharing feature often and the teammate-awareness feature less.

The experiment indicates that SCIC could lead to more effective individual tasking and less effective teaming. It is therefore recommended to carefully balance task effectiveness with teaming intelligence.

Acknowledgments

Writing this master thesis was not easy. But easy should not be the goal. Over the course of multiple months, I have learned so much about what it means to do research, about finding and generating knowledge, and about how to write it all down. Fortunately, I was not alone during the process.

I sincerely appreciate my supervisors, Jonathan Barnhoorn, Jan Maarten Schraagen, and Dirk Heylen, for their time, guidance, and for sharing their expertise during the entire process. You have helped me learn so much about doing research, executing experiments, writing, and planning. With you I have shared many wonderful conversations, not only about the research subject or the process, but also about personal interests and motives. Thank you for always having your door open and for treating me as an equal.

I am also thankful for my family and friends for their support throughout the project. I have thoroughly enjoyed our discussions and immensely appreciate your comments and ideas.

Finally, a big thank you to TNO and the entire department of Human Behaviour & Organisational Innovation for all your insights and advice, and for the prior research that I hereby attempt to build upon. I am glad to be joining you soon.

It was a pleasure sharing all of this with you. This project has made me aware of the long road ahead in this area of research. I for one am really looking forward to contributing improvements in human-computer interaction. Using better methods of collaboration, we can make the world a better place (for example, by making some flights unnecessary and thereby reducing carbon emissions).

I have tried to make this document somewhat pleasurable to read, hopefully this did not cause me to drift too far off course.

Contents

1 Introduction

Imagine a cave. A cave that is so big that no sunlight can get to the end. At this end of this cave, several prisoners are chained to face the back wall in such a way that they cannot move their bodies or heads and cannot see each other or themselves. They can only see the back wall and have been chained in these positions for their entire lives; they do not know anything else. Behind the prisoners is a fire that casts shadows of everything you put in front of the fire on the back wall. Now, to the prisoners, these shadows span their entire reality. They would think that reality solely consists of shadows. If one of these prisoners was able to remove his chains, he would be hardly able to move or to observe the fire directly. If he were to escape the cave and spend the time to get used to the sunlight in the outside world, upon his return his fellow prisoners would not understand him. His descriptions alone would provoke the other prisoners and he would appear as confused or mad. If he attempted to free the other prisoners, it is not unlikely that they would stop or even try to kill him.

The previous passage is a description of Plato's 'Allegory of the cave' and is a metaphor to the human condition which is, according to Plato, forever bound to the impressions that are received through our sensory experience. Metaphors, other forms of rhetoric language and fictional stories have been widely used by people throughout history. They can illustrate complex concepts in ways that are easier understood or more effectively passed down generations, they can inspire people and bring pleasure to author, narrator and audience. Alternative worlds thus form an important part of human history.

But only recently in human history has it become so easy to generate and so immersive to experience these alternative worlds. Research and developments in Virtual Reality technology have increased the fidelity of virtual environments to such a level that they can be and are used as shared collaboration spaces. Usually, this means that both persons need to be in the same virtual environment, or reality, which is not always desirable or possible. This thesis researches the possibility of collaborating *between* realities, or interreality collaboration.

Chapter 1 introduces the subject and background and narrows down the scope of this specific research project. It also provides the project's goals and shows why it is important to research this topic. Chapter 2 shows work that is related to the main subject to find problems that can be expected and to form strategies that could be used to overcome these problems.

Interreality collaboration is still a small research area, as the lack of research and projects using this phenomenon clearly demonstrate. It is therefore hard to explore the subject further and to test hypotheses concerning the expected problems and formed strategies. In Chapter 3, I design and build a research environment that can be used to accept or reject such hypotheses. Chapter 4 describes an experiment set-up that uses this research environment to test a set of novel hypotheses, or solutions for interreality collaboration. Chapter 5 then combines these results with knowledge from previous chapters to show what has been learned and what should still be explored further.

But before one can properly understand interreality collaboration, it is important to explore its background.

1.1 Background

At the start of the computer age, "*mathematicians were so conscious of efficiency considerations that they could not imagine wasting any extra computer time for something a programmer could do by himself*" (Belzer, Holzman, & Kent, 1977, p. 434). Today, computers are so powerful that programmers can hardly imagine wasting any mental energy for something a computer could do by itself.

The increase of computing power allowed for many developments, such as the creation of Virtual Environments (VEs). VEs are synthetic environments that can be created, for example, by use of computers. People that experience such an environment need not believe that it is non-synthetic. They also need not feel as if existing within this environment.

Immersive Virtual Environments

But if this VE creates "*a psychological state in which the individual perceives himself or herself as existing within the VE*" (Blascovich, 2002, p. 129), the VE has entered the realm of Immersive Virtual Environments (IVEs). Just like virtual environments and alternative worlds, IVEs are not a new phenomenon. For example, haunted houses in theme parks are IVEs. Even before the Common Era, panoramic paintings were used to immerse observers in a virtual environment. What **is** new, is the technology that can be used to develop these IVEs in much less time and for much less money.

The literature is not consistent with the use of the term immersion and there are multiple attempts to define and categorize it (cf. Zhang, Perkis, & Arndt (2017, pp. 1-2)). Witmer and Singer regard immersion, like involvement and presence, as "*something the individual experiences*" (Witmer & Singer, 1998, p. 227). Slater disagrees and considers immersion as "what the technology delivers from an objective point of view" (Slater, 2003, p. 1). Slater views this deviation as a "*very profound difference in methodology regarding the elicitation of presence*" (Slater, 1999, p. 2).

In the context of IVEs, I consider immersion as the extent to which the IVE conveys the virtual environment. It is thus an objective measurement of a system, which can be used to assess one system as being more immersive than another.

A lot of IVEs use immersion to let users experience presence in the virtual environment. This is often referred to as Virtual Reality (VR). Often in literature, immersion is said to simply precede presence (as shown but disagreed with by Bowman and McMahan (2007), but the reality is more complex. Bowman and McMahan suggest (a) that presence might not be the only benefit of immersion, and (b) that we should not consider immersion a binary construct, but rather a multidimensional continuum of which any or all of the components could potentially benefit the application.

As pointed out by Hartmann, Wirth, Vorderer, Klimmt, Schramm, and Böcking (2015, p. 116), as the concept of presence became more complex and multi-faceted, it caused a differentiation into sub-concepts such as physical, social, and self-presence; or spatial, social, and co-presence. Especially spatial presence obtained a lot of attention by researchers. It refers to the perception to be located in an environment that is conveyed by some sort of media technology (Hartmann, et al., 2015, p. 116).

In this report, I refer to presence as the sensation of ‘being there’ that humans often feel as a consequence of immersion in a virtual environment. It is a subjective response that can be seen as an illusion. One IVE thus delivers the same immersion to all its users but can generate a different experience of presence for different users.

From the 70s to the 90s, the VR industry was primarily interesting for military and medical simulation purposes. When VR began to find its way into popular culture in the 90s, commercial products started to appear ranging from science fiction books to toys and TV programs. The increased interest in VR combined with technological developments stimulated more research and developments which produced better devices that were also cheaper and more accessible.

IVEs now have many applications in areas such as simulation training, product prototyping, data visualization, education, telecommunication, and entertainment. Most of the implementations focus on the experience of one user in a virtual environment. But for many real-world tasks, more is required. Often, a certain working context is necessary that includes communication and collaboration with other persons or computer systems.

Collaborative Computing

“*Let me mention another bonus feature that wasn't easily foreseen. We have experimented with having several people work together from working stations that can provide inter-communication via their computer or computers. That is, each person is equipped as I am here, with free access to the common working structures. There proves to be a really phenomenal boost in group effectiveness over any previous form of cooperation we have experienced.*” (Engelbart, 1962, p. 105). This was a quote from Doug Engelbart in 1962 when he showed his concept of collaborative computing.

Two decades later, the term Computer-Supported Cooperative Work (CSCW) came into existence. CSCW can be broadly defined as “*the attempt to provide computer-based solutions to the problems that arise when two or more people attempt to cooperate to perform a task or solve a problem*” (Borenstein, 1992, p. 67).

Working together within or between teams involves communication, coordination, cooperation, and collaboration with colleagues, superiors, and other stakeholders. For this, Johnson and Vera (2019) propose the term teaming intelligence and describe its importance as follows: “*For any intelligent agent to leverage their talents within a larger group outside themselves, having the knowledge, skills, and strategies to effectively team will be essential.*” (Johnson & Vera, 2019, p. 21).

Plentiful research has been carried out on co-located collaboration (simply ‘teamwork’) and on distributed collaboration (‘CSCW’, ‘remote collaboration’ and much of tabletop research). Tang, Boyle, and Greenberg (2004) describe another form of groupwork, Mixed Presence Groupware (MPG), which occurs in real-time, but partially occurs both co-located as well as distributed (see Table 1). In their article, they describe the surprising lack of literature on MPG (and present their own system that allows all mixed-presence participants to manipulate a shared space simultaneously).

	Same place (co-located)	Different place (distributed)
Same time	Face-to-face[1] teamwork	Real-time distributed teamwork
	Mixed-Presence Groupware	
Different time	Co-located ongoing teamwork	Asynchronous distributed teamwork

Table 1: Mixed Presence Groupware. Adapted from Tang, Boyle, and Greenberg (2004)

Collaboration is thus possible at the same place (co-located), between different places (distributed), or in the form of mixed presence. Traditionally, these places only existed in the ‘real’ world, but nowadays it is also possible for collaboration to exist in a fully virtual environment. A Collaborative Virtual Environment (CVE) is “*a distributed, virtual reality that is designed to support collaborative activities*” (Churchill & Snowdon, 1998, p. 1).

In a CVE, not all people necessarily have the same device, perspective or even scale. This concept of having asymmetry between users of a virtual environment is in the literature referred to as *asymmetric collaboration*. Such asymmetry can also exist between the environment, or *reality*, that users experience (most) presence in. And just as MPG crosses the barrier between co-located and distributed collaboration, another form of collaboration crosses the barrier between the real world and a virtual environment.

Interreality Collaboration

Head-Mounted Displays (HMDs; headsets often used for VR) are getting more powerful, accessible, and cheaper, which gives a growing number of companies and individuals the option to use the technology. When combining these hardware improvements with the growing number of applications and advantages that immersion can offer for collaborative work, it is not hard to see CVEs as a promising research area.

But it isn’t always viable to put HMDs on every member of a team. It is sometimes handy for a teammate to feel most presence not in a virtual environment, but in the real world. For example, if your task includes any dependence on other team members, it could be difficult to see them when wearing an HMD.

In the literature on VEs, IVEs, CVEs, and collaboration, team members often experience presence in the same (real or virtual) environment. But by using a single HMD, one user could feel present in a virtual environment while communicating (for example through voice or chat) with another user that is present in the real world. This communication of information between realities could bridge the gap between real- and virtual environments and could foster interesting collaboration challenges and opportunities.

To describe collaboration between different realities, I propose the term interreality collaboration. I prefer to refrain from the cross-reality terminology (e.g. in Paradiso & Landay (2009)) as the term and its acronym (XR) tend to cause confusion (e.g. with the term Extended Reality and its acronym, XR). Moreover, cross- usually takes the form of going *through* or *over* something (e.g. cross-country, cross-border), while inter- usually means

[1] By face-to-face collaboration, I mean traditional teamwork without the use of information- or communication technologies. Confusion can arise because contemporary video conferencing could also be considered face-to-face. In this project I do not consider that face-to-face communication or -collaboration.

between or *among* (e.g. interstate, intercellular, intercity). Although exceptions can be found to these examples, I still believe the term *interreality* better represents the concept.

I define interreality collaboration as “*the active working together of agents that experience most presence in different realities*”. In this definition, ‘*active working together*’ is used to indicate collaboration as opposed to cooperation (which is a more passive form of working together), ‘*agents*’ implies that at least two members are required, and ‘*experience most presence*’ allows for the experience of two realities simultaneously. If you experience virtual reality and still notice the real world, this makes you experience at least some presence in two realities; terms such as “*he is present in a VE*” are therefore less accurate.

IVEs will often at some point integrate elements of collaboration as they allow for more realistic and useful scenarios. While there is plenty of literature available on IVEs for individuals and on dimensions of collaboration such as locality and synchronicity, there is a seeming paucity of literature that considers their integration into interreality collaboration.

This is unfortunate as interreality collaboration could support incredibly useful interactions. For example, the experiment described later in this report includes one person that looks inside a virtual world from the perspective of a drone while another person sees a top-down map in the real world. The collaboration of these individuals can bring about a complex understanding of the environment that is hard to obtain using only one of these perspectives.

The benefit of researching interreality collaboration in such an immature phase is that there is still much more to discover. I believe this report discusses important benefits and describes interesting results of this novel form of collaboration that will hopefully inspire future research. Just as collaborative computing once seemed unnecessary or unpractical, interreality collaboration could become just as common and useful throughout the world. The real world, that is.

1.2 Scope

The previous section explained that it is possible to collaborate not only between different locations or at different times, but also between different realities, for which I proposed and defined the term interreality collaboration. But what does 'between realities' imply? And what kind of collaboration is meant? This paragraph attempts to answer these questions and explains the scope of this research project.

As we have seen in the previous chapter, interreality collaboration can be seen as a form of asymmetric collaboration. It can be further divided into synchronized collaboration (at the same time) and asynchronized collaboration (at different times). If you are working with your team in real-time, you're performing synchronized collaboration. Conversely, if your team left some ideas on the whiteboard for the next team to work with, you are collaborating with them asynchronously. Although I consider asynchronous interreality collaboration an interesting subject for further research, in this project I will solely focus on synchronized interreality collaboration.

Interreality collaboration can also be divided into co-located and distributed collaboration. Co-located collaboration indicates that the collaboration occurs at the same physical location while distributed collaboration indicates that it occurs between different physical locations. In this research project I focus exclusively on co-located interreality collaboration.

In 1994, Milgram and Kishino distinguished different levels of virtuality[2], starting at the real environment and ending at a fully virtual environment. They illustrated this spectrum and named it the Virtuality Continuum (see Figure 1).

Figure 1: The Virtuality Continuum. From Milgram and Kishino (1994)

At this point in time, augmented reality was sometimes mentioned in the literature, but mixed reality was a fairly new concept. The left extremity of the virtuality continuum shows the real environment, not involving any virtuality at all. This is as 'real' as it can get. Once we introduce a certain element of virtuality, as small as it may be, we enter the realm of Mixed Reality (MR). At a certain point the combination of the real world plus this small element of virtuality can be called Augmented Reality (AR) to indicate an additional (virtual) layer on top of the real world. Once you introduce more and more virtual elements into a world, at some point your world is more virtual than real. A world that is fully virtual is then called a fully virtual environment and in the same way we added a bit of virtuality to the real environment to go into augmented reality, we can add a bit of reality to a fully virtual environment to enter Augmented Virtuality (AV). Mixed reality, indicating that it mixes the real and the virtual, thus stops when reaching a fully virtual environment.

[2] These 'levels of virtuality' are currently often treated as separate concepts but can just as well be considered a gradient.

Interreality collaboration refers to collaboration between different levels of mediation. With regards to the amount of virtuality, this leaves open several options. Table 2 visualizes different types of interreality collaboration that are possible between two agents.

Level of Virtuality	Reality	Mixed Reality	Virtual Reality
Reality		**A**	**B**
Mixed Reality	-		**C**
Virtual Reality	-	-	

Table 2: Types of interreality collaboration that are possible between two agents based on level of virtuality.

In type A interreality collaboration, agents collaborate between reality and mixed reality. If the amount of virtuality in the mixed reality agent is quite low (towards the left of the virtuality continuum from Figure 1), the agents have little possible difference in available information. But if the amount of virtuality is high, the agents could possibly have very different visual information. The same can occur in type C interreality collaboration, in which agents collaborate between mixed reality and virtual reality.

Conversely, agents that perform type B interreality collaboration do not depend on this possible difference in amount of virtuality. The amount of virtuality in Reality is zero percent and the amount of virtuality in Virtual Reality is a hundred percent. Type B interreality collaboration is therefore likely to be more consistent in experiments. The rest of this document will solely consider this type of interreality collaboration.

While the difference between *communication*, *coordination*, and *collaboration* is clear to most, the difference between *cooperation* and *collaboration* is not. The etymological roots do not help much here. Cooperate stems from *co-* (together) + *operari* and collaborate stems from *col-* (together) + *laborare*. Both operari and laborari can be translated as 'work', but potential subtle differences are in this case lost in translation.

By cooperation, one usually means "*to enable the other to work*", while collaboration takes on a sense of "*to actively work together*". You cooperate with an officer of the law, but you collaborate with a colleague. In this research project, I consider people working together *actively* instead of having one person do most of the work.

This research thus focuses on synchronized co-located interreality collaboration.

1.3 Goals and Research Questions

This research project explores what happens when people collaborate at the same time, at the same location, between reality and virtual reality. I call this specific form of interreality collaboration Synchronized Co-located Interreality Collaboration (SCIC). The current paragraph covers how I explored this topic by explaining the project goals and research questions.

At the end of Section 1.1, I mentioned the scarcity on interreality collaboration literature, especially literature focusing on SCIC. Finding problems that can be expected when performing SCIC was therefore not an easy task. To supplement, I investigated work that is related to the main topic and attempted to extract what problems could be translated to SCIC. This goal is summarized in the first research question:

1. **What problems can be expected when two co-located persons synchronously collaborate between reality and virtual reality?**

The scope of this project is not to list all problems that can occur when performing SCIC but rather to explore the type of problems that are likely to occur and to see how people respond to these. Since people cannot see each other directly while collaborating between reality and virtual reality, I suspect some collaboration hiccups to occur. These could, for example, be caused by one person physically pointing to something that the other cannot see or by a person not knowing if the other is available to talk or too busy with a task.

Analysis of the literature and related work could also yield strategies on how these problems can be overcome. An example of such a strategy is allowing collaborators to communicate verbally, which could aid their problem-solving abilities. This is summarized in the second research question:

2. **What strategies can be applied to mitigate or eliminate these problems?**

Besides the lack of literature, there is also a lack of available research environments or other projects that can be used to experiment with SCIC. So, to test the effectiveness of the formed strategies, I have designed and built a prototype research environment that supports synchronized interreality collaboration. Several characteristics that the environment should possess were considered when answering this research question:

3. **What are the characteristics of a research environment that can be used to test strategies for supporting Synchronized Co-located Interreality Collaboration?**

Several of the formed strategies were implemented in the research environment as a toolset which I have called the Interreality Support System (ISS). The goal of the ISS is to support synchronized interreality collaboration and allow users to collaborate optimally. But to test if the ISS can indeed lead to more effective and more efficient SCIC, I have set-up an experiment to answer this final research question:

4. **Can the Interreality Support System lead to more effective and more efficient Synchronized Co-located Interreality Collaboration?**

Besides answering this research question, the experiment could also support or oppose the problems found, strategies formed, and the implemented system characteristics by observing participants and discussing their actions. Analysis of the literature and related work, combined with results from this experiment, could then indicate what problems can arise when performing SCIC, how these problems can be overcome, and if and how the ISS mitigates or eliminates these problems.

2 Related Work

Although performing interreality collaboration and especially SCIC is still in its infancy, there are multiple related concepts that can help understand the peculiarities of collaborating between realities. These concepts provide us with problems that can be expected and strategies that should be adhered to in order to optimize the effectiveness of interreality teams. This chapter explores SCIC by discussing several of these related concepts.

Before the 19th century, collaboration often occurred between people who could directly see and talk to each other face-to-face. Of course, oral and written communication also allowed for collaboration over distance (and often necessarily over time), but this was less suited for time-sensitive and/or complex tasks. Then came the 19th century in which the first electrical telegraphs were built. Communication technologies such as the fax machine, the telephone, and later email and videoconferencing have since allowed people do more collaborative work over distance than ever before.

Collaboration can have multiple attributes which are often split into categories such as synchrony, locality, and scale (Schooler, 1996, p. 211). Such categories can be considered dimensions of collaboration. I have visualized an example of this concept in Figure 2 in which I replaced scale with reality to better suit the current work.

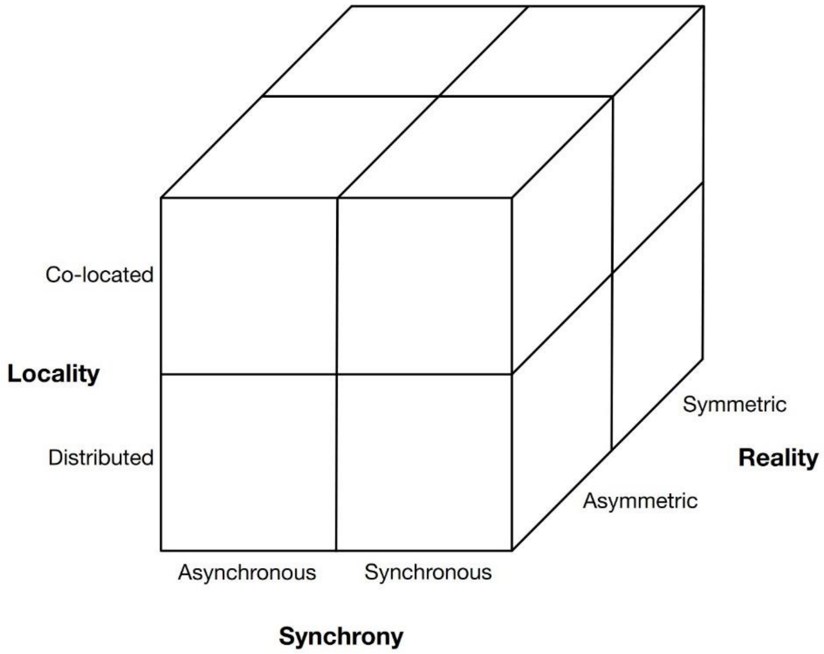


Figure 2: Three dimensions of collaboration visualized as a matrix. Adapted from Schooler (1996, p. 211).

In this three-dimensional matrix, a collaboration system can then be seen as a volume in this multidimensional space. For example, Figure 3 shows the same collaboration matrix, but with a colored volume indicating Synchronized Co-located Interreality Collaboration (SCIC). I will use this collaboration matrix several times in this section to indicate what type of collaboration is discussed.

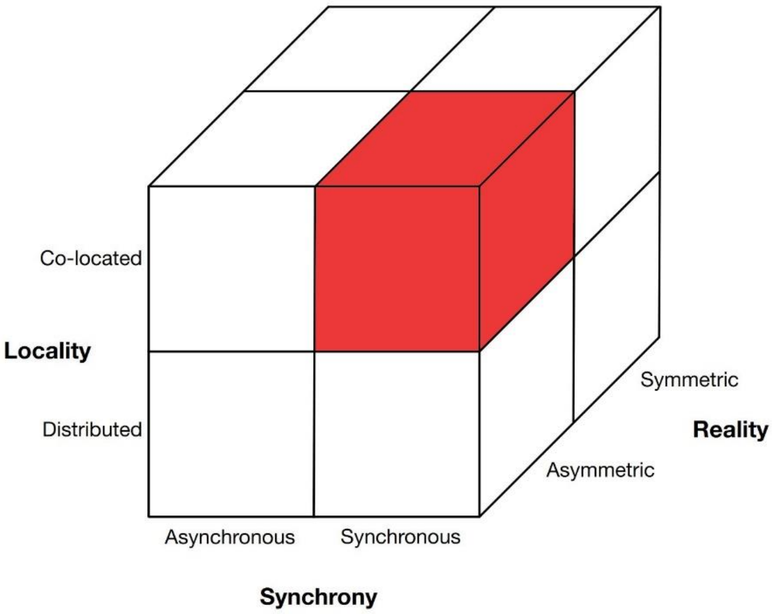


Figure 3: Collaboration Matrix: Synchronized Co-located Interreality Collaboration

Collaboration between people that have a distributed locality means that the people are dispersed by geographical location. This does not diminish all collaboration but does make face-to-face collaboration impossible. A difference in synchrony appears when the people that are collaborating are not working at the same time. For example, crews that work in different shifts or time zones can pick up the work by the previous crew and thus collaborate with them asynchronously. Teams that work in location- or time dispersed conditions can have several benefits over face-to-face teams, but they also face several extra challenges. These benefits and challenges are discussed in the next section.

2.1 Virtual Teams

Because of communication and information technologies, teams do not need face-to-face communication to collaborate. They do not even need to be in the same physical location or work at the same time. Even though "*a large body of evidence suggests that close proximity is beneficial to relationships and group interaction*" (Kiesler & Cummings, 2002, p. 1), these teams are not necessarily ineffective.

In the literature, groups of people working together by relying on communication and information technologies are referred to as virtual teams. Powell, Piccoli, and Ives define them as "*groups of geographically, organizationally and/or time dispersed workers brought together by information and telecommunication technologies to accomplish one or more organizational tasks*" (Powell, Piccoli, & Ives, 2004, p. 7). As virtual teams can be geographically- or time dispersed, Figure 4 and Figure 5 show the collaboration matrix for these possibilities respectively.

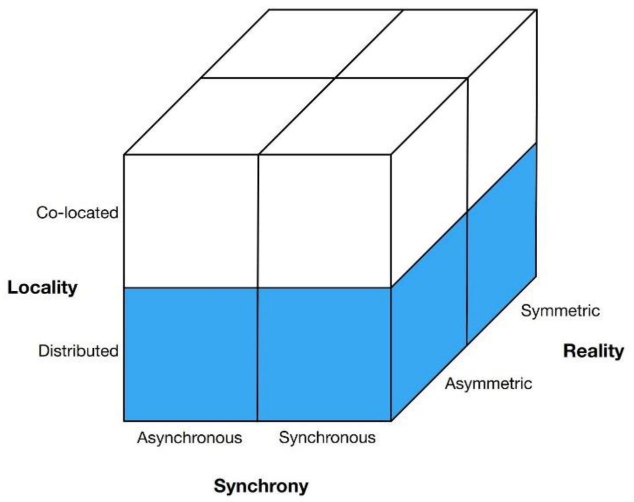


Figure 4: Collaboration Matrix: Virtual Teams (geographically dispersed)

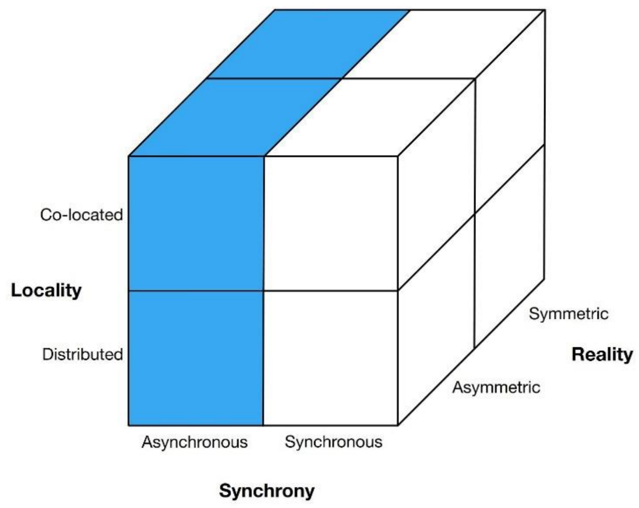


Figure 5: Collaboration Matrix: Virtual Teams (time dispersed)

When extending the definition of virtual teams to include dispersion for the (virtual) environment in which a team member experiences most presence, interreality teams could also be considered virtual teams. When a team collaborates between different IVEs or between an IVE and the real world, team members can be geographically, organizationally and time undispersed while still needing information and telecommunication technologies to properly accomplish organizational tasks. We can therefore utilize virtual team literature and extract problems and strategies translatable to SCIC.

Thompson and Coovert (2006) propose several challenges to the effectiveness of virtual teams and classify them in three categories:

1. Failure to develop effective interpersonal relationships
2. Communication mishaps
3. Lack of awareness of team members' endeavors

The first category considers the dispersed nature of virtual teams to reduce the amount of social information communicated between team members and therefore limiting relational development. In SCIC, team members are not dispersed by location or time. Although team members may still encounter a cut in available social context cues compared to face-to-face teams while working, I believe the social context cues that are available before work, after work and in breaks can help prevent failure in developing effective interpersonal relationships. I am therefore not as concerned with this challenge in effectiveness when considering SCIC.

The 'communication mishaps' category is about the used communication technology which could restrict information flow between team members and therefore impact quality of discussion. The configuration of SCIC that I consider (i.e. one team member wearing a head-mounted display) is indeed likely to hinder nonverbal communication as team members cannot directly see each other. Problems in this category partly depend on the choice of allowing or disallowing verbal communication.

The third category regards the lack of information normally gained from first-hand observations of team members to complicate coordinated teamwork. This includes knowledge on task progression and activities of team members. Again, the configuration that I consider indeed probably hinders the awareness of team members' endeavors when compared with face-to-face collaboration. Compared with virtual teams however, I believe the co-location of interreality teams can help with obtaining information on team members, for example through hearing task-related physical actions (e.g. clicking of a keyboard) or through hearing or feeling movement of a team member. Nevertheless, these observations will not be as rich and frequent as those during face-to-face collaboration and the lack of awareness of team members' endeavors is therefore still likely an important challenge to interreality team effectiveness.

2.2 Asymmetric Collaboration

Another related concept worth exploring is that of asymmetric collaboration. Paragraph 1.1 briefly mentions asymmetric collaboration as asymmetry between users of a collaboration system. This asymmetry can manifest itself in different ways.

Grandi, Debarba, and Maciel (2019) mention possible variations in scale, point-of-view, roles, realities, devices, and design-dependent linkage. They also describe users collaborating in such an environment to "*interact through completely different sensorimotor configurations and build distinct perspectives of the shared experience*" (Grandi, Debarba, & Maciel, 2019, p. 127). Users can thus have a distinct experience even when in the same (virtual) environment.

When this asymmetry is due to a difference in reality that users experience most presence in, this form of asymmetric collaboration can be described as interreality collaboration. Figure 6 shows the corresponding collaboration matrix.

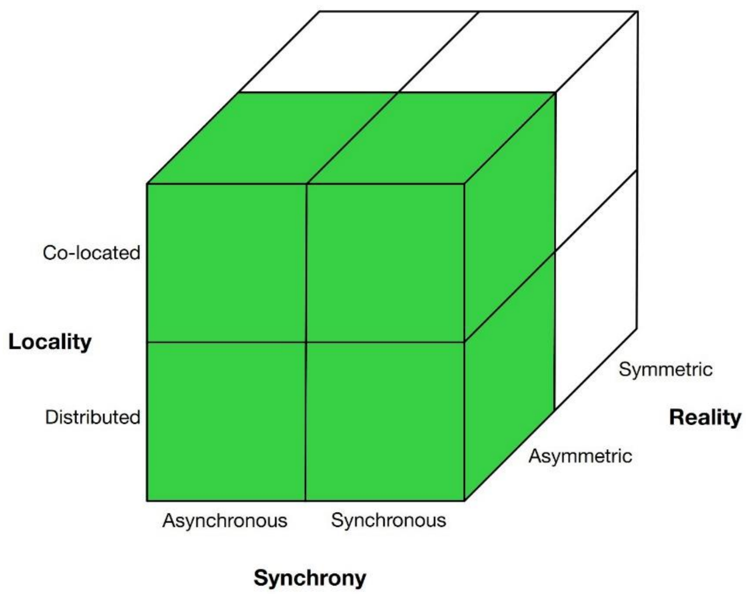


Figure 6: Collaboration Matrix: Interreality Collaboration

An example of asymmetry in scale, point-of-view, role, reality, and device can be seen in the videogame *DAVIGO*[3]. In this game, one player wears an HMD and plays a mighty giant fighting against another player using a computer and playing a nimble warrior. In another game called *Keep Talking and Nobody Explodes*[4], one player wearing an HMD is trapped in a virtual room with a bomb they must defuse. Other non-HMD players have the bomb's instruction manual and together the HMD and non-HMD players must discuss what steps should be taken to defuse the bomb. Even though the AR/VR gaming industry is still quite young, more examples can be found that utilize asymmetry to create interesting gameplay concepts[5].

Examples of asymmetric collaboration can also be found in the literature. Ibayashi et al. focused on architecture-scale problem-solving requiring two different viewpoints. One or multiple users represent the architect(s) and see a top-down overview of the design space on a multi-touch tabletop device. Another user wearing an HMD represents the person for which the space is being designed and can take a first-person internal look in the space (Ibayashi, et al., 2015).

Clergeaud et al. (2017) were inspired by the current limitations in asymmetric collaboration as expressed by industrial engineers. They created several interaction techniques based on the literature to improve the awareness, communication, and interaction between locations. These could inspire or help the development of asymmetric collaboration systems.

Grandi, Debarba, and Maciel present an assessment of asymmetric interactions (VR-AR) in CVEs and compare these with symmetric scenarios (VR-VR and AR-AR). Results indicate that "*pairs in asymmetric VR-AR achieved significantly better performance than the AR symmetric condition, and similar performance to VR symmetric*" (Grandi, Debarba, & Maciel, 2019, p. 127). Grandi et al. also provide more examples of how asymmetry is used in navigation, 3D object manipulation, data exploration, architectural design, and sports (Grandi, Debarba, & Maciel, 2019, p. 128). Asymmetric collaboration thus does not kowtow to symmetric collaboration and can even have significant benefits.

Based on feedback of early VR adopters, Gugenheimer et al. designed and implemented a prototype for co-located asymmetric experiences named *ShareVR*. Their system uses positional tracking with floor projection and displays for one user and an HMD for the other. They then explored the impact of this system on enjoyment, presence, and social interaction. Results indicated an increase in all these factors compared to a baseline consisting of a television and gamepad (Gugenheimer, Stemasov, Frommel, & Rukzio, 2017).

So far in this section on asymmetric collaboration, discussed collaboration methods are or can be performed while co-located. But asymmetric collaboration does not necessarily imply co-location. In Mixed Reality remote collaboration systems, physically distributed users are virtually co-located by means of mixed reality techniques. An example of this phenomenon is provided by Kolkmeier et al. in which a local novice can receive real-time support from a remote expert using their telepresence toolkit *OpenIMPRESS* (Kolkmeier, et al., 2018). They also validated how several design variations contributed to usability, performance and social presence.

[3] Created by Erik Roystan Ross. See also https://roystan.net/davigo
[4] Created by Steel Crate Games. See also https://keeptalkinggame.com/
[5] For example, see https://xinreality.com/wiki/List_of_Asymmetrical_Party_VR_Games

Another example of physically distributed asymmetric collaboration is given by Morde et al. in which a novice in the real world (with a superimposed augmented reality view) plays chess with an expert in a virtual world. They are assisted by an intelligent agent that has knowledge about chess and the board set-up (Morde, et al., 2004). This and OpenIMPRESS are both examples of telepresence systems in which presence in a virtual environment is generated despite physical distance.

Ashdown and Cummings's article on Asymmetric Synchronous Collaboration within Distributed Teams focuses especially on military command and control. According to them *"in a dynamic domain it is not just workspace awareness regarding shared digital data that is necessary, but also situation awareness: knowing what is going on in the external world"* (Ashdown & Cummings, 2007, p. 6). Situational awareness is an important aspect for many collaboration systems. But it can be especially interesting in asymmetric collaboration in which people are likely to have very distinct experiences and knowledge about the same environment.

In this section we have discussed several forms of asymmetric collaboration in which there is asymmetry between collaborators. This asymmetry can, for example, be caused by differences in reality, scale, point-of-view, role or device. We have also seen that asymmetric collaboration can have significant benefits over symmetric collaboration. The next paragraph discusses what this means for teams that work between realities, what we can expect from these teams and what strategies we should apply to guide these teams in collaborating between realities.

2.3 Expectations and Strategies

Based on insights from virtual teams and asymmetric collaboration literature, several problems surfaced that can be expected in a scenario involving interreality collaboration. This section discusses these problems, if and how they apply to SCIC, and shows several strategies for overcoming them. These strategies form the basis for building the SCIC research environment which is discussed in the next chapter.

From the virtual teams literature, several possible problems arose. The first considered a failure in developing effective interpersonal relationships. For interreality collaboration as a whole, this could indeed form a problem, but for the scope of this project I only considered co-located and synchronized collaboration. This means that the collaborators will probably see each other regularly in breaks or before-/after work so there is not a likely cause for developing ineffective interpersonal relationships.

The second problem involved communication mishaps due to the communication technology restricting social context cues. Contemporary VR devices block the users visual field, which provides a high level of immersion but can also isolate the user from the environment.

Human teams achieve better teaming performance when team members "*track and take into account one another's goals, intentions, beliefs, as well as other performance and task-related states—that is, when they use a 'Shared Mental Model' (SMM)*" (Scheutz, DeLoach, & Adams, 2017, p. 203). Not seeing each other in the research environment could thus impact the users' team, task, and situational awareness. This could cause a dissimilarity in their SMMs. And while a non-identical SMM is not considered problematic (there is always at least a small difference in mental models due to a difference in user experience, perspective, etc.), a dissimilar SMM can cause problems as users may hold very different ideas on each other's tasks, status, or overall situation.

I therefore indeed expect some communication mishaps to occur. These could, for example, be caused by one person physically pointing to something that the other cannot see, by a person not knowing if the other is available to talk, or when sharing information that is dependent on the user's perspective or presence. Although such mishaps could hinder interreality collaboration, the impact of these mishaps on the efficiency and effectiveness of SCIC may be reduced as synchronization and co-location could increase the speed at which mishaps are resolved.

The lack of awareness of team members' endeavors was described as a possible third problem. Again, because contemporary VR devices block the visual field of its user, keeping track of the status and activities of team members is indeed likely to be harder in interreality collaboration than in face-to-face collaboration. Even in SCIC, it is hard for the person in VR to keep track of the other user.

There are many possible strategies when building a research environment for testing SCIC concepts. First of all, to clearly identify problems that arise while collaborating, it can be useful to observe only two persons instead of a bigger team. Few current examples of these teams can be found, but for such a team to have only two members is not unlikely.

People behave differently when executing a collaborative task based on the experience they have with each other and with that task. In order for a real-life two-person SCIC team to perform optimally, it would likely include users that are highly trained with each other and for their task (i.e. professionals). Because these professionals are co-located, it is assumed that they at least communicate face-to-face before- and after work and during breaks. This forms a crucial distinction between SCIC teams and Virtual Teams in which the former does not have the same likelihood of failure in developing interpersonal relationships (Van der Kleij, 2007, pp. 18-21).

Because of the immaturity of the research subject, I did not investigate a specific part of collaboration but was instead interested in what happens in general. For this purpose, what the collaborators said to each other helped show and explain problems that occurred during their collaboration. I have therefore allowed verbal communication between collaborators. This also provides a high-fidelity method for the collaborators to solve problems quickly.

Gugenheimer et al. (2017) share four guidelines for designing asymmetric co-located VR experiences. The first of which states the importance of leveraging asymmetry and is described as follows: *"Instead of assigning irrelevant tasks to the Non-HMD user to create any form of dependence and force collaboration, leverage the inherent advantages of each role. Offer isometric or orthogonal visualizations to the Non-HMD user since those help to perceive spatial relations in the virtual scene and allow the Non-HMD user to engage with further observers on the couch."* (Gugenheimer, Stemasov, Frommel, & Rukzio, 2017, p. 10). It can thus be important to create a task that challenges both users in a way that suits their role.

Van der Kleij (2007, pp. 25-35) combines results from his experiments with knowledge obtained from literature to form three strategies for addressing the aforementioned challenges for virtual teams:

1. Match communication media capabilities to the fundamental communication processes required to perform the task and the situation in which the team members have to interact.
2. Allow teams to adapt to environmental opportunities and constraints.
3. Help teams to maintain awareness of the situation, task, and team during distributed meetings.

The first of the above strategies highlights the importance of a proper communication medium. As we have established that users will be allowed to talk to each other, a lot of information can be shared already. But if the research environment requires information that is not easily shared by verbal communication, it can be useful to create a capability of the system to handle this as well.

Verbal communication could also help teams in adapting to environmental opportunities and constraints. In the research environment, users should be granted some leeway in how they want to perform the task.

The third strategy suggests helping teams maintain awareness during collaboration. Ashdown and Cummings agree and emphasize "*the importance of supporting awareness, both at the operational and the tactical level*" (Ashdown & Cummings, 2007, p. 5). Helping teams maintain awareness is thus an important strategy for developing the research environment. According to Kraut et al., a major challenge is to develop tools for aiding this awareness (Kraut, Fussell, Brennan, & Siegel, 2002, p. 155).

Though many teams could benefit from collaboration between realities, few teams are presently using this technique. This chapter used insights from virtual teams and asymmetric collaboration literature to show some of the problems that can be expected when performing SCIC and several strategies that should be applied. The next chapter applies many of these strategies to the design of a prototype research environment which was used to test SCIC concepts.

3 Design

"The future cannot be predicted, but futures can be invented"

Dennis Gabor (1963, p. 207)

Previous chapters noted the scarcity of literature on interreality collaboration and especially SCIC. Not to mention virtual environments or projects that can be used to test SCIC concepts. I have therefore built a prototype research environment which was then used to experiment with several SCIC-related concepts.

This chapter discusses considerations that went into this design process (Paragraph 3.1), requirements for the research environment (3.2), the creation of an imaginary scenario that was first used to develop the research environment and later to stimulate its users (3.3), the development of the virtual environment (3.4), and the addition of several tools to the research environment to support user collaboration (3.5).

3.1 Considerations

Before designing an immersive virtual environment, there are human- and hardware related aspects that must be considered besides the project's timespan. On the human side, several physiological limitations and usability criteria must be met. On the computer side, the application should be optimized to find a balance between looks and performance and the system should not stop working after a software dependency update. Expected problems and suitable strategies from the previous chapter should be taken into account.

This paragraph does not attempt to list all possible considerations but merely gives a short summary on the most important aspects. Far better and more complete lists can be found online[6].

In the early days of videogaming, even big screens caused some people to get simulation sickness, a subset of motion sickness which can cause symptoms as discomfort, nausea or disorientation. Motion sickness is thought to be caused by a disparity of what one expects to sense and what one actually senses (Takov & Tadi, 2019).

The screen in contemporary Virtual Reality systems covers most of the user's field-of-view which causes the user to have no stable reference and therefore can cause severe motion sickness. Some VR games attempt to alleviate this by having players stand in a virtual space that corresponds with the player's physical tracking area.

Not maintaining a stable horizon line can also cause motion sickness (Takov & Tadi, 2019). Great heights, big spaces, and small spaces can create discomfort for the user and fast-moving objects near or towards the user can cause instinctive defensive actions (Lambooij, IJsselsteijn, & Heynderickx, 2007) and should therefore be taken into account as well.

[6] For example at designguidelines.withgoogle.com or xr.design

When designing for humans, some actions are harder to perform than others or hard to perform over time. Futuristic movies tend to show impressive looking interfaces for human-computer interactions that are often not feasible to perform continuously. Examples can be found in movies like Iron Man 2 (Favreau, 2010) or Minority Report (Spielberg, 2002) of which stills are shown in Figure 7 and Figure 8.

Figure 7: A still from the movie "Iron Man 2" (Favreau, 2010)

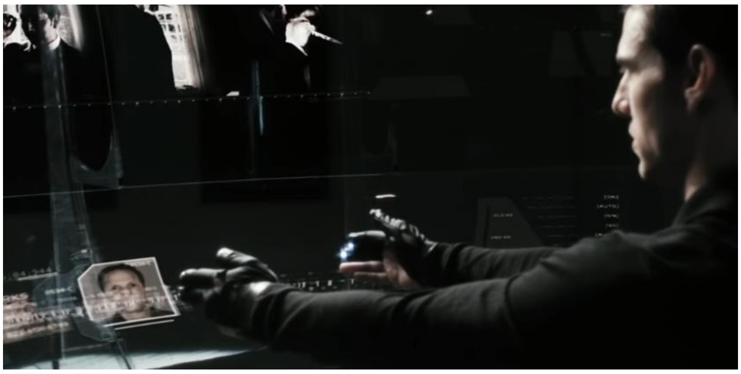


Figure 8: A still from the movie "Minority Report" (Spielberg, 2002)

Though it can sometimes be hard to create properly usable applications, it is generally not a good idea to make interfaces that require shoulder-height interactions for prolonged periods of time. The intuitiveness of an application is different depending on the user and his previous experience. A general rule is to test interactions for usability by actual people.

When designing immersive virtual environments, it is crucial to retain a steady framerate as the user can otherwise feel nauseous (as mentioned above). It is therefore important to optimize the application performance-wise which means to not add more environmental details than necessary and not show all objects in the highest fidelity when appearing at a distance from the user's viewpoint.

Since most of these considerations are application-specific, a later paragraph will discuss how these were implemented in the research environment. The next paragraph uses these considerations and strategies from the previous chapter to set-up system requirements for the research environment.

3.2 System Requirements

Chapter 2.3 describes several strategies for overcoming problems that can be expected when performing SCIC. This section attempts to shape these into requirements for the research environment. Together with the considerations from previous paragraph, the requirements form the basis on which the research environment is built.

One of the strategies states that the research environment involves two collaborators. The collaborators should be able to adapt to the environment and have some leeway in how they want to execute their task. These adaptations can be performed, for example, by means of verbal communication.

The collaborators can usually be considered highly trained with each other and for their task. But to make the experiment more feasible, only a short amount of training is possible. Their task should thus not be too difficult as to require more training than possible, but also not too easy as this could cause the users to become distracted.

The task should look as much as possible like a real-world interreality collaboration task. In a real-world scenario, collaborators are likely to have different roles because this situation benefits the most from interreality collaboration. Having different perspectives of an environment (or experiencing it by means of different realities) can provide unique benefits. For example, these different perspectives could be merged to quickly generate a complex situation awareness. Collaborators in the research environment should therefore each have a task that suits their role in a way that the collaboration leverages asymmetry.

One of the two users of the research environment experiences the virtual environment using a Virtual Reality HMD. This person is referred to as P_{VR}. The person not immersed in the virtual environment is referred to as P_{map}.

The short amount of training possible and the feasibility of the experiment also set a limit on the complexity of the system itself. This means that the system should not be too complex, and participants must be able to quickly learn how it works and what the controls are.

If communication processes are required that are hard to do by verbal communication, the system should provide this functionality and support the users. It should also help teams maintain awareness of the situation, task, and team. How this is done exactly depends on the scenario that the users will be playing. The next paragraph describes the scenario that users of the research environment will find themselves in.

3.3 The Embassy Scenario

On April 30th, 1980, six armed men stormed the Iranian embassy in South Kensington, London. The men were members of a group fighting for Arab national sovereignty in the south of Iran. They took 26 hostages, including staff, visitors, and a guarding police officer and demanded the release of prisoners in Khuzestan and a safe escape out of the country for themselves. The government responded by informing the gunmen that they would not provide a way out of the country, which started a siege. Five hostages were released over the next few days, but the gunmen became so frustrated with the slowness with which their demands were met that they killed one of the hostages and threw his body out of the embassy. The government responded by ordering a special forces regiment of the British Army, the Special Air Service (SAS), to enter the building and rescue the remaining hostages. During Operation Nimrod, as the raid would be called, the SAS killed five of the six hostage-takers and rescued all but one of the hostages. The one captured hostage-taker spent 27 years in prison and the SAS received a big increase in status, new applicants and demand for their skillset.

The Iranian Embassy Siege was real and would later inspire several films and video games. The events during the siege also inspired me in this project as I was looking for a story for the custom research environment. The story helped me create an imaginary scenario that I first used to develop the research environment, and which would later help immerse users in the environment.

Even though I later adapted the scenario to fit my specific needs, there were several reasons for choosing this specific scenario as inspiration. First, it is complex enough that actively working together to solve it is necessary but would still not make it too easy for the users to take their time (this is preferable because complex situations could increase the difficulty in maintaining awareness of situation, task, and team, as strategized in Section 2.3). The complexity also makes it plausible for the people involved to assume different roles in the process which is necessary to leverage asymmetry (also mentioned in Section 2.3). Lastly, this scenario would fit well within other projects at TNO that focus on the future of naval warfare (e.g. by using drones to inspect areas of interest) and novel ways for team collaboration.

3.4 The Virtual Environment

The custom research environment was designed by first setting up design considerations and discussing a scenario around which the environment will revolve. The next step was to build the virtual environment in such a way that it tests the hypotheses from Section 1.3 using the strategies formed in Section 2.3, the design considerations from Section 3.1, the system requirements from Section 3.2, while incorporating the scenario from Section 3.3.

The full research environment consists of a virtual environment, a physical experiment set-up (discussed in a later chapter), several tools that are used to collaborate between the virtual environment and the real environment, and a scenario that users of the research environment play. Two persons will be collaborating of which one experiences presence mostly in the virtual environment and one mostly in the real environment. This paragraph discusses the virtual environment and is thus mainly focused on the experience of one person, which we will refer to as 'the user'. I will chronologically go over the steps I took in building the virtual environment. More details and tips on specific problems and solutions can be found in Appendix 1.

I started off by creating a simple terrain in Unity with a ship on a river and two pieces of land, one for the 'blue team' and on for the 'red team'. The blue team refers to the people that the user works with, the red team to the people that are targeted as 'the enemy'.

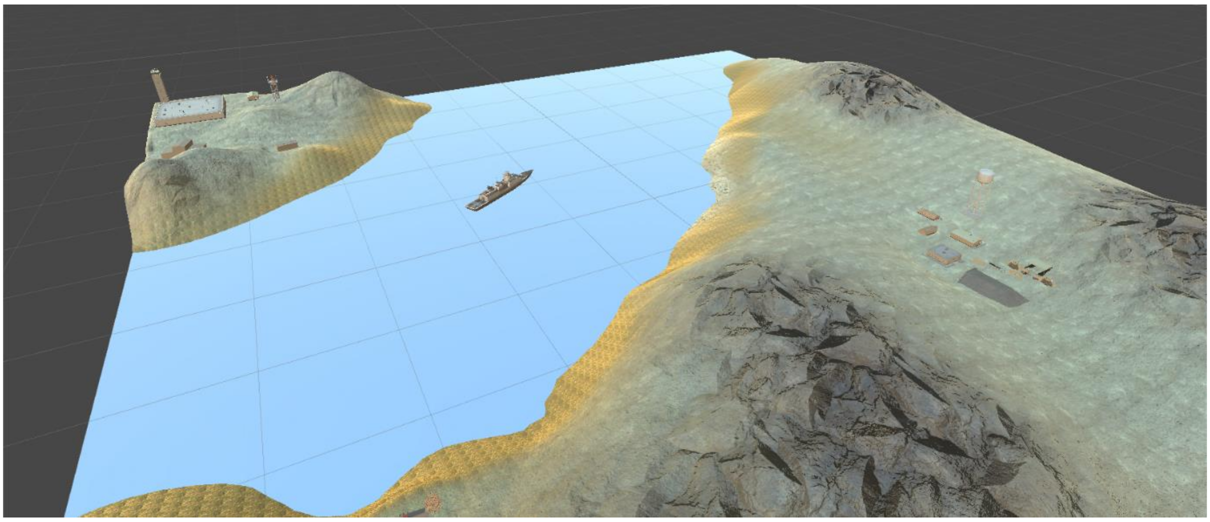


Figure 9: A simple terrain

The blue team land base turned out to not be necessary because the base of the blue team would be the ship itself, a ‘sea base’. This part of the map was removed, and the water was given a custom shader.

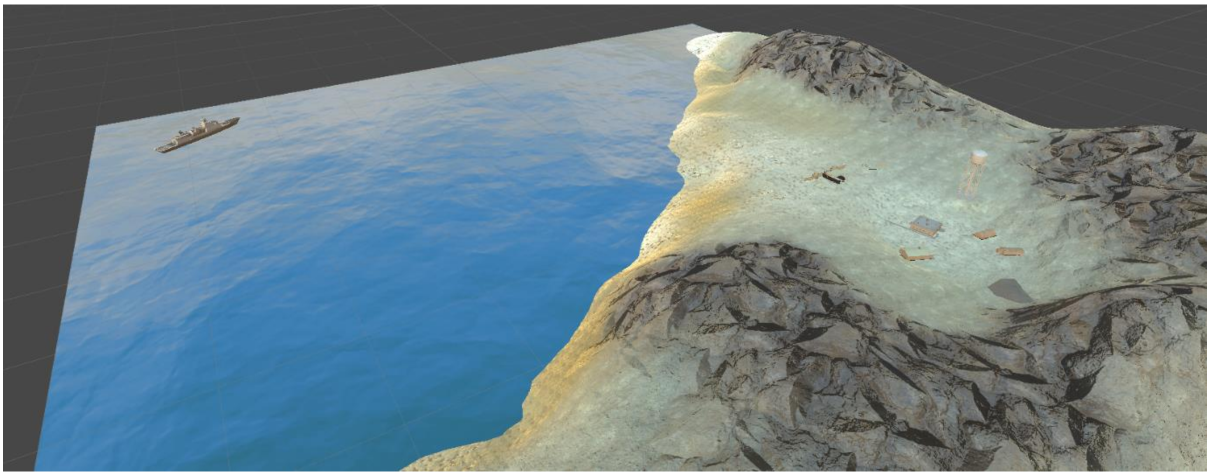


Figure 10: Blue base removed and custom shaded water

Several drones were added, including a script that can track the drones both in first-person using a VR headset and in third-person using a monitor. In-game you can also see the newly added sky.

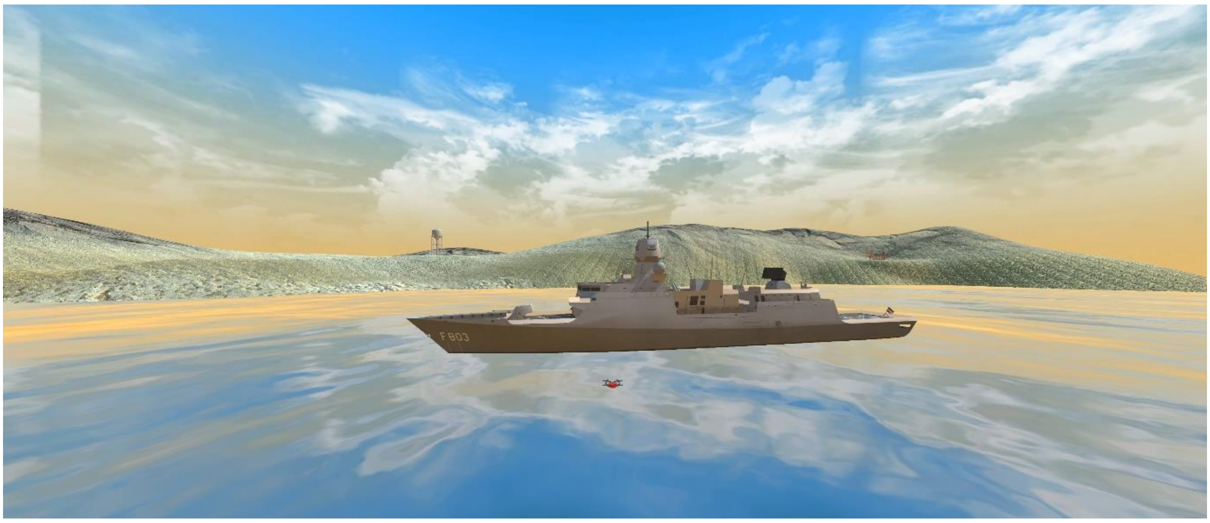


Figure 11: Drones were added and a custom sky was applied

At this moment the drones fly from the ship to the red ‘base’ and survey it by following several waypoints. P_{VR} can select any of the four drones by using the keyboard and can look around freely using the HMD.

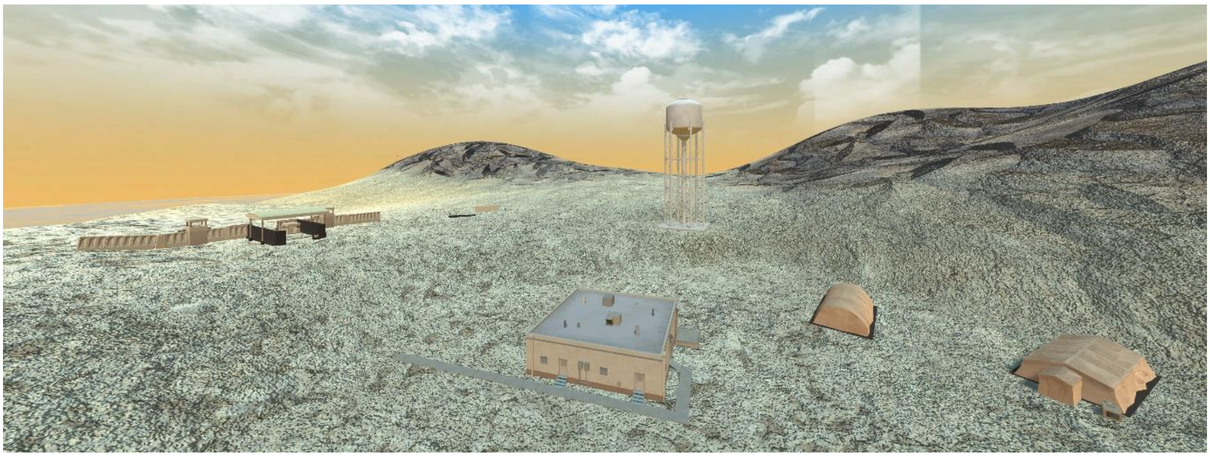


Figure 12: The 'red base' in an early form

A second display was added that shows a live top-down map of the area on a secondary monitor using an orthographic camera. This is shown to P_{map}. Drone icons and an arrow showing the virtual position and viewing direction P_{VR} were added. I later redesigned the drone icons to be sharper and show the current direction.

Figure 11: A live top-down map of the area for P_{map} (left) and the first-person perspective of P_{VR} (right)

At this point, performance started to become an issue. The buildings used until this point would always render at maximum quality and were therefore not really optimized. As discussed in Chapter 3.1, this needed to change. I removed the mountains as they did not improve the scenario enough to justify the decrease in performance and increase in render time.

The buildings were replaced by models that use the Level of Detail (LOD) technique which reduces the number of triangles that are rendered as the distance from the camera increases. This means that in practice, hardware load was reduced and rendering performance was increased. I reshaped the terrain to fit a small city on it and added a river with a bridge for aesthetics.

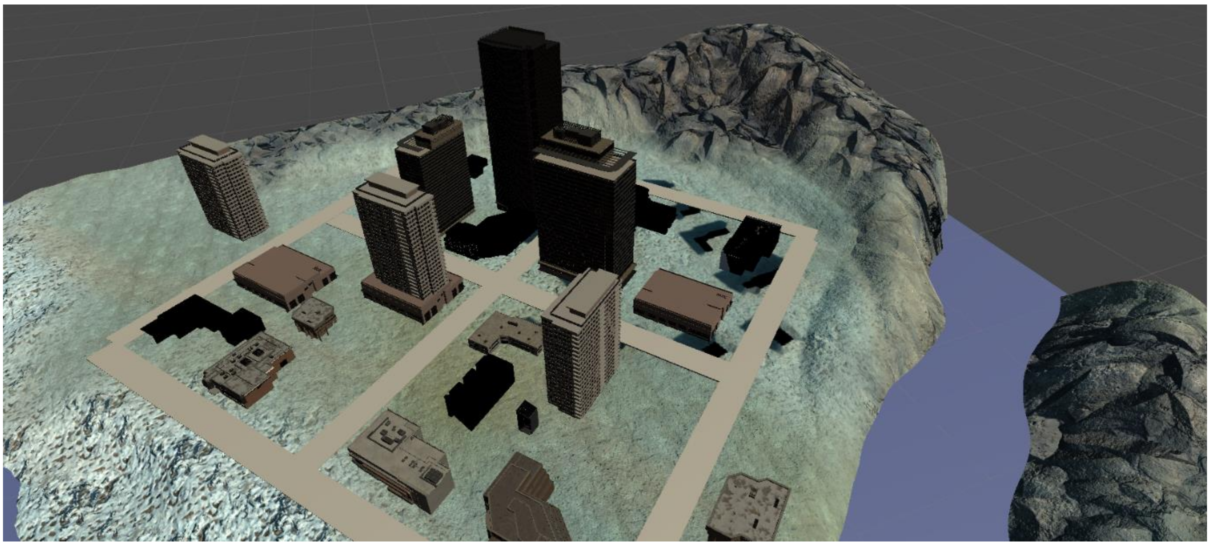


Figure 14: The city before performance optimizations

The optimizations caused the environment to render properly when compiled into a build but did not do much for performance while editing. I switched to a much more powerful desktop computer and tweaked several performance settings. I further shaped the terrain, added a road network around the city, a foundation below it and some crosshairs to aid the user with aiming.

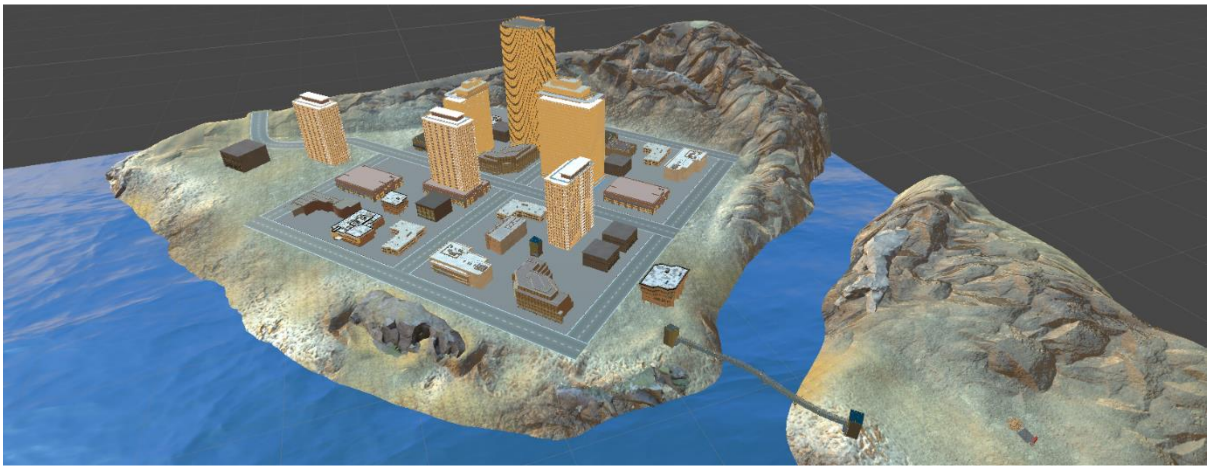


Figure 13: The city after performance optimizations and other improvements

I added functionality that lets the user switch drones by using the HMD's controllers instead of keyboard buttons. I also added red models as 'targets' that the user is supposed to find across the map.

When testing this functionality on other people (as is done for every function, see also Section 3.1), the drones flying around to a random waypoint turned out to be confusing. I did not want to hand over the controls of the drones to the user as this would add another layer of difficulty and make experiment rounds less consistent. I changed the drones' flying pattern (see Figure 15) to start near each other on the ship and fly in formation to the most important building in the city, *the embassy* (step 1). Once the drones arrived, they would spread out (step 2) and circle around the building (step 3).

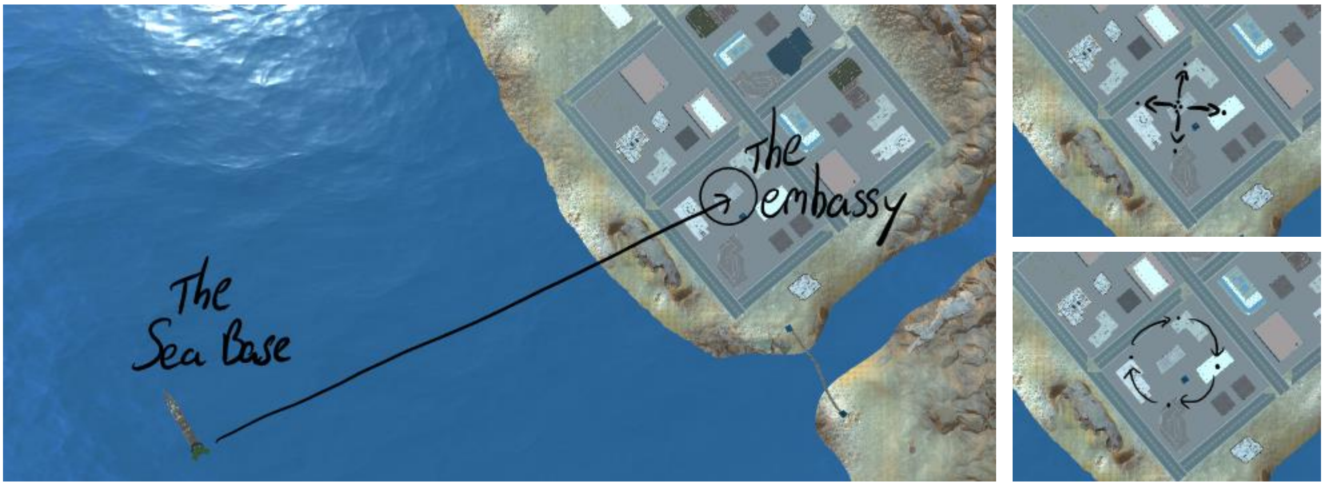


Figure 15: Flight pattern of the drones: Step 1 (left), Step 2 (top right), and Step 3 (bottom right)

To keep the user from becoming disoriënted or even sick, I did not take the rotation of the drone into account when calculating the viewing direction. This made sure that when a user is looking north and switches to a drone that is rotated towards another direction, the user would still look north. The drones also move with a speed that can change instantly as acceleration in VR could cause simulation sickness (see Section 3.1).

I added a second map which can be used for training purposes to get users familiar with the VE at the start of the experiment.

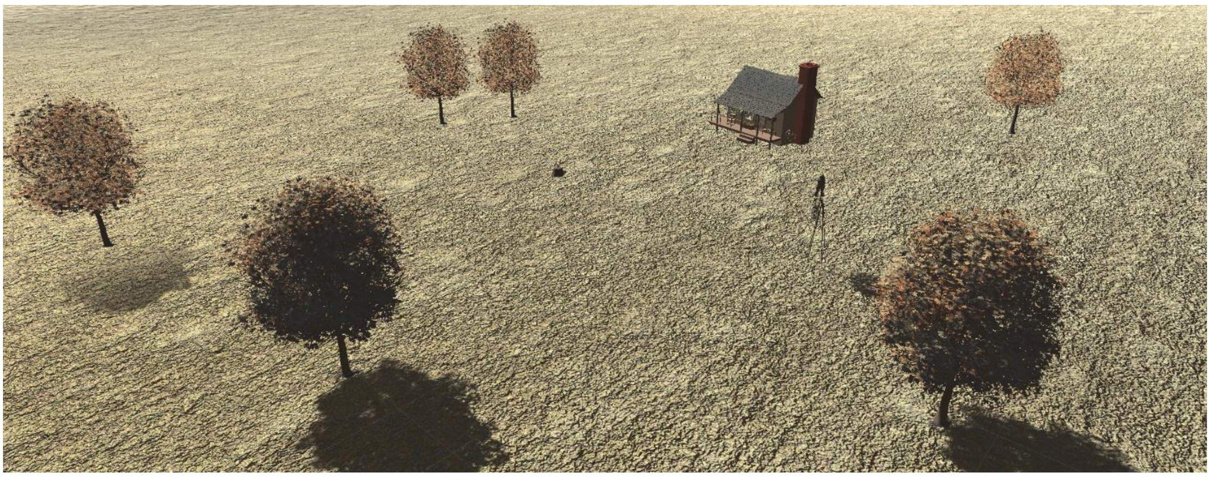
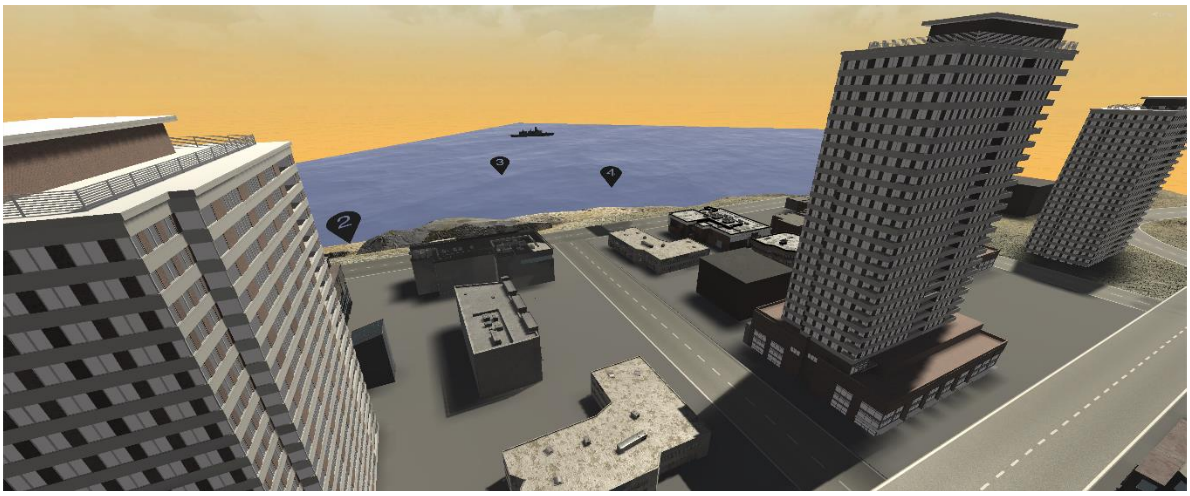


Figure 16: Secondary map used for training users

Finally, I designed several icons for each of the drones both for the (2D) map display and for the HMD. I then wrote a script that keeps each icon above the correct drone (showing its number) while keeping the HMD icons pointing towards the user, even when he is switching between drones. I rewrote the input system to abstract away the specific device that is used which causes the system to work with most HMDs and controllers. This is also due to one of the considerations from Section 3.1 (the system should not stop working after a software update). Other performance adaptations, as well as an overview of how all custom scripts work together can be found in Appendix 1.



3.5 The Interreality Support System

In Section 3.2, I defined several functions that the system should provide such as a high-fidelity communication method, and awareness of the situation, task, and team. To help the two users of the system collaborate, I have built these functions into the virtual environment as a set of tools which I call the Interreality Support System (ISS). As you can imagine, building the ISS is no easy task. This paragraph discusses how the tools were built and how they work in supporting interreality collaboration.

Location Sharing

When people cannot see each other while collaborating, something as intuitive as pointing to an object or map is suddenly not as effective anymore. In the current research environment, it is very important for the users to share locational information. I therefore built a tool that shares locational information between the real world and the virtual world. The person with the HMD (referred to as P_{VR}) can use one of the HMD's controllers to share the location he or she is currently looking at with the non-HMD player (who is looking at the map and is referred to as P_{map}). P_{VR} will then see this location as indicated by a green 'flagpole' (see Figure 17).

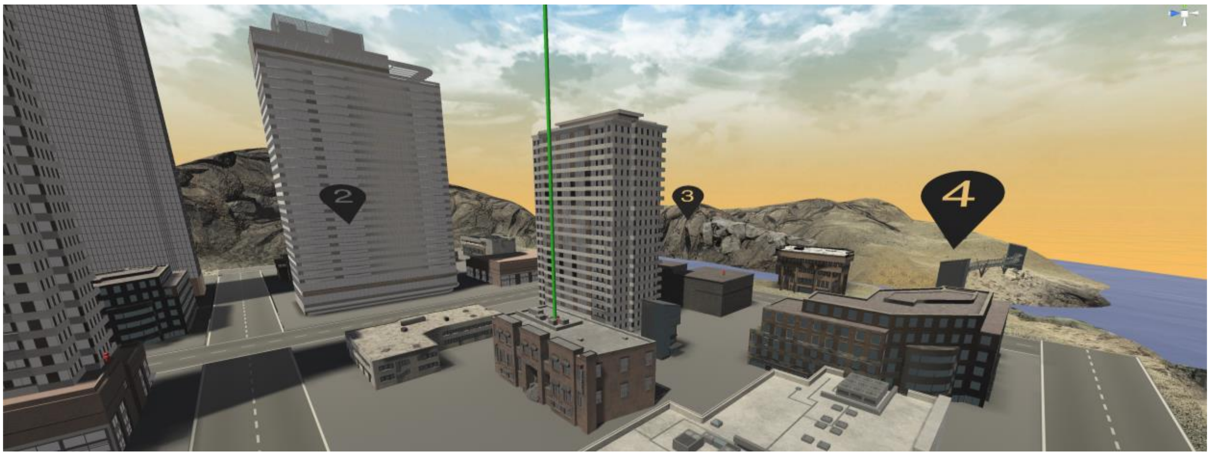


Figure 17: P_{VR} sees the last shared location as indicated by a flagpole

P_{map} can also see this location on the (2D) map display as indicated by a green arrow (see Figure 18).

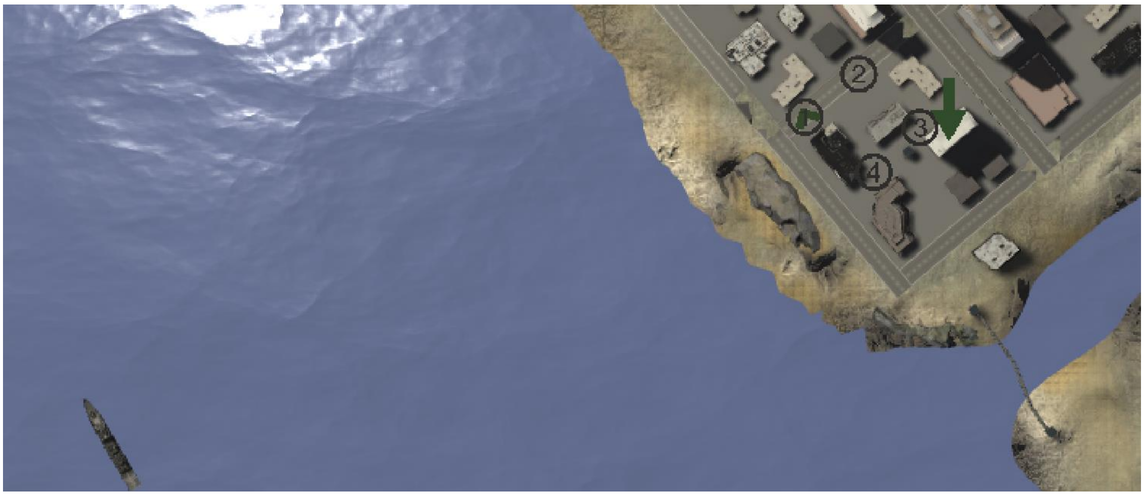


Figure 18: P_{map} sees the last shared location as indicated by an arrow

P_{map} also has the ability to share a location by clicking on the map with his mouse. This then activates the same flagpole/arrow combination at the location where the user clicked on the map. The flagpole and arrow will now be marked blue to indicate that this location was shared by P_{map} instead of P_{VR}. To avoid confusion, when a new location is shared, the previous one is overwritten so a maximum of one flagpole/arrow combination is shown at the same time.

In a small user test, people liked referring to wind directions, so I also included a simple stationary compass on the top right of the map screen.

Teammate Awareness

Besides the ability of conveniently sharing locational information, providing users with awareness of the situation, task, and team is also an important property of the system (cf. Chapter 3.2 and Ashdown & Cummings (2007)).

A goal of the research environment is to create a shared understanding of the situation, i.e. a shared form of s*ituational awareness*, in which P_{VR} has in-depth knowledge of the virtual environment and P_{map} possesses more broadly oriented knowledge. Some situational information is already shared between the users, such as the location of the drones and the virtual location and orientation of P_{VR} which shows up on the map and can be seen by P_{map}. Other situational information must be obtained by communicating with the other person.

The task that the users must execute is locating and marking enemy '*targets*' and does not change during the experiment. Because the task itself is fixed, because users can freely discuss progress, and because of time restrictions, I did not implement a tool for keeping track of task progress.

At this state of the research environment, users still cannot see each other while collaborating. In Section 2.3, we saw that this could result in difficulty in determining the other's mental and physical availability, attention, urgency, and whether you are being understood. I therefore considered it important to create a method of gaining insight as to what your teammate is doing. This has been implemented by projecting the front view of what P_{VR} is seeing on another regular (2D) monitor, separate from the map display (which is common in similar set-ups). P_{map} can thus look at this monitor whenever he wants to observe what P_{VR} is doing and therefore estimate his status and workload.

Similarly, it could be helpful for P_{VR} to observe what P_{map} is doing, though this process is not as straightforward as the other way around. For example, because P_{VR} benefits from looking around in 360 degrees, where do you position the video stream without blocking potentially important parts of the virtual environment? How do you ensure P_{VR} always knows where to look for this video stream? And how can you make sure that P_{VR} is not continuously distracted by the video stream?

The positioning problem is discussed in an article by Stoev and Schmalstieg (2002) in which they show three possible options for a window into a secondary world to be shown in a primary world (see Figure 19). (a) shows the secondary world to be fixed in a location in the primary world, (b) shows the secondary world to be fixed to the user's image plane, and (c) shows the secondary world as held by the user in the primary world.

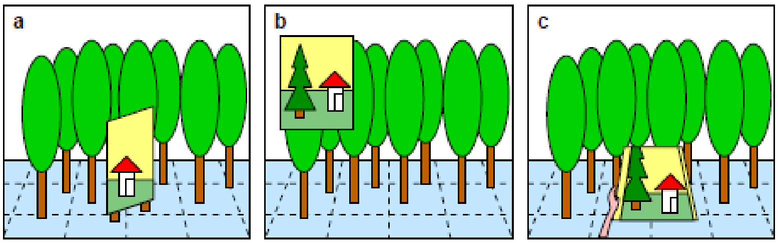


Figure 19: Different ways to show a secondary world in a primary world. From Stoev & Schmalstieg (2002, p. 59)

For our purpose, we should refrain from option b as images fixed to the user's plane tend to cause discomfort in virtual reality. Option a could work, but because P_{VR} moves all the time in the virtual world, it would need to be situated in a position that does not infringe P_{VR}'s visual field. Option c could work as well but could also (perhaps unintentionally) block an important part of P_{VR}'s visual field.

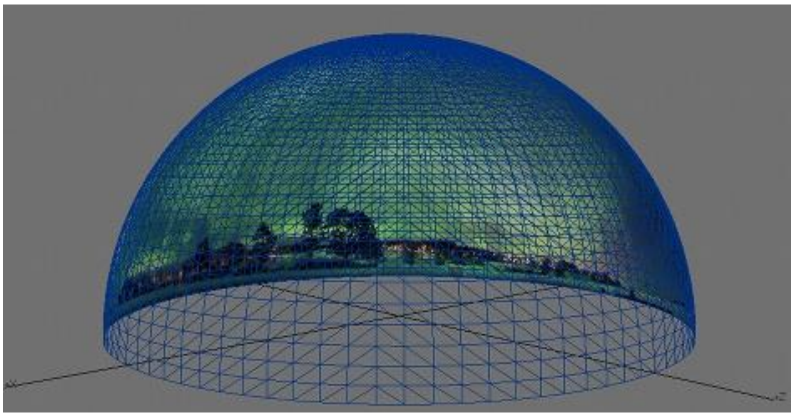


Figure 20: A skydome showing the Aurora Borealis. Source: http://www.garagegames.com/community/blogs/view/22255

I ended up by projecting a live video feed to the skydome of the virtual environment. A skydome is a sphere or hemisphere that is rendered in the sky of the virtual environment to make the environment look bigger than it really is (see Figure 20). P_{VR} will thus be able to see the video feed from the camera projected in the sky of the virtual environment. Because this is projected behind the virtual environment geometry, it does not block important parts of the virtual environment and is also always in the same location. One issue was that the skydome requires a 360° feed, so I used a 360° camera positioned near P_{map} to project a live video feed. To make sure that P_{VR} is not continuously distracted by this feed, I configured a controller button to enable or disable the feed. When the feed is turned off, the skydome shows a stationary sky with clouds.

By projecting live video of P_{map} in the virtual world, P_{VR} can now also obtain information on the current task, status and workload of P_{map}. I believe this mutual information sharing and observing increases knowledge about a teammate's current task, status and workload, i.e. teammate awareness.

Now that the custom research environment is built, it was time to see if the ISS can indeed lead to more effective and more efficient synchronized interreality collaboration. The next chapter describes an experiment that was used to, among other things, test this hypothesis.

4 Experiment

Previous chapters describe what I expect to happen when co-located persons collaborate synchronously between reality and virtual reality. This chapter puts these expectations to the test. Using the scenario, virtual environment, and interreality support system from Chapter 3, an experiment was set-up. In this chapter I will explain the goals, expectations, method, set-up, procedure, and results of that experiment and give my interpretation of the results.

Although the research environment and user information both use English as the main language, the rest of the experiment was done in Dutch as this was the primary language for all participants and, I assumed, the language they were most comfortable in.

4.1 Goals and Expectations

The primary goal of the experiment was to find out if the ISS can indeed lead to more effective and efficient SCIC. I use the word 'can' here, as the experiment is not meant to determine whether the ISS consistently improves SCIC. Rather, it explores how users respond to the toolset, whether it is *likely* that the toolset supports SCIC, and why this is the case.

I expected the ISS to be used often throughout the experiment and the tools to be considered as an important addition. My hypothesis is that while users find the 'skydome camera projection' uncanny (partially because the small but noticeable delay and partially due to seeing the real world from a different perspective than usual), they would find it useful in increasing teammate awareness. Furthermore, I expected that the ISS would help users in sharing locational information and that it increases teammate awareness, which together indeed seems likely to lead to more efficient and effective collaboration.

By observing participants and discussing their actions, we can additionally find evidence that supports or opposes the problems, strategies, and system characteristics from earlier chapters. I expected that despite the ISS, users would still (1) find it problematic not being able to see each other (due to the head-mounted display), preventing social cues and hindering collaboration, (2) have difficulties understanding some information that is shared between users due to a difference in perspective, and (3) experience hiccups when incorrectly assuming that their teammate is conversationally available.

The ISS includes a few tools that I suspect to be important in improving SCIC. But there are most likely more methods of improving SCIC. During the experiment I interviewed users about their experience, asking them about experienced difficulties and discussing other potential solutions.

Combined with the analyzed literature and related work, the experiment was conducted to generate interesting insights on what problems arise when performing SCIC, how these problems can be overcome, and whether the ISS contributes to mitigating or eliminating these problems.

4.2 Method

The experiment involved the interaction between people and between people and technology. These interactions can quickly become complex, so I considered it more practical to investigate only two participants at a time. A total of eight persons, working at TNO (some as an intern), participated in the experiment, divided into four groups of two persons.

The experiment consisted of a questionnaire on participant information and past experiences, a short training session of the system, two or three runs of the task with a structured interview after each run, and another structured interview at the end of the experiment.

The questionnaire provides the possibility to link results or patterns to user characteristics. For example, it could be that participants that know each other show more effective collaboration. The training session makes the participants familiar with the experiment set-up and virtual environment and lets them practice with the controls and ISS. Participants were trained in both roles.

Having a training session before the experiment rounds caused all participants to share a similar base level, independent of experience with similar hardware or software. It also allowed participants to better understand the perspective of the other person, which more accurately depicts a real-life scenario in which users of such a system are often well trained with each other and the system.

As the scope of this project is synchronized and co-located interreality collaboration, the participants were located near each other but experienced most presence in different realities. This was done by having one participant (P_{VR}) wear a virtual reality headset through which (s)he can see the virtual environment in 360 degrees. The other participant (P_{map}) did not wear such a headset but is viewing a live map that shows the top-down perspective of the virtual environment on a two-dimensional screen (i.e. experiences most presence in the real world).

The participants were asked to perform a task in which each had to take advantage of their own perspective on the virtual environment and combine their knowledge. The latter could be done by talking freely (see Section 3.2 for an explanation on why this was allowed) and by using the ISS (e.g., the location sharing feature). This generates a shared understanding of the situation, i.e. a shared situational awareness, in which P_{VR} is likely to have more in-depth knowledge of the virtual environment and P_{map} is more likely to possess more broadly oriented knowledge.

The task the participants performed was to find and write down the locations of multiple *targets*. Targets are red human-sized models located in the virtual environment (see Figure 21 for an example). P_{VR} is therefore the only participant that can directly see the targets (P_{map} can still look at the secondary monitor where P_{VR}'s visual field is projected to see the targets as well). His job is thus to find the targets and provide P_{map} with their locations.

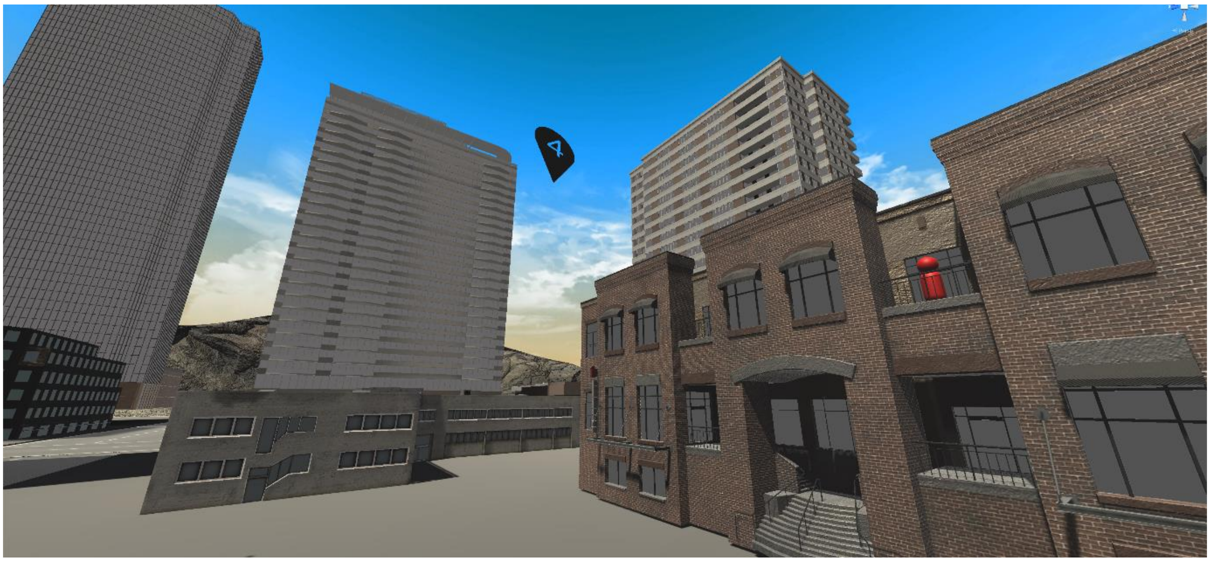


Figure 21: A target located on the embassy balcony in the virtual environment

There are three different target set-ups available for the virtual environment, each containing 10 targets in different locations. They are located such that 4 were easy to find, 3 had a medium difficulty, and 3 a hard difficulty. The difficulty was determined subjectively based on distance from the embassy and visibility. By using a keyboard shortcut, a set-up could be chosen by the experimenter at the start of each round. The order of which set-up was used for each round was the same for all participants.

Each round took as long as participants needed to find all targets, or until five minutes had passed, whichever came first. After each passing minute except for Minute 5, a hint was given to P_{map} in the form of a short message on a post-it note. The hints were meant to provide a secondary task to P_{map} to prevent him or her from always looking at the secondary monitor and to stimulate P_{map} to look at the map for information. Hints included information on the total number of targets for that round (subjects did not know beforehand that each round contained exactly 10 targets) or on how many targets were located in a specific area (such as in which city quadrant, near the embassy, in the shadow, or at an unusual height).

After each round of the experiment, I asked the participants multiple questions in the form of a structured interview. This form enables comparison of specific subjects between participants but still allows additional information to be provided and specifics to be discussed. The questions concerned how the collaboration went, the problems that the participants faced, any strategies that were used to complete the task, whether strategies changed during the rounds, how the exchange of information went, if they sufficiently knew what their teammate was doing, and their opinions on- and usage of the ISS. Some of the questions were split up in the communication direct of P_{map} to P_{VR} or the other way around. The exact questions can be found in Appendix 3.

After all rounds were finished (two or three depending on the amount of time participants were available), a final structured interview took place. Here, participants were asked how they would diminish or eliminate the problems that they faced during the rounds and if they had any final remarks. This interview could surface other problems that went unnoticed by me and provided a place for participants to think about how they would go about solving the problems they encountered.

4.3 Set-up

The experiment took place at TNO, location Soesterberg. The department of TNO at which I am executing this research is called Human Behaviour and Organisational Innovation (HOI). HOI develops and applies knowledge in the field of social innovation and one of their facilities is the Control Organisation Research Environment (CORE; see Figure 22). The CORE functions as an inspirational tool for research on collaboration in control rooms. Control rooms are spaces in which large, dispersed or otherwise complex facilities can be monitored and controlled. The CORE seemed like an ideal space to simulate a complex environment in which SCIC could take place.

Figure 22: The Control Organisation Research Environment (CORE). Source: TNO

The set-up used in the experiment can be seen in Figure 23. P_{map} is seated in the chair in the middle of the picture while P_{VR} is seated behind him/her, in the chair near the VR headset and controller. As the experiment leader, I was seated in the chair to the far right. The 360° camera can be seen on the table in the bottom of the picture. This location causes P_{VR} to have the ability to virtually sit at the table as well by projecting the surroundings for this position to the background of the virtual environment.

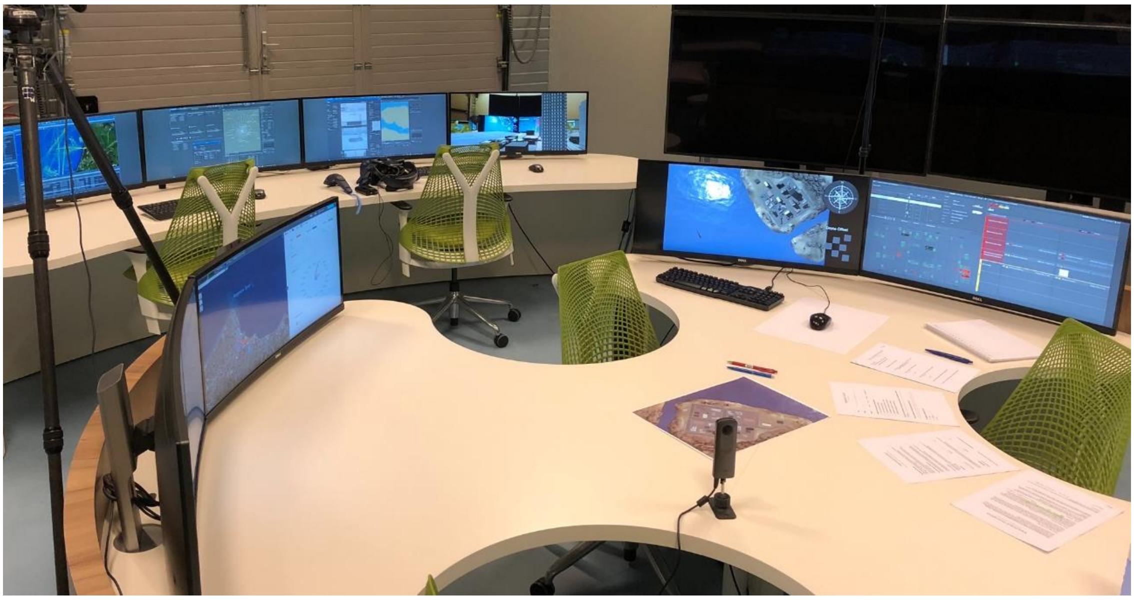


Figure 23: The experiment set-up. P_{map} is seated in the chair in the middle of the picture while P_{VR} is seated behind him/her, in the chair near the VR headset. The experiment leader is seated in the chair to the far right.

4.4 Procedure

This section shows all steps that were taken at the start of the experiment, during and between the experiment rounds, and at the end of the experiment. They are shown in bullet point format and are in the exact order that I executed them.

At the start of the experiment

1. Welcome participants and note the current time.
2. Let them read the experiment information document (see Appendix 2). Ask if they have any questions and answer them.
3. Mention that we're going to do 2-3 rounds depending on the time that they have available and that several questions will be asked between rounds and at the end of the experiment.
4. Let them read and sign an informed consent document. I sign the document as well.
5. Ask participants to fill in a questionnaire with their name, age, and sex.
6. Ask them to fill in another questionnaire with the amount of experience they have with VR techniques, how quickly they experience motion sickness (from VR but also from cars), how much experience they have in the safety domain or with defence, and how well they know the other participant.
7. Turn on the 360° camera, start the training scenario, and let the users experience both roles while explaining the controls.
8. Have the participants select a role (that will stay the same throughout the entire experiment) and ask if they are ready to start the first experiment round.

During and after each experiment round (repeat 2-3 times depending on the available time)

9. Start the main scenario and the timer. Select the correct target set-up.
10. Write down the time at which each target is found.
11. Write down any peculiarities or other remarks.
12. Give P_{map} a hint (on a post-it note) after every minute except for the last.
13. After all targets are found or after five minutes (whichever comes first): tell the participants to stop and for P_{VR} to take his/her VR device off.
14. Ask questions from the structured interview and discuss any peculiar answers. Write down these answers in an Excel sheet.
15. Ask if the participants are ready to start the next experiment round.
16. Write down the current time.

At the end of the experiment

17. Ask the questions from the second structured interview and discuss any peculiar answers. Write down these answers in an Excel sheet.
18. Thank the participants for their participation.
19. Note down the current time.

4.5 Results and Interpretation

Four teams of two participants played through three rounds of the scenario (except for one team that played through two rounds) and were asked questions at the start of the experiment, after each round, and at the end of the experiment. This section will show experiment results and observations and discuss my interpretation of them. The full list of questions and answers per team can be found in Appendix 3, the experiment notes and issues that occurred during the experiment in Appendix 4, and the times at which each of the sequential targets were found in Appendix 5.

In Chapter 5 (Discussion) results of this experiment are combined with knowledge from literature and related work to form more generalized SCIC recommendations.

Problems

Although all participants were able to collaborate during the experiment, several problems arose that seemed to impact collaboration efficiency. For example, on several occasions P_{VR} shared a piece of information but did not notice that P_{map} was still working on the previous piece of information. P_{map} then had to slow down P_{VR} or ask him/her to repeat the new information while writing down the current piece of information. This seems like a problem with teammate awareness that I originally tried to tackle using the teammate awareness tool that will be discussed later in this section.

Another problem that showed up was that on some occasions, P_{VR} pointed to a target that he/she had already communicated. P_{map} then had to compare this location to the physical map and concluded that this target had already been spotted. P_{map} then had to communicate this information back to P_{VR} for the team to continue. This looks like a problem with situational awareness.

Efficiency and Effectiveness over Time

Participants improved efficiency as the rounds progressed. From Round 1 to Round 2, the average time between targets found was reduced from 24.75 seconds to 20.25 seconds. From Round 2 to Round 3, this slightly increased again from 20.67 seconds to 21 seconds (I did not count the group here that did not execute Round 3). The average time between targets found between the start and the end of the experiment thus decreased overall, supporting an improved efficiency.

Evidence also supports improved effectiveness. Participants consistently increased the number of targets that were found (until the maximum number of targets was reached) over the rounds. One team even knew which sides of which buildings were going to be visible later on and adapted their strategy accordingly by marking these locations to come back to later.

Over the course of several rounds, participants started to understand the other person’s perspective better, learning the advantages and limitations the other perspective could offer and the communication and collaboration strategies that helped them in the task at hand.

The Interreality Support System

There were several tools available to the participants, such as the location sharing tool (the mutual ability to share a specific location by placing a marker) and the teammate awareness tool (P_{map} being able to see the perspective of P_{VR} and P_{VR} being able to see the space in which P_{map} worked).

Participants mentioned that they enjoyed using the location sharing tool. It was indeed used a lot, though mostly from P_{VR} to P_{map}. Some P_{map} participants used it to communicate which direction was north. One P_{map} participant forgot it existed in the first round and hardly used it in the second round. Participants found this tool useful and mentioned that P_{VR} would be more dependent on P_{map} if this tool was not available. One P_{VR} found it hard to share a location and did not know what a crosshair was at first. He/she thought the movement of the controller determined the arrow direction.

Most participants wanted P_{VR} to also have a map like P_{map}. Most participants who mentioned this also said that they would like P_{map} to be able to directly mark targets on the live map. Even though this would help solve the aforementioned problem of P_{VR} not remembering which targets were already shared, in this experiment it was done deliberately in order to give P_{map} more to do so that he/she would not look at the secondary monitor the entire time.

Even though P_{VR} was sometimes too little aware of P_{map} (as indicated by problems mentioned above), the 360° camera view was almost never used. Most participants forgot about it during the rounds or did not directly see the need to use it. Some found the view too distracting and one participant mentioned that P_{VR} could indeed see the room that P_{map} was in but that he/she would much rather see P_{map}'s screen.

Participants mentioned that they enjoyed the secondary monitor part of the teammate awareness tool. Sometimes P_{VR} could see something in his/her peripherals which P_{map} could not see on the secondary screen. The horizontal part of this could be solved by showing the outer lines of sight on the live map. One participant suggested showing P_{VR}'s perspective in a corner of the map screen, so everything is closer together and easier to find.

Other comments by participants are briefly mentioned below:

- Participants did not like that the drones stayed in one area, mentioning that they would prefer having it fly all over the city or having manual control over it.
- Some participants did not expect the drones to stay in one location but to go all over town.
- Some participants did not get that the drones flew in a circle, which is why (according to them) they did not switch drones often. Because as they found out the drones circled around, this was solved.
- Some participants mentioned that they at first did not understand the size of the search area.
- One participant found the biggest problem writing the targets down on paper after seeing them on the screen.
- Some participants wanted a zoom function for the map
- Some participants wanted a compass for P_{VR}

Learning and Experience

Several problems that showed up at the start of the experiment were later consciously or unconsciously solved by participants. For example, at the start of the experiment, participants did not have a clear role distinction or task strategy. Some participants mentioned that they did not yet know who was leading and who was following which could impact collaboration effectiveness. In later rounds, all participants tended towards having P_{VR} focus solely on the task of finding targets, while P_{map} switched between writing down targets on the physical map, communicating intelligence and looking at the secondary monitor to guide P_{VR} in where he/she could look next.

Some P_{map} participants were looking less at the secondary monitor as the experiment progressed. Participants said that this was because they did not feel the need to as they understood better what P_{VR} meant, but also because P_{VR} described more about the environment. Indeed, all participants started the experiment being relatively quiet compared to later in the experiment.

P_{map} participants improved in determining hint relevance and timing. At the start of the experiment, P_{map} usually communicated every hint to P_{VR} shortly after it was given to them while at the end, P_{map} first read the hint, interpreted it and determined its relevance before either sharing it with P_{VR} or not at all.

Participants also switched drones more often later in the experiment. This could be because they only understood the flying pattern and the usefulness of this function later on. Next to learning the flying pattern of the drones, participants talked about more probable locations for targets according to the approximate distance and spread of the targets that were already found. This helped them in better understanding the search area.

Experience with defense situations could also be beneficial to collaboration efficiency and effectiveness. In the experiment, participants with experience in defense situations performed better than those without. One such team started using a building-by-building-swipe technique to thoroughly search all buildings.

One thing that could help participants reach a higher level of collaboration efficiency is knowing the other person. One participant team stated that they liked that they knew each other so they better knew what the other person meant.

In the next chapter, results of this experiment are combined with knowledge from literature and related work to form more generalized SCIC recommendations.

5 Discussion

"People do not make accommodation for how different it really is when they and their colleagues no longer work face-to-face. Teams fail when they do not adjust to this new reality."

Lipnack and Stamps (1997, p. 7).

Chapter 1 introduced the phenomenon of interreality collaboration and reduced its scope to Synchronized Co-located Interreality Collaboration (SCIC). It also explained the goals of this research project. Chapter 2 discussed problems that can be expected when performing SCIC and proposed several strategies to overcome these problems. In Chapter 3 I showed the process of designing and building a custom research environment, which enabled the possibility of testing these strategies. An experiment was then set-up and executed, of which the process and results are described in Chapter 4. This generated interesting insights, but which are still bound to the specifics of that experiment.

In this section, I take a step back and incorporate all knowledge learned so far while providing an explanation for the results. This chapter will also illuminate some limitations that must be kept in mind while reading said explanations and results. At the end of the chapter I demonstrate what future research on interreality collaboration could entail and conclude the current work.

5.1 Interpretation

In Paragraph 1.3 I proposed four research questions that capture the goals of this research project. This paragraph attempts to answer these questions and will therefore be structured similarly.

Interreality Collaboration Problems

The goal of the first research question was to find problems that can be expected when performing SCIC. This was done by looking at previous work in interreality collaboration and supplementing work related to it. Problems from related work are filtered in their translatability to SCIC. The question was formulated as:

1. *What problems can be expected when two co-located persons synchronously collaborate between reality and virtual reality?*

When people collaborate between realities it is currently likely that anyone feeling presence in a virtual environment uses a Head-Mounted Display (HMD) to achieve this result. This causes the people collaborating between reality and virtual reality to not directly see each other, which in turn can cause some small collaboration errors, or hiccups, to occur.

For example, physically pointing to something does not imply that the other person sees this action. It can also be hard to estimate the other's mental and physical availability, which is useful in determining the correct timing when asking questions or sharing information. These hiccups could hinder collaboration.

Related work on virtual teams indicates problems with the lack of awareness of team members' endeavors (Thompson & Coovert, 2006) as well. Because, as in virtual teams, members of interreality teams lack the ability to see each other, problems could be transferable to interreality teams. Indeed, in the experiment executed during this research project, participants repeatedly shared information while their teammate was not ready. Most of the time, the problem occurred when the person immersed in the virtual environment (P_{VR}) initiated communication towards the person in the real world (P_{map}).

Evidence of participants having a dissimilar situational awareness surfaced as well. On several occasions, P_{VR} shared information that had already been shared before, after which P_{map} immediately corrected this error without looking at the map. Furthermore, during the experiment, P_{map} tended to take the lead and focus on the situation overview while P_{VR} played a more active, in-depth role. Of course, it is possible that these differences were simply caused by human memory limitations and coincidence, but the frequency with which it happened combined with its one-sidedness suggest the possibility of a link with interreality collaboration. And although I expected participants to have problems with understanding shared information due to a difference in presence, I now expect the difference in perspective to also play a role in this.

These problems, combined with P_{VR} forgetting about the camera function and with the general enthusiasm that P_{VR} showed during the experiment rounds, make it clear that P_{VR} was immersed in the virtual environment. This immersion probably helped in focusing on the task at hand (finding the targets) but also apparently decreased teammate awareness.

Strategies for Interreality Collaboration

The literature analysis and related work also allowed me to form strategies to overcome problems from the previous section. The strategies were then put to the test in an experimental set-up. These strategies are related to the second research question:

2. *What strategies can be applied to mitigate or eliminate these problems?*

In the experiment, participants quickly learned to work around certain problems. The problem of not knowing what your teammate is doing, for example, was first tackled by P_{map} regularly looking at the P_{VR}'s screen but later became less of a problem when participants communicated more and better understood the other's actions. Throughout the experiment rounds, participants also switched tactics to include a specific role distinction that worked better for them, P_{map} consistently became better in determining hint relevance, and participants even predicted where targets were likely to be.

This demonstrates that teams can adapt to environment constraints which corresponds with one of the strategies from virtual teams literature mentioning the importance of allowing teams to adapt to environmental opportunities and constraints (Van der Kleij, 2007, pp. 30-32).

During the experiment, participants were purposely permitted to communicate verbally, which when looking at the amount of communication regarding strategy, allowed participants to execute these adaptations swiftly.

Another strategy from virtual teams literature is to "*help teams to maintain awareness of the situation, task, and team during distributed meetings*" (Van der Kleij, 2007, pp. 32-35). Next to distributed meetings, this concept is also important in defense contexts. Ashdown and Cummings "*emphasize the importance of supporting awareness, both at the operational and the tactical level*" (Ashdown & Cummings, 2007, p. 5).

In the experiment, helping teams maintain situation, task, and team awareness was done by implementing several tools in the research environment. The next section discusses the characteristics of this research environment and how it can be used to test strategies for supporting SCIC.

An Interreality Research Environment

Because of the scarcity of available research environments and projects that could be used to experiment with the formed SCIC strategies, I have designed and built a prototype research environment. To build a research environment that allows testing these SCIC strategies, several characteristics must be integrated or purposely left out. For this purpose, the third research question was used:

3. *What are the characteristics of a research environment that can be used to test strategies for supporting Synchronized Co-located Interreality Collaboration?*

In order to determine which characteristics were important when building the research environment, the first step was to note the problems and sub-problems that occur when performing SCIC. These were categorized in two main problems: (1) the persons cannot see each other, and (2) the persons see different information.

Section 2.3 discusses the basis for these problems, as well as which strategies should be applied to solve them. These strategies are formulated in the form of two main system characteristics:

1. Provide a high-fidelity communication method that lets users adapt to environmental opportunities and constraints
2. Provide awareness of the situation, task, and team

Chapter 3 further describes the exact considerations, requirements, and design choices of this research environment, in which these characteristics have been implemented in the form of the Interreality Support System (ISS). The next paragraph elaborates on whether the ISS could actually lead to improved collaboration.

Improving Collaboration Using the ISS

The goal of the Interreality Support System (ISS) is supporting synchronized interreality collaboration. Whether the system is indeed able to lead to improved collaboration is discussed according to this final research question:

4. *Can the Interreality Support System lead to more effective and more efficient Synchronized Co-located Interreality Collaboration?*

The ISS is built out of two main parts: (1) a feature that supports the sharing of locations, and (2) a function that supports teammate awareness. How people used the system and what they thought of it was tested in an experiment in which participants located targets in a virtual world and marked them on a map in the real world. This required them to collaborate between realities.

Participants of the experiment liked and frequently used the **location-sharing feature**, though mostly from the person in the virtual environment (P_{VR}) to the person in the real world with the map (P_{map}). None of the participants discarded the feature and attempted to share a location by, for example, describing its surroundings. It is possible that the training session at the start of the experiment primed the participants to use the feature.

The **teammate-awareness feature** consists of two parts: (a) a normal computer monitor showing the perspective of P_{VR} to P_{map}, and (b) a 360° camera located near P_{map} that streams live video to the background of the virtual environment, which P_{VR} can see and turn on and off. At the start of the experiment, part a was used regularly by P_{map} to also see the target before marking its location. Later in the experiment, the usage of part a declined as P_{map} wrote down the location of targets more often solely based on the location marked by P_{VR} instead of checking to see it on the monitor. I suspect that P_{map} therefore learned to better trust the accuracy of the locations shared by P_{VR} as the experiment progressed. Participants nonetheless mentioned that they enjoyed the feature.

Part b was barely used and was even called distracting. Any collaboration hiccups, potentially caused by not being sufficiently aware of P_{map}, were quickly overcome by delaying the message or request for a few seconds. Checking to see if P_{map} was available was therefore likely not as important in this experiment. It could even cause P_{VR} to become less immersed in the virtual environment and therefore temporarily cause P_{VR} to lose task effectiveness.

Even though part b of the teammate-awareness feature was hardly used, part a and the location-sharing feature were used regularly. Combined with the improving results, it shows that there is evidence that the ISS is an important asset for the research environment and that it can indeed lead to more effective and more efficient Synchronized Co-located Interreality Collaboration.

5.2 Limitations

There is a scarcity in interreality collaboration literature, especially literature focusing on SCIC. The previous knowledge used in this research project is therefore not very developed and agreed upon.

One of the features built as part of the ISS was meant to increase teammate-awareness. The experiment was set-up to test this, but results were scarce as the tool was hardly used. This is likely because there was no need for it during the experiment.

During the experiment, the order of which target set-up was used each round was not randomized over participants. Therefore, although the targets were systematically placed, there could be differences in target-placement difficulty between rounds.

Participants of the experiment could also have been trained for longer. This could remove even more differences between participants and would better simulate a real-world scenario in which I consider most of such teams to be trained with the task and with each other.

There were eight participants in my experiment. Of course, having an increased number of participants is more likely to result in more accurate data and better recommendations.

5.3 Conclusion

Interreality collaboration occurs when collaborators experience most presence in different environments (which can be real, virtual, or somewhere in between). If these collaborators are also co-located and perform this collaboration at the same time, it is called Synchronized Co-located Interreality Collaboration (SCIC). SCIC can foster interesting challenges and opportunities for collaboration.

Related work and the experiment performed in this research project hint at several challenges that are likely to surface (such as communication mishaps and the lack of teammate awareness) but also demonstrate several strategies to help mitigate or prevent some of these challenges (such as using a suitable communication medium, allowing teams to adapt to opportunities and constraints, and helping teams maintain awareness).

These strategies were tested in a prototype research environment which includes features that support location-sharing and teammate-awareness. How people used the system and what they thought of it was tested in an experiment which showed that participants used the location-sharing feature often and the teammate-awareness feature less.

Participants were allowed to communicate verbally which provided some evidence hinting at a dissimilar situational awareness between participants which could be caused by a difference in perspective. The experiment indicates that SCIC could lead to more effective individual tasking and less effective teaming. It is therefore recommended to carefully balance task effectiveness with teaming intelligence when performing SCIC.

If done correctly, interreality collaboration can bring about a complex understanding of an environment that is hard to obtain using only one perspective or reality.

5.4 Future Work

Some of the technology available at the end of the project was not or hardly available at its start. Examples include the flip-up display, eye tracking, optical pass-through, hand tracking, and inside-out tracking. This demonstrates the speed of developments in this research area. In this section I would like to mention several subjects or areas that I think could be interesting for future research. It starts with my specific implementation of the research environment but will gradually increase in scope.

The research environment from this project can be used as inspiration or starting point for future collaboration systems. It would be useful to verify if the location-sharing- and teammate-awareness features improve collaboration efficiency and effectiveness, rather than merely indicating that this is possible. I would also suggest investigating to what extend teammate awareness is required for SCIC or if more focus should be on task- and/or situational awareness.

Next versions of the research environment and ISS could include a world map for P_{VR}, possibly increasing P_{VR}'s situational awareness, and/or a way of digitally marking targets in the environment, possibly increasing task-awareness. The latter could be implemented such that the number of targets already found is digitally displayed for the participants. Both features were considered in this project but omitted due to time restrictions and both were mentioned by participants of the experiment as welcome additions. For a further overview of environment components that could be interesting to work with or to elaborate upon, see Appendix 1.

The collaboration problems that I found in related work and that appeared in the experiment should be validated with more users to see if they consistently occur during SCIC and are therefore the right problems to solve. Strategies that were proposed to mitigate or prevent these problems should also be further examined to validate their utility. For future interreality collaboration experiments, I would recommend a longer duration in which participants are better trained for the task and/or each other to more accurately simulate what happens when professionals use this form of collaboration.

This research project specifically focuses on collaboration between reality and virtual reality. But it could just as well be interesting to investigate *reality-augmented reality* collaboration, or *augmented reality-virtual reality* collaboration. Furthermore, *asynchronized* or *dispersed* interreality collaboration could also bring about very interesting collaboration concepts that must not be forgotten.

Finally, just as mixed-presence groupware blurs the boundaries between co-located and dispersed collaboration, future collaboration systems could allow for both synchronous and asynchronous collaboration. Perhaps the next generation HMDs will even include hardware or software features that (further) blur the line between realities and thus make it even more important and prevailing to investigate interreality collaboration.

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Appendix 1: Building Interreality Environments

These tips and personal preferences are for people interested in building an environment for interreality collaboration. They are based on an early version of Unity 2019.2. At the end I have included a visual overview of the code I used in the interreality research environment.

Selecting a game engine

Developing a VE usually requires a game engine. As the user needs to feel presence in the VE, we will use VR technology and thus need a 3D game engine which supports it. There are several options:

1. Unreal Engine (UE) is known for its graphics but can become hard to work with on your own. The Blueprint editor lets users create gameplay without requiring too much coding skills. It started out as meant for AA games but has become more accesible for smaller teams.
2. Unity is known to work well for independent developers. It has fewer power requirements than UE but makes it harder to get the graphics right. It requires some C# coding skills and while originally meant for independent developers, it has added more professional features.
3. Godot is an open-source game engine. It makes it easier for teams to collaborate on projects by saving all game resources to the file system which is useful for version control.

From these 3D game engines I only had experience with Unity. Because I did not have time to learn another game engine and also because it seemed like a good fit, I chose Unity.

Performance

When performance becomes an issue, it is useful to select specific models that use the Level of Detail (LOD) technique. Models that use this technique reduce the number of triangles that are rendered as the distance from the camera increases. This means that in practice, hardware load is often reduced and rendering performance will increase.

The buildings I used at the start of this project were from an air base that TNO already possessed. I replaced them with models that I took out of a free asset pack called *Windridge City*. They were built by the Nature Manufacture team in cooperation with Unity and include multiple nice assets (with LOD functionality).

Apparently, looking in the HMD (at this point I used the Oculus Rift which enables/disabled the screen based on a sensor in the HMD) while also having two editor windows open causes a lot of lag. Turning off one of the editor windows fixes this mostly, but I still temporarily replaced the water shader with a solid blue. I also tried to lower the refresh rate of the secondary (map) display, but the window did not follow this refresh rate setting.

Unity provides some nice tips on obtaining the best performance[7], but watch out with mono rendering modes, as these will render the image only from one eye instead of two, removing the depth effect that we try to achieve for our system in the first place (the theory that VR >

[7] https://learn.unity.com/tutorial/vr-best-practice#5c7f8528edbc2a002053b450

one screen is then less applicable). Static batching and decreasing lightmap settings (e.g. resolution and map size) can help with performance as well!

Interreality Functionality

Unity does not support both HMD and non-HMD displays simultaneously, so some glitches and bugs can be expected. For example, you will get a warning that wants you to disable the UI as you would normally not see this UI in the HMD, but if you are both showing a HMD display and a non-HMD display, you would want to show the UI in the latter.

The positional tracking was disabled in this project to prevent the HMD-user from moving into the drone. A setting can be found which disables only the positional tracking but keeps rotational tracking, but in my case this setting was ignored by Unity. Disabling positional tracking with code did work, use the line:

```
UnityEngine.XR.InputTracking.disablePositionalTracking = true;
```

Make sure the target eye of the cameras is correct as otherwise all screens will follow the VR headset's movement. Use the Unity SDK manager, this will give you options to have multiple SDKs (Oculus, SteamVR etc.) enabled correctly after which device is connected.

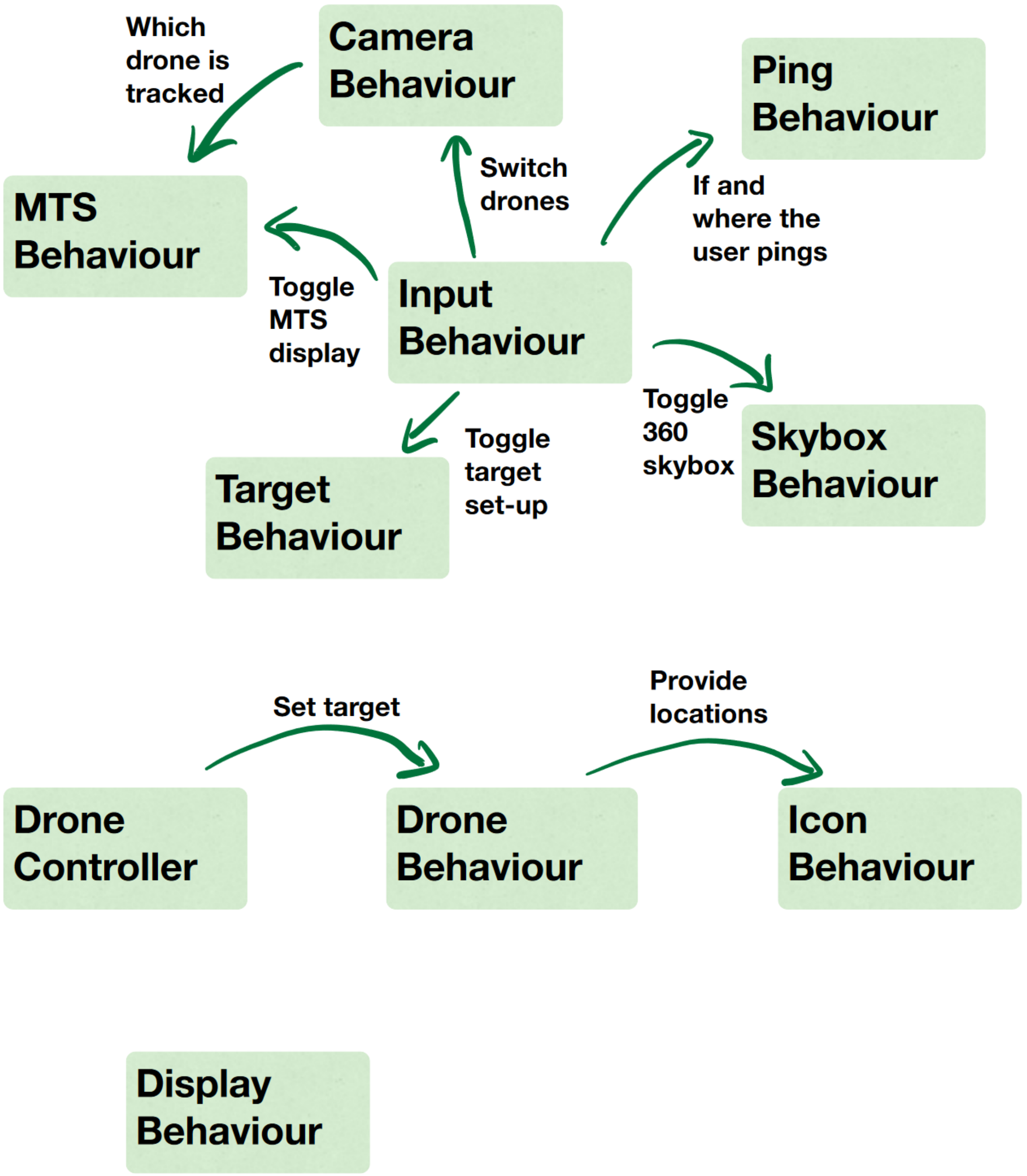
Multiple Monitors

The first Unity display is always enabled, but you have to enable each additional monitor manually (by code). There are multiple issues with Unity and multiple monitors. For example, if you set the primary monitor to full screen or windowed mode, all other monitors will automatically adjust to that resolution.

Unity also does not track the correct mouse position over multiple displays and when you want to create this functionality, you have to build a separate part for when working with the editor and when playing a compiled version of your application. RelativeMouseAt can be used to query relative mouse input coordinates and the screen in which Mouse Input is recorded. This is **only valid on the Windows Desktop platforms** with Multiple Displays. x, y returns the coordinates in relative space and z returns the screen in which Mouse Input is handled. The z coordinate is only available in a build, not in the editor, so a custom function was used to test this in the editing phase. The clicking accuracy can also be a problem, so make sure both monitors have the same height and width.

Code

This overview shows how different scripts are connected. The green boxes indicate scripts and arrows indicate information being sent between two scripts. The MTS stands for Multiteam System and was used for another project which visually shows the drone that is currently being tracked.



Appendix 2: Participant Information

The next section (between double quotation marks) is an exact copy of the document that participants obtained at the start of the experiment.

"Technical developments can change the way people collaborate with each other. Especially immersive technologies such as mixed- and virtual reality offer new possibilities for collaboration. But those possibilities generate complications as well. For example, how do I look someone in the eyes if that person is wearing a virtual reality headset? How do I know if that person heard what I was saying or if he has time to respond to me at all?

The Experiment

I'm investigating how two people can work together while one is experiencing a virtual reality. Two people will work together in this experiment. One is wearing a virtual reality headset in which (s)he can see a virtual world through a 360° camera suspended beneath a drone (we will call this person P_{VR}). The other person is viewing a live, interactive map that shows the top-down perspective of the virtual world on a two-dimensional screen (we will call this person P_{map}).

The Scenario

*The virtual world consists of an ocean, a ship, several **autonomous** drones and a coastal city. The drones will fly from the ship to the city and then spread out and circle a building of interest. Around this building will be multiple targets (red characters). It is the job of P_{VR} to spot these targets and provide P_{map} with information on their locations. P_{map} then has to write down these locations on the paper map in front of him/her. Sporadically, the experiment leader will provide P_{map} with a piece of **intelligence** written on a note. You also have several tools at your disposal to help you with the task of **finding all the targets as fast and accurate as possible**.*

The Tools

*Both players can place a **marker** on a location of interest. P_{VR} can do this by pointing the headset crosshairs to a location and pressing the trigger on the controller. P_{map} can do this by clicking a location on the map. These markers are visible for both players.*

P_{VR} can switch to the next or previous drone by using the right and left buttons on the controller. Both players can see which drone P_{VR} is currently looking through and towards what direction (s)he is looking.

*P_{map} can see the **live perspective** of P_{VR} on a secondary computer screen. P_{VR} can see from the perspective of the 360° camera that is projected in the sky of the virtual world.*

Don't worry if it sounds complicated right now; we will start off in a training scenario where you can get to know the tools and explore them!

Good luck!"

Appendix 3: Experiment Questions and Answers

Four teams of two participants played through three rounds of the scenario (except for one team that played through two rounds) and were asked questions after each round and at the end of the experiment. This appendix shows the answers to these questions. The questions and answers were originally discussed in Dutch. Below I have translated these in English using first Google Translate and then briefly refined them by hand.

Answers are provided per team with the rounds concatenated; sentences like 'it went better' can thus refer to earlier rounds. Some questions are split up into two sections that refer to the direction of communication (from P_{VR} to P_{map} or the other way around). Below the answers per team are my interpretations.

Questions after each round

How did you think the collaboration went?

1. Team 1: Good in itself. The problem is that P_{VR} already saw a lot and wanted to pass on the targets too quickly. Difficult if you see everything for yourself not to be able to say. [It goes] still good. You know better how it works. P_{map} asked earlier if someone was standing on the building or land, that is quite crucial. P_{map}: I don't see if a doll is on a building or next to it, because of 2d instead of 3d (for P_{VR}). According to P_{VR}, P_{map} gave more suggestions because we were looking pretty fast.
2. Team 2: P_{VR}: it took some getting used to. P_{map}: we were not clear what the tasks are. Are you going to direct me or you for example. P_{map}: I thought you were going to direct me, but I could probably take over because I have the overview. Both thought it went much better. Collaboration began because we both moved more into each other and started to say more. P_{map} was able to conclude more quickly whether or not a hint is relevant. P_{VR} is now often switched drone while in previous rounds not.
3. Team 3: P_{map}: pretty good, pretty difficult what the search area was. P_{VR}: you (P_{map}) had the overview so it is better to point out where you have looked or not. P_{map} found both screens to be chill but would have preferred to tick on one screen.
4. Team 4: P_{VR}: fine, maybe I should have said a little more at the start. Nice that P_{map} could also click on something.

It seems that P_{VR} was often really immersed. P_{VR} was sometimes too quick for P_{map} and often forgot about the existence of the 360-camera function. There was not always a clear role distinction on who is directing who.

Participants started the experiment being relatively quiet compared to later moments in which they started talking more. It seemed that over the course of several rounds, participants learned the advantages and limitations of other perspective based on the speed of finding the targets and the decrease in communication frequency. Participants also improved in determining hint relevance and as time progressed, switched more between drones.

What problems have you encountered?

1. Team 1: Awkward that the drones remained in this area. Not once did I switch to that view where P_{VR} could see P_{map} (don't know exactly why, maybe next run). Maybe that is extra information that I missed. P_{map} sometimes looked at the P_{VR} screen to see if he had seen it. Sometimes as a P_{VR} you can see something in the corners of your

eyes while it was not visible on the image. 360-camera did not switch on at a given time, did not stand in the way of cooperation. Switching between drones was quite difficult (did not understand the circle completely). That's why I didn't switch very much (P_{VR}). Because you circle you can afford to stay on one drone.

2. Team 2: P_{VR} did not know the previous arrows disappeared. P_{map} did not know exactly where the targets would be now and sometimes finds the hints distracting. P_{map}: if we do this three times we would get used to it much better. Nothing different from the previous round. P_{map}: P_{VR} went through quite quickly.
3. Team 3: P_{map} thought the biggest problem was that the mapping from live folder to paper folder did not go well. Because you have to overwrite. P_{VR} found the camera too distracting so could not watch well with P_{map}, P_{VR} would also like to see such a card. Maybe images for P_{map} at the same time.
4. Team 4: P_{VR} sometimes found it difficult to indicate which location is something. P_{map} is dependent on P_{VR} because it only sees the top.

P_{VR} almost never switched to the 360-camera view. When asked about this, participants did not have a specific reason. The 360-camera also stops working after a certain amount of time of not using it. This meant the experiment leader had to step in and turn it on during a few occasions. Some participants found the 360 view too distracting.

Some participants did not understand that the drones flew in a circle, which is why (according to them) they did not switch drones often. But precisely because they flew in a circle, it was not necessary to switch.

Sometimes, P_{VR} went over targets too quick for P_{map} to write them all down. Sometimes P_{VR} could see something in his/her peripherals which P_{map} could not see on the secondary screen. P_{map} is dependent on P_{VR} as P_{VR} mostly sees the top-down view (when not looking at the secondary monitor). One participant with the P_{VR} role found it hard to share at what location something was. One participant found the biggest problem writing the targets down on paper after seeing them on the screen. Several participants mention that P_{VR} could use a minimap too.

One participant did not understand that previous arrows disappeared. Some participants found the hints distracting (this was on purpose). Some participants did not know what to expect on the locations of targets.

Have you used a strategy to perform the task? If yes which one?

1. Team 1: Not in the beginning, start a bit of searching. P_{map}: you could also ask me which drone is useful, as I can see that too. P_{map} hoped to be able to see through the camera what was ticked on the paper. P_{VR} has the idea of not needing the camera image. P_{map} noticed that she was watching less on the viewing screen (also because P_{VR} described more according to P_{map}). P_{VR}: I can only sit in the room that contains P_{map}, but I'd rather see P_{map}'s screen.
2. Team 2: No, zero. P_{VR}: my strategy was click on the figures. Meanwhile, P_{map} started thinking about strategies. P_{map}: shall we devise a strategy while we are still in the

water? What is useful? P_{VR}: maybe I will indicate if I click on such a thing. P_{map}: it's better to go back to drone 3. P_{map}: I didn't realize it was useful before. P_{map}: if I put an arrow, it will turn green and I will tell you what is happening.

3. Team 3: P_{VR}: too little, I think that's the problem. P_{map} found it difficult to find out exactly what the task was and what exactly the info was, for example search area. P_{VR} did not know what happened to the drones. P_{map} first thought we were going to do the whole city. P_{map} noted which side of buildings P_{VR} had not yet seen. P_{VR}: we talk a lot more. P_{map}: building by building works but you get distracted from it (because you see other targets). P_{map}: maybe you can do the best building per building if the drones are already flying around. P_{VR}: you already know which buildings you are not going to see so you know what you can and cannot see. We skip that hard to see quadrant and only do north east and south. You couldn't see the southern side of some buildings at the beginning, so they skipped at the beginning. You can estimate a little where they should be and how it all works.
4. Team 4: P_{VR} assumed that she had to write down as much as possible. That was my strategy. P_{map} started thinking about which buildings. P_{map} had a better idea where it could be and so had the feeling that the person could think along more. P_{VR} knew more about how things work, so I know better where to look.

Before the first targets were visible, most participants did not discuss a strategy and according to the participants, during most of the first round they did not use a strategy. P_{map} sometimes started telling P_{VR} what drone could be advantageous to follow or telling P_{map} that he/she could ask P_{VR} if this information was necessary.

Multiple participants started thinking about strategies right before or at the start of Round 2. One participant mentioned "shall we come up with a strategy while we're still in the water?". They then started discussing communication strategies such as sharing more information on a location when sharing one.

One P_{map} started marking which sides of buildings were not yet observed by P_{VR} to come back to later. The same dyad briefly used a building-by-building swipe at the start of the round but then stopped because other targets were already clearly visible and distracting them. They then decided to come back to this strategy once the drones were flying in a circle and the first targets were already spotted. They also knew at this point which sides of the buildings and map were going to be visible later on and which were not and adapted their strategy accordingly.

P_{VR} in one occasion hoped to see what targets were already cross off on the paper map by using the 360-camera. This did not work. One participant mentioned that P_{VR} could see the room that P_{map} was in but that P_{VR} would much rather see the screen of P_{map}. P_{map} sometimes started thinking with P_{VR} to see which buildings were likely to contain a target. P_{map} sometimes looked at P_{VR}'s screen to check if P_{VR} has noticed something.

One P_{VR} started by considering writing down as much as possible but quickly abandoned this idea.

Did this strategy change during the round?

1. Team 1: At a certain point they went everything. Gradually, some techniques emerged. P_{map} asked more specifically for the ground building. P_{VR} planned to look at the map but did not succeed. P_{map} doubts whether that helps. P_{VR}: I want to know which you have marked and that I see it on the map. P_{map}: I intended to hold the paper folder in front of the screen for comparison. P_{VR} wanted to know which ones are checked. P_{VR}: perhaps on a mini map in VR display. P_{map} said at a given moment: "I don't have any targets for this building yet". P_{map} looked more globally than watching the screen. If P_{VR} searches for a next target, there is a moment for P_{map} to write it down.
2. Team 2: P_{map} occasionally tried to say that you had already had a building. P_{map} says that it might be a good idea that P_{VR} itself designates a target so that I don't have to do that too.
3. Team 3: At a certain point P_{VR} realized everything better. P_{map} proposes a building-by-building swipe. Check off which blind spots have not yet been.
4. Team 4: -

Several teams started using a building-by-building strategy in later rounds. One P_{map} planned on holding the paper map in front of the map screen to see if something has already been marked. One P_{map} at some point mentioned that one building did not yet have any targets, hinting that there might be an even spread that they could consider when finding remaining targets.

Most P_{map} wrote down the targets on the paper map while P_{VR} was already looking for the next target. Some P_{VR}'s placed markers approximately, causing P_{map} to have to look at the secondary monitor to see where exactly the target was and causing delay. One P_{map} told P_{VR} to more accurately place markers so P_{map} could copy their locations onto the map faster.

There was a seemingly high learning rate between and within rounds. P_{map} slowly started to give more and more suggestions on potential locations to P_{VR}, probably because P_{map} has the overview and can see target patterns more clearly.

One strategy that a lot of participants used but none mentioned was that P_{map}, when receiving a hint, first let P_{VR} finish in describing a target before reading out the hint.

How did the exchange of information about targets go?

Participants liked the information sharing feature but considered it useful that they could talk as well.

$P_{VR} \rightarrow P_{map}$

1. Team 1: Difficult to decipher which building it was, resemble each other. Feeling from north south was difficult.
2. Team 2: -
3. Team 3: P_{map} wants P_{VR} to get a compass in the virtual world too.

4. Team 4: Arrows were useful. Thanks for talking.

Most P_{VR} participants immediately got how to send a location by aiming at something with their crosshairs and then pressing the trigger on the controller. One participant did not get this from the start and first attempted to move the controller itself. In asking about this, the participant said to have never really played any videogames and therefore did not understand the crosshairs.

Some P_{VR} participants did not know what direction north was and asked P_{map} after which most P_{map} participants placed an arrow in the north side of the map. One P_{map} participant did not see the compass on the screen.

$P_{map} \rightarrow P_{VR}$

1. Team 1: P_{map} sometimes watched. Tells that it is possible to copy directly from the live map so that P_{VR} can put the arrow exactly on it. Try to pass direction by placing an arrow in the north.
2. Team 2: It was quite difficult for the other person to pinpoint exactly where such a target is. Was not really necessary to put an arrow for me.
3. Team 3: P_{map} already knew where P_{VR} was because they agreed on buildings. Then P_{map} could see quickly.
4. Team 4: -

P_{map} participants did not often use the location sharing feature. In some teams P_{map} did share what direction north was through an arrow. P_{map} sometimes asked P_{VR} to place arrow with more accuracy so he/she could note the location quicker.

Did you know enough about what your teammate was doing?

$P_{VR} \rightarrow P_{map}$

1. Team 1: -
2. Team 2: Semi: I knew but not exactly what P_{map} was shown. I did not know exactly what information you had and how well you could see this. I often do, not really. We were also talking quite a lot.
3. Team 3: Me too because I always asked if you had this and I knew that P_{map} was watching.
4. Team 4: I sometimes asked if you already had this because I was going too fast.

Participants had trouble with this question. One P_{VR} said to not always understand what P_{map} saw, even though this was shown at the start. "I often knew, actually, not really." While time progressed P_{VR} started to understand that he/she sometimes needs to slow down. It seemed as if P_{VR} got better and better at understanding what tempo works well.

I have not noticed one situation in which P_{VR} used the 360-camera view to see if P_{map} was busy or not. There were several occasions in which P_{map} said to P_{VR} to hold on for a bit or to repeat a target location because P_{map} was busy with something else. It seemed that teams did not have much communication problems despite P_{VR} not visually observing what P_{map} was doing.

$P_{map} \rightarrow P_{VR}$

1. Team 1: -
2. Team 2: I think I have a better idea of what is happening in the situation. I could see where P_{VR} was and I assumed that P_{VR} was going to find dolls.
3. Team 3: I do because P_{VR} was always busy with a building.
4. Team 4: -

Not one P_{map} participant expressed a problem with a lack of awareness of his/her teammate. This may be because P_{map} could always look at the screen of P_{VR} and because P_{VR} had a single, clear task.

What did you think of the location-sharing function? Did you use this?

1. Team 1: -
2. Team 2: P_{map}: I didn't know I could put an arrow, I forgot. P_{map}, I didn't really put an arrow, but that is mainly because P_{VR} immediately saw a new one all the time.
3. Team 3: P_{VR}: for me it was very handy, nice that you could see where I put them. P_{map}: you always get an approximate [approximate] location, that arrow can be on it or in front of it, I would like to have a zoom in function or, on the contrary, that the map is a bit 3d.
4. Team 4: P_{map} also sometimes used it for confirmation.

All participants expressed that they liked the location-sharing feature from P_{VR} to P_{map}. In some rounds, P_{map} forgot that he/she could also share a location to P_{VR}. A few times, P_{map} used this function to confirm a location or direction mentioned or approximately pointed at by P_{VR}.

What did you think of the teammate observation function? Did you use this?

1. Team 1: -
2. Team 2: P_{map}: I watch P_{VR} a lot. P_{VR}: I don't look with you (P_{map}), I can try, sometimes it can be useful. P_{map}: I don't know if that is useful for you i.v.m. fierce world. P_{VR}: Did not use the camera, I was not at all concerned with what P_{map} was doing, only finding targets.
3. Team 3: P_{map} thought it was perfect, P_{VR} had not used it at all, did not find it very useful in this scenario and a little distracting. P_{VR} didn't think it was necessary either. P_{VR} didn't need it because it might take you a bit out of your immersion.
4. Team 4: P_{VR}: I hadn't really thought that it was possible, I was too busy with the targets. P_{map} was watching a lot, moved the folder to at the keyboard so she could see all three at the same time.

Participants seemed to like the teammate-observation function from P_{VR} to P_{map}, i.e. the secondary monitor showing what P_{VR} is looking at. They used it a lot, but it seemed that some participants used it less in later rounds. One P_{VR} said that it is P_{map}'s responsibility to keep following P_{VR}.

The teammate-observation function from P_{map} to P_{VR} was almost never used and when asking participants about it, most said they forgot about it during the round. Some participants called it distracting and one P_{map} mentioned that it might be too distracting for P_{VR} as P_{VR}'s task and world is already intense. One P_{VR} said that they just wanted to see what is happening on the screen of P_{map} instead of in the room that P_{map} is in.

Questions at the end

How would you solve or reduce the recurring problems?

1. Team 1: Both players would like to mark it on the live map. P_{map} wanted to mark it on it. P_{map} may want the image to be in the corner of the map screen so that she felt a bit like where P_{VR} is looking. Perhaps add a line of sight that P_{map} knows the field of view of P_{VR}. Then P_{map} will see if P_{VR} had seen it sooner.
2. Team 2: P_{map}: there are many different options here, maybe too many, so you don't know exactly what works best. We can both watch together, so you hardly know what to choose. P_{VR}: You do not use all techniques, but others may benefit from it. P_{VR} would especially recommend training. You have already noticed three times that it went best the third time.
3. Team 3: P_{map} would like to have both screens side by side. Paper wants P_{map} to be digitally mapped so that it can be digitally signed. Also so that P_{VR} can see them because P_{VR} cannot see what has or has not been, I had to remember that. P_{map} proposes a minimap in the view of P_{VR} so that the person can see it. P_{VR} proposes a touchscreen for P_{map}.
4. Team 4: P_{VR}: I sometimes found communication difficult. You grow in that you notice what the other sees. P_{map} found it less difficult because she could watch P_{VR}. P_{VR}: it might be handy that I can place permanent crosses and P_{map} too so that this is easier. P_{map}: that you can click on the dolls and give them a color so that you can see which you have had and can discuss.

[In this question most participants drifted off from evaluating communication problems to evaluating this specific experiment set-up with the ISS toolkit even though I explained several times that I am more interested in evaluating collaboration problems and methods.]

Most participants wanted P_{VR} to also have a map like P_{map}. Some mentioned that this was important as P_{VR} could not see which targets had already been marked [on the paper map]. Most participants who said that P_{VR} should also have a (live) map also mentioned that they would like P_{map} (or both participants) to directly mark targets on the live map. One participant mentioned that this marking could be done in different colors so they can be used as reference points for discussion later on.

One P_{map} wanted to see the P_{VR} perspective in the corner of the map screen instead of on a secondary monitor. This same participant also mentioned that he/she would like viewing lines on the map display to see what P_{VR} could and could not see. Another participant suggested a touch screen for P_{map}.

Most participants mentioned that they performed best in the third round and that they thought training was an important aspect of working well in this scenario.

One participant mentioned that there are multiple methods of executing this task and that this can cause participants to not know exactly what works the best [this is not a problem, the point was not to test what works best after participants trained for a while].

Do you have any final comments?

1. Team 1: P_{VR}: I just want to see what happens on the screen and not what happens in the room. In the defense context you have so many work agreements (from the line = checkout) so the camera about what is happening in space is less important. Perhaps distracts earlier. P_{VR}: it is your responsibility (P_{map}) that you continue to follow me. P_{map} started by finishing the target before reading the hint. You resolve it fairly quickly through your verbal communication. Also depends on the type of task you perform. P_{VR}: if I put a marker, in principle I don't have an extra person. In the meantime, P_{map} could also do something else. P_{VR}: if I didn't have the controller I would be much more dependent on P_{map}. P_{VR}: if I cannot click the target myself, I am much more dependent on P_{map} and I have to look a lot more.
2. Team 2: I really enjoyed it.
3. Team 3: If you know each other a little bit and how you normally talk to each other and how you both know how that person works, it is nice. That you can respond to each other. Even more important in such an interreality team because you have fewer cues from each other. Learn to use explicit communication and your tools. P_{map} says that he said something about a location while he could click, of course, he forgot. P_{map} also wanted to have a missile.
4. Team 4: P_{map} did not know if the shadows matched the perspectives. I also did not know what the western quadrant was. P_{map} had not seen the compass.

Several participants mentioned that dependent on the task, small inconsistencies and disputes are usually quickly solved using verbal communication.

One team [with experience in defense projects] mentioned that in defense contexts, people often have communication agreements that can be very useful for these situations. One team mentioned that it was nice to know each other as they “knew how the other person normally talks and works.” They said it was especially important in an interreality team because there are fewer social cues.

One participant mentioned that if P_{VR} would not have a controller or could not share locations, P_{VR} would be way more dependent on P_{map}.

Most participants really liked the scenario. Some expressed that they wanted to beat the scores of last round. Even when time set for the experiment ran out, people were willing to do another round.

One participant’s biggest wish was that the drones should be able to fire missiles.

Appendix 4: Experiment Issues and Notes

Practical issues during the experiment

Some practical issues occurred during the experiment:

- The Vive controller turns itself off after a couple minutes of not using it. This had to be kept in mind between rounds but did not form an issue.
- The 360-camera also turns itself off after a couple minutes of not using it. This caused some participants that wanted to try this function at the end of a round to not be able to turn it on. This only happened at the end of two rounds and was according to the participants not a hindrance in finding the targets.
- At one point, the scenario stopped working right after turning it on. The computer had to be restarted eventually to fix this problem.

Notes during the experiment

1. Team 1: I handed out hint 1 too late (approximately after two minutes instead of one). Unclear what the embassy was. Target 1 written down too late (corrected later).
2. Team 2: P_{VR} did not know at first that the previous arrows disappeared. In the meantime, people often like to discuss strategy for a while.
3. Team 3: Vive did not respond anymore, then try to restart, then PC did not work anymore, hard reset, then SteamVR did not work anymore, had to be reinstalled, I had to have the password for that. This took a while but I was able to solve it fairly quickly (this could have been problematic). People are often more motivated in the second round, also to be better (game element?). At a certain point, P_{map} found out that targets were very lightly visible on the 2D map as red pixels, but he decided not to look any further at this (was only visible if you held your head right in front of the screen).
4. Team 4: They said they had not understood the intersection hint (that it had already been found and was therefore no longer relevant). P_{VR} did not understand that the arrows came where you looked through the crosshairs. I assumed that people did understand this, via films, games or stories, but apparently this is not entirely true.

Appendix 5: Experiment Target Times

These results show per team, per round, at which time each sequential target was found. A dash indicates that that target was not found within the available time.

Team 1

Round 1

1	01:10	**6**	02:33
2	01:32	**7**	02:45
3	01:40	**8**	03:02
4	01:58	**9**	04:27
5	02:16	**10**	-

Round 2

1	00:57	**6**	01:36
2	01:02	**7**	01:40
3	01:10	**8**	02:06
4	01:17	**9**	02:10
5	01:23	**10**	04:16

Round 3

1	01:00	**6**	01:39
2	01:07	**7**	01:58
3	01:18	**8**	02:10
4	01:30	**9**	02:38
5	01:35	**10**	04:14

Team 2

Round 1

1	01:38	**6**	04:00
2	01:50	**7**	-
3	02:20	**8**	-
4	02:50	**9**	-
5	03:08	**10**	-

Round 2

1	01:35	**6**	03:07
2	01:53	**7**	04:02
3	02:05	**8**	-
4	02:23	**9**	-
5	02:35	**10**	-

Round 3

1	01:15	**6**	02:32
2	01:28	**7**	03:14
3	01:43	**8**	03:47
4	02:00	**9**	04:00
5	02:16	**10**	04:25

Team 3

Round 1

1	01:23	**6**	02:07
2	01:29	**7**	02:25
3	01:34	**8**	03:04
4	01:46	**9**	04:17
5	01:55	**10**	-

Round 2

1	00:54	**6**	02:15
2	01:22	**7**	02:26
3	01:30	**8**	02:35
4	01:57	**9**	02:50
5	02:10	**10**	03:18

Round 3

1	01:13	**6**	01:50
2	01:19	**7**	01:58
3	01:34	**8**	02:32
4	01:40	**9**	04:10
5	01:45	**10**	04:24

Team 4

Round 1

1	01:25	**6**	02:55
2	01:35	**7**	03:35
3	01:56	**8**	04:35
4	02:05	**9**	05:00
5	02:36	**10**	-

Round 2

1	01:10	**6**	02:08
2	01:15	**7**	02:32
3	01:22	**8**	03:10
4	01:28	**9**	03:56
5	01:57	**10**	04:06